DEVELOPMENT OF A RISK-HEDGING CO_2-EMISSION POLICY, PART II: RISKS ASSOCIATED WITH MEASURES TO LIMIT EMISSIONS, SYNTHESIS, AND CONCLUSIONS

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Abstract. This paper is Part II of a two-part series in which the risks associated with unrestrained greenhouse-gas emissions, and with measures to limit emissions, are reviewed. A sustained limitation of global CO_2 emissions requires global population stabilization, a reduction in per capita emissions in the developed world, and a limitation of the increase in per capita emissions in the developing world. Reducing or limiting per capita emissions requires a major effort to improve the efficiency with which energy is transformed and used; urban development which minimizes the need for the private automobile and facilitates district heating, cooling, and cogeneration systems; and accelerated development of renewable energy. The following risks associated with these efforts to limit CO_2 emissions are reviewed here: (i) resources might be diverted from other urgent needs; (ii) economic growth might be reduced; (iii) reduction measures might cost more than expected; (iv) early action might cost more than later action; (v) reduction measures might have undesired side effects; (vi) reduction measures might require heavy-handed government intervention; and (vii) reduction measures might not work. With gradual implementation of a diversified portfolio of measures, these risks can be greatly reduced. Net risk is further reduced by the fact that a number of non-climatic benefits would result from measures to limit CO_2 emissions. Based on the review of risks associated with measures to limit emissions here, and the review of the risks associated with unrestrained emissions presented in Part I, it is concluded that a reasonable near-term (20–30 year) risk hedging strategy is one which seeks to stabilize global fossil CO_2 emissions at the present (early 1990's) level. This in turn implies an emission reduction of 26% for industrialized countries as a whole and 40–50% for Canada and the USA if developing country emissions are to increase by no more than 60%, which in itself would require major assistance from the industrialized countries. The effectiveness of global CO_2-emission stabilization in slowing down the buildup of atmospheric CO_2 is enhanced by the fact that the airborne fraction (ratio of annual atmospheric CO_2 increase to total annual anthropogenic emissions) decreases if emissions are stabilized, whereas it increases if emissions continue to grow exponentially. The framework and conclusions presented here are critically compared with so-called optimization frameworks.

1. Introduction

This is the second of a two-part series in which the risks associated with CO_2-emission policy are reviewed. These risks consist of the risks associated with unrestrained emissions of greenhouse gases (GHG's), which are reviewed in Part I (Harvey, 1996), and the risks associated with measures to limit emissions, which are reviewed here. The review presented in Part I indicates that the climate is very likely to respond significantly to a CO_2 doubling (greater than 1.5 °C global mean warming in equilibrium) and, with the prospect of GHG concentrations eventually

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far exceeding the equivalent of a CO_2 doubling and swamping the effect of other natural and anthropogenic causes of climatic change, significant warming during the coming century is a near certainty for business-as-usual scenarios (and most likely under aggressive emission-reduction scenarios as well, although to a much smaller extent). Projected climatic change would have far-reaching effects on global agriculture, ecosystems, and human welfare. Although limited global warming (i.e. that associated with a CO_2 doubling) could have very small or positive effects on agriculture in aggregate (although not without significant negative effects in some regions), there are a number of compelling reasons for expecting the likelihood of negative impacts to increase sharply if climate continues to warm beyond the doubled CO_2 level, as reviewed in Part I.

Assessment of risks associated with measures to restrain GHG emissions requires consideration of the various emission-reduction options, and the hazards associated with alterations to the status quo in order to achieve emission levels that would not otherwise occur. In this paper, the options available to reduce CO_2 emissions associated with the use of energy are briefly reviewed, followed by a discussion of risks associated with efforts to implement these options. Assessment of the net risk associated with emission-reduction measures requires taking into account known or possible non-climatic benefits associated with these measures, as well as down-side risks. Attention is restricted here largely to CO_2 because it will be the single largest contributor to future increases in heating due to GHG's, because of the long atmospheric lifespan of CO_2 relative to other GHG's (see Harvey, 1993a, for a discussion of issues related to differing atmospheric lifespans), because emissions of CH_4 (the next most important GHG) and the buildup of tropospheric ozone (another GHG) can be reduced as a by-product of some of the measures needed to reduce energy-related CO_2 emissions, and because the extra growth of CO_2 emissions that can be bought by increasingly stringent controls on CH_4 is limited and subject to diminishing returns (Grubb et al., 1991a).

A rational global strategy with respect to GHG emissions will seek to minimize the sum of the risk of negative impacts due to climatic change associated with a given level of emissions, and the risk associated with the process of achieving that emission level. However, as discussed in Part I, the assessment of risk depends on the state of knowledge at the time of the assessment, and as knowledge changes, the risk minimizing emissions trajectory will also change. The preferred strategy is therefore a risk-hedging strategy – a strategy which adopts the likely minimum required constraint on emissions associated with any present or future risk minimizing trajectory while creating the conditions which will facilitate tougher constraints in the future, should this be required to minimize revised assessments of risks.

The risks which must be compared in the development of a risk-hedging strategy are fundamentally different in nature, and policy decisions must ultimately rest on subjective judgement. Based on the reviews presented here and in Part I, it will be argued here that a reasonable interim (20–30 year) risk-hedging strategy is one which seeks to stabilize global emissions of carbon dioxide. A slightly more stringent target than stabilization of total emissions is to stabilize global fossil fuel emissions and reduce net land use emissions to zero over a period of 1–2 decades. Given the need for international equity and the current disparities between developed and developing nations, either target implies substantial fossil fuel emission reductions for industrialized countries. Climate and carbon-cycle models are used here to compare the effect on climate of emission stabilization compared to typical business-as-usual scenarios as well as more stringent emission strategies.

2. Risks Associated with Actions to Limit CO_2 Emissions

In this section a set of risks associated with measures to reduce energy-related CO_2 emissions is compiled and the likelihood of those risks being realized is assessed. In order to compile a set of risks for discussion, the measures that would be taken to limit CO_2 emissions must first be identified.

2.1. MEASURES TO LIMIT ENERGY-RELATED CO_2 EMISSIONS

Since population growth rates are small to zero in most of the developed world but per capita emissions of CO_2 are large, whereas per capita emissions are small but population and population growth rates are large in the developing world, the most important strategies required for a sustained limitation of global CO_2 emission are a reduction in the per capita emissions in the developed world, and population stabilization in the developing world (and those parts of the developed world where not yet achieved) combined with limited increases in per capita CO_2 emissions. Per capita emissions can be limited or reduced through improvements in end-use energy efficiency and in the efficiency of electricity generation, by switching from carbon-intensive fossil fuels (such as coal) to natural gas, through increased use of non-carbon based energy sources, and through an orientation of new urban development toward compact urban form in which distances that need to be travelled are minimized and public transit, cycling, or walking are viable alternatives to the private automobile.

Although expenditures to limit population growth have been cast as being in competition with expenditures to limit CO_2 emissions (i.e. Schelling, 1991), eventual stabilization of global population is clearly a prerequisite for long-term limitation of GHG emissions. Nevertheless, limitation of population growth is almost completely ignored in discussions of GHG emission limitation (see, for example, Mendoza et al. (1992), who make no mention of family-planning programmes in their discussion of policy options to limit Mexico's long-term CO_2 emissions). Bongaarts (1994) discusses policy options for limiting population growth in the developing world. These options include reducing the demand for large families through investments which reduce child mortality, improve the educational level and status of women, and provide old-age security; reducing the momentum of population growth by increasing the average age of women at child bearing (by facilitating a longer time for women in school) and increasing the interval between births; and by reducing unwanted pregnancies through strengthened family-planning programmes. Even under current conditions, one in four births in the developing world outside China is unwanted (Bongaarts, 1990); if the demand for large families is reduced and the desired interval between births increased, the need for better contraceptive services will be even larger. Hence, an effective response to the problem of population growth in the developing world requires both immediate investments in improved family-planning programmes and long-term emphasis on development focused on meeting basic human needs (health, education, sanitation, old-age security). If other CO_2 limitation measures impede this kind of economic development in the third world, these could very well have counter-productive effects in the long run. The key, then, is to achieve economic development and population stabilization in a manner which minimizes the near-term increase in CO_2 emissions from developing countries.

For a given GNP (and associated population) scenario, two distinctly different approaches have been used to estimate the potential for and cost of reducing per capita carbon-dioxide emissions. The first is a top-down approach based on economic models which use highly simplified relationships between energy, non-energy factors of production, and economic growth. The second is a bottom-up approach based on a detailed, item-by-item comparison of energy-using technologies currently in use with the most efficient technologies currently available or confidently anticipated to become available within the time period under consideration.

As summarized by Cline (1992, p. 184), economic models project a global GNP loss of 0–1% for a 30% reduction of emissions relative to a growing business-as-usual emission level, and a 3–4% GNP loss for a 70% reduction from business-as-usual emissions. This is a small percentage loss from a world GNP which is projected to increase severalfold by the time the emission reduction would be achieved. Furthermore, as discussed by Cline (1992, p. 191), the estimated loss is likely to be too high because it does not allow for the adoption of currently available technologies which could reduce CO_2 emissions at no net cost (by improving the efficiency of energy use), nor does it allow for accelerated technological development in response to policies to limit CO_2 emissions.

For current energy prices, the bottom-up analyses generally find or imply economically attractive end-use energy savings potentials in OECD countries on the order of 25–60% compared to present energy demand, by the time the current equipment stock has been completely replaced and all existing buildings have gone through one renovation cycle (Electric Power Research Institute, 1990; Lovins and Lovins, 1991; Grubb et al., 1991b, Chapter 2). However, it is not expected that the full energy efficiency potential identified in engineering studies can be achieved in practice. On the other hand, most engineering analyses are restricted to presently available and cost-effective technologies; over time, even more cost-effective opportunities to reduce CO_2 emissions should arise. In any case, the CO_2 emission-reduction potential due to improved end-use energy efficiency is substantial.

Further large CO_2 emission reductions can be achieved by readily available measures to substantially improve electricity generation efficiency, through fuel switching and, on a longer time scale, through increased use of renewable energy sources. As reviewed in Harvey (1995a), emerging technologies involving generation of electricity from coal will reduce emissions per unit of electricity by up to 50%, while fuel switching from coal to high efficiency natural gas-based generation will reduce emissions by a factor of three to five. A number of renewable energy options are near the threshold of commercial viability in large-scale applications, including photovoltaic electricity (Kelly, 1993; Zweibel and Barnett, 1993), base-load solar thermal electricity (Mills and Keepin, 1993), biomass for electricity and liquid or gaseous fuels (Hall et al., 1991; Larson, 1993), and wind energy (Cavallo et al., 1993). Advances in any one of these could facilitate significant further reductions in emissions of CO_2 and other GHG's.

Recent analyses of the net effect of end use and supply-side measures lead to the conclusion that CO_2 emissions in industrialized countries could be reduced by 25–50% from present levels over a 20–30-year time frame with no adverse economic effects at the national level (see, for example, Williams, 1987, and Alliance et al., 1992, for the US; Harvey et al., 1996, for Canada; Bodlund et al., 1989 for Sweden; Blok et al., 1993 for The Netherlands (only the technical potential is presented, but in other studies there is generally little difference between the economic potential and identified technical potential); and Morthorst (1993) for Denmark (where a 24% reduction from 1992 emissions by 2005 is estimated to save 100 DKK/ton C or about US$16/ton C))*. The analysis by Goldemberg et al. (1988), while not explicitly considering CO_2 emissions, implies that global CO_2 emissions could be held approximately constant to the year 2020 through the application of all cost-effective technologies and expansion of renewable energy supplies, where economically viable, even with attainment of a western European

* Other U.S. studies, by the Office of Technology Assessment (OTA, 1991) and the Environmental Protection Agency (EPA, 1990), obtained smaller emission-reduction potentials. In the above studies, well-known energy efficiency measures have not been included in the analysis, for reasons not specified, or costs much higher than can be obtained in the present market place are assumed. For example, the lifespan of coal-fired power plants is assumed to be extended to 60 years in the OTA reference scenario with no refurbishing costs, while combined cycle-gas turbines (which produce 1/4 the CO_2 per unit of electricity generated) are assumed to cost more than new coal-fired power plants, whereas current costs are about one half those of coal-fired plants. Similarly, electricity from cogeneration is assumed to cost more than electricity from coal, when in reality it provides a significant cost savings, as evidenced by the large number of private sector power producers which are adopting this technology. The EPA (1990) and OTA (1991) studies are thus more appropriately regarded as judgements concerning the achievable emission-reduction potential rather than assessments of the economic savings potential based on the summation of measures which pass objectively definable tests. The recent UNEP-sponsored abatement costing study (Halsnaes et al., 1994) also considers only a subset of possible emission-reduction measures.

1970's standard of living throughout the developing world. A global synthesis by Johansson et al. (1993) indicates that, with use of renewable energy to the extent likely to be economically competitive during the coming decades combined with the energy demand of the Accelerated Policies scenario of the Intergovernmental Panel on Climate Change (IPCC)*, global CO_2 emissions can be reduced to 5.0 Gt C (gigaton of carbon, or billions of ton of carbon) in 2025 and 4.2 Gt G in 2050, compared to about 5.5–6.0 Gt C at present.

Since energy-efficiency improvements of the magnitude assumed in the above studies are not expected to occur by themselves, some degree of government intervention will be required to make them happen. Some of the perceived risks associated with CO_2-emission reduction arise from the need for government intervention and the side-effects such intervention might have. Clearly, these risks depend on the nature and extent of government intervention, and the prospects for mid-course corrections. As discussed below, some of the required interventions are at the national level, while others are at the local level.

One reason why much of the energy-efficiency potential will not be realized without government intervention is the existence of a number of informational, financial, organizational, and institutional barriers to the use of cost-effective energy-using technologies, as discussed by Jochem and Gruber (1990), Reddy (1991), and DeCanio (1993). Related to the existence of market barriers are a number of market imperfections, as discussed by Sanstad and Howarth (1994) and Koomey and Sanstad (1994). The existence of these market barriers and imperfections indicates that policies which rely on economic instruments alone (such as a carbon tax) will not be particularly effective in reducing CO_2 emissions, compared to a strategy which, among other things, addresses market barriers and imperfections.

A further factor in developing countries is the lack of adequate human resources and local capabilities. Technology imported to developing countries rarely reaches its design capacity, and performance often deteriorates significantly during its operational life. An effective strategy to limit CO_2 emissions from developing countries will therefore include the need to strengthen local technical capabilities.

Most policy analysis has focused on national measures and international instruments to reduce GHG emissions, and existing macro-economic models have been used to assess the effectiveness and cost of carbon taxes as the sole means to achieve emission reduction. Comparatively little attention has been devoted to actions that can be taken by local governments to promote GHG-emission reduction. However, most of the energy-related GHG emissions occur in the urban environment and can be influenced, to some degree, by local municipal governments (Harvey, 1992). The City of Toronto has an official target of reducing CO_2 emissions associated with energy use in the city by 20% from the 1988 level by 2005, and is actively

* This scenario assumes significant adoption of end-use energy-efficiency measures, such that global electricity demand increases to only 236% of the 1985 demand by 2025, while direct fuel use increases to 130% of the 1985 demand by 2025.

pursuing policies to achieve this target (Harvey, 1993b). Two major components of Toronto's programme to reduce CO_2 emissions by 20% are the development of a comprehensive building retrofit programme, which will target the maximum cost-effective energy and water savings potential in the entire building stock of the city, and the incremental expansion of the district heating system accompanied by the construction of satellite district cooling systems and the addition of cogeneration. A two-year building retrofit pilot phase was launched in June 1996, to be followed by scaling up to the entire city. Both the pilot phase and intended full-scale program will use private sector financing and a number of innovative institutional and organizational arrangements to minimize overall costs and achieve high rates of participation, as explained in Harvey (1995b). Many opportunities also exist to significantly reduce GHG emissions through municipal district heating and cooling systems, coupled with cogeneration of electricity. Costs are highly site-specific, and realization of the potential savings to a large extent requires proceeding incrementally on an opportunistic basis. This in turn requires a detailed knowledge of local circumstances, as well as long-term policies in support of integrated energy systems. Municipal governments, because they are more directly involved in local activities and more aware of local conditions and opportunities, are therefore well positioned to be able to capitalize on emission-reduction opportunities within their own jurisdiction.

A third key area where municipal level action will be needed in order to realize the full potential for GHG-emission reduction is through planning of new urban developments and/or redevelopment and intensification of the existing urbanized area. In North America especially, land-use planning and property-taxation policies have favoured low density development in which workplaces, residential areas, and social amenities are deliberately separated, creating strong automobile dependence and large transportation energy demand. The greatest long-term impact on transportation energy use will likely result from a reorientation of urban planning toward higher density development in which various land uses and services are located within a short distance of one another. More compact urban form also improves the economics of integrated energy systems.

2.2. RISKS ASSOCIATED WITH CO_2 EMISSION-REDUCTION MEASURES

It is clear from the above review that significant reductions in CO_2 (and other GHG) emissions from developed countries are possible at little or no net cost; in particular, CO_2-emission reductions of 25–50% from present emissions (depending on the country) are achievable in principle over a 20–30-year time frame with no adverse economic effects at the national level. Nevertheless, a number of objections have been raised against limiting fossil fuel GHG emissions. These objections are cast in the following sections in the form of risk. The significance of these risks, and ways in which they can be minimized, are then discussed.

2.2.1. *Resources Might be Diverted from Other Urgent Needs*
This is a real risk if (i) CO_2-emission reduction measures turn out to be costly, and (ii) CO_2-emission reduction does not simultaneously address other needs. Among the most pressing non-greenhouse concerns are local air-pollution problems, which are particularly acute in many developing country and former East Bloc cities, the provision of clean water in developing country cities, and the need for greater provision of health services and education in developing countries. Resources are also needed to clean up local environmental hot spots, related primarily to toxic waste disposal in developed countries. The first issue can be addressed as a by-product of measures to reduce GHG emissions; indeed, alleviation of urban air-pollution problems, to the extent that it reduces ozone concentrations, will reduce net GHG heating.

As for the remaining issues, these are important and must be addressed. However, by placing a strong emphasis on the efficient use of energy, total capital costs associated with development will be reduced since the capital cost of improving the efficiency with which existing energy sources are used is generally less than that of expanding energy surplus. This is particularly important in developing countries, whose growth is generally constrained by a lack of capital (Sathaye and Gadgil, 1992). Geller et al. (1988), for example, find that end-use electrical efficiency measures requiring an investment of $8 billion could avoid 2/3 of the new electric power plants planned for 1985–2000 in Brazil which would otherwise cost $38 billion*. A specific example is a factory to build compact fluorescent light bulbs – which provide the same light as incandescent light bulbs with one quarter the electricity – and which can be built for about $7.5 million, while building a power plant to produce the amount of electricity saved by the light bulbs would cost about $135 million**. As well, capital costs for energy-efficient commercial and institutional buildings are sometimes less than that of less efficient buildings, because of the downsizing in the heating, ventilation, and air-conditioning equipment which is possible in an efficient building.

Hence, to the extent that CO_2 emission-reduction strategies emphasize increasing the overall efficiency of energy utilization, CO_2 emission-reduction will not divert resources from other urgent social priorities. Rather, it is more likely to free up additional resources for use in addressing other problems.

* This analysis is restricted to potential savings in motors, lighting, and refrigerators, which account for 2/3 of Brazilian energy use. The identified savings potential amounts to 30% of electricity demand by these three end-uses, or 20% of total electricity demand.

** This assumes a plant producing 2 million compact fluorescent light bulbs plus ballasts per year, which could displace a baseload power requirement of 208 MW according to Gadgil, A. and Rosenfeld, A. H. (*Conserving Energy with Compact Fluorescent Lamps*, Lawrence Berkeley Laboratory, Center for Building Science, Berkeley, 1990). I have assumed the least expensive power generation costs – $650/KW, corresponding to advanced combined cycle gas turbines – in deriving an avoided power plant capital cost of $135 million. Capital costs for coal-fired plants are typically $1200–1450/kW, depending on the extent of pollution controls.

2.2.2. *Economic Growth Might Be Reduced*

A number of analysts have uncritically adopted the assumption that economic growth will be reduced by measures to limit GHG emission. Economic models which predict a decrease in economic growth when CO_2 emissions are constrained do so because they are formulated to respond that way (see Harvey (1994) for a discussion of one such model). However, there is no compelling reason to believe that this would be the case, at least for initial emission-reduction measures. Given that development which stresses energy efficiency generally requires less capital than energy-inefficient development (as discussed above), lower growth of carbon dioxide emissions due to an emphasis on energy efficiency is more likely to lead to faster economic growth in developing countries, as recognized by Zongxin and Zhihong (1992) in the case of China. Mahgary et al. (1994) find, in the case of Egypt, that slight modifications to a macro-economic model which had predicted a large reduction in GDP as a result of measures to significantly reduce CO_2 emissions, instead produces a significant enhancement in GDP, with the enhancement increasing the more stringent the CO_2-emission reduction! For countries which are net energy importers, a partial shift in expenditures from payment of energy costs to labour-intensive retrofitting activities will have positive economic effects, as would accelerated development of new technologies, which would be stimulated by policies to limit CO_2 emissions.

A number of recent economic modelling exercises indicate that the reduction in distortionary taxes which is possible after the introduction of a domestic carbon tax can lead to increased rather than decreased economic growth as CO_2 emissions are reduced (i.e. Jorgenson and Wilcoxen, 1993; Barker, 1995). The impact on GDP of a carbon tax depends on which other taxes are reduced. Shackleton et al. (1992) show that, for four models of the US economy, offsetting a carbon tax through an increase in the investment tax credit and a cut in corporate income tax can produce net GDP growth, while offsetting the carbon tax entirely through a cut in payroll and personal income taxes does not entirely offset the GDP loss due to the carbon tax. Since part of the revenue from a domestic carbon tax would need to be used to compensate poorer members of society based on equity considerations, the scope for enhancing GDP growth through a carbon tax is reduced, as discussed by Zhang (1994).

It is possible that a very large CO_2-emission reduction (such as the 50–60% global reduction needed to stabilize concentrations) will reduce economic growth, depending on how fast such a reduction is achieved. However, a deliberate reduction in economic growth in order to avoid damage due to climatic change represents trading a decrease in an economically quantifiable measure of human welfare (GDP) against increases in other measures of human welfare which cannot be quantified economically. As observed by Lave (1991, p. 102), "rather than lament the slowdown in economic growth, we should recognize that society appears to believe that growth with current environmental externalities is undesirable ... thus, slowing economic growth is entirely desirable, at least to some extent, until the most important externalities have been managed satisfactorily". Nevertheless, economic growth is needed at present in the developing world to improve living standards, alleviate human suffering, and to ensure eventual population stabilization. As argued above, appropriate initial steps to limit CO_2 emissions are more likely to enhance rather than hinder the required economic growth.

2.2.3. *Reduction Measures Might Cost More Than Expected*

Although engineering-based estimates indicate that significant emission reductions can be achieved at a net cost savings, these analyses generally consider only the direct purchase and installation costs of new technologies, and differences in operating costs (including maintenance costs) between currently-used and new technologies. In the case of end-use energy-efficiency measures, significant additional transaction costs can occur. These transaction costs involve the managerial time required to learn about new, energy-saving opportunities and to decide which measures to implement. However, governments can substantially reduce the transaction costs by serving as a clearing house for objective and credible information about energy-saving technologies. Workplace disruption and interruption of industrial manufacturing processes are a further cost not included in most cost-benefit analyses of energy efficiency. These costs can be greatly reduced or eliminated if energy efficiency retrofits are combined with renovation, industrial process changes, or retooling that would occur anyway.

In the case of utility-sponsored energy efficiency and building retrofit programmes, programme-delivery costs arise in addition to the equipment and installation costs*. These costs include programme promotion, administration, and quality control, and are one factor which reduces the achievable savings potential below the apparent economically attractive potential. In past utility-sponsored energy-efficiency programmes, these overhead costs have sometimes exceeded the direct costs (Joskow and Marron, 1992). However, the programme-delivery cost per unit of saved energy can be kept small (15–20% of purchase and installation costs, and possibly less) by (i) targeting the maximum cost-effective potential; (ii) simultaneously addressing electricity and oil or natural gas-use in buildings (which requires coordination between energy utilities); (iii) combining energy-conservation measures with water conservation (which is often very attractive economically in its own right); (iv) piggy-backing the programme on other revenue generating, cost-saving, or required programmes such as electrical or pumping upgrades and CFC phase-out; and (v) taking full advantage of community-based organizations to

* Energy-efficiency programmes are part of a comparatively new activity for power utilities referred to as 'demand side management' (DSM). The process of comparing the costs of freeing up existing power through energy-efficiency programmes with the cost of adding new supply, and choosing the less expensive option, is referred to a 'least-cost planning' or 'integrated resource planning'. For introductory reviews, see Moskovitz (1990) or Hirst and Goldman (1991). Most DSM programmes to date have attempted to slow the growth in energy demand, rather than to achieve absolute reductions in energy demand which, according to engineering-based analysis, should be economically attractive if phased to match normal power plant and equipment retirement schedules.

disseminate information about the programme, gain credibility, and achieve high participation rates. All of these measures will be adopted in the aforementioned city-wide building retrofit programme currently being developed by the City of Toronto.

Another way in which emission reductions might end up costing more than expected is if significant fuel switching from coal to natural gas drives up the price of natural gas, thereby rendering fuel switching an expensive option. This is of particular concern with regard to electricity generation. However, there are two considerations which could keep natural gas electricity generation competitive with coal even if natural gas cost increases sharply. First, the capital cost for natural gas-fired electricity is substantially less than that using coal with comparable emissions of acid rain precursors; such 'clean' coal power plants cost around \$1450/kW (Streets et al., 1991), compared to \$650/kW for combined cycle-gas turbines. Secondly, natural gas can be used more efficiently than coal (48% versus 35% at present; 60% versus 50% in the future; up to 95% with cogeneration, which often cannot be sited in cities if coal-based). As discussed in Harvey (1995a), natural gas at \$5–7/GJ (depending on interest rates) can remain competitive with coal at \$2/GJ for electricity generation (current prices to utilities are about \$1.5–2/GJ for coal and \$2–4/GJ for natural gas). Even if higher natural gas prices result in greater electricity costs than using coal, the costs of typical end-use energy services need not be any higher than in a business-as-usual scenario if fuel switching is part of a portfolio of measures which includes accelerated end-use efficiency improvements. Furthermore, stringent efforts to achieve maximum end-use efficiency in existing and new uses of natural gas could substantially reduce the growth in natural gas demand compared to the case without enhanced fuel switching and efficiency improvements.

A carbon tax is one policy option for encouraging adoption of measures which will reduce CO_2 emissions, and, in spite of the potential to reduce unemployment by using the revenues from such a tax to reduce employers' payroll taxes, there are at least two ways in which the imposition of a carbon tax could impose long-term economic costs. First, recycling the tax by reducing employer payroll taxes could lead to wage inflation from those already employed, since their takehome pay would be unaltered while the cost of energy (and the energy component of purchased goods) will have increased (Mabey et al., 1996). The wage-inflation pressure will depend on the extent to which firms respond to reduced payroll taxes by increasing employment or profits rather than reducing prices. If workers negotiate wage increases to offset more than a given fraction of the extra money spent on energy, then the increase in interest rates required to offset the inflationary tendencies and the resultant suppression of investment will wipe out the macroeconomic benefits of reduced payroll taxes, and it becomes better to recycle the carbon tax through reduced income tax (for which there would be no immediate wage-inflation pressure). The threshold at which it becomes better for long-term growth to reduce income taxes rather than payroll taxes varies from country to country (Mabey et al., 1996). If governments prefer to recycle a carbon tax through reduced payroll taxes for social equity reasons (to reduce unemployment), then there is a risk of inflation sufficiently large to negate the GDP benefits of reduced unemployment. The wage expectations following imposition of a carbon tax which is recycled in this way will depend in part on the extent to which governments can convince workers that higher energy costs can be offset through more efficient use of energy – that is, by the extent to which attention can be shifted from the cost of energy to the cost of energy services. If a carbon tax is used to complement other policy measures, such as increased equipment energy-efficiency standards, then the net effect of a carbon tax might simply be to prevent the effective price of energy from falling. Effective communication of this result might also reduce wage-inflation pressure.

The second potential long-term cost of a carbon tax arises from the uncertain effect on GDP growth of shifting research and development effort and capital investments directed toward enhancing labor productivity to those directed toward enhancing energy productivity. This would appear to be of possible concern primarily in the industrial sector, and is based on the premise that a carbon tax would not stimulate innovations which simultaneously enhance both labor and energy productivity. As discussed by Mabey et al. (1996), this possibility cannot be modelled in a traditional general equilibrium/scarcity approach to factor production and pricing, and so is rejected a priori in economic models. Even if GDP growth is reduced by the shift in investment emphasis, the lower growth in labor productivity might imply greater employment and thus greater human welfare.

The final risk under the category of 'costing more than expected' is political in nature. This is the risk associated with over-dependence on gas supplies from politically unstable, or potentially unstable regions, the unexpected cutoff of which would exact significant economic and social costs. About 70% of proven natural gas reserves are found in the former Soviet Union, Eastern Europe, and the Middle East, and supply routes to Europe would need to cross several international borders (Grubb et al., 1991b). Prior (1994) discusses the magnitude of supply investments needed to meet projected European demand from these regions. Clearly, failure to achieve political stability and long-term security in these regions could be an important constraint on the extent to which gas can be substituted for coal. On the other hand, the prosperity flowing from continued investment in natural gas supplies in these regions would likely contribute to the stability needed for further investment. Nevertheless, the risk of political instability underlines the need to minimize the growth in total natural gas demand as fuel switching occurs by using natural gas as efficiently as possible. Risks of supply interruption will be minimized to some extent if some gas can be delivered by liquified natural gas tankers rather than by overland pipeline.

In short, the main factors which could increase the cost of CO_2-emission reduction beyond current expectations – unaccounted for transaction costs, energy efficiency programme-delivery costs, increases in the cost of natural gas, and negative long-term macroeconomic impacts of a carbon tax – can be minimized through a comprehensive and gradually introduced programme of fuel switching and supply – and demand-side energy efficiency measures, and effective communication.

2.2.4. *Early Action Might Cost More Than Later Action*

One argument for not taking action now to limit industrial CO_2 emissions is that the cost of limitation measures will decrease over time, while the additional climatic change due to, say, a 10-year delay is very small. Delaying action would therefore decrease the cost of emission control while having negligible effect on future climate. This argument assumes (a) that the near-term actions that would be undertaken to reduce emissions entail net cost, and (b) that there are no windows of opportunity that are irreversibly lost due to delay.

As indicated in this paper, there is an overwhelming body of evidence which indicates that there are many measures to reduce CO_2 emissions which are economically attractive in their own right and, which collectively, imply significant emission reductions. Other measures, such as use of advanced renewable energy technologies, generally lead to greater costs. However, in this case the appropriate policy response is to reverse the current trend in OECD countries of decreasing government research and development support for energy efficiency and renewable energy, rather than forcing the early use of currently-expensive technologies. Clearly, delay in this policy response will increase rather than decrease the future cost of CO_2-emission reduction, since it will delay the time when advanced renewable energy and the next generation of end-use technologies become commercially viable. Geller et al. (1989) documents the significant returns from previous US government support for energy-efficiency technologies in the building sector, and, as already discussed, a number of renewable technologies are near the threshold of commercial viability.

The loss of windows of opportunities is another way in which delay will increase rather than decrease the cost of CO_2-emission reduction, particularly if delay in implementation of the initial emission-reduction measures is to be compensated by a faster reduction later. An early strengthening of family-planning programmes and other measures to stabilize population will have benefits which grow over time, and each decade lost in this battle is effectively lost forever. With regard to per capita energy use, the windows of opportunity include the construction of new buildings and power plants, major renovations of existing buildings (which can be expected once every 30–50 years on average), and difficult-to-reverse decisions concerning the density, land-use mix, and infrastructure in newly urbanized areas. As soon as pro-active policies are in place, one can rely on normal rates of equipment and power-plant turnover and building stock renovation to achieve significant gains in energy efficiency, and one can achieve the significant cost advantages of designing new buildings to minimize energy use rather than having to retrofit them (with much less energy savings) at a later date. Creation of 'public transit-friendly' cities and installation of district-energy systems in cities initially designed without attention to these services will be more expensive than designing cities from the beginning to facilitate high quality public transit and district energy. Delay until there is greater scientific certainty might require accelerated capital turnover, which would significantly increase costs, especially if the impacts of GHG emissions are judged to be worse than believed at present. Delay could also lead to a crash-programme approach later, in which the risk of error and misallocation of resources is greater than if more gradual policy implementation is possible.

In short, a strong argument can be made that there is a greater risk that delay in responding to the threat of global warming will lead to higher costs rather than lower costs in reducing CO_2 emissions.

2.2.5. *Reduction Measures Might Have Undesired Side Effects*

An often-cited example of an undesired side effect would be if, during the era of widespread enthusiasm for nuclear power, a major nuclear-power plant programme had been undertaken in response to concern about global warming. Apart from problems pertaining to safety and nuclear waste disposal, such a programme would have been counterproductive in reducing CO_2 emissions. This is because large amounts of capital would have been consumed which would have resulted in smaller CO_2-emission reductions than if used to improve end-use efficiency (Keepin and Kats, 1988). Other examples include a large-scale shift to methane-fuelled automobiles (in which upstream emissions and methane leakage would largely cancel reduced CO_2 emissions) or use of electric vehicles when coal supplies the electricity at the margin. Clearly, the risk of undesired side effects is largest if a mega-project approach to CO_2-emission reduction is taken, if reliance is placed on a small number of measures, and if political considerations are allowed to override technical considerations. Risks can be reduced through a highly diversified portfolio of carefully analyzed emission-reduction measures.

Urban intensification was identified above as an important long-term strategy in reducing transportation energy use and improving the economics of integrated heating, cooling, and cogeneration energy systems. To some, this implies disruption of existing neighbourhoods and construction of high-rise apartment buildings, with associated negative impacts. However, significantly greater densities than exist in many North American (and some European) cities can be achieved in an architecturally pleasing and socially acceptable manner through low rise, medium density residential development in which better use is made of allotted space (Duarne and Plater-Zyberg, 1990). The 1980's have seen several innovative and well-designed redevelopment projects which have involved a healthy mix of land uses, building heights, income levels, and tenure (Canadian Urban Institute, 1991). There is a rapidly growing recognition that urban sprawl is not economically sustainable, and that significant social costs are imposed by currently favoured models of urban development. This has lead to the development of the 'New Urbanism' school of urban planning, which seeks a return to more traditional and compact urban forms (Katz, 1994; Barnett, 1995). In addition to a number of economic and social benefits which are discussed in the preceding references, urban intensification can limit or stop the loss of farmland due to urban sprawl. Thus, rather than creating undesired side effects, carefully planned intensification (in which local community groups are actively involved) can create a number of beneficial side effects.

2.2.6. *Reduction Measures Might Require Heavy-Handed Government Intervention*

If anything, quite the opposite is required. The present energy system is highly distorted by massive government subsidies of fossil fuel (and nuclear) energy sources. Coal, the most-carbon-intensive fossil fuel, is heavily subsidized within the European Community (Okogu and Birol, 1992), and energy prices in former and present Communist regions, as well as in much the developing world, are below international market prices. Unterwurzacher and Wirl (cited in Grubb et al., 1993) estimate that increasing energy prices to world-market levels in Poland, Hungary, and the former Czechoslovakia would reduce CO_2 emissions by 30%. In some countries, oil exploration and development is heavily subsidized by government. Studies by the OECD and World Bank indicate that the fossil fuel subsidy in non-OECD countries averages \$92/ton carbon (Grubb et al., 1993, p. 461). Removal of fossil fuel subsidies would create strong economic incentives to use energy more efficiently and to use less fossil fuels, especially coal, thereby reducing CO_2 emissions. With regard to urban form, low density urban sprawl (which promotes greater transportation energy use) is also subsidized in some jurisdictions (by, for example, placing the burden for funding of primary and secondary education costs on municipalities, which decreases with decreasing density, while sharing the cost of infrastructure with regional governments, which increases with decreasing density). In the electricity sector, less centralized decision making and greater competition in the supply of electricity would allow independent power producers to provide a growing share of the electricity demand. Since independent power producers generally provide electricity more efficiently than from centralized power plants (through cogeneration) or tap small scale, renewable energy sources, such measures would also tend to reduce CO_2 emissions.

Although there is a role for national governments in CO_2-emission reduction, this need not involve an oppressive command-and-control response. Effective policies involve gradually improving efficiency standards for automobiles and trucks, appliances, and furnaces and boilers; support for research, development, and demonstration of a wide array of promising end-use technologies, improved electricity generation from fossil fuels, and renewable energy sources; support for urban rapid transit and regional rail systems; and implementation of a modest carbon tax which is offset by a reduction in other taxes. Realization of close to the full cost-effective emission reduction potential will also require the full participation of local governments and community-based organizations, as discussed by Harvey (1992, 1993b, 1995b) and Robinson (1991) – in essence, a bottom-up approach to implementation of emission-reduction measures. This implies greater democracy and local involvement in decision-making.

In short, given the significant inefficiencies in energy use which have resulted from government subsidies of fossil fuels and centralized decision-making, the positive roles that national and regional level governments can play, and the need for strong involvement of local governments, there is certainly no *need* for heavy-handed government intervention in reducing CO_2 emissions.

2.2.7. *Reduction Measures Might Not Work*

Failure of CO_2-emission reduction measures to achieve the desired reduction could occur at the micro-economic and macro-economic levels. At the micro-economic level, individual energy-saving technologies might fail to perform as expected, or biomass energy plantations (should they be used) may turn out not to be sustainable. The risks associated with new technologies can be reduced if they are introduced on a small scale, and through demonstration projects in which performance and costs are carefully documented. Risks associated with new energy-supply technologies can be reduced through diversification and gradual implementation.

At the macro-economic level, a number of feedbacks would occur which would at least partially cancel the environmental benefits of improved efficiency of energy use. These feedbacks involve (i) a fall in the *real* price of energy as demand falls due to more efficient use; (ii) a fall in the *effective* price of energy, even when the real price is constant, because it can be used more efficiently; and (iii) the effect on total energy demand of the purchasing power released when energy-cost savings are made. Feedbacks (i) and (ii) are likely to be small in the developed world, where many energy uses are already saturated, and can be countered by taxes to prevent the effective price of energy from falling (as opposed to a top-down approach of using taxes to induce more efficient energy use in the first place). Feedback (iii) also appears to be small in the developed world (see Grubb, 1992a, b; Brookes, 1992). All three feedbacks are likely to be large in the developing world, where economic activity is constrained at least in part by the availability of energy. More efficient use of energy would stimulate greater economic growth, with little reduction in the growth of energy demand in the near term. However, faster development – if channelled to meet basic human needs – will reduce population growth rates and hence long-term GHG emissions (see World Bank (1984) for a discussion of the relationship between development and population growth rate). In short, macro-economic feedbacks arising from more efficient energy use are likely to be small in the developed world and, although probably large in the developing world, will nevertheless indirectly contribute to reducing growth of GHG emissions by reducing the rate of population growth if economic growth is appropriately channelled. An interesting research task is to attempt to quantify this relationship based on historical data and to incorporate it into formal integrated assessment models.

Another example of a macro-economic (and partly political) feedback which could partly neutralize the expected CO_2-emission-reduction impact is the application of a carbon tax which is countered by a reduction in the price of oil by Middle Eastern producers (Green, 1992). As discussed by Green (1992), Middle Eastern oil producers might see a carbon tax as the beginning of a world policy to shift away from fossil fuels, and might increase production as part of a 'use it or lose it' strategy.

The macro-economic feedbacks discussed above indicate the need for careful economic analysis of CO_2-emission-reduction measures. Unfortunately, current global economic models have been largely used to assess the magnitude of a carbon tax which would be needed to achieve emission reductions, assuming that the underlying barriers and obstacles to improved energy efficiency are not addressed. A more useful application of economic models would be to investigate the impact of macro-economic feedbacks on emissions when the underlying efficiency of energy use is increased (in response to government policies) and of the impact of carbon taxes when used simply to maintain current effective energy prices rather than as the only policy to achieve emission reductions.

2.3. POTENTIAL NON-CLIMATIC BENEFITS

Symmetry in the assessment of risk associated with measures to reduce CO_2 emissions requires that one also consider the non-climatic benefits associated with, or likely to result from, emission reductions. From a policy point of view, the relevant risk is the net risk, which takes into account the possibility of both negative and positive non-climatic impacts. As in many of the down-side risks, the potential non-climatic benefits of CO_2-emission reduction occur at both the individual and societal scales. Examples of potential benefits are outlined below.

At the individual scale, improved efficiency of energy use can convey a number of benefits besides reduced energy costs. For example, advanced windows reduce noise and allow higher indoor air humidities in buildings in cold climates in winter, resulting in improved human comfort. Indeed, these benefits – rather than energy-cost savings – are often the primary motivation for window upgrades, with energy savings perceived as a side-benefit. Advanced (and highly efficient) ventilation and air-conditioning systems in commercial buildings lead to improved indoor-climate control and air quality compared to existing systems (see, for example, Croxton and Childs, 1992), and can therefore be used to address the 'sick-building' syndrome.

At the societal scale, a number of non-climatic benefits of CO_2-emission-reduction measures can be identified. An overall reduction in the use of fossil fuels will lead to reduced emissions of ozone precursors (CO, reactive hydrocarbons, NO_x) and reduced emissions of trace toxic substances*. A shift from coal

* Automobiles, for example, are significant sources of benzene, toluene, and formaldehyde, all of which are known or suspected to have a number of adverse health effects. Coal-fired power plants are significant sources of arsenic, mercury, cadmium, and other heavy metals, which also have a variety of adverse health effects.

to natural gas will also reduce emissions of most pollutants. Many of the major food-producing regions occur in the major fossil-fuel using regions, and the resultant elevated ozone concentrations probably reduce food production by 5–10% (Chameides et al., 1994). In the case of the UK, a reduction of CO_2 emissions in 2005 to 91% of the 1990 emission through a carbon tax is estimated to yield secondary benefits through reduced air pollution and traffic congestion equal to 0.4–0.7% of GDP (Barker, 1995). A shift to more compact urban form will reduce loss of prime farmland due to urban sprawl – farmland which might be increasingly needed if climatic change affects regional agricultural productivity adversely – and could create more 'liveable' and pleasing cities if carefully planned. Other benefits include reduced dependence on imported fuels in some cases, and increased employment through the reduction in payroll taxes that would be made possible through implementation of a domestic carbon tax.

2.4. Perspectives on Emission Reduction Risks

Many of the measures needed to reduce GHG emissions (population control, improved efficiency of electricity generation, improved end-use energy efficiency, and increased and more efficient use of renewable energy) simultaneously address some of the most pressing environmental and development problems facing humanity. The lower capital requirements associated with energy-efficient scenarios should permit more rapid economic growth in developing countries, with indirect benefits through reduced population growth. The risk of misallocating resources is small, particularly if GHG-emission control policies are implemented early and gradually, and a mega-project approach is avoided. The risk of undesired side effects, unexpected costs, or failure to achieve the expected results can be reduced through a portfolio of carefully designed and diversified measures, backed up by appropriate economic analysis. There is a considerable inertia in the global energy system, and changes cannot be brought about quickly. A delay in implementation of measures to limit emissions (including accelerated research and development of options not yet ready) could create a future need for crash programmes, in which the possibility of error and misallocation of emission-reduction expenditures is greater.

3. An Interim Risk-Hedging Strategy

The analysis of the risks associated with continuing GHG emissions presented in Part I indicates that there is a substantial risk of significant negative consequences, but there is also significant uncertainty concerning the full ramifications of global warming. Even if the eventual impacts of GHG increases limited to, say, the equivalent of a carbon dioxide doubling should prove to be beneficial in aggregate, there will still be a need to limit GHG emissions (i) so as to avoid climatic changes faster than the rate at which most ecosystems can adapt; (ii) to avoid larger increases for which the impacts are less likely to be beneficial in aggregate; and (iii) because even if the net impact is beneficial, there will be a distribution of positive and negative impacts and those groups experiencing negative impacts might not regard any degree of compensation from beneficiaries as adequate. On the other hand, there is a potential for a significant CO_2 emission reduction at zero to very low cost, and with small associated risks if emission-reduction measures are implemented gradually. Significant non-greenhouse benefits are associated with many of the measures needed to stabilize fossil fuel CO_2 emissions.

Although we have not dealt with land-use emissions here, a number of studies indicate a potential to reduce net biosphere emissions due to direct anthropogenic actions (i.e. excluding effects of CO_2 fertilization or climatic change due to past anthropogenic CO_2 emissions) to zero or to create a net sink through land use changes (i.e. Brown et al., 1992), although major socio-economic and political obstacles stand in the way. Inasmuch as total emissions rather than the breakdown between fossil fuel and land-use emissions are all that matter (to first order) with regard to atmospheric CO_2 buildup, any global emission target could in principal be applied to the combined fossil-fuel + land-use emissions. There are, however, two difficult measurement problems associated with such a constraint. First, land-use-related emissions are uncertain to at least a factor of two. Second, estimated net biosphere emissions would include the effect of enhanced photosynthesis due to higher atmospheric CO_2 and the effect of climatic change due to GHG increases. Assuming that these effects could be separated from the effects of management practices, international attribution of that portion of the national biosphere sink (or source) due to CO_2– and climate–biosphere feedbacks would be difficult politically. Nevertheless, if a solution can be found to these problems – perhaps by discounting emission credits associated with reforestation, to account for uncertainty and risk – then any future constraint on global fossil-fuel emissions could be relaxed slightly.

In light of the above survey of risks and the difficulty of including land-use emissions together with fossil-fuel emissions, this paper proposes stabilization of global CO_2 emissions from fossil-fuel use as a reasonable interim target which is likely to come close to minimizing total risk. This should be accompanied by measures to reduce net deforestation to zero as rapidly as possible. The reasons for this choice are as follows: (1) The comprehensive global analysis by Johansson et al. (1993) demonstrates that it would be technically feasible and economically attractive to approximately stabilize global CO_2 emissions for the next several decades, based on currently available or soon-to-be-available technologies, as discussed in the introduction. Similarly, in an analysis with a global energy model in which scenarios were generated by randomly selecting the values of uncertain input parameters used, Edmonds et al. (1986; their Figure 6) found global emissions to be near constant between 1990 and 2025 in just under half of the scenarios generated, with only a modest increase between 2025 and 2075. (2) Stabilization of global emissions will nevertheless require major and significant efforts worldwide, and it is a sufficiently challenging target that it can be expected to induce further technological developments that will provide the means for eventually reducing global CO_2 emissions. (3) At some point it will in fact be necessary to significantly reduce global emissions below the present level, in order to eventually stabilize the atmospheric CO_2 concentration. Given this and point (2), stabilization meets our definition of risk-hedging: it represents what is very likely to be the minimum required constraint, whatever the outcome of current uncertainties, and will create the conditions which will facilitate tougher constraints in the future. (4) Stabilization of global emissions will significantly reduce projected rates of climatic change, as discussed below. This, combined with a greatly improved ability to limit absolute temperature changes by affording more time to develop stronger measures while simultaneously catalyzing technological development, will significantly reduce the risks of global warming.

No attempt has been made here to justify the choice of emission stabilization through a formal quantitative analysis (i.e. Nordhaus, 1992; Peck and Teisberg, 1992), because the results of such analyses are entirely dependent on subjectively chosen inputs and on the functional form of the damage equations. Nevertheless, Grubb et al. (1995) demonstrate two conditions under which global emission stabilization emerges as the 'optimal' emission pathway. In both cases, the damage due to global warming (including the valuation of non-economic assets) is assumed to be 4% of GWP, while the cost of reducing emissions to 50% below the baseline is assumed to be 2% of GWP. In the first case, emission abatement costs are assumed to depend only on the rate of change of abatement, rather than absolute abatement, and all costs are discounted at 3% yr^{-1}. The second case, where emission stabilization is deemed to be optimal, assumes that abatement costs depend about 15–20% on the absolute abatement and the rest on the rate of abatement, but all costs are discounted at 2% yr^{-1}. Furthermore, slight variations in the assumed discount rate can compensate for large differences in the assumed abatement and damage costs. However, the very concept of discounting, when applied to irreplaceable natural assets, is contrary to widely held values, in which the well-being of future generations and passing on an intact environment to one's descendants are important (Kempton, 1991; Kempton and Craig, 1993).

To assess the impact of global emission stabilization on atmospheric CO_2 and temperature, the coupled climate–carbon-cycle model of Harvey (1989) was run for scenarios in which global fossil-fuel emissions increase by 1% and 2% per year from 1990 to 2100, are stabilized at the 1990 level until 2100, or decrease by 1% per year from 1990 to 2100. Figure 1a compares the buildup of atmospheric CO_2 concentration. These results were obtained assuming a modest stimulation of photosynthesis by higher atmospheric CO_2 concentration (obtained by setting $\beta = 0.4$, where β is explained in Harvey, 1989); by assuming enhanced plant, detrital, and soil-respiration rates by warmer temperatures; and by assuming land-use emissions to be maintained at an assumed 1990 level of 1.9 Gt C yr^{-1} to 2020, followed by a gradual decrease to zero by 2050. Also shown in Figure 1a are the CO_2 buildup if land-use emissions decrease linearly to zero between 1995 and 2005 for the cases in which fossil-fuel emissions are stabilized or decrease. Successive decreases in the rate of fossil-fuel emission growth have a diminishing effect on atmospheric CO_2 concentration: that is, the switch from 2% per year growth to 1% per year growth has a larger effect than the switch from 1% to 0% per year growth, and so on. Early elimination of net land-use emissions has a comparatively small effect (there are much stronger, non-climatic reasons for eliminating deforestation as soon as possible). Inasmuch as the results presented here do not allow for a biosphere source due to forest dieback which increases with the rate of climatic change, the difference in reality between the different emission scenarios would probably be greater than indicated in Figure 1a. An important parameter in the carbon-cycle response to anthropogenic CO_2 emissions is the so-called airborne fraction, which is defined here as the yearly increase in atmospheric CO_2 amount divided by the yearly anthropogenic CO_2 emission. At present the airborne fraction is about 0.6. The future behavior of the airborne fraction for the emission scenarios considered here is shown in Figure 1b. With increasing emission the airborne fraction tends to increase, reaching a value of 0.71 by 2100 with 2% per year growth in emissions – that is, an increasing fraction of an increasing emission accumulates in the atmosphere. If emissions are stabilized, the airborne fraction decreases – dropping to less than 0.35 by 2100, which is half the value of the case where emissions grow by 2% per year (the reasons for the changing airborne fraction in both cases are discussed in the Appendix to Harvey, 1989). This increases the effectiveness of emission stabilization in slowing down the buildup of atmospheric CO_2.

Figure 2 compares the globally averaged temperature response for the high land-use emission scenarios, assuming two different climate sensitivities to radiative heating perturbations: a 2 °C steady-state warming in response to a CO_2 doubling (Low Sensitivity), and a 4 °C warming (High Sensitivity). Because the model used here does not include the partially offsetting cooling effect of sulphur pollution, the initial temperature change is somewhat too large although, as discussed in Part I, this offsetting effect should weaken relative to the greenhouse heating effect since sulphur emissions can be expected to be reduced for non-climatic reasons. It can be seen from Figures 1 and 2 that, although emission stabilization is not sufficient to stabilize atmospheric CO_2 concentration or temperature, both the absolute temperature change and rates of temperature change are dramatically reduced compared to the two exponential growth scenarios. However, since even CO_2-emission stabilization eventually leads to a carbon dioxide concentration far in excess of a doubling of the pre-industrial value of 280 ppmv, emission stabilization is unlikely to be acceptable indefinitely.

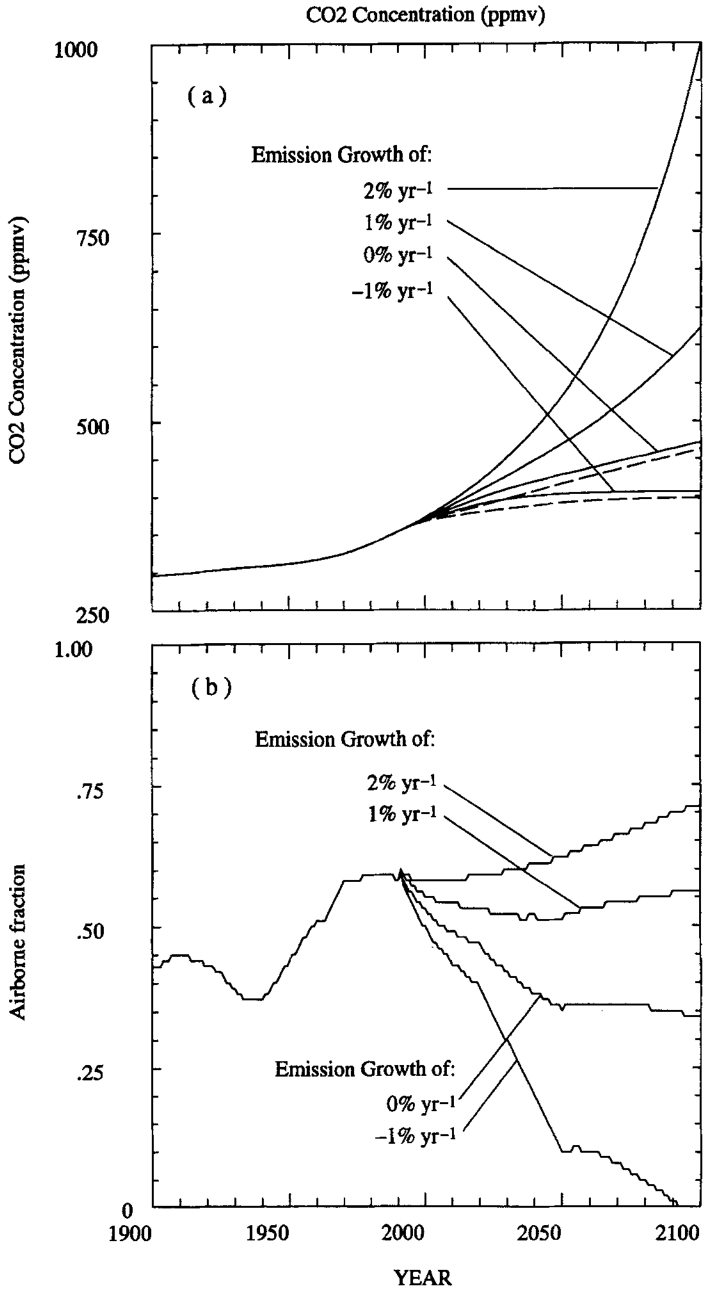

Figure 1. (a) Atmospheric CO_2 concentration for scenarios in which fossil emissions change by −1%, 0%, 1%, or 2% per year from 1990 to 2100. The solid lines correspond to cases in which net emissions due to land-use changes are constant at 1.9 Gt C yr^{-1} from 1990 to 2020, then gradually decrease to zero by 2050. The dashed lines correspond to cases in which land-use emissions decrease to zero between 1995 and 2005. (b) Airborne fraction for the high land-use emission scenarios given in part (a).

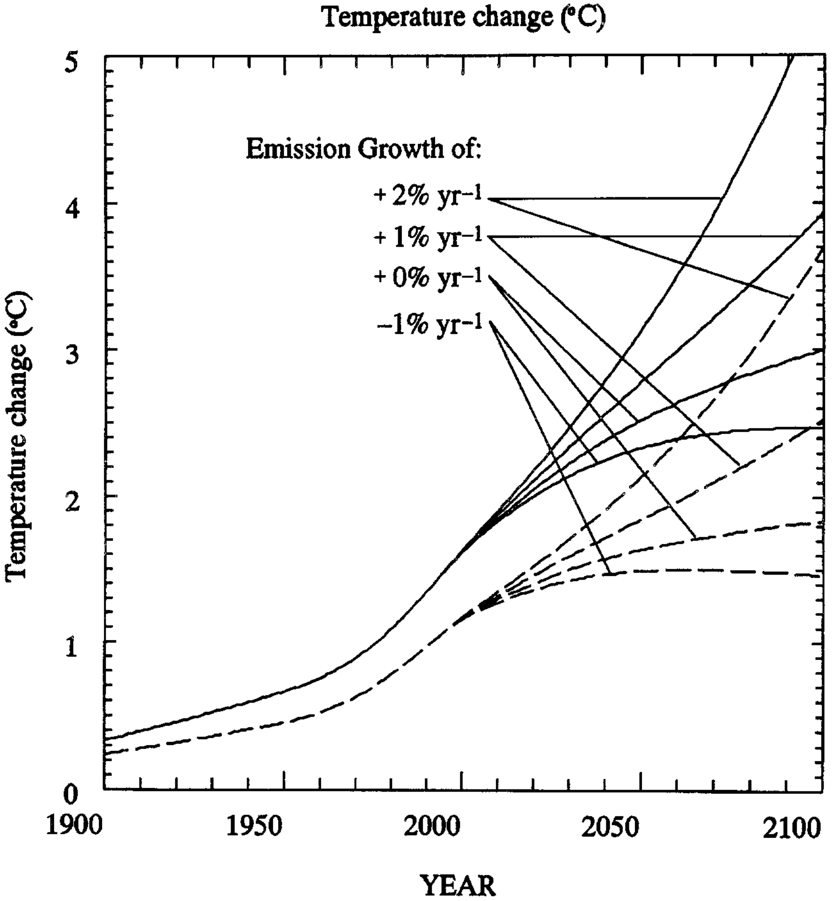

Figure 2. Globally averaged surface-air temperature change for the high land-use emission scenarios used in Figure 1. Solid lines: assuming a climate sensitivity of 4 °C for a CO_2 doubling and an upwelling-diffusion ocean model with vertical diffusion coefficient K of 1×10^{-4} m^2 s^{-1} and an upwelling velocity of 4 m yr^{-1}; long dashes: assuming a climate sensitivity of 2 °C for a CO_2 doubling and a pure diffusion ocean model with $K = 6 \times 10^{-5}$ m^2 s^{-1}.

4. Implications for National Fossil-Fuel Emissions

A global target of fossil-fuel CO_2-emission stabilization implies that emissions from industrialized countries will need to be reduced so as to permit emission increases by developing countries as they build a modern infrastructure and increase their standard of living. Further differentiation within both developed and developing country groups is justified. For example, developed countries can be classified as economically strong, economically less strong, and economically weak, with correspondingly less stringent emission-reduction targets, while developing countries can be classified as rapidly and less rapidly industrializing. Table I presents such a classification, modified slightly from one proposed by Bach and Jain (1991). Economically strong, high emitting countries (Canada, USA, Australia) have an

Table I

Classification of major carbon dioxide-emitting countries in terms of development and economic strength (modified from Bach and Jain, 1991), with data on 1990 population, 1989 fossil-fuel carbon emissions and per capita emissions, and average population growth rate for the period 1985–1990 as computed by the World Resources Institute (1992)

Country and group	1990 Population (millions)	1989 Emissions (Mt C)	1989 Per capita emissions (ton C)	Population growth rate (% per year)
1. Economically strong, high emitters				
1. USA	249.2	1326.7	5.36	0.81
2. Canada	26.5	124.1	4.72	0.88
3. Australia	16.9	70.2	4.21	1.37
Total	292.6	1521.0	5.20	0.85
2. Economically strong, low emitters				
1. Japan	123.5	283.5	2.31	0.43
2. Germany	76.6	175.8	2.86	0.08
3. UK	57.2	154.9	2.69	0.22
4. Italy	57.1	106.2	1.86	0.00
5. France	56.1	97.3	1.74	0.35
6. Netherlands	15.0	34.1	2.30	0.33
7. Belgium	9.9	26.7	2.72	0.00
8. Sweden	8.4	16.0	1.91	0.22
9. Austria	7.6	14.1	1.85	0.07
10. Finland	5.0	14.0	2.81	0.30
11. Denmark	5.1	12.8	2.50	0.08
12. Norway	4.2	12.5	2.99	0.28
Total	425.7	947.9	2.23	0.27
3. Economically less strong				
1. Spain	38.2	55.4	1.42	0.30
2. Greece	10.1	19.3	1.93	0.23
3. Portugal	10.3	11.1	1.09	0.25
4. Ireland	3.7	8.0	2.17	0.92
Total	62.3	93.8	1.51	0.32
4. Economically weak				
1. Former USSR	288.6	1036.5	3.61	0.78
2. Poland	38.4	120.1	3.14	0.55
3. Former Czechoslovakia	15.7	61.7	3.94	0.21
4. Rumania	23.3	57.8	2.50	0.46
5. Former Yugoslavia	23.8	36.2	1.53	0.58

Table I
(Continued)

Country and group	1990 Population (millions)	1989 Emissions (Mt C)	1989 Per capita emissions (ton C)	Population growth rate (% per year)
6. Bulgaria	9.0	29.2	3.23	0.11
7. Hungary	10.6	17.5	1.65	0.00
Total	409.4	1359.0	3.31	0.67
5. Arab oil-producing				
1. Saudi Arabia	14.1	47.4	3.49	3.96
2. Iran	54.6	45.3	0.85	2.74
3. Algeria	25.0	12.7	0.52	2.72
4. Libya	4.6	10.3	2.35	3.66
5. Kuwait	2.0	8.5	4.29	3.40
6. Oman	1.5	2.8	1.93	3.79
Total	101.8	127.0	1.25	2.97
6. Rapidly developing countries				
1. South Korea	42.8	60.2	1.42	0.96
2. Thailand	55.7	21.1	0.39	1.53
3. Singapore	2.7	9.8	3.63	1.25
4. Mexico	88.6	87.1	1.01	2.20
Total	189.8	178.2	0.94	1.71
7. Other major developing countries				
1. China	1139.1	645.6	0.59	1.45
2. India	853.1	177.6	0.21	2.07
3. South Africa	35.3	75.9	2.20	2.22
4. Brazil	150.4	56.4	0.38	2.07
5. North Korea	21.8	60.2	1.42	1.81
6. Turkey	55.8	34.4	0.63	2.08
7. Argentina	32.3	32.2	1.01	1.27
8. Indonesia	184.3	37.5	0.21	1.93
9. Venezuela	19.7	26.1	1.36	2.61
Total	2491.8	1145.9	0.46	1.77
8. Total of above	3973.4	5372.8		
9. World total	5292.2	5957.2	1.15	1.74

Table II
Hypothetical distribution of fossil-fuel carbon dioxide emission changes relative to 1989 emissions which is consistent with global emission stabilization, third-world development, and a possible distribution of economic and technical potentials for emission limitation

Country group	1989 Emissions (Mt C)	Percent emission change
Industrialized countries	3921.7	−27%
Economicall strong high	1521.0	−50%
Economically strong low	947.9	−20%
Economically less strong	93.8	0%
Economically weak	1359.0	−10%
Rapidly developing countries	178.2	+20%
Arab oil producing	127.0	0%
Other developing countries	1730.3	+60%
World total	5957.2	0%

average per capita emission which is over twice that of Japan and Western European countries, combined with a substantially higher population growth rate. At the other extreme, India has a per capita fossil-fuel CO_2 emission which is about 1/6 the world average and 1/25 that of the USA, but a very high population growth rate.

Table II gives a distribution of emission increases and decreases which results in stabilization of global fossil-fuel CO_2 emissions at the 1990 amount. Simply stabilizing emissions at the present global level with only a 60% increase in emissions from developing countries implies emission reductions on the order of 40–50% for economically strong, high emitting countries such as the USA and Canada. Current policy in these countries, which calls for stabilization of *domestic* emissions at the 1990 level by 2000, thus falls substantially short of a policy which would be consistent with *global* emission stabilization.

5. Discussion and Summary

This paper and Part I argue that a guiding principle in the formulation of global CO_2 emission targets should be that of minimizing total risk, involving both risks associated with climatic change and the risks associated with measures to limit CO_2 emissions. Many of the risks associated with climatic change (such as ecosystem and biodiversity loss) cannot be quantified in economic terms, and fall unequally on developed and developing countries. The primary justification for limiting climatic change is thus ecological and ethical, rather than economic, although for very large climatic change, severe economic impacts are also likely. Although selection of a risk-minimizing emission trajectory ultimately rests on subjective judgement combined with individual or collective value systems (because it involves weighing factors which cannot be strictly compared with one-another in quantitative terms, as they involve economic and non-economic costs), this approach is superior to so-called optimization approaches which pretend (i) that all costs can be reduced to economic terms and added up; and (ii) that these costs are known well enough that an 'optimal' emission trajectory from the present to the end of the next century (or longer) can be computed.

However, quantitative determination of a risk-minimizing trajectory still depends on current knowledge, and would therefore change over time as knowledge improves. This paper therefore advocates implementation of a global scale risk-hedging strategy, which adopts as an interim emission constraint the smallest emission reduction likely to be associated with any future risk-minimizing trajectory, provided that the flexibility to strengthen the constraint is created. It is argued here that a target of stabilizing global CO_2 emissions from fossil-fuel use at about the present value satisfies these conditions. It is extremely unlikely that improved scientific knowledge will dispense with the need for any emission restraint whatsoever. Rather, improved scientific knowledge will almost certainly confirm the need for an absolute emission reduction, the only questions being how much and how fast. Thus, global emission stabilization is a safe minimum constraint in the sense that it is unlikely to turn out to have been unnecessary.

Global emission stabilization is also a sufficiently challenging target that it will stimulate new development in energy-using technologies, more rapid improvements in the performance and cost of renewable-based energy supplies, will likely add to existing pressures to modify current patterns of urban development, and, with the right incentives at the international level, will likely lead to adjustments in population policy. In so doing, the future range of options will be increased, and the risk associated with likely more stringent emission constraints in the future will be reduced. Furthermore, a significant amount of time will have been bought through emission stabilization, due in part to the behaviour of the atmospheric airborne fraction. This implies that the deadlines for improved scientific knowledge will not be as strict, so that long-term policy decisions can be based on better knowledge.

Some may argue that an interim target more stringent than global emission stabilization is justified, given the likelihood of significant impacts associated merely with a doubled CO_2 climate and the large cost-effective potential for limiting emissions. This might be true, and the global community is likely to eventually adopt an absolute emission-reduction target. However, emission reduction must be preceded by emission stabilization, and pressures for emission increases will persist for at least two to three decades. This paper argues for a two to three decade delay in attempting to *reduce* global emissions, but does not support calls for a delay in actions to *limit* GHG emissions, as advocated by Schlesinger and Jiang (1991).

A target of global emission stabilization does not imply that all national emissions should be frozen at their current level. Rather, substantial near-term emission increases are unavoidable as Third-World nations undergo economic development and build a modern infrastructure. Within developed nations, there are likely to be vast differences in the extent to which emissions can be easily reduced. For high emitting, economically strong countries such as the United States and Canada, CO_2-emission reductions on the order of 40–50% are consistent with global emission stabilization. It is important that the actual distribution of emission constraints be such as to minimize total cost, which implies that some sort of international market mechanism involving tradeable permits and/or a carbon tax is required. These issues are explored elsewhere (Harvey, 1995c).

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