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January 31, 1997 Pre-decisional draft: Do Not Cite or Quote

THE ROLE OF R&D IN LIMITING GREENHOUSE GAS EMISSIONS

One of the key issues in developing a domestic climate change policy will be the emphasis placed on potentially expanding the Federal R&D effort into technologies that promise to reduce future greenhouse gas emissions and/or lower the cost of achieving a given greenhouse gas reduction target. While advances in technology clearly will play a pivotal role in long-term emission reductions, the key decisions will involve:

- the emphasis placed on medium term vs. long term emission reductions;
- the near-term budget implications of enhanced investments in technology development;
- the extent and character of private-sector participation in an expanded R&D effort;
- the relationship between R&D and near-term technology deployment efforts; and
- the role, if any, of international coordination on R&D efforts.

Achieving greenhouse gas emission reductions that would stabilize atmospheric concentrations at "safe" levels will require major advances in technology in every sector of the economy. Fortunately, many of the necessary advances are within plausible pathways of current research and development efforts. Federal R&D is already pursuing most of the important CO_2-mitigating technologies because they provide other benefits that have long been the basis of national policy, such as reducing criteria air pollutants and other environmental harms; decreasing dependence on foreign oil; increasing the competitiveness of domestic industries; and providing leadership in industries likely to achieve an international market of several hundred billion dollars per year in the next century.

Achieving these goals will nonetheless be difficult at a time of constrained federal spending and sharp reductions in long-term private sector R&D. Since 1978, federal investment in energy R&D has declined 75%. Energy R&D investment by industry fell 33% from 1983 to 1993; the electric utility and the gas industry have cut their R&D investments sharply. Industry as a whole has reduced its basic and applied research from 27% of its total R&D in 1988 to 17% in 1994. A viable R&D component of a climate strategy would entail both expanding federal resources and stimulating additional private sector R&D activity.

The need for major technology advances can be seen from the following equation:
Emissions = *Population* x *Affluence* (GDP/capita) x *Technology* (Emissions/GDP)

From 1990 to 2060, we may well see global population double and affluence increase by a factor of four. At the same time, the world may ultimately need to *lower* emissions from 1990 levels, requiring the average emissions-related technology to improve by more than a factor of ten during the next few decades and then be rapidly deployed throughout the world.

Any R&D effort is intrinsically valuable but inherently risky. We can confidently expect significant benefits (based on empirically high returns on federal, private or blended investment) as well as some unexpected benefits (e.g. much of the gas turbine technology that is today generating cleaner, low-cost electricity had its roots in government-funded work on military jet engines). However, we cannot predict ahead of time the technology "winners" from R&D. The operational risks are making premature commitments to development programs that prove to be technical or economic dead ends, such as the breeder reactor or synfuels debacles of the 1970s. At the other extreme, underfunding the most promising areas by spreading an R&D effort too thinly across a spectrum of technologies, as we did during the 1980's in energy efficiency and renewable energy R&D, misuses scarce resources while foregoing substantial progress. Lessons learned form the past two decades have shaped our current R&D strategy, which chart a sensible middle course between the two extremes.

This paper will examine the most promising R&D for mitigating CO_2, focusing on four strategic thrusts: (1) clean power generation, (2) energy efficiency, (3) carbon sequestration accompanying a transition to a hydrogen-based economy, and (4) very advanced research, such as superconductivity, nanotechnology, and photosynthetic mechanisms. Responding to the climate problem may require breakthroughs in all of these areas, and in any case the high-risk nature of R&D requires the pursuit of multiple pathways. From a technology development standpoint, successful (i.e. low-cost) climate stabilization will require:

- Accelerated diffusion of existing low-CO_2 technologies by 2010 (see "Market Transformation" paper);

- Significant penetration of new very-low-CO_2 technologies from 2010 to 2020 (the period of greatest economic concern in the current negotiations); and

- Substantial or nearly universal deployment of near-zero-CO_2 technologies in the succeeding decades (where the opportunity exists for fundamental alterations in the energy system).

Increasing the probability of achieving these desirable outcomes will require expanding the government's current R&D spending in these areas, which is roughly $1.3 billion per year. Also, partnerships with industry, "market pull" deployment initiatives, improved regulations, and other policies will be required to ensure technological success and accelerated market penetration. The benefits could be enormous, including the avoidance of the costs associated with the other approaches to CO_2 mitigation such as higher taxes and regulation. A 1997 study by Pacific Northwest Laboratory found that developing and deploying advanced technologies over the next 15 to 30 years could lower the present value cost to the global economy of stabilizing the atmosphere at 550 ppm CO_2 from one trillion dollars down to nearly zero.

CLEAN POWER GENERATION

Natural gas technologies now set the benchmark for low cost, cleaner power generation. Moreover, advances in natural gas turbines will yield overall energy conversion efficiencies of 60% or more in the next decade, doubling the efficiency of traditional coal-fired plants. Fuel cells, which generate electricity directly from hydrogen derived from fuels such as natural gas, are promising because of their high efficiency and low emissions. High temperature fuel-cells, such as molten carbonate and solid oxide, may have significant application in power generation with further R&D. Molten carbonate fuel cells are expected to reach 50-60% efficiency by 2000, and perhaps 70% by 2005.

High efficiency coal-fueled power plants, such as integrated gasification combined cycle (IGCC) are now being demonstrated at efficiencies (40 to 43%) that are competitive with more traditional coal-fired power plants but with much lower emissions, including 35-45% lower CO_2 emissions. The efficiency of the next generation IGCC plant could exceed 55%, and, in combination with a fuel cell, achieve 60% by

Given the uncertain nature of R&D, the level of funding necessary to achieve such a world cannot be known, but is likely to be considerably higher than today's investment levels, especially if the Nation seeks to maintain world leadership in these technologies. In PVs, deep R&D cuts in the 1980's have left us with only 40% of the world market. The Japanese outspend our $60 million R&D effort in PVs by more than two to one. The relatively high price for electricity in other developed nations, and the far greater financial incentives they offer industry, means alternative energy will be cost-effective in foreign countries before it is here. Our primary competitive advantage can come only from technological leadership.

ENERGY EFFICIENCY

Another key response to climate change is R&D to improve the efficiency of energy use. A major R&D effort aimed at improving energy efficiency could have a significant impact on greenhouse gas emissions. Shell's "DEMATERIALISATION" scenario imagines such a world with improvements in energy intensity reaching a sustained 2% per annum, which has been seen for only limited periods in the past, from a "New Generation Vehicle" and other relentless advances in efficient technology (see Figure 4).

The market for clean technologies could be a few hundred billion dollars per year. Figure 5 shows global CO_2 emissions through 2100 in this scenario. Again, emissions of the criteria air pollutants would show an even sharper decline. National and world dependence on Persian Gulf oil would be severely reduced. Carbon dioxide content in the atmosphere would stabilize at about 550 to 600 ppm. Three sectors are particularly important for energy efficiency gains: transportation, industry, and buildings.

TRANSPORTATION

Transportation R&D is essential because the sector uses very little electricity, so advances in clean power generation offer little hope of lowering its CO_2 emissions in the near term. Also, two other major national problems-- urban air pollution and dependence on foreign oil --stem largely from the transportation sector. The current federal strategy is to develop cars and trucks that are highly fuel-efficient as well as ones that run on fuels other than petroleum, including natural gas, electricity, and biofuels (ethanol).

The partnership for a New Generation of Vehicles (PNGV) is a collaboration among federal agencies, national laboratories, and the auto industry to design and build a prototype clean car by 2004 with three times the fuel efficiency of existing cars and very low emissions, but comparable or improved performance, safety, and cost. Multiple technology paths are being pursued to build a hybrid vehicle that has both an advanced engine (such as a clean diesel, Stirling or gas turbine) and an energy storage device (such as a battery, fly-wheel or ultra capacitor). Supporting R&D includes lightweight, super-strong materials such as composites; high-temperature ceramics; regenerative breaking; and advanced power electronics.

Biofuels are one of the most attractive options for lowering transportation's CO_2 emissions. Federal R&D has brought the cost of ethanol from $3.60 per gallon in 1980 to $1.20 per gallon. With continued R&D in bio-engineered organisms and fast-growing crops, the biofuels program is expected to produce ethanol from waste paper, crop waste, and dedicated crops for under 70 cents a gallon by 2005, competitive with oil at $25 a barrel, its current price. Significant penetration of biofuels is possible in the next two decades.

Proton-exchange membrane (PEM) fuel cells have perhaps the greatest long-term potential for reducing transportation CO_2. Recently PNGV developed an on-board reformer for converting gasoline into hydrogen to run a PEM fuel cell, which would have a 50% increase in fuel efficiency over an internal combustion engine, half the CO_2, and a 99% reduction in conventional pollutants below ultra-low emission vehicle standards. A PEM fuel cell running on ethanol would have virtually no net CO_2

emission. A decade of R&D may be needed to bring costs down and integrate the fuel cell into a commercial vehicle. Maximum efficiency and emissions reductions would come from running the car on hydrogen directly, which will require even more research.

The ultimate low-CO_2 vehicles and the fuels they would use cannot be known today. To ensure that the R&D leads to commercially viable vehicles, a number of programs are needed to ensure that the infrastructure is available to support vehicles that run on non-traditional fuels.

INDUSTRY

The industrial sector consumes about one-third of the nation's energy. The seven most energy-intensive industries—steel, aluminum, petroleum refining, chemicals, pulp and paper products, glass, and metal casting—account for about 80% of the energy consumed in U.S. manufacturing and more than 90% of the hazardous waste. They represent the largest opportunity for reducing industrial CO_2 emissions.

The Department of Energy has formed partnerships with each of these industries to develop visions of energy-efficient, low-polluting, highly competitive "Industries of the Future" and then technology roadmaps to identify the best R&D opportunities. These include advanced materials development, such as ceramic composites; separation technology, such as advanced membranes; catalysis; bioprocessing, biocatalysis, and renewable feedstocks; sensors and controls; and industrial cogeneration of electricity and heat, which can achieve overall efficiencies of more than 80% and could ultimately utilize biomass.

These industries (except chemicals) significantly under invest in R&D compared to the industry averages. What R&D they have devoted to the environment has traditionally been focused on compliance- end-of-pipe treatment and control, as opposed to prevention—since that is how our regulatory system is designed. While increased R&D is needed, if Federal pollution prevention technology development is to achieve maximum industry cost-share, market penetration, and significant greenhouse gas reduction, the Administration must complete its regulatory reinvention revolution, exploring innovative approaches through Project XL, the Common Sense Initiative, and the Environmental Leadership Program.

Traditional point-source controls that address a single waste at a time and only after the waste has been generated must be replaced by prevention-based, innovation friendly strategies. These include basing standards on desired performance, not "best available technology"; focusing on facilities, communities, and ecosystems, not the waste, the media nor the pipe; emphasizing multi-media solutions that address all wastes; emphasizing continuous improvement, not bright-line fixed compliance; expanding the use of information, measurement, and feedback, such as the Toxic Release Inventory; and wherever possibly, using fiscal tools and market mechanisms such as trading schemes and bankable emissions credits. Prevention R&D, as opposed to end-of-pipe R&D, is the key to CO_2 mitigation, and prevention-oriented regulations can help shift private-sector R&D dollars in the industrial sector to the development of low-CO_2 industrial technologies.

BUILDINGS

The buildings sector consumes one-third of the nation's energy and two-thirds of its electricity. Federal R&D into buildings technologies has been remarkably successful. Consider just five technologies developed or advanced by the national laboratories in the past two decades at a cost of roughly $40 million— building design software and advanced lighting, windows, oil burners, and refrigerator compressors. These have provided cumulative net savings of more than $15 *billion* to consumers and businesses, exceeding the $14 billion spent on *all* energy efficiency R&D since 1978. They are today providing more than 10 million metric tons of annual CO_2 savings.

Continued R&D in the buildings sector is likely to prove just as cost-effective. Key near-term technologies include improvements in lighting, superwindows, advanced design software, high-efficiency clothes washing, heat-pump water heaters, gas heat pumps, improved insulation and duct systems, more efficient cooling including gas cooling, solar heating and cooling, and day lighting. Urban heat island mitigation R&D could enable deep and highly cost-effective energy savings in air conditioning, while dramatically reducing smog formation. Relevant R&D includes developing highly reflective roofing and road materials, and modeling the impact of those materials and shade trees on buildings and cities.

Longer term R&D needs include electrochromic glazes for windows, building-integrated PV systems, and PEM fuel cells. In 2010, a building using efficient technologies with electricity and hot water provided by an 80% efficient fuel cell could have no first-cost penalty with well under half the energy of a typical

1990 building and one-tenth the CO_2 emissions.

CAPTURE AND SEQUESTRATION

In addition to the portfolio of R&D options related to less CO2 intensive technologies for energy supply and use, capture and disposal of CO2 offers an additional alternative for reducing atmospheric concentrations of CO2. If major reductions in CO2 emissions are necessary, and global reliance on fossil fuels continues beyond the middle of the next century, then some form of CO2 sequestration will almost certainly be needed as part of the CO2 solution mix. The Climate Technology Initiative, launched under the auspices of the Framework Convention on Climate Change and supported by the US, stresses the need to "assess the feasibility of developing longer term technologies to capture, remove or dispose of greenhouse gases...."

Moreover, a successful program to develop save, low cost greenhouse gas sequestration options should garner bipartisan support for progress on climate change issues by allowing for continued use of fossil fuels while minimizing the direct costs of mitigation programs. If these disposal techniques are sufficiently low in cost, they could also be a means to induce developing country participation in a climate change mitigation program, thereby overcoming another institutional barrier to implementing an effective mitigation program.

A long-term R&D strategy would include demonstration of a number of sequestration options and research into their possible environmental impacts; converting CO_2 into an industrial chemical feedstocks; other novel sequestration options, such as CO_2 fixation by micro-algae; selectively permeable membranes for CO_2 capture; processes for converting fossil fuels and biomass into CO_2 and hydrogen; development of hydrogen infrastructure technology, including transportation and storage; and PEM fuel cells.

As noted earlier, R&D into clean power generation and energy efficiency support many long-standing national goals and have been pursued for years. Carbon dioxide capture and sequestration, however, makes sense on a massive scale only in a greenhouse-gas constrained world. So, at least in this country, this area has been relatively under funded; since 1990 Japan has spent more than 30 times what we have on CO_2 capture and sequestration.

- within a zero-sum constraint toward Federal R&D resources that would necessitate reducing investments in other R&D areas, or

- expand the overall Federal R&D effort

2) Expand current partnerships with industry to focus on key CO_2 objectives through sectoral R&D initiatives in electric utilities, natural gas industry, industrial processes (e.g. Industries of the Future), transportation (e.g. PNGV), and buildings.

3) Lay the R&D foundation for longer-term radical energy system shifts, e.g. a hydrogen-based energy economy or building CO_2 sequestration technologies into the energy system.

4) Fiscal policy adjustments (not contemplated in this paper), e.g., accelerated depreciation for low-carbon technologies, tax credits for low-carbon technology development and deployment.

5) Design legislation to support CO_2 reduction goals, including reinventing environmental regulation to encourage energy efficiency investments as a key compliance strategy. Ensure that expected legislation, such as utility restructing, supports CO_2 goals.

6) Engage in internationally-coordinated R&D efforts, either under the aegis of a negotiated protocol to the Framework Convention on Climate Change or through other mechanisms.

FIGURE 4

DEMATERIALISATION

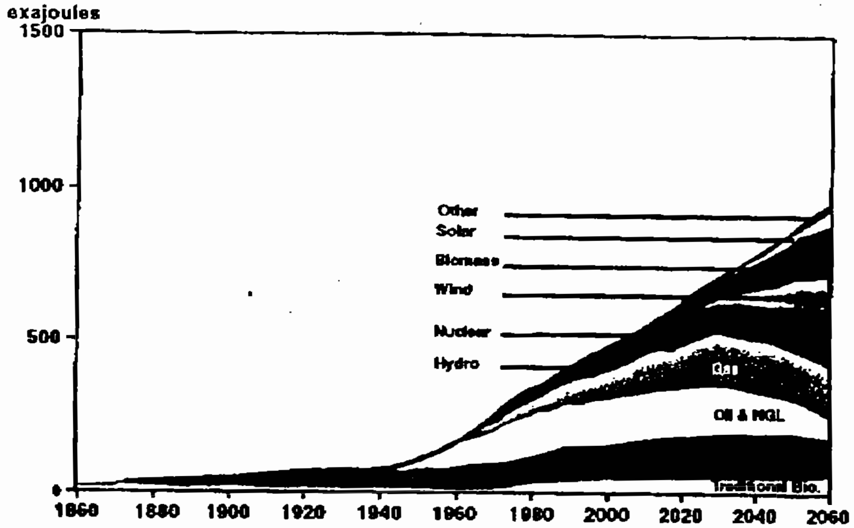
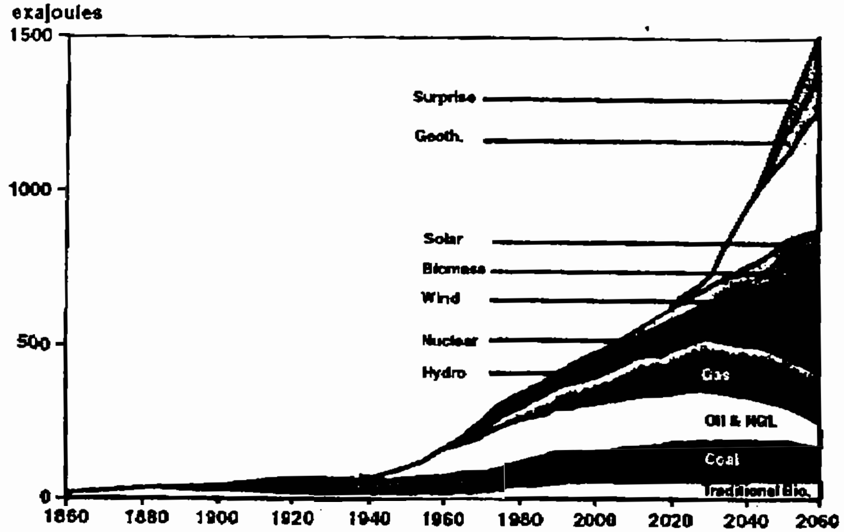


FIGURE 2

SUSTAINED GROWTH



FIGURES 3 and 5

CO2 EMISSION - FOSSIL FUELS

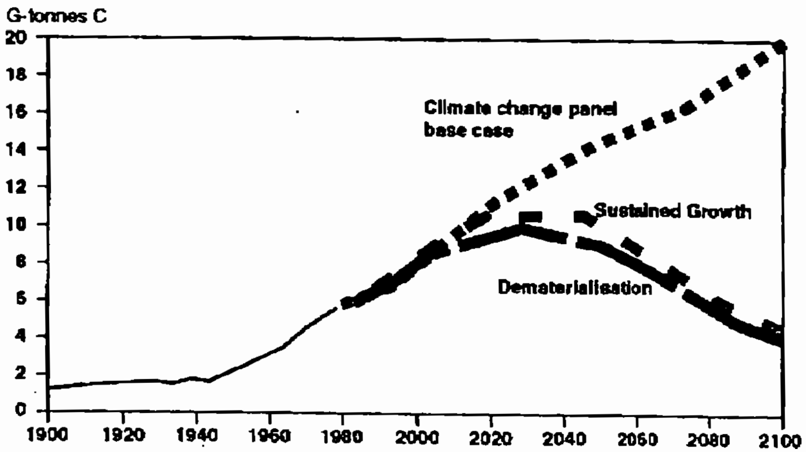
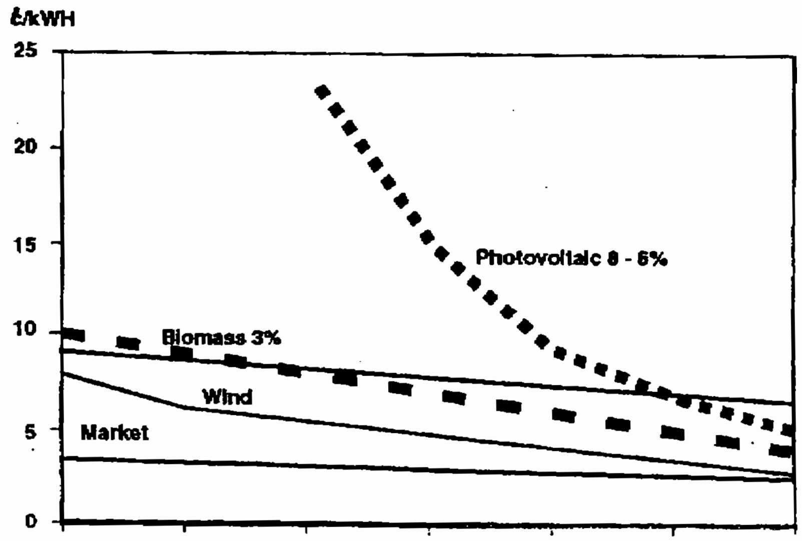


FIGURE 1

COST OF ELECTRICITY



cc: SES
JHF
RP
JF

TO: *See attached list

FROM: OES - Eileen B. Claussen

SUBJECT: Revised Climate Change Paper

Thank you for the valuable comments on the climate change paper, both at our meeting last Friday and subsequently. We have substantially revised the paper, shortening it and incorporating comments received. Please review it quickly and let us know by noon today, November 26, whether there are any serious problems. We will plan to transmit it to the White House for formal distribution this afternoon.

Attachment:
As stated.

Climate Change: U.S. Position for December 1996
(draft 11/26/96 9:00 a.m.)

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I. Introduction and Background

At the second meeting of the Conference of the Parties (COP-2) to the United Nations Framework Convention on Climate Change (FCCC), the United States called for next steps under the Climate Convention for the post-2000 period to include verifiable, realistic and achievable, legally binding medium term targets for developed countries with maximum flexibility that would be implemented through national programs and begin to reduce the threat of climate change consistent with economic prosperity. The U.S. position also underscored the need for all nations, including developing nations, to take actions to limit greenhouse gas emissions. Finally, we called for continued work on a longer-term global concentration goal (e.g. 50-100 years). We continue to believe that this is the approach that will produce a successful outcome at the third session of the Parties in Kyoto in December 1997.

To this end, we would like to call attention again to the conclusions of the IPCC Second Assessment Report, which found that "the balance of evidence suggests a discernible human influence on global climate." The potential for impacts of climate change on natural systems, the economy and the quality of life for future generations is truly significant. The scientific evidence suggests climate change, if unabated, could be detrimental for human health, food security and water resources in many regions of the world. The potential for such impacts makes climate change a "high-risk" problem. In our view, all Parties should act on the conclusion Ministers reached last July: that the science provides a compelling basis for urgent action to address climate change.

Notwithstanding the compelling evidence compiled so far, we must continue our efforts to further develop and refine our understanding of the science of climate change, even as we seek to ameliorate its impacts. Such understanding, coupled with advances in the development and application of new technology, will ultimately enable a more targeted and successful long-term approach to solving this pressing problem.

We believe that next steps must be as cost-effective as possible. Our analyses completed to date suggest that more flexible approaches offer significant cost-saving opportunities, and these must be brought into the Convention's basic framework. Flexibility includes allowing Parties nationally to determine the most appropriate policies and measures to meet the agreed target, and allowing emissions trading and joint implementation between Parties to minimize the cost of reductions.

The United States arrived at this basic framework for a number of reasons. It is clear that the Convention's existing framework of a non-binding "aim" is not working, even though, at the national level, numerous voluntary partnerships with industry are working well. Most developed countries, including the United States, will not achieve the goal of returning emissions in 2000 to 1990 levels. A binding commitment will create a stronger incentive for nations to decide on a realistic target, to make the effort required to meet the target, to ensure a level playing field, and to foster development and deployment of advanced technologies.

Our focus must be on appropriate steps over the medium term, while we continue to develop a longer term goal. We reiterate that short term targets (i.e., before 2010) are unrealistic, and we cannot accept them. Short-term targets would be unnecessarily burdensome to national and global economic growth and development. They could mean that few if any countries would ratify the agreement.

Finally, the United States recognizes the need for global climate change to be addressed on a global basis. As a result, we believe it is imperative that the agreement we reach in Kyoto include an enhanced commitment by developing nations to take further steps to mitigate their emissions of greenhouse gases. While recognizing that developed countries must show leadership in addressing this problem, we believe it is very clear that all nations must be part of the solution.

The Ministerial Declaration in Geneva at the Second Conference of the Parties to the Convention provides climate negotiators with a blueprint for action; we strongly endorse its approach. However, it is now time to develop and agree on concrete proposals.

This paper outlines our view on a number of issues about which we feel strongly, as well as others where several options merit closer scrutiny.

We expect to have further views on specific numbers that should be included in targets and timetables in the future as the results of our continuing analysis and assessment emerge. We hope that other Parties will join us in developing new proposals to meet our environmental and economic goals.

II. Linkages

A number of key variables under consideration are interdependent. This interdependency must be recognized in negotiating our next steps. The United States proposed a three-part framework for the target in Geneva, including that the target be legally binding, that it focus on the medium term, and that it maximize national flexibility in implementation. In addition, the United States believes it will be critical to include developing countries in next steps; finding a solution to the climate change problem will require a concerted global effort. In our view, all four of these concepts are linked, and all four must be included in the legal instrument.

III. Defining the Form of the Target

As noted above, at COP-2 in July, the United States specifically called for focusing negotiations on a legally binding, medium-term emissions target, incorporating flexibility in time and place of implementation. The United States also expressed an interest in continuing to work toward a longer-term concentration goal. We rejected any target which called for an unrealistic near term goal -- and we continue to reject such an approach. We also remain convinced that the target should be designed in manner that allows for adjustment on the basis of new and evolving science. This paper outlines some of our current thinking on the form and structure of the target.

<u>Multi-year Targets</u>

- The United States believes that the target set in the next step should cover a multi-year period in order to accomplish several objectives. First, a multi-year target would smooth year-to-year variability in weather and economic cycles. U.S. analyses of the effects of such variability provide a striking example of the importance of this issue: unusually hot or cold years can change U.S. gross national emissions by as much as two percent -- or about 40 percent of the emissions reductions sought from the energy sector by the year 2000. Because swings in weather, energy prices or economic cycles cannot be predicted with confidence, a single year target would require each country to build in an extra margin of GHG reductions to ensure compliance, significantly and unnecessarily raising the cost.

Second, a multi-year average would give Parties important flexibility to determine the pace at which their emissions budget would be expended over the period (evenly, front-loaded, or back-loaded). This flexibility may be particularly important in helping Parties to reduce their compliance costs in view of differing national circumstances. To provide this flexibility, targets could be set with budgets covering a multi-year period, for example, 2010-2020.

Banking/Borrowing

The United States strongly urges consideration of banking between multi-year average target periods. Such a process would allow emissions below the target in one period to be used to offset higher than target emissions in later periods. Banking of emissions could reward efforts to make reductions in earlier periods. Similarly, we also strongly urge that consideration be given to allowing Parties to borrow against their targets for the next period in order to emit more in a current period. We recognize that borrowing will require that a credible accounting and repayment mechanism be put in place.

Differentiation Among Annex I Parties

A number of Annex I Parties have suggested proposals for differentiation of commitments of the members of this group. While the United States acknowledges the clear distinctions that can be (and are) drawn between different Parties and groups of Parties, we do not believe that developing a complex, formulaic approach which differentiates at an individual Party level is a viable alternative at this stage in the negotiations. To date, we have seen no formula for a differentiated approach which equitably addresses all Parties' concerns.

An effort to define an acceptable differentiation scheme in this legal instrument will likely derail the negotiations, by being too divisive and time-consuming, or by disadvantaging a group of countries which might then choose not to sign or ratify. Either outcome could negate the value of the differentiation effort.

Instead we endorse the adoption of a common approach with respect to targets that maximizes each Party's flexibility with respect to the choice of domestic policies and measures to implement the target, coupled with international trading instruments to minimize and equalize Parties' costs of making reductions. Such an approach would enable the completion of the agreement by December 1997.

Comprehensive Approach

The United States continues to support the inclusion of all greenhouse gases, both sources and sinks, in a comprehensive, verifiable approach to addressing the climate change problem. Gases other than carbon dioxide account for about 30 percent of the radiative forcing from all emissions since the industrial revolution. Furthermore, different gases represent different strategic opportunities from the perspective of effects on the climate system. For example, reductions in methane emissions could yield a lower rate of warming over the next several decades than comparable reductions in carbon dioxide. To forego such a significant source of reduction potential would be both to reduce flexibility and to decrease the cost-effectiveness of the overall effort.

Assuming a comprehensive approach, several issues still require additional consideration, including the different level of certainty with regard to measurement of non-CO2 emissions in various sectors, problems with verification, and the relative importance or weighting to be assigned to different gases. There are also significant technical difficulties concerning accounting of sinks which need to be addressed. We will continue to insist that any agreed approach be fully quantifiable and verifiable, and include appropriate accounting procedures prior to inclusion into the legal instrument. The United States is currently working to address these concerns, and believes that a solution that is technically and politically satisfactory is achievable within the Kyoto timeframe.

IV. Emissions trading and Joint Implementation

The United States believes commitments adopted in Kyoto must be structured so as to allow Parties flexibility to achieve their emissions target as cost-effectively as possible. It is critical that provisions for international greenhouse gas emissions trading and joint implementation be included in the Kyoto agreement in order to meet the new commitments at the lowest cost.

Definitions: Emissions Trading, Joint Implementation, Activities Implemented Jointly

In the U.S. view, some common definitions and distinctions will help clarify discussions in this area. We envision emissions trading as applying between Parties that have assumed a legally binding target for their greenhouse gas emissions. We envision joint implementation as a mechanism to allow credits for emission reductions between Parties with a target as well as between a Party with a target and a Party without a target. Activities implemented jointly (AIJ) is a pilot program to evaluate the viability of project-based reductions in the absence of targets and without credit. While AIJ will provide valuable insights for JI, we see no role for it in FCCC commitments beyond the year 2000.

Emissions Trading Among Parties With Targets

The United States believes that the Kyoto agreement should include provisions for emissions trading among Parties which have assumed a binding quantified emissions target. This includes Parties that assume such a target in the Kyoto agreement, and additional Parties that do so subsequently. Through emissions trading, such Parties would have the opportunity to meet their emissions target at the lowest cost. This is a matter of ensuring environmental gains in the most cost-effective way.

Trading makes sense when costs of controlling greenhouse gas emissions differ among Parties. In this case, it is more cost-effective for the high-cost Party to buy a portion of the emissions budget of the low-cost Party than to undertake those reductions domestically. This rationalization of emissions reductions would be strictly voluntary, and would occur only if both Parties agreed. Under such an approach, the environment is protected, the high-cost Party saves money, the low-cost Party is compensated, and the combined cost of meeting the targets is reduced.

The United States has had success domestically using emissions trading substantially to reduce the costs of complying with clean air standards for acid rain. Experience with international emissions trading has also been gained under the Montreal Protocol on Substances that Deplete the Ozone Layer through the industrial rationalization provision of the London Amendments.

Based on such successes, the United States believes that an effective and enforceable regime for emissions trading among Parties with a binding target should be developed and must be included in the Kyoto agreement. A number of issues need to be addressed regarding how such an international regime might be structured.

Emissions trading, as noted, would take place only between Parties that have assumed a legally binding emissions target. The target will give each such Party an allowable amount of greenhouse gases it can emit during a time period -- in other words, an "emissions budget" for the relevant period, expressed in metric tons of carbon equivalent. In its most basic form, the emissions trading regime would allow one Party to transfer (sell or trade) some of its allowable emissions to another Party. The first Party would then be responsible for meeting its emissions target, minus the amount transferred. The second Party would be responsible for meeting its emissions target, plus the amount transferred.

We anticipate that many Parties will desire to develop emissions trading further, in order to allow private firms or other entities within their borders to engage in emissions trades with counterparts in other nations. In addition to government-to-government trades and firm-to-firm trades, we can also envision mixed transactions, in which firms from one Party buy directly from the government of another Party.

Under such a system, it would be necessary for the firms involved in international emissions trades to report the amounts bought or sold to their respective governments. One Party would then have the responsibility to meet its target as augmented by purchases by its firms. The other Party would have the responsibility to meet its target as reduced by the emissions sold by its firms.

Certain fundamental institutional features are necessary for Parties that engage in international emissions trading to ensure that trading is verifiable, efficient, and environmentally beneficial. These include compatible mechanisms for accurately measuring, tracking, and reporting domestic emissions. Parties also must have the means to track amounts of emissions transferred to or from other Parties, to reduce or augment their national emissions target accordingly, and to ensure the integrity of trades undertaken by their nationals. The United States believes that guidance for these areas must be developed by and agreed to at COP-3 in Kyoto.

Joint Implementation

The FCCC Parties have been engaged in discussions of joint implementation for several years. During this time, support has grown regarding the value of joint implementation involving a Party that is subject to an emission target and another Party that is not (whereby a Party with a target gains credit for taking actions that reduce emissions in a Party without a target). Such an approach has the potential to reduce the first Party's cost of meeting its target, while increasing investment in and diffusion of technology to the second Party.

The United States believes that the Kyoto agreement must include the establishment of a joint implementation regime providing for emissions credits. Such a regime will encourage the rapid development and implementation of cooperative, mutually voluntary projects between partners; encourage private sector investment and innovation in development and dissemination of technologies; and provide an incentive through financial and technical assistance to further the development of non-Annex I country programs to limit increases in greenhouse gas emissions.

In order to realize the potential of joint implementation, the process of developing criteria, currently underway in the Subsidiary Body for Scientific and Technological Advice (SBSTA), must continue. Such criteria will be essential to ensure that joint implementation becomes a credible and significant contributor in solving the climate change problem. The U.S. Initiative on Joint Implementation (USIJI) has been one of the most successful and aggressive programs in the development and application of criteria. We intend to remain active in the further development of criteria (working both in the domestic context of the USIJI and internationally). We reiterate our view that criteria development can be completed prior to the year 2000, in time to include JI credits in national GHG reduction compliance programs.

We continue to stress the importance of three criteria in particular: (1) acceptance by the governments of the participating countries; and (2) the importance of the reporting of data and methodological information with regard to the project, and (3) the need to insure "additionality" (i.e., a reduction in net greenhouse gas emissions as a result of the project).

V. Continuing to Advance the Implementation of Commitments for All Parties (Article 4.1 Commitments)

Recognition is widespread that the threat of climate change is a global problem that can only be overcome through global action. While industrialized countries now account for the majority of the world's past and current greenhouse gas emissions, greenhouse gas emissions are growing most rapidly in the developing countries; emissions there are projected to exceed those of the developed countries by about 2020. The Climate Convention, and the Parties (based on their decisions to date) recognize both realities.

The Berlin Mandate began a process to enable the Parties to take appropriate action for the period beyond 2000. It provides for developed countries to elaborate on policies and measures, and to set quantified emission limitation and reduction objectives for greenhouse gas emissions. For developing country Parties, the Berlin Mandate process will not introduce any new commitments but calls upon Parties to reaffirm existing commitments in Article 4.1 and continue to advance the implementation of those commitments. The Geneva Declaration from the Second Conference of the Parties last July provides that the outcome of the current negotiating effort should fully encompass the remit of the Berlin Mandate.

Two key points emerge from these documents: (1) next steps under the Convention must include all Parties, and (2) actions ultimately taken by developed and developing country Parties should be appropriately balanced, recognizing the common but differentiated responsibilities and respective capabilities noted in the Convention and upheld both in the Berlin Mandate and the Geneva Declaration.

To date, all Parties have been making progress toward implementing their commitments under the Convention, including those related to the submission of first national communications under Article 12. Through the U.S. Country Studies Program, we are aware that many developing countries are already far along in preparing national inventories of greenhouse gas emissions and in developing national action plans. A number of developing countries have also initiated projects under the Pilot Phase for Activities Implemented Jointly.

Beyond these current efforts to implement existing Convention commitments, a wide range of possibilities exist through which we can "continue to advance the implementation of existing commitments" as contemplated by the Berlin Mandate. Much work remains to be done to gauge the level of effort developed country Parties will undertake pursuant to the Berlin Mandate. Still, it is not too early to advance our thinking about the range of possibilities for continuing to advance the implementation of existing commitments, recognizing the need for all Parties to take action.

<u>National Communications/Policies and Measures</u>

While the Parties have adopted guidelines for the preparation of initial communications from developing countries, they have yet to consider options for reviewing those communications. Such a review process could include systematic efforts to assist developing country Parties in identifying and implementing no-regrets and cost-effective options for mitigating greenhouse gas emissions.

The review could seek to identify key sectors and technological options within them. It could also consider the possibilities for promoting voluntary agreements with industry aimed at identifying and encouraging the implementation of "no regrets" measures. Partnership agreements have proven highly effective in the United States at enlisting private sector support for mitigating greenhouse gas emissions, and in helping to capture efficient emissions reductions opportunities that are otherwise obstructed by market barriers.

In addition, we could explore various means through which Parties could obtain both the know-how and the technology needed to implement the options identified.

Next Steps

Beyond these kinds of efforts, we could consider agreeing in the context of the Berlin Mandate negotiations on a specified date in the future by which all Parties would be expected to have quantitative commitments with respect to their greenhouse gas emissions. Two variables might also be considered. First, the date need not be the same for all Parties -- we could envision a schedule for phasing in quantitative commitments. Second, the nature of the quantitative commitments need not be the same for all Parties -- we could also envision establishing different levels of commitment based on various factors, including levels of development.

While it would not be necessary to reach specific agreement now on all issues, it would be important to consider carefully the mandate for such discussions, including when they could begin, when they would conclude and what results should be anticipated.

Another option for consideration would be the development of guidelines for revising the Convention Annexes (that establish which Parties assume which commitments under the Convention), and for considering how better to reflect the common but differentiated responsibilities and capabilities of Parties. In our view, as countries develop to -- and beyond -- a certain point, they must graduate to assume responsibilities commensurate with their development. The present groupings do not reflect dynamic changes in the world that have occurred since 1992 and that will only accelerate in the future.

As noted, the range of possibilities is very wide. It represents a kind of continuum beginning with modest efforts, but potentially extending to those which would bring us significantly closer to a truly global response and to the Convention's ultimate objective. It is as yet too soon to determine precisely where along this continuum we should strive to reach as part of the Berlin Mandate process. Inevitably, this will depend in large measure on the level of action that developed countries are prepared to undertake, and it is not yet clear what that level will be. Still, in our view, it is not too early to think boldly about the possibilities and about how best to position ourselves for the future, recognizing that the steps we take in Kyoto will represent only a second milestone along a much longer path toward the Convention's ultimate objective.

VI. Compliance

The U.S. has called for a legally binding target both to promote a realistic negotiation and to promote compliance with the result. The question is what other elements should be included in the compliance regime, recognizing that, on the one hand, effective compliance is important for both environmental and economic competitiveness reasons and, on the other hand, that too stringent a compliance regime could result in vague commitments and/or scare off countries from joining the agreement.

There are several categories of elements that could promote compliance; they are discussed below.

Structure of commitments

In terms of the target, as a matter of drafting, it needs to be articulated as clearly and quantitatively as possible; as a matter of substance, it should be as objectively measurable as possible. In terms of commitments to advance implementation of Article 4.1, these should, ideally, also be as specific as possible. The desire of developing countries for flexibility could be met by providing flexibility in the choice of implementation options rather than by vague, heavily qualified commitments (such as those in the current Convention).

Ascertaining compliance

Ascertaining compliance will involve a combination of: requirements on parties to monitor and report on their emissions; and an international mechanism to verify such monitoring/reporting. The Convention's current obligations regarding national inventories, national communications, and an international in-depth review process are an excellent basis. The new agreement may require strengthened national and/or international mechanisms. (For example, parties bound by the target could be required to have in place a domestic emissions monitoring system, at a minimum for CO2, at a minimum for specified sources.) There will also be a need to promote uniformity of measurement.

Supporting implementation

Particularly in terms of developing country performance, the availability of sources of technical assistance (such as systematic support for efforts to develop national action plans) and expanded programs aimed at developing, diffusing and deploying climate-friendly technologies could be effective in promoting compliance.

Dispute settlement

The current Convention allows any party to challenge another party's compliance with its obligations before a neutral third party, with a recommendatory result. (Parties can opt for a binding result, but it is not required.) Whether this system would suffice for the new agreement, or whether it would need to be enhanced needs to be considered, taking into account, among other things, the extent to which the target is clear and objectively measurable (which is not currently known). Ways to enhance the system include, for example, requiring the issuance of binding judgments or specifying particular consequences flowing from a binding judgment of non-compliance, such as monetary penalties or trade sanctions.

Additionally or alternatively, the dispute settlement system could be supplemented by a multilateral consultative process, akin to that being developed under the current Convention. Unlike dispute settlement, such a process is considered non-adversarial in that implementation issues can be raised without asserting an actual treaty violation; the parties, rather than third parties, consider issues; and it is multilateral rather than State-against-State.

Non-parties

Development of a compliance regime regarding a global issue also requires consideration of how to deal with non-parties (the so-called "free rider" problem), so that the environmental objective of the agreement is not undermined. Ways to seek to minimize the non-party problem include: the provision of positive incentives for countries to join the regime (for example, assistance, differentiated obligations, allowing opt-outs from certain obligations, side payments, other participatory privileges); through an entry into force clause that requires ratification by countries that account for a particular percentage of global emissions of greenhouse gases; and/or the use of trade measures against non-parties.

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JED

Copy to Alicia, Jeff

Climate Change

October 17, 1996

Dr. Joseph Stiglitz
Chairman
Council of Economic Advisers
Old Executive Office Building
Washington, D.C.

Dear Joe:

Rumor has it that in addition to all your other responsibilities you will be a major architect of the administration's analytic framework for climate change policy analysis (I first heard about this when I testified before the Senate Energy and Resources Committee on September 17th in a hearing that started with testimony by Under Secretary of State Tim Wirth). As you may know, I have spent a great deal of my time during the last six years on studies, reviews, and model comparisons on a broad range of climate change policy issues. If you need any input from me or any of our various working groups (which include most of the analysts working on these issues) at any time do not hesitate to call on me. In fact, I met with Larry Lau today on some projects we are doing together, and told him what was going on in the administration and he said he would also be willing to serve as an external reviewer if that would be helpful to you. Unfortunately, I will not be in Washington again until November 12-15, but hope to see you at the discount rate workshop Paul Portney and I have put together at RFF on the 14th and 15th of November (I was at a brunch with Kenneth Arrow on Saturday and he convinced me he has yet another round of new ideas on that subject).

Sincerely yours,

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THE WHITE HOUSE

Office of the Press Secretary
(Port Douglas, Australia)

For Immediate Release November 22, 1996

REMARKS BY THE PRESIDENT
AT INTERNATIONAL CORAL REEF INITIATIVE EVENT

Port Douglas Park
Port Douglas, Australia

1:45 P.M. (L)

THE PRESIDENT: Thank you very much. Premier and Mrs. Borbidge, Mayor Berwick, Minister Hill and Mrs. Hill, members of the Great Barrier Reef Marine Park Authority, and to Minister Moore and Mrs. Moore. Especially to Alicia Stevens for reminding us what this is all about today. (Applause.)

Hillary and I and our party have had a wonderful visit to Australia. We understand now why it is called the Lucky Country. But we believe that there is more than luck involved here. Today we celebrate the commitment of a people of this country, of the United States and people all over the world to the proposition that we must preserve the natural resources that God has given us. We are here near the biggest, best managed protected marine and coastal area in the world, for a clear reason: Australia has made a national commitment to be good stewards of the land with which God blessed you.

I am especially pleased today, as has already been said, that the government of Australia is honoring the United States by naming a section of the Great Barrier Reef after Rachel Carson. Rachel Carson was the great American environmentalist; she was a marine biologist. Vice President Gore wrote about Rachel Carson: She brought us back to a fundamental idea lost to an amazing degree in modern civilization -- the interconnection of human beings and the natural environment. That interconnection clearly imposes upon all of us a shared responsibility. To preserve a future for our children and grandchildren, we must care for our shared environment. It is a practical and a moral imperative.

We are citizens not only of individuals nations, but of this small and fragile planet. We know that pollution has contempt for borders -- that what comes out of a smokestack in one nation can wind up on the shores of another an ocean away. We know, too, that recovery and preservation also benefits people beyond the borders of the nation in which it occurs. We know

MORE

that protecting the environment can affect not only our health and our quality of life, it can even affect the peace. In too many places, including those about which we read too often now on the troubled continent of Africa, abuses like deforestation breed scarcity, and scarcity aggravates the turmoil which exists all over the world. (Applause.)

I am very proud of the work our two nations have done to preserve our natural heritage. Just as we have been allies for peace and freedom, we must be allies in the 21st century to protect the Earth's environment. Our work together on the International Coral Reef Initiative is a shining example of what we can achieve. Founded in 1994 by Australia, the United States and six other governments, this initiative helps nations and regions to conserve, manage, and monitor coral reefs.

Pollution, overfishing, and overuse have put many of our unique reefs at risk. Their disappearance would destroy the habitat of countless species. It would unravel the web of marine life that holds the potential for new chemicals, new medicines, unlocking new mysteries. It would have a devastating effect on the coastal communities from Cairns to Key West, Florida -- communities whose livelihood depends upon the reefs.

Steadily we are making progress. In this part of the world the ICRI has played a crucial role in slowing the use of cyanide to harvest coral reef fish. Around the world, more than 75 nations and scores of organizations have participated in ICRI programs. Today, with your knowledge and leadership, we are seeing to it that the world's reefs make it into the next century safe and secure. And I thank you for that. (Applause.)

Let me say that our effort to save the world's reefs is a model for the work that we can do together in other environment areas, and there is a lot of work to do. Deforestation is claiming an area of South Korea every year. Let us, together with the United Nations, develop a strategy for the sustainable management of all our forests. (Applause.)

Toxic chemicals and pesticides banned here and in the United States can still find their way into our lives, endangering our land, our water and our children. Rachel Carson, whom we honor here today, helped alert us in the United States to these dangers. Let us now forge a global agreement to stop these toxic substances from being released into the world around us. (Applause.)

Today, thanks to the Montreal Protocol, we are slowing the production and the consumption of chlorofluorocarbons, the chemicals that have been eating a hole in the Earth's ozone layer. We're on our way to closing the ozone hole that threatens Antarctica and Australia. Now we must see to it that this landmark treaty is enforced from one corner

MORE

of the Earth to the other. We need no more new holes in the ozone. (Applause.)

Finally, we must work to reduce harmful greenhouse gas emissions. These gases released by cars and power plants and burning forests affect our health and our climate. They are literally warming out planet. If they continue unabated, the consequences will be nothing short of devastating for the children here in this audience and their children.

New weather patterns, lost species, the spread of infectious diseases, damaged economies, rising sea levels -- if present trends continue, there is a real risk that sometime in the next century, parts of this very parks we are here in today could disappear, submerged by a rising ocean. That is why today, from this remarkable place, I call upon the community of nations to agree to legally binding commitments to fight climate change. (Applause.)

We must stand together against the threat of global warming. A greenhouse may be a good place to raise plants; it is no place to nurture our children. And we can avoid dangerous global warming if we begin today and if we begin together.

If we meet all there challenges, we can make 1997 a milestone year in protecting the global environment. We can do it in a way that encourages sustainable development. One thing we've learned in recent years is that protecting the environment and promoting human progress are not incompatible goals, they go hand in hand. I am very pleased that the United Nations General Assembly will have a special session in New York next year to review our progress in advancing sustainable development since the Earth Summit in Rio.

An Australian folk tale has it that in the beginning the sky was so close to the Earth that it blocked out all the light. Everyone was forced to crawl in the darkness, collecting with their hands whatever they could find to eat. But the birds of that land decided that if they worked together they could raise the sky and make more room to move about. Slowly, with long sticks, they lifted the sky. The darkness passed and everyone stood upright.

If we work together as those birds did, we can preserve our environment for our children, for their children, for generations beyond. Let us lift our sights and ourselves to that great challenge.

Thank you very much. (Applause.)

END

1:52 P.M. (L)

Climate Change

5

Applicability of Techniques of Cost-Benefit Analysis to Climate Change

M. MUNASINGHE, P. MEIER, M. HOEL, S.W. HONG, A. AAHEIM

The authors would like to acknowledge the helpful comments provided by P. Brown, E. Haites, L. Lorentsen, I. Mintzer, J.G. Oh, and R. Raufer.

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SUMMARY

In public policymaking, decision makers routinely compare the perceived costs and perceived benefits of an action. Cost-benefit analysis (CBA) provides an analytical framework that seeks to compare the consequences of alternative policy actions on a quantitative rather than a qualitative basis. The basic principles are well understood and straightforward: For an action to be justified, the costs of the action should be less than the benefits derived therefrom.

Traditional cost-benefit analysis requires that all costs and all benefits be expressed in a common monetary unit to facilitate the comparison. Modern cost-benefit analysis also includes techniques such as cost-effectiveness analysis and multicriteria analysis to analyze trade-offs when some of the benefits and/or costs can be quantified but cannot be expressed in monetary units.

This chapter examines how and under what circumstances CBA can make a contribution to the resolution of the following central questions now facing decision makers about global climate change.

By *how much* should emissions of greenhouse gases be reduced?

Provided costs and benefits can be estimated with adequate accuracy, this question is answerable by CBA: The measures whose marginal costs are less than the marginal benefits should be implemented. The marginal benefits are the marginal damage costs avoided. However, the difficulty of estimating the marginal damage costs of climate change make the practical application of CBA difficult. Although such analyses could be performed from a national perspective, it is a fundamental premise of CBA that the global perspective is the proper one.

When should emissions be reduced?

This question is more complicated because it also involves judgments about uncertainty. If the marginal damage cost (benefit) is known with certainty, and if future technological advances that might significantly change the marginal cost curve are known with certainty, then the timing of abatement is given by that portfolio of implementation options that maximizes the present value of avoided damage costs (benefits) less abatement costs. This is a relatively straightforward calculation; however, neither damages nor costs are known with certainty. Consequently, extensions of CBA – such as decision analysis – are required.

How should emissions be reduced?

This is closely related to the question of how much emissions should be reduced and is directly addressed by CBA. Attempts to determine the extent of reductions must usually consider the specific methods that might be used to reduce emissions. A bottom-up, empirical estimation of the marginal cost curve involves analysis of the broad spectrum of possible abatement options from which marginal cost curves can be derived. Top-down models also require explicit consideration of specific policy or technology options. Clear economic analysis and identification of the most cost-effective abatement options through the use of CBA are critical for practical policymaking.

Who should reduce emissions?

None of the family of techniques considered in this chapter can by itself resolve the question of who should reduce emissions – which involves considerations of equity. However, these techniques do provide a framework for understanding the trade-offs to be made between equity and economic efficiency.

The value of CBA

Practical application of cost-benefit analysis to climate change is difficult because of the global and intergenerational nature of the problem. It is further complicated by the difficulties of valuing some categories of ecological, cultural, and human health impacts. Nevertheless, CBA remains a valuable framework for identifying the essential questions that policymakers must face when dealing with climate change. The CBA approach forces decision makers to compare the consequences of alternative actions, including that of no action, on a quantitative basis. Indeed, the most important benefit of applying CBA may be the *process itself* (which forces a rigorous approach to decision making) rather than the predicted outcome (which always depends on the particular assumptions and techniques used).

5.1 Introduction

In public policymaking, decision makers routinely compare the perceived costs and perceived benefits of an action. Nevertheless, their decisions are frequently made on intuitive and qualitative grounds. Cost-benefit analysis (CBA) provides an analytical framework that seeks to compare the consequences of alternative policy actions on a quantitative rather than a qualitative basis. The basic principles are well understood and straightforward: For an action to be justified, the costs of the action should be less than the benefits derived therefrom.[1] If there are several alternatives, then one ought to pick that option whose benefits most exceed the costs.[2] Traditional cost-benefit analysis requires that all costs and all benefits be expressed in a common monetary unit to facilitate the comparison. Modern cost-benefit analysis also includes techniques such as cost-effectiveness analysis and multicriteria analysis to analyze trade-offs when some of the benefits and/or costs can be quantified but cannot be expressed in monetary units.

The objective of this chapter is to examine how and under what circumstances CBA can make a contribution to the resolution of the central questions now facing decision makers about global climate change:

(1) By *how much* should emissions of greenhouse gases be reduced?
(2) *When* should emissions be reduced?
(3) *How* should emissions be reduced?
(4) *Who* should reduce emissions?

CBA can at least theoretically and conceptually answer the first three questions. The fourth question is one of equity and is not amenable to resolution by CBA, even in simple, traditional applications not complicated by the complexities of the climate change problem.[3]

Section 5.2 defines more carefully what is meant by CBA. The term has come to encompass a wide variety of specific techniques. We also review the basic concepts. In Section 5.3 we examine the unique features of global warming and climate change as they pertain to decision making. Section 5.4 presents a discussion of the application of CBA to the climate change problem in light of these unique features. In Section 5.5 we discuss the key issues: risk, uncertainty, irreversibility, valuation, discounting, equity, and multiple criteria.

5.2 Cost-Benefit Analysis

Cost-benefit analysis is a generic term that presently subsumes a wide body of specific techniques. The method was developed initially as a means to evaluate projects that were limited in scale, geographic extent, and time span. Such traditional project level CBA (see Box 5.1) is too narrow to be relevant for evaluating climate change issues. However, the original technique has been extended to cover applications of increasing complexity. Modern CBA, more widely defined, includes a family of approaches that are more useful in assessing climate change options. Indeed, one of these approaches, cost-effectiveness analysis, has been widely used in climate change studies.

However, to evaluate cost-effectiveness, it is crucial to clarify how the policy target is defined, because there are several options in the global climate change context. Most recent analyses of mitigation costs have focussed on a target based on future emission levels,[4] such as stabilization of the emission of certain greenhouse gases by a given year. However, it might be more relevant to express the targets in terms of concentrations of atmospheric greenhouse gases at some future time.

To change the target for climate policy from emissions to atmospheric concentrations indicates a radically different cost-effectiveness strategy. A stabilization of CO_2 emissions at present levels is not sufficient to stabilize the atmospheric concentrations. Richels and Edmonds (1995) have compared the costs of reaching a particular concentration by 2100 for a variety of strategies. They show that a given concentration in 2100 could be achieved at a considerably lower cost if emissions were not stabilized immediately. The reason is that a more gradual reduction of emissions would avoid the economic shock that would follow a sudden stabilization, enable future advanced technologies to be utilized to a larger extent, and facilitate the postponement of sizable abatement costs.

Another possible target, also affecting the cost-effectiveness of alternative measures, refers to the physical consequences of climate change. Apart from the fact that predictions of these consequences are far more difficult to make than forecasts of emissions and atmospheric concentrations of greenhouse gases, the effects of regional differences would have to be included if targets were based on the consequences. For instance, whether climate change contributes to sea level rise or to an increase in the frequency of rain storms will be of quite different importance to people in Nepal and the Netherlands. In this context, an additional problem arises as to how to assess benefits from abatement of different consequences for different countries.

A further refinement of modern CBA is multicriteria analysis (MCA), a body of techniques developed to deal with the difficulties of economically valuing certain types of impacts (see box). Indeed, even if one attempted to place economic value on certain impacts – such as human life – not everyone would agree that it is appropriate to do so.[5] Moreover, cost-benefit analysis presupposes that the relevant costs and benefits are those that ultimately affect human welfare.[6]

Such views further support the need for MCA-based approaches to decision making. Similarly, there are concerns that monetized values themselves may be inaccurately estimated, and, in any case, such values might not reflect welfare. However, the question of who is affected, and how they will perceive the impact, is an issue that needs careful definition within an MCA analysis.

As noted earlier, conventional CBA cannot provide answers about the optimum level of equity in the same way that it provides answers about the optimum level of economic efficiency. But MCA *can* identify the *trade-offs* between equity

BOX 5.1: TECHNIQUES OF MODERN COST-BENEFIT ANALYSIS (CBA)

Traditional project level CBA

CBA evolved as a technique to evaluate and compare project alternatives. In the early years of its application, there was little concern with externalities, and the analysis took into account just the direct costs of projects and the direct benefits. As it was originally developed for use in industrial market economies, market prices provided appropriate guidance on how to evaluate benefits. When the World Bank began to apply the technique to nonmarket economies, where prices were subject to significant distortions, shadow pricing techniques provided simple corrections. For example, if an oil-importing country kept the domestic price of oil at artificially low levels, CBA would require the use of the border price, not the domestic price, as a basis for valuing oil.

One of the central concepts in CBA is that of discounting, which addresses the fact that costs and benefits may not occur at the same point in time. For example, whereas costly actions to avoid future climate change may need to be taken in the near future, most of the benefits of such actions will occur in the distant future. Discounting enables one to take into account the time value of money. In the case of evaluating simple investment alternatives over shorter time horizons (e.g., 15 years), the use of the opportunity cost of capital as the discount rate to be applied to both costs and benefits is well established and uncontroversial. However, in the case of complex public policy applications, particularly those whose time horizons are very great and involve environmental impacts or the depletion of natural resources – essential characteristics of the global climate change issue – there is sharp disagreement as to what discount rate is appropriate. This issue is dealt with in Section 5.5.2.1.

Cost-effectiveness analysis

As CBA began to be applied to much broader contexts, and particularly to the comparison of alternative *portfolios* of projects and to broad policy choices, the increasing complexity made it desirable to keep the level of benefits constant and to analyze the problem simply in terms of finding the most effective, or "least-cost" option to meet the desired level of benefits. This has the additional advantage that benefits in some cases need not be explicitly valued. For example, in power sector planning, models are applied to identify the capacity expansion plan whose present value of system costs is minimized, given some exogenously specified time path of electricity demand and some exogenously specified level of reliability. As we shall see below, this is the variant of CBA that has seen the most widespread application to the climate change problem, in which one seeks to identify the least-cost option to achieve given levels of greenhouse gas emission reductions, without any explicit attempt to specify what the *benefits* of that level of emission reduction may be.

Multicriteria analysis

The most basic requirement for the application of CBA is that both costs and benefits can be given economic value. This is typically a two-step process: first the costs and benefits must be quantified in terms of the physical measures that apply, and then those physical impacts must be valued in economic terms. Some applications of valuation techniques are likely to be controversial. Putting a value on human health and illness has been a major problem in the practical application of cost-benefit analysis in the past, even in those situations where one can agree on the levels of increased morbidity and mortality that might be caused by some policy or project. Efforts to place economic value on the loss of biodiversity have been equally difficult. Recognizing this problem has led to the development of so-called multicriteria analysis (MCA) techniques. These are expressly designed to deal with multiple objectives, of which economic efficiency may be only one. MCA is a particularly powerful tool for quantifying and displaying the trade-offs that must be made between conflicting objectives.

Decision analysis

MCA addresses certain shortcomings of conventional CBA (like valuation problems), but it does not necessarily deal more effectively with uncertainty. This complication has led to the development of a further extension of CBA known as decision analysis. Here the focus is expressly on how one makes decisions under conditions of uncertainty. These techniques find application in a wide variety of situations, from decision making in the high-risk field of wildcat oil drilling to analysis of financial options. As we shall see below, such techniques provide a rational approach for dealing with irreversibility, one of the more important characteristics of the climate change problem.

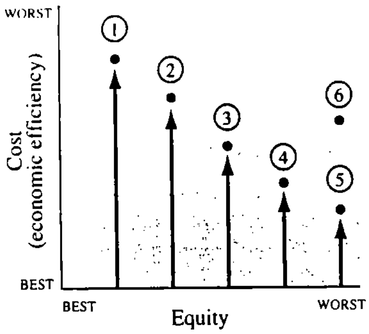

Figure 5.1: Multicriteria analysis.

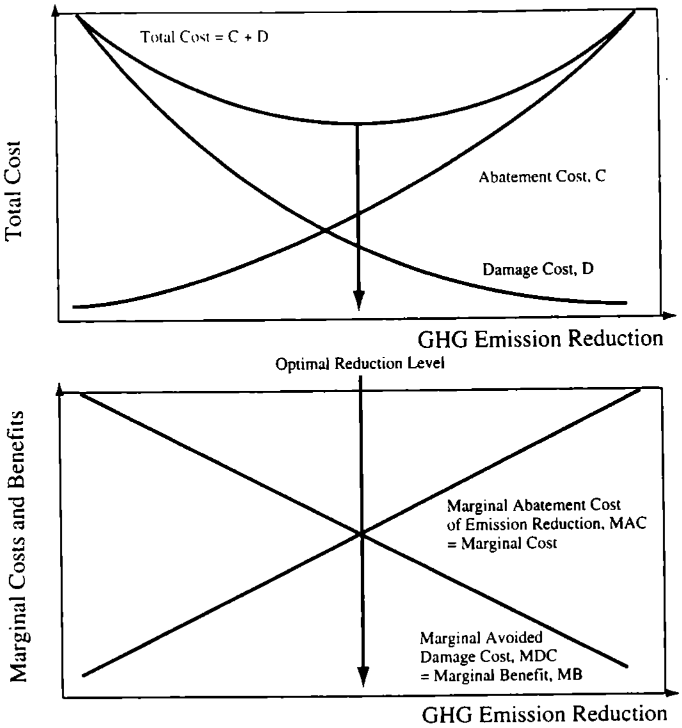

Figure 5.2: Total and marginal costs and emission reductions.

objectives and economic efficiency, as suggested by Figure 5.1. Thus, the best equity result (indicated by option 1, say an equal per capita sharing of the burden of greenhouse gas emission reduction) may have the highest cost, whereas the worst equity result (indicated by option 5, say based on the present distribution of emissions) may have the lowest economic cost.[7] Nevertheless, even MCA requires a quantification or at least an ordinal ranking of the noneconomic efficiency criteria, as suggested in the figure. However, even such a noncardinal ranking may prove problematic when a global issue like climate change requires comparisons across countries and cultures.[8]

More generally, it is increasingly accepted that the pursuit of sustainable development will require recognition of goals related to economic efficiency, social equity, and environmental protection (Munasinghe, 1993). Economic valuation of the impacts of climate change on certain social and environmental aspects (e.g., biodiversity or cultural assets) will be difficult, and MCA-related approaches will be needed to make the trade-offs among otherwise noncompensable costs and benefits.

5.2.1 *Basic concepts*

An economically efficient policy for emissions reduction is one that maximizes the net benefits (i.e., the benefits of reduced climate change less the associated costs of emissions reductions).[9] Economic theory indicates that emission reduction efforts should be pursued up to the level where the environmental benefits of an additional unit of reduced warming (the marginal benefit) is equal to the cost of an additional unit of emission reduction (the marginal cost). Figure 5.2 illustrates the concepts of total and marginal costs in simplified form – the marginal cost at any level of emission reduction is equal to the slope of the total cost curve at the same level.

The shape of the total cost and benefit curves reflects the idea of diminishing returns. Each additional unit of emission reduction will have a higher unit cost: The first 10% reduction can be done cheaply, but the next 10% will cost considerably more, and so on.[10] Thus, the abatement cost curve is upward sloping as shown in Figure 5.2. Similarly, the marginal benefit (avoided greenhouse gas damages) falls as emission levels are reduced. The consequence of the foregoing is that the total cost (TC) has a minimum at the point where the positive slope of the abatement cost curve equals the negative slope of the damage cost curve.[11]

The foregoing analysis ignores many complications. For example, the emission of a unit of CO_2 may give rise to a varying stream of environmental costs that must be discounted to yield a present value aggregate. The environmental damage function may be discontinuous and nonconvex. Because of technological progress, abatement costs may change over time, depending on when the technologies are applied. Similarly, abatement costs may exhibit economies of scale (e.g., mass production of solar photovoltaic cells), resulting in a marginal cost curve that actually declines beyond a certain point. Finally, the abatement costs are net costs, to the extent that certain technologies (e.g., renewables) may produce other (nonclimate-related) benefits and costs – the so-called joint products complication (discussed below).

5.3 Unique Features of Climate Change

Several important characteristics define the context in which traditional CBA is applied. The first is that costs and benefits arise within a time span typically no more than 15 to 25 years, corresponding roughly to the physical life of most projects over which benefits are derived. The second is that the elements of uncertainty are relatively tractable and can often be characterized by probability distributions.

These characteristics are very different in the context of climate change. The relevant time spans extend to a century or more. The uncertainties are extremely large, and few elements of uncertainty are amenable to characterization as probability distributions. Moreover, the cascaded uncertainty implied in each link of the chain of causality greatly amplifies the total uncertainty in the final outcome, namely, the extent of damage caused by climate change.

5.3.1 The complex chain of causality

Figure 5.3 shows the chain of causality. It begins with emissions of greenhouse gases. Although the most important of these is CO_2, it should be noted that there are many other gases that contribute to the climate change phenomenon, including methane and CFCs. Estimates of CO_2 emissions from fossil fuel combustion are fairly straightforward, but emissions from other sources are subject to much higher uncertainty. Moreover, the separation of anthropogenic and natural causes of climate change is much more difficult than in the case of other important regional/global pollution issues (such as CFCs or nuclear wastes). Indeed, the calculus of CBA may be significantly affected by natural events such as major volcanic eruptions.

The first link in the chain of causality (1 in the diagram) is between emissions and the resultant ambient concentration of CO_2 in the atmosphere. Unlike other pollutants, which are subject to complex chemical transformations in the atmosphere,[12] the calculation of the ambient concentration increase that follows from a given increment of emissions of CO_2 is relatively simple. However, because of the role of natural sources and sinks (particularly the ocean), even this calculation is subject to a considerable degree of complexity and uncertainty.[13]

The next link (2), between atmospheric concentration and temperature, is subject to much greater scientific uncertainty. The greenhouse effect itself – the trapping of outgoing infrared radiation – is subject to additional factors that are highly complex, particularly feedback effects, such as those from clouds, that complicate the calculation of equilibrium temperatures.

The subsequent link (3), between temperature increase and physical effects such as sea level rise, involves many different components, all of which are somewhat difficult to calculate. For example, calculating the rise in sea level associated with increases in mean sea temperature proves to be far from simple in some cases (as noted in Volume 1 in the case of the West Antarctic ice sheet). There are also large time lags associated with sea level rise, which are likely to continue for several centuries after the concentration of greenhouse gases has been stabilized. Even more complicated are estimates of how precipitation patterns might change, especially the spatial and temporal distribution of rainfall. Perhaps of even greater concern in developing countries will be the changes in the patterns of extreme weather events, to which they are particularly vulnerable.

If these physical effects (climatic and sea level changes) are understood in general terms, quantifying their impacts on flora, fauna, and human beings (link 4) is much more difficult. To illustrate, suppose it were possible to predict the change in precipitation and temperature regime for some given region.

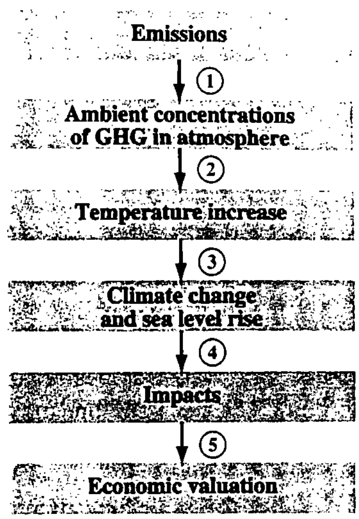

Figure 5.3: The chain of causality.

What can be said about the shifts in vegetation patterns? Although general poleward shifts of vegetation and agricultural production zones can be predicted, quantifying the effect is quite difficult. What is the impact on biodiversity? On wetlands? On the water table? On human communities? Clearly these are very difficult assessments to make.

Finally, to estimate the damage costs, one must be able to value these effects (link 5). Some valuation tasks will be relatively straightforward: For example, the cost of engineering structures to protect against sea level rise is relatively easy to establish, given the existing experience in this field (in such countries as the Netherlands). Other calculations will be more complex, but at least tractable, as, for example, the calculation of increased cooling and decreased heating costs or the impact on electricity demand of increased irrigation pumping requirements associated with drier climates in some regions. But a very large number of potentially important impacts will be very difficult to value – such as the impacts on forests, wetlands, and biodiversity, especially if the physical, biological, and social effects have not been accurately quantified.

5.3.2 Other special features

Beyond the complexity of the causal chain and the high degree of uncertainty surrounding the issue, what makes the analysis of climate change so different from other environmental analysis problems? The main reasons can be summarized as follows.

Greenhouse gases are stock, not flow, pollutants. Many pollutants (e.g., sulphate aerosols) have relatively short atmospheric lifetimes. As a result, the damages they cause are closely related to the current rate of emissions, and reducing emissions at major sources will likely have a relatively rapid impact on atmospheric concentrations and their associated effects. Greenhouse gases, however, have relatively long atmospheric lifetimes, and concentrations therefore respond slowly to changes in emissions. Consequently, the damages they cause are a result of the current atmospheric concentrations that have built up due to all past emissions – in other words, they are related to the stock of the pollutant, not to the current rate of emissions.[14] Similarly, a change in emissions of a greenhouse gas at any time will affect the atmospheric concentrations of this gas, and thus the climate, in all future periods. Therefore, in the context of the climate problem, global climate change is a lagged function of the emissions of the various greenhouse gases. At any time, atmospheric concentrations (or stocks) of these gases depend on the whole history of their emissions up to that time.

To calculate the marginal environmental cost of increased current emissions of a greenhouse gas, one must first calculate the physical impact of such an emission increase on the future atmospheric concentration of the gas. This will depend on the physical characteristics of the gas, which affect how rapidly an increased atmospheric concentration depreciates. There are large differences between different greenhouse gases, with atmospheric lifetimes varying from roughly fifteen years for methane[15] to more than 100 years for N_20 and some CFCs.

Once the impact of current emissions of a greenhouse gas on future atmospheric concentrations has been calculated, one can in principle calculate the effect of the increase in current emissions on future climate development. If one has specified a function which measures the monetary cost of climate change, one may calculate the incremental costs and thus obtain a present value measure of the marginal cost of increased current emissions of a greenhouse gas.

It is clear from the description above that the marginal monetary cost of greenhouse gas emissions is a complex concept. Several assumptions of an economic nature must be made, such as the appropriate discount rate and the monetary costs of climate change for the whole future. In particular, the relative importance of different greenhouse gases is much more complex than is implied by a simple physical conversion index such as the global warming potential (GWP) discussed in Volume 1 of this report. In the context of the climate problem, a reasonable definition of the importance of a greenhouse gas relative to, say, CO_2, is the marginal environmental cost of current emissions of this gas relative to the corresponding marginal cost of CO_2. It follows from the discussion above that the relative importance of greenhouse gases depends on a number of economic assumptions that must be made.[16]

Inertia and irreversibility. Since emissions of greenhouse gases in any one year represent a relatively small fraction of the total global stock, the system has great inertia. This means that even if all emissions went to zero, it would be decades, if not centuries, before the stock of greenhouse gases was reduced significantly. Therefore, decisions about emission levels are effectively irreversible, at least over the 100–200-year timespan of interest. In other words, failure to reduce emissions in the short to medium term may be irreversible in the sense that once the effects of climate change become apparent, it will then be too late to do anything about it.

Global characteristics. Most environmental pollution problems are local or regional in scale.[17] Thus, the benefits of emission reductions generally accrue to the same geographic areas as bear the costs. The damages associated with greenhouse gases, however, depend on the global greenhouse gas concentration, which is largely independent of the regional meteorological patterns that usually define the geographic scope of other transnational environmental problems such as acid rain. Therefore, the distribution of the benefits of emission reduction is global, not local. *Per contra,* even a country that emits no greenhouse gases can incur the damages of emissions by other countries.

Geographical distribution of impacts. Poorer nations are likely to be the most vulnerable to the impacts of climate change, since they lack the resources to protect themselves against sea level rise, extreme weather events, or desertification. In contrast, the impacts of acid rain from emissions in some poorer countries or regions may be concentrated in richer countries[18] (e.g., the effects of emissions from Eastern Europe on western Germany[19]). These richer areas therefore have powerful incentives to promote emission reduction programmes in the source areas, including the provision of financial assistance.[20] However, in the case of greenhouse gas emission reductions, countries such as the U.S. (where there is the *perception* that the *direct* impacts of climate change on the U.S. itself are relatively small) may have fewer obvious economic incentives to reduce emissions.[21] Considerations of humanitarian solidarity and equity alone are unlikely to be sufficient motivators.

Absence of actual impact data. In the case of climate change, unlike almost all other environmental externalities, actual impact data are scarce, and estimates of physical impacts are based entirely on the predictions, judgments, and models of scientists.[22] Only once (or if) climate change does in fact occur, will the impacts be known. The evidence of cause and effect will be difficult to substantiate, because of the likelihood that, at least initially, changes will be incremental. It should be noted, however, that there does exist a significant body of verifiable scientific theory that underlies the estimates and models of scientists.

Nonlinearity. Global climate change is determined by complicated interactions involving a chain of nonlinear linkages (i.e., greenhouse gas emissions, atmospheric concentration, temperature change, climate system feedbacks, and physical impacts). Therefore, climate change phenomena and risks are likely to be much more nonlinear than the relationship between conventional emissions and more local pollution.

Very long time frame. The very long time frames involved in climate change cause some normally external variables to become internal factors of change. For example, the economic impact of sea level rise depends on the size of the population living in low-lying coastal areas, which may decrease once a sea level rise becomes evident. The costs of such adaptation mechanisms may be especially difficult to estimate.

5.4 Cost-Benefit Analysis in the Context of Climate Change

In light of these unique characteristics of the climate change problem, what can we say about the suitability of CBA? How and under what circumstances can CBA make a contribution to the central questions now facing decision makers, in particular:

- By *how much* should emissions be reduced?
- *When* should emissions be reduced?
- *How* should emissions be reduced?

The fundamental problem in applying CBA to the climate change problem follows directly from the chain of causality discussed in Figure 5.3 above: whereas estimating the costs of emission reduction involves the beginning of the chain, estimating the benefits (the avoided damages) involves the very end of the chain. Since there is some level of uncertainty associated with each of the links, estimates at the last stage of the chain are subject to compound uncertainties that may be very large indeed.

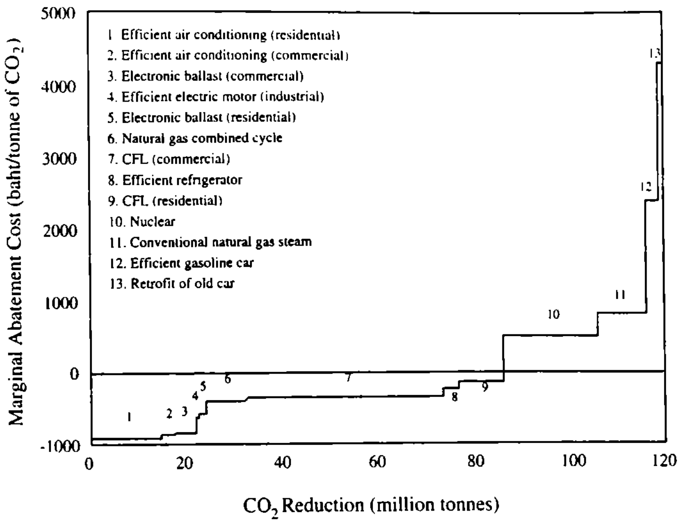

Figure 5.4: The marginal abatement curve for Thailand.

5.4.1 Estimates of the marginal cost curve

Marginal abatement cost (MAC) curves for greenhouse gas emission reductions have been derived for many industrialized countries, but for only a few developing countries.[23] Figure 5.4 shows such a curve for Thailand. This curve is derived by a rank ordering of the individual measures by cost per tonne of CO_2 saved (the height of each block), with the width of each block representing the tonnes of CO_2 so saved. The shape of the MAC curve, when smoothed, is indeed of the type indicated in Figure 5.2, a result confirmed by many other examples.[24] Generally, these studies rely on known or near-term technical options and ignore effects due to joint products (see Section 5.4.4), economies of scale, and capacity building that might reduce the upward slope of the cost curve. Such marginal cost curves depend on discount rate and price assumptions and may evolve over time as options are taken up and new technologies develop. A more detailed discussion of estimates of the MAC curves is contained in Chapters 8 and 9.

What is interesting in these (and other studies[25]) is the significance of "below the line" options (i.e., where MAC is negative but still upward sloping). These are measures that appear to have negative costs associated with them – in other words, when these options are implemented, both costs and emissions go down, relative to the reference case.[26] Compact fluorescent lighting, other energy-efficient devices, and demand-side management measures typically fall into this category, and in developing countries, measures such as reducing electricity transmission and distribution losses or instituting vehicle maintenance programmes also appear here. These, then, are measures that should be implemented in any least-cost energy development strategy, even in the absence of any desire to reduce greenhouse gas emissions. The fact that they are not implemented reflects either market failures, the influence of powerful vested interests, or other factors, such as high transaction costs (which might exceed the potential benefits).[27] Indeed, in developing countries, there may be more such "below the line" options because education and information about the availability and benefits of options in this segment of the MAC curve are less available than in developed countries.

This issue highlights a practical problem for the Global Environment Facility (GEF). The GEF has been set up as the funding mechanism, on an interim basis, to provide financial resources needed by developing countries to meet the "full incremental costs incurred" in complying with their obligations under the Framework Convention on Climate Change.[28] If the GEF is to fund the "incremental costs" of greenhouse gas reduction measures, this presupposes that a baseline can be unambiguously defined, against which such incremental costs are to be measured.[29] But under such a definition, should demand-side management (DSM) programmes that have negative incremental costs – such as energy-efficient lighting – be funded by the GEF?[30]

5.4.2 The marginal benefits curve

It follows from the discussion of the previous section that the level of uncertainty in benefits is much greater than the level of uncertainty in costs. The practical implication of this, depicted in Figure 5.5, is that the optimum point of emission reduction is also subject to significant uncertainty. Whether the marginal benefits curve is MB_1, or MB_2, or MB_3 has a much greater impact on the location of the optimum point of emission reduction (indicated by points A, B, and C) than the much smaller uncertainties in the marginal cost curve. Therefore, with such wide uncertainty about the economic optimum, CBA may not be very helpful. In this situation, an arbitrary level of emission reduction at P has a very high probability of at least meeting the criterion that MB (marginal benefit) > MC (marginal cost). By contrast, C may represent a risk-averse, "precautionary" level of abatement, in which the expected value of MC may be greater than the expected value of MB (see Section 5.5 and Figure 5.10 for further details).

In fact, there exist few if any estimates of the benefits curve, and most of the estimates that do exist are not much more than single point estimates for some presumed level of greenhouse gases in the atmosphere. A complete discussion of benefit estimates is provided in Chapter 6.

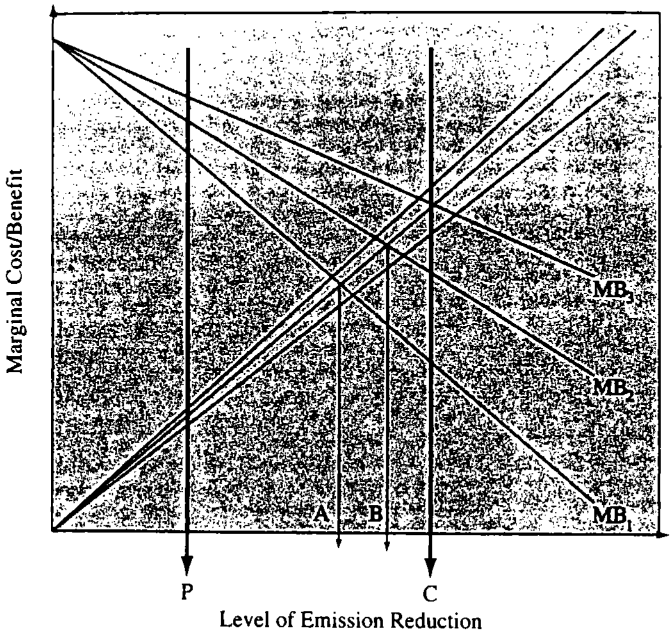

Figure 5.5: Uncertainty in the benefits curve.

A number of estimates (see, for example, Nordhaus, 1994b) suggest that the economic impact of climate change on the industrialized countries is quite small. However, Nordhaus, as well as others, is quick to concede that such results may not apply to developing countries, where typically much larger shares of national income are in agriculture, and much of it in subsistence farming in marginal areas where even small changes in climate may have devastating effects and where the ability of the farming population to adapt may be very small indeed.[31] The types of human settlements most vulnerable to climate change are concentrated in developing countries, including low-income communities, residents of coastal lowlands and tropical islands (such as coastal Bangladesh or the Maldives), populations in areas already significantly affected by desertification, and the urban poor in squatter settlements.[32]

Unfortunately, to date, most of the discussions of impacts of climate change on the developing countries have been qualitative in nature,[33] and there is an urgent need for more quantitative estimates. According to a recent GEF survey of country studies (Fuglestvedt *et al.*, 1994),[34] there are now almost as many studies underway on effects as on mitigation, but it is difficult to ascertain how many of these studies will result in the sort of quantitative information necessary to construct an impact cost curve. Certainly none of the studies and papers published to date for developing countries contains quantitative estimates of the type derived by Nordhaus for the U.S.[35]

5.4.3 Measuring costs and benefits

Most of the work on the benefit (avoided cost) side, and much of the work on the cost side, assumes that the relevant measure by which to evaluate options is loss of GDP. This raises a separate set of questions about the extent to which GDP (or loss of GDP growth) is the appropriate measure.[36] It is well established (Weitzman, 1976; Brekke, 1994) that GDP is not a welfare measure *per se*, but rather a convenient way to aggregate goods and services that clearly contribute to welfare. Nevertheless, Figure 5.6 summarizes some of the estimates that have been made for GDP impacts. Chapter 9 discusses such estimates in more detail.

Since GDP is an imperfect measure of social welfare, it should not be surprising that the cost-effectiveness of policy options can differ significantly when analyzed in terms of their impact on GDP and on social welfare. Recent studies have found this to be the case for industrialized countries such as Norway (Alfsen *et al.*, 1992) as well as for developing countries such as Sri Lanka (Meier *et al.*, 1993; see Table 5.1). The "consumer impact" is an estimate of the impact or social welfare not reflected in traditional GDP measures. At 10-50% of the total, the consumer impact is clearly a significant fraction of social welfare.

Of course, the magnitude of such impacts as those shown in Table 5.1 is a function of how much of the technology is adopted, how soon, and what discount rate is used. The effect of a single 25 MW wind plant will obviously be much less than if a 300 MW wind farm displaces a plant using imported coal in the near term. Generally, what these results do underscore is the need for great caution when interpreting the so-called costs of greenhouse gas emission reductions attributable to specific technologies.

Equally important are the concerns over the extent to which conventional measurements of GDP growth take into account the depletion of natural resources ("green accounting"). For many developing countries this is a particularly important issue, and there is a growing literature suggesting that conventional accounting substantially overstates GDP growth. The corollary is that estimates of GDP impacts of climate change that *fail* to take account of changes in the rate at which natural resources are depleted, or changes in environmental impacts, may be understating the true effect of these impacts.[37]

Some of these problems are evident from the numerical estimates. In Figure 5.6 we display the results of recent studies of the impact of emission reduction strategies on loss of GDP.[38] As is evident, these estimates show considerable variation. Even so, none of these estimates reflects "green accounting" or any margin for no-regrets options, and only one (Glomsrod *et al.*, 1990) takes into account joint products. Most of these studies are national studies. Many researchers argue that unilateral actions by the U.S. or by OECD countries are likely to be less effective than global action, and that unilateral actions are likely to exaggerate the impact on GDP.[39] However, these studies also neglect the benefits of the development of advanced technologies in the market economies, which could then be more quickly adapted in the developing world.

Traditional CBA basically relies on a partial equilibrium analysis, in which only the relevant portion or subsystem of the more complete economic system is studied in depth, and many parameters (and prices) outside this system are taken as exogenously fixed. For questions relating to climate change (whose consequences may have major effects on prices),

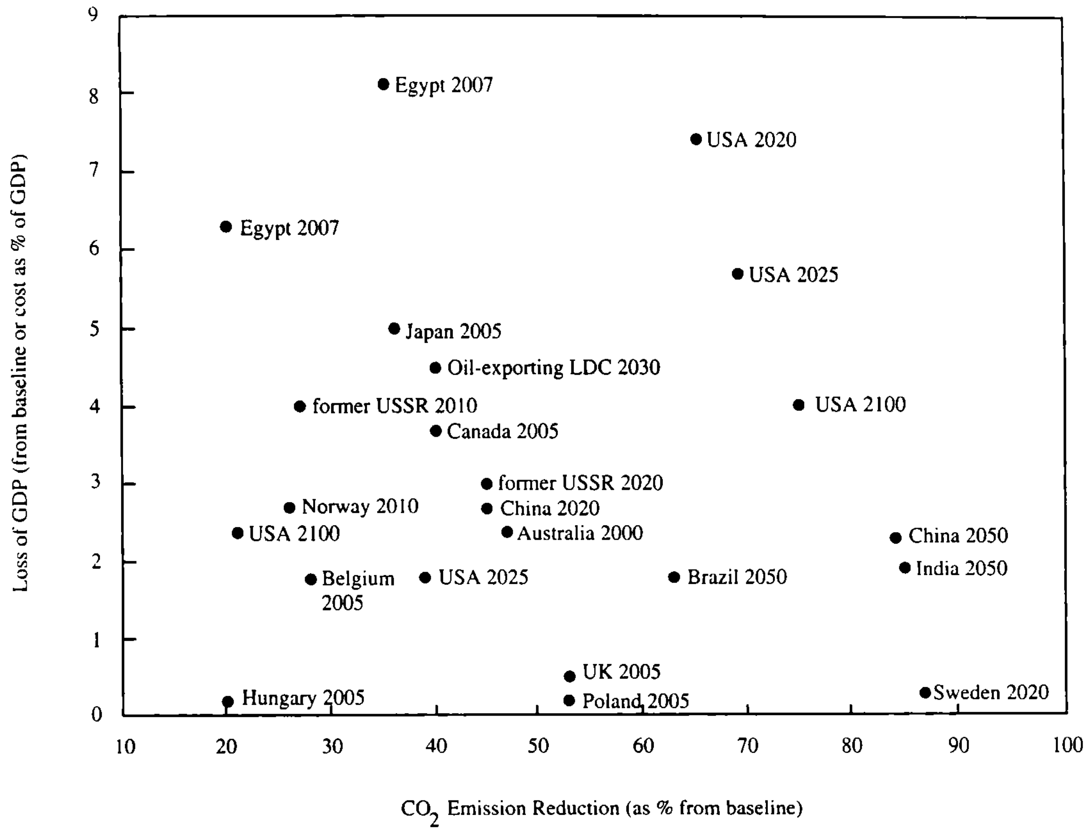

Figure 5.6: Impact of GHG emission reduction on GDP.

Table 5.1. *Welfare losses due to different greenhouse gas abatement options in Sri Lanka (in $/tonne of avoided carbon)*

	No coal	Wind	CFL[a]
Supply cost impact	16	67	-472[b]
Consumer impact	10	66	-66
Total	26	131	-538

aCompact fluorescent lighting.
[b]Negative numbers indicate a benefit.
Source: Meier *et al.* (1993)

the more far-reaching and inclusive general equilibrium approach – in which the properties and relationships of the entire economic system are analyzed – is appropriate. For this reason, computable general equilibrium models are widely used in climate change studies.

5.4.4 The joint products problem

A related question concerns the joint benefits and costs of emission reduction. Options that reduce greenhouse gas emissions may also provide significant changes in other pollutants whose impacts are of a quite different scale. For example, the substitution of renewable energy technologies for coal will reduce not just CO_2 emissions – a *global* benefit – but also SO_2 and particulate emissions, thus bringing a reduction in *local* environmental damages. On the other hand, the increased use of renewable energy technologies (such as hydroelectric generation), which also reduce CO_2 emissions, may also impose new and different local environmental *costs* (such as loss of biodiversity associated with reservoir inundation).[40]

Estimates of the importance of joint benefits and costs vary widely (in part, because valuing the costs and benefits of other environmental impacts may be subject to similar difficulties of valuation and scientific uncertainty as greenhouse gas emissions).[41] A recent study (Alfsen *et al.,* 1992) found that the joint products of carbon reduction (reduction in environmental damages to forests and lakes, health damages, reduced traffic congestion, road damage, etc.), offset about 30-50% of the initial abatement costs in the case of Norway.[42] A British study (Barker, 1993) found that the secondary benefits exceeded the cost of the greenhouse gas abatement measures.

Adding the benefits of reductions in conjoint pollutants to the MB measure is one possibility. The other is to subtract these benefits from the MC measure. Since most of such benefits go to the country that bears the costs of abating the CO_2 emissions, while the benefits of lower CO_2 emissions go to all countries, it follows that the preferred approach is to adjust the marginal cost curves.

5.4.5 The aggregation problem

We now turn to the matter of implementing policy. Consider first Figure 5.7, which depicts the situation faced by a hypo-

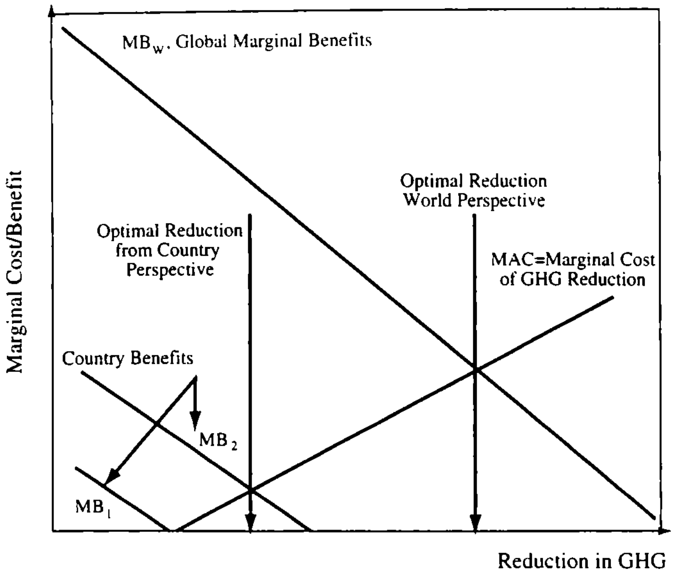

Figure 5.7: The marginal cost and benefits curve for an industrial country.

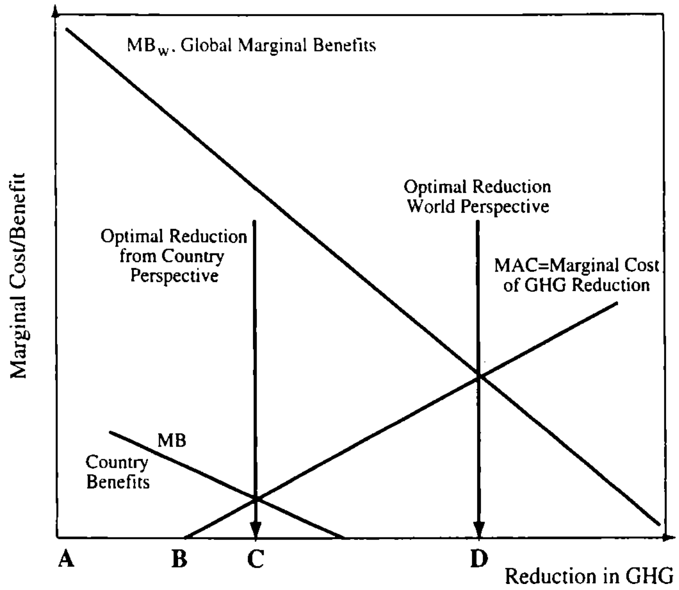

Figure 5.8: The marginal cost and benefits curve for a developing country.

thetical country. Its marginal cost curve is upward sloping, in the manner discussed above. It begins with negative values (the "no-regrets" or "win-win" options), again in the manner indicated earlier.

Suppose Figure 5.7 depicts the situation for an industrialized country, say the U.S. Suppose that indeed Nordhaus is correct in his estimates that the benefits to the U.S. are rather small. If MB_1 were true, then the optimal policy would be to implement only the win-win policies – demand-side management, more efficient end-use devices, economically efficient pricing, and the like. If MB_2 were true from the U.S. perspective, then perhaps only small emission reductions are warranted. We assume, of course, an appropriate adjustment for the evaluation of the benefits of the reduction of joint costs.

However, the benefits of emission reductions are likely to be much higher to the rest of the world, and hence the curve MB_w lies as shown, far above the MB_1 and MB_2 curves. Therefore, when the global benefits of emission cost reductions are taken into account, the optimum level of emission reduction shifts to the right, as shown. How one persuades decision makers in the U.S. (and in other industrialized countries) to take a global perspective is the main question.[43]

Consider now the situation for a developing country (Figure 5.8). Again the global benefits curve lies far above the curve for an individual country. Evidence from empirical studies suggests that a far larger portion of the MC curve is in the no-regrets zone. Several multicountry studies point to this result.[44]

In the case of developing countries, the GEF funding mechanism provides the means for shifting the level of emission reduction undertaken by any specific country to the right. But in what range does the GEF mechanism operate? Conceptually, it should operate in the range CD; that is, it should provide funding only beyond the optimal level from the country perspective. But since the MB curve is so difficult to determine, an easier definition, operationally, is for the GEF to operate in the range BD; that is, from the conventional "least-cost" point that would normally apply, and in which any benefits, even locally, from greenhouse gas reductions are simply taken as zero. For example, wind plants would not normally lie in the least-cost expansion path for an electric utility (if environmental externalities are valued at zero); GEF provides the mechanism to fund such technologies. Yet, in fact, the GEF has also funded projects in the range AB – such as the energy-efficient lighting project in Mexico.[45]

The difference between the optimal level of reduction from the national perspective and that from the global perspective lies at the heart of the practical problem of implementation. A related but different issue – involving equity – concerns one of the premises of CBA, namely that sunk costs and past actions are not relevant. Yet developing countries argue that in the case of the climate change problem, past emissions are relevant, because it is the industrial countries, not the developing countries, that have accounted for the bulk of the anthropogenic greenhouse gases present in the atmosphere (e.g., see Munasinghe, 1991).

5.4.6 Systemic evaluation

The comparison of abatement cost estimates shown in Table 5.2 also points to the importance of systemic evaluation. The cost per tonne of avoided emissions for both wind and the no-coal option are much lower in the Sri Lankan than in the GEF or Indian estimates for the exact same technology. The reason lies in the fact that the incremental cost of, say, wind power, depends on what technology is being substituted, and this will be very different from case to case. For example, in Sri Lanka, imported coal baseload plants largely determine the future system expansion cost. This is much more expensive than in

Table 5.2. *Comparisons of cost estimates for CO_2 abatement (in \$/tonne of CO_2)*

	Study type	Wind	No coal
Sri Lanka	Systemic, single 300 MW wind farm	67-131	16-26
GEF	Generic	116-223	45-89
India	Supply cost	150-600	

Sources: For Sri Lanka, Meier *et al.* (1993); for India, Hossein and Sinha (1993). The generic estimate is from London Economics (1992).

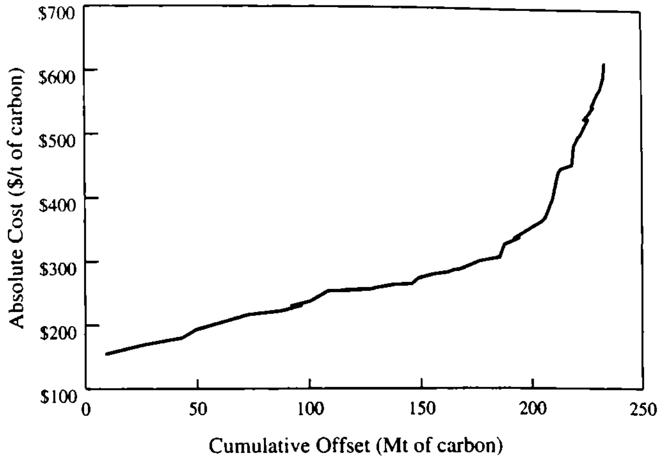

Figure 5.9: Supply cost curve for wind farms in India.

India, which has available relatively large quantities of low-cost domestic coal. Similarly, in the generic cost estimates made by the GEF for no-coal options, the presumed substitute fuel is domestic oil or gas, not imported oil (as is the case for Sri Lanka). The point is that there likely exist very large, country-specific variations in estimates of the cost of greenhouse gas emission abatement through given technologies. Joint costs and benefits that are local in nature will very likely vary even more from place to place.

Another way of making the same point is by noting that single-point cost estimates for many technologies can be quite meaningless, because the supply curve for even an individual technology is not flat. For example, as Hossein and Sinha (1993) have shown in a recent study of wind and hydro for India, the supply curves have the expected classical upward sloping shape as illustrated in Figure 5.9 for the supply cost of wind farms in India. Such static cost curves neglect the counterargument that, in a more dynamic analysis, cost may decline due to economies of scale and technological advances.

5.5 Issues

5.5.1 Risk, uncertainty, and irreversibility

Our knowledge about how anthropogenic emissions of greenhouse gases affect global temperature, what kind of effects a change in global temperature may have, and how efforts to mitigate climate change may work is clearly restricted. How different greenhouse gases react in the atmosphere is not fully understood, and even if exact predictions of the average increase in global temperature could be made, the different regional effects of these increases will be exceedingly difficult to foresee. There is also considerable uncertainty about the economic and social effects of abatement measures, which are decisive for determining their associated costs and benefits.

One cannot, therefore, evaluate climate measures without taking these uncertainties into account. On the other hand, acknowledgment of vast uncertainties should not lead to an inert attitude but rather to the development of rational strategies for acting under uncertainty. Economic analysis under uncertainty aims at developing strategies for decision makers who face uncertainties in future costs and benefits. The uncertainty in the outcome of a variable is often described by a probability attached to each possible outcome. In some cases, the probability distribution is objectively presented; in such cases one normally talks about risk. More often, subjective probability distributions are assumed, in which case one talks about uncertainty.

In Section 5.4 we noted that the level of uncertainty is greater in the benefits curve than in the cost curve (recall Figure 5.5). Figure 5.10 illustrates the practical consequence of uncertainty in a different way. Figure 5.10a depicts the *cost-benefit analysis* of the optimum level of emission reduction. The optimal reduction, R_{opt}, is given by the point at which MB = MC. If the marginal mitigation cost and marginal damage cost functions were known with certainty or if, in the absence of risk aversion, one were to use expected values of the uncertain mitigation cost and damage functions, then the optimum degree of emission reduction would be as shown.

However, given uncertainty in the marginal mitigation cost and damage functions, the optimal emission reduction cannot be determined precisely. It could lie anywhere within a relatively wide range. Uncertainty in the damage function and risk aversion lead one to a "precautionary approach," which requires more stringent emission reductions, lying to the right of the expected value R_{opt} and roughly determined by the intersection of the cost curve and some notional upper envelope estimate of the damage function, as indicated by C in Figure 5.5.

Figure 5.10b illustrates the case in which the damages are sufficiently uncertain that a marginal damage function cannot be defined. The risks associated with various emission levels are considered, using the best available evidence. This information, together with the associated costs, is used to select an emission reduction, R_{ASM}, that constitutes an *affordable safe minimum standard.* Analytically, such a standard would have to be based on a multicriteria analysis.

Finally, in Figure 5.10c the emission reduction R_{AS} is based solely on a scientific assessment. This corresponds to the first of the two views of the sustainability approach discussed in Chapter 6. Since the obligation to avoid harm is absolute, the cost of avoiding harm is irrelevant. The benefits of

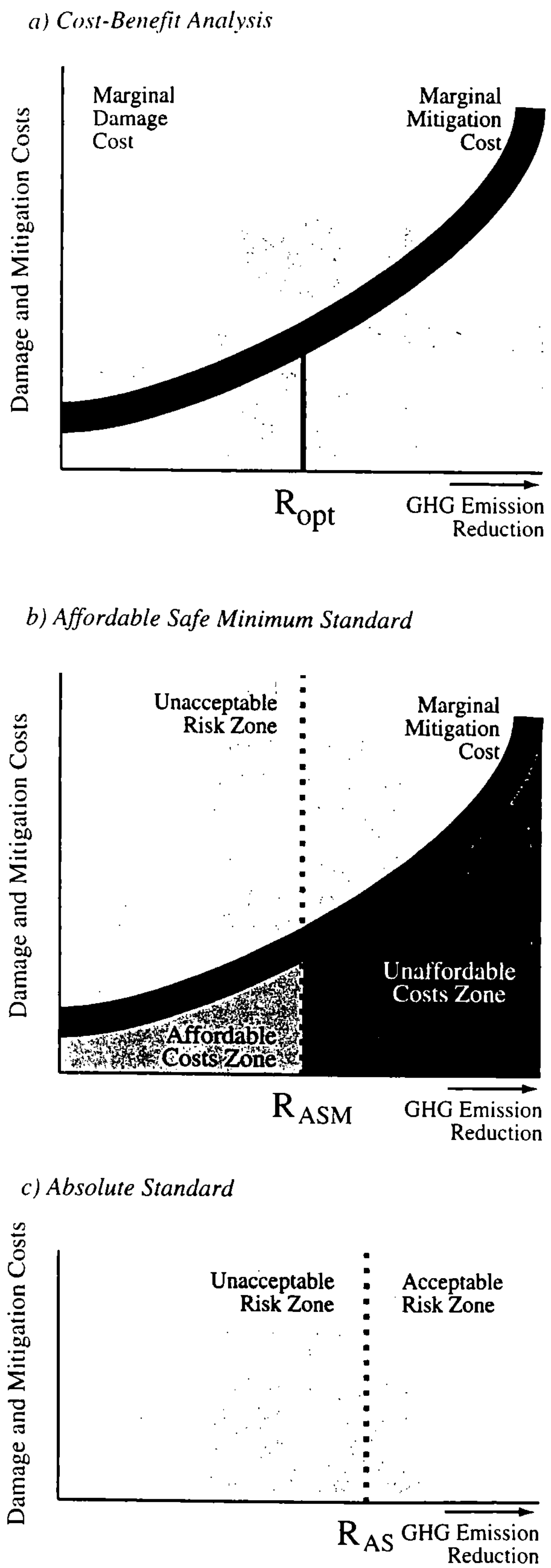

Figure 5.10: Methods and rules for determining mitigation targets.

control are so large that consideration of costs is unhelpful. This can be termed the *absolute standards* approach.

The attitude towards risky outcomes is often expressed in terms of a risk premium, which is the minimum compensation required to accept a lottery with expected return x compared to a certain return of x. Such a premium may be required because the decision maker prefers certain to uncertain outcomes, but may also occur if the net benefit of his investment is nonproportionate in quantity. For instance, suppose a country commits itself to reduce emissions by 100 tonnes and considers two alternative measures. One alternative reduces emissions by 100 tonnes with certainty. The other measure has a 50% chance of reducing emissions by 200 tonnes. Even if the expected reductions are equal (i.e., 100 tonnes), it is evident that a decision maker will prefer the certain alternative unless the uncertain alternative is considerably less costly, as there is a chance of having to impose additional measures if unlucky. Assessments of the uncertainty involved in the analysis of climate change may therefore be of great importance to decision making.

However, given the uncertainty it is also important to emphasize that some actions will be less attractive than others. The mirror of the above argument is that some actions may be acceptable, even with negative net expected benefit, if they reduce the uncertainty. One way to do so is to spread the risk among several measures. Then, if one fails to meet its expected target, another may satisfy the achievements that were expected. The total risk would thus be lower than if all efforts were concentrated on one single measure.

One is scarcely able to account for all the uncertainties involved when analyzing climate change. In some cases it may be equally difficult to assess a probability distribution of a variable as a single expected estimate. Ignorance about certain effects of a measure indicate that they should be left out of the analysis. However, CBA may be of great help to decision making even when limited to effects on which reasonably well-founded value estimates can be provided.

One issue that has attracted a lot of interest in the literature of environmental economics is the problem of making irreversible decisions under conditions of uncertainty. Because of the long atmospheric lifetimes of greenhouse gases, irreversibility is a central characteristic of the climate change problem. A former, more benign climate cannot be reestablished if decisions lead to worse-than-expected climatic outcomes.

To incorporate the cost of irreversible effects in the CBA, a vast amount of information is required about such factors as how the uncertainty evolves over time. Such information is rarely available, but we may assume that increased knowledge about climate change will narrow the range of uncertainties in the future. This possibility also enhances the importance of keeping future options open. This is an extra cost of irreversibility – the so-called quasi-option value – and it suggests that decision makers should follow flexible strategies when faced with uncertainty.

The strategy that leaves most future options open is difficult to determine, however. Investing in abatement of climate change opens possibilities for increasing emissions at a later stage if the effects turn out to be less serious than expected. On the other hand, it reduces the potential use of adaptation. In addition, it is difficult to predict the effect of increased knowledge, especially whether anticipated outcomes will become more certain. When dealing with many of the effects of climate change, ignorance is perhaps a more appropriate concept than uncertainty. Increased knowledge may change ignorance to uncertainty, but the range of possibilities will not necessarily narrow for that reason.

In applying CBA to the global climate change problem, and in particular to the evaluation of alternative policies to optimize net benefits, several major sources of uncertainty need to be considered:[46]

- *Uncertainty about the actual rates of emission.*[47] Most of the many studies cited earlier make assumptions about current and future rates of emissions, taking some "business-as-usual" case as a starting point. Current CO_2 emissions from fossil fuel use may be reasonably well known, but the level of uncertainty increases as one considers levels of possible fossil fuel use in the more distant future,[48] the impact of deforestation,[49] or the emissions of other greenhouse gases such as methane.[50]
- *Uncertainty about the costs of emission reduction.* Again there are significant differences between estimating such costs in electric utility systems (which are relatively well known for conventional technologies) and those elsewhere, particularly for reforestation.
- *Uncertainty about scientific linkages.* As already noted in Section 5.3, there exists a chain of scientific uncertainty (see Figure 5.3). The extent to which these uncertainties can be resolved by further research is itself subject to uncertainty (especially in light of the previously noted fact that by its very nature, *ex ante* verification of models by actual data is difficult). Thus, it is unclear that similar arguments invoked in the context of other environmental problems have validity for global climate change. In contrast, the argument that further understanding of atmospheric chemistry, or of the chemistry of lake acidification, or of the exact nature of forest damage mechanisms was necessary before very costly efforts were undertaken to control SO_2 and NO_x emissions did at least have the merit that data on the actual damage of acid rain could be found.
- *Uncertainty in valuing the costs and benefits of the physical impacts.* Here there may exist quite large variations in the level of uncertainty: For example, evaluating the cost of protective dikes to protect against sea level rise or estimating the opportunity cost of inundated land is subject to significantly less uncertainty than estimating the impact on agriculture or on biodiversity. However, estimating the costs of more extreme climate conditions (e.g., more intense storms) will be very difficult.
- *Uncertainty about the assumptions underlying policy options.* A number of studies, for example, have estimated the impact on greenhouse gas emissions of eliminating subsidies on coal or electricity, using assumed values of price elasticity.[51] General equilibrium models require all kinds of assumptions about the elasticities of substitution: The actual values used in these numerical simulations are either based on historically estimated elasticities or on the judgment of the modeller. In either case, there is uncertainty about the extent to which such values match actual behaviour.
- *Uncertainty about the effectiveness of policies.* For example, the proposition that a certain level of carbon tax will in fact result in a certain hypothesized fuel substitution makes a number of assumptions about the functioning of markets. As noted earlier, the very fact that many apparently "no-regret" options are not being implemented suggests a higher level of market imperfection than economists like to admit, and/or substantially higher transaction costs or discount rates.
- *Uncertainty about joint benefits and costs.* As noted earlier, joint benefits and costs may be a very significant factor in evaluating options for greenhouse gas abatement. However, these joint benefits and costs are also subject to significant uncertainties (and also measurement problems).

The application of valuation techniques is difficult even where the impacts themselves can be quantified with relative confidence. But in the case of global climate change, uncertainties in economic valuation techniques may be significantly smaller than the *scientific* uncertainties that surround the impacts of increasing concentrations of greenhouse gases. Advocates of immediate mitigation action to reduce emissions argue that even if the probabilities of some of the important impacts are unknown and subject to great uncertainty, they are not zero. Low probability/high impact events are especially complex to model, and concern about such events may also provoke extreme risk-averse behaviour. Further, the process of climate change, once underway, will be irreversible (at least during a period measured in centuries), and the damages that may result are so catastrophic that action may be warranted even in the absence of more precise scientific knowledge about the impacts.

A good analogy is a nuclear power plant accident. The Chernobyl incident notwithstanding, the risk of a catastrophic accident is extremely small. But the cost of a major accident is undoubtedly very large. Both the probabilities[52] and the costs of the impacts are very difficult to estimate. But even if one could agree on appropriate values to use, and one were able to calculate an expected value, decision making on the basis of the expected value may still not reflect the preferences either of the public or of decision makers. The consequences of even an extremely unlikely event may be perceived as so undesirable (especially in the case of extreme risk aversion), that "normal" decision rules may simply not be viewed as appropriate. In other words, cost-benefit analysis must deal not just with expected values, but also with the risk preferences of the decision makers and those they represent.

The traditional and simple way of incorporating uncertainty considerations in CBA has been through sensitivity analysis. Using optimistic and pessimistic values for different variables can indicate which variables will have the most pronounced effects on benefits and costs. Although sensitivity analysis need not reflect the probability of occurrence of the upper or lower values, it is useful for determining which variables are most important to the success or failure of a project. Indeed decision makers often assign probabilities (even if only implicitly) to the various outcomes. Admittedly, the sheer magnitude of the costs of catastrophic climate change will make the sensitivity analysis problematic.

One might note that for certain types of uncertainty, something akin to risk insurance is available in the form of futures and options markets. For example, one can hedge against uncertainty in the future price of oil by transactions in the oil futures markets, but their efficient functioning depends on there being some balance between those who are buyers of oil (who are primarily interested in protecting themselves against a rise in the price), and sellers of oil (who are interested in protecting themselves against a fall in the price).[53] (See Box 5.2.)

Finally, extreme uncertainty might also influence the nature of the economic instruments employed for policy purposes. For example, a price-oriented mechanism (such as a carbon tax) which limits economic dislocation might be preferred over a quantity-based mechanism (such as tradable permits) in a situation where there are both uncertain control costs and an uncertain environmental response (see Lave and Gruenspecht, 1991).[54]

5.5.2 *Valuation*

The robustness of a cost-benefit analysis depends critically on how reliable the values attached to each item are. The prices of marketable goods and services express social values as long as the goods in question are not rationed and there are no externalities.[55] For nonmarketed goods and services, such as many environmental services, values have to be estimated in order to aggregate costs and benefits and obtain an overall evaluation of choice of policy. Estimated prices may depend on the methodology chosen to create them, and one should therefore interpret with caution results which include such prices.

One reason why avoiding climate change may have a value is that climate change will cause a change in economic activities. Sea level rise will force people to move, for example, or more turbulent weather conditions may increase the need to rebuild damaged structures or replace damaged materials. A second reason is that people attach subjective values to the climate where they live – values that are to some extent reflected in the notions of "good" and "bad" weather.

However, it is difficult to assess these values. To simplify somewhat, one may base an estimate on the anticipated costs of achieving a certain target at observed market prices: for instance, the minimum abatement cost of attaining the same level of greenhouse gas emissions as a previous year. Alternatively, one may estimate the willingness to pay for reaching such a target. In neither of the cases, however, would one be able to assess the benefits in terms of avoided future damages.

Valuation of environmental effects in CBA may be helpful in attaining cost-effective decisions. However, the valuation should be based on a reasonably well-founded methodology. Speculative assumptions will not contribute to decision making. A measure that yields negative net benefits according to an analysis may be worthwhile if effects that are assumed to be positive but not explicitly valued in the calculation are well documented. Decision makers will normally manage to consider more than one measure simultaneously. CBA usually simplifies the decision by aggregating several effects, but there is no necessity for all effects to be aggregated into one single measure.

There are several fundamentally different types of costs and benefits that must be addressed, each of which requires somewhat different approaches to quantification and valuation:

- *Mitigation actions taken before the actual impacts are observed.* These are primarily a matter of reducing emissions or of removing greenhouse gases through reforestation. The vast majority of the applications of cost-benefit analysis have addressed the question of how best to achieve given levels of emission reduction. Valuation issues generally do not arise in this category.
- *Costs of mitigation actions taken after impacts become apparent.* These will necessarily occur in the future, and would be undertaken only if (1) climate change actually does occur and (2) climate change does indeed result in specific impacts. The cost of dikes to prevent inundation of coastal areas is a typical example in this category. Based on actual experience (such as in the Netherlands), the cost of such mitigation actions are relatively easy to establish.[56] Climatic engineering options, such as painting roads and roofs white or putting particles into the stratosphere also fall into this category. Again, there are few valuation issues here.
- *Costs (and benefits) of adaptation.* Society will adapt with varying degrees of pain to many of the impacts of climate change – indeed, society has already adapted to changes in climate that have occurred in the past. For example, climate change will affect crop yields and may result in poleward shifts in the distribution of cultivated land. Some areas will gain, and some will lose, and the consequences become an equity issue (between regions and countries) as much as a cost issue. Estimates of net losses for U.S. agriculture, for example, suggest a tolerable impact for the U.S. as a whole, but significant regional variations.[57] Some of the costs of adaptation will vary, depending on *ex ante* actions (e.g., the development of drought- or saline-resistant crops).[58]
- *Costs (and benefits) of nonadaptation.* In some cases, adaptation may not be possible or the cost of mitigation may be higher than the loss incurred in its absence. For ex-

BOX 5.2: APPLICATIONS OF DECISION ANALYSIS

Option analysis

In conventional CBA analysis, the usual decision rule is to take some action if the expected benefits exceed the expected costs. Depending on the degree of irreversibility present, a more appropriate rule is to take the action when benefits exceed costs by an amount at least equal to the value of the forgone option. Suppose some investment depends on some assumptions that are subject to great uncertainty – such as future world oil prices. If one makes an investment decision that is largely irreversible – such as building a large hydroelectric power project – then one loses the flexibility associated with waiting to learn more about the factors that affect oil prices. Preserving that flexibility has some economic value, namely the so-called option value. In financial and commodity markets such options to buy (and sell) are traded, with option prices determined by the market itself. But option value theory is now being applied to other fields involving capital-intensive investments, such as power generation.[1]

In applying these concepts to the climate change problem, there are many key differences. First, in one sense the problem is exactly opposite to that faced by, say, the power sector. In climate change, one loses flexibility if one does *not* make short-term investments to reduce greenhouse gas emissions. However, investment in reductions now is not free: Resources have to be diverted from other uses, and better emission technologies may be available in the future. Thus to some extent, committing now to current technology restricts the option to use better technology later. Second, unlike the financial and commodity context, there is no marketplace to set the value of the option.[2]

Decision analysis and hedging strategies

Among the early attempts at applying decision analysis to the climate change problem are those of Manne and Richels,[3] who have developed an approach for determining the optimal hedging strategy. The paradigm they use is that of a portfolio of insurance options:[4] What combination of insurance should be bought, if indeed any at all? What portion goes to R&D to resolve scientific uncertainties? What portion goes to the development of new supply and conservation technologies to reduce abatement costs? And what portion goes to immediate abatement of emissions? In particular, they focus on the value of information[5] and on how much accuracy is needed in climate modelling and impact assessment. Clearly, with *perfect information,* the best course of action can be charted immediately, and there is no need to hedge bets. Manne and Richels conclude that the need for precautionary near-term emission reductions is inversely related to the sustained commitment to R&D to develop better climate information (which reduces the need to hedge against an uncertain and potentially hostile future). However, given the inherent predictive uncertainty of climate change (and in particular the reliability of indicators), the limitations of such approaches need to be recognized.

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[1]See, for example, Crousillat and Martzoukos (1991). This study reviewed power sector investment decisions in Costa Rica, Hungary, and West Africa. For a general review, see Dixit and Pindyck (1994).

[2]A marketplace might emerge if a tradable emission permit system were to be instituted. Chao and Wilson (1993) outline a means of using option values to quantify the flexibility associated with the purchase of a tradable emission permit instead of fixed capital investment in control technology.

[3]See, for example, Manne and Richels (1992).

[4]Lave (1991) notes that the concern about global climate change is not concentrated just in the rich nations but in the upper income groups in those nations. These are the same groups that voluntarily purchase insurance to protect themselves against other losses, such as those related to health, floods, and earthquakes. Persuading poor people to buy flood or earthquake insurance is exceptionally difficult even in the developed countries.

[5]The value of information under uncertain conditions is a concept much used in the private sector. For example, before embarking on the expensive proposition of drilling a wildcat well, oil drillers must decide how much ought to be spent on much less expensive prior survey work: Will general magnetic surveys suffice or are more expensive seismic surveys needed? Neither yields perfect information. For details of how such decision-theory models are applied in this field, see, for example, Newendorp (1976).

Table 5.3. *Potential impacts to be valued (for the U.S.)*†

Systems	Potential Impacts
Forests and terrestrial vegetation	Migration of vegetation Reduction in inhabited range Altered ecosystem composition
Species diversity	Loss of diversity Migration of species Invasion of new species
Coastal wetlands	Inundation of wetlands Migration of wetlands
Aquatic ecosystems	Loss of habitat Migration to new habitat Invasion of new species
Coastal resources	Inundation of coastal development Increased risk of flooding
Water resources	Changes in supplies Changes in drought and floods Changes in water quality + hydropower production
Agriculture	Changes in crop yields Shifts in relative productivity and production
Human health	Shifts in range of infectious disease Changes in heat-stress and cold-weather afflictions Changes in fertility due to stress
Energy	Increase in cooling demand Decrease in heating demand Changes in hydropower output
Transportation	Fewer disruptions in winter transportation Increased risk for summer inland transportation Risks to coastal roads
Weather-related damages	Damages related to changes in the frequency and severity of extreme weather events like storms

†Systems and potential impacts as listed in OTA (1993), except for weather-related damages.

> ample, in some areas, the cost of construction of dikes may be far higher than the value of the land lost to coastal flooding; in such a case, the relevant cost to be estimated for purposes of CBA is the value of the land lost.

It is thus in the third and fourth of these categories that valuation issues arise. Table 5.3 lists the specific categories of impacts that may be encountered as a result of global climate change.

Conceptually, the total economic value (*TEV*) of a resource consists of its use value (*UV*) and non-use value (*NUV*).[59] Use values may be broken down further into the direct use value (*DUV*), the indirect use value (*IUV*), and the option value (*OV*) (potential use value).[60] One needs to be careful not to double-count both the value of indirect supporting functions and the value of the resulting direct use. One major category of non-use value is existence value (*EV*). Thus

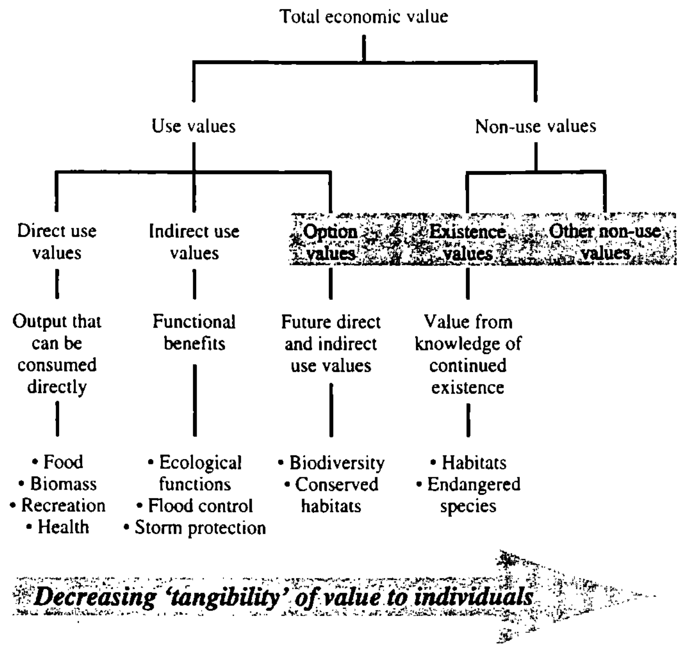


Figure 5.11: Categories of economic values attributed to environmental assets.

$$TEV = UV + NUV$$

or

$$TEV = [DUV + IUV + OV] + [NUV]$$

Figure 5.11 shows this disaggregation of *TEV* in schematic form. Below each valuation concept, a short description of its meaning and a few typical examples (based on a tropical rainforest) of the environmental resources underlying the perceived value are provided. Option values, non-use values, and existence values are shaded as a caution that some ambiguities are associated with defining these concepts. (As shown in the examples, they can spring from similar or identical resources, and their estimation can be interlinked also.) However, these concepts of value are generally quite distinct. Option value is based on how much individuals are willing to pay today for the option of preserving the asset for future (personal) direct and indirect use (see Box 5.3). In the context of uncertainty, quasi-option value is said to define the value of preserving options for future use in the expectation that knowledge – about the potential benefits or costs associated with the option (see Pearce and Turner, 1990; Fisher and Hanemann, 1987) – will grow over time. This approach may be quite relevant, given the great uncertainties associated with climate change. Existence value is the perceived value of the environmental asset unrelated either to current or optional use (i.e., the value it has simply because it exists). A variety of valuation techniques may be used to quantify the above concepts of value.[61]

The basic concept of economic valuation underlying all these techniques is the willingness to pay (WTP) of individuals for an environmental service or resource.[62] As shown in the box, valuation methods can be categorized according to which type of market they rely on and by considering how they make use of actual or potential behaviour.

BOX 5.3: TAXONOMY OF VALUATION TECHNIQUES

	Type of Market		
Type of Behaviour	Conventional market	Implicit market	Constructed market
Based on actual behaviour	Effect on production Effect on health Defensive or preventive costs	Travel cost Wage differences Property values Proxy marketed goods	Artificial market
Based on intended behaviour	Replacement cost Shadow project		Contingent valuation

Effect on production. An investment decision often has environmental impacts, which in turn affect the quantity, quality, or production costs of a range of productive outputs that may be valued readily in economic terms.

Effect on health. This approach is based on health impacts caused by pollution and environmental degradation. One practical measure related to the effect on production is the value of human output lost due to ill health or premature death. The loss of potential net earnings (called the human capital technique) is one proxy for forgone output, to which the costs of health care or prevention may be added.

Defensive or preventive costs. Often, costs may be incurred to mitigate the damage caused by an adverse environmental impact. For example, if drinking water is polluted, extra purification may be needed. Then, such additional defensive or preventive expenditures after the fact could be taken as a minimum estimate of the benefits of mitigation beforehand.

Replacement cost and shadow project. If an environmental resource that has been impaired is likely to be replaced in the future by another asset that provides equivalent services, then the costs of replacement may be used as a proxy for the environmental damage – assuming that the benefits from the original resource are at least as valuable as the replacement expenses. A shadow project is usually designed specifically to offset the environmental damage caused by another project. For example, if the original project was a dam that inundated some forest land, then the shadow project might involve the replanting of an equivalent area of forest elsewhere.

Travel cost. This method seeks to determine the demand for a recreational site (e.g., number of visits per year to a park) as a function of variables like price, visitor income, and socioeconomic characteristics. The price is usually the sum of entry fees to the site, costs of travel, and opportunity cost of time spent. The consumer surplus associated with the demand curve provides an estimate of the value of the recreational site in question.

Property value. In areas where relatively competitive markets exist for land, it is possible to decompose real estate prices into components attributable to different characteristics like house and lot size, air and water quality. The marginal WTP (willingness to pay) for improved local environmental quality is reflected in the increased price of housing in cleaner neighbourhoods. This method has limited application in developing countries, since it requires a competitive housing market, as well as sophisticated data and tools of statistical analysis.

Wage differences. As in the case of property values, the wage differential method attempts to relate changes in the wage rate to environmental conditions, after accounting for the effects of all factors other than environment (e.g., age, skill level, job responsibility, etc.) that might influence wages.

Proxy marketed goods. This method is useful when an environmental good or service has no readily determined market value, but a close substitute exists which does have a competitively determined price. In such a case, the market price of the substitute may be used as a proxy for the value of the environmental resource.

Artificial market. Such markets are constructed for experimental purposes, to determine consumer WTP for a good or service. For example, a home water purification kit might be marketed at various price levels, or access to a game reserve may be offered on the basis of different admission fees, thereby facilitating the estimation of values.

Contingent valuation. This method puts direct questions to individuals to determine how much they might be willing to pay for an environmental resource, or how much compensation they would be willing to accept (WTA) if they were deprived of the same resource. The contingent valuation method (CVM) is more effective when the respondents are familiar with the environmental good or service and have adequate information on which to base their preferences. Recent studies indicate that CVM, cautiously and rigorously applied, could provide rough estimates of value that would be helpful in economic decision making, especially when other valuation methods are unavailable.

Source: Munasinghe (1993).

Valuation techniques obviously need to be selected with some care, and in particular one must recognize that a given valuation technique may not necessarily capture the entire value. For example, if the replacement cost approach is being used to value the loss of forest area being inundated by a dam, it would likely capture only the *use* value. The value of biodiversity loss involved in the loss of primary forest, or a developed ecosystem, may not be included.[63]

We note that these valuation techniques have been developed for more conventional environmental impact analysis and would require significant modification and/or careful interpretation when applied to issues connected with global climate change (e.g., long-term intergenerational impacts, biodiversity loss, welfare comparisons across cultures or where there are wide gaps between gainers and losers, etc.). Nevertheless, whatever the difficulties, the importance of valuation remains, and the development of better techniques should be viewed as an important item in the overall climate change research agenda. Certainly, ignoring an impact because it cannot be satisfactorily valued carries high risk and is one of the reasons for the use of MCA (see below).

5.5.2.1 *Discount rate*

We noted in the introduction that CBA requires a very specific and explicit way of dealing with time. The first principle is that past (or "sunk") costs are ignored, based on the premise that, since past decisions cannot be changed, they have no bearing on decisions regarding the efficiency of resource use that are to be made in the present or in the future.[64]

The second principle is that a discount rate is applied to future costs and benefits to yield their present values. The issue of choosing an appropriate discount rate has been discussed in the context of general CBA for many years (Dasgupta *et al.*, 1972; Harberger, 1976; Little and Mirrlees, 1974; Sen, 1967). The long-term perspective required for sustainable development suggests that the discount rate might play a critical role in intertemporal decisions concerning the use of environmental resources (Arrow, 1982). We briefly discuss below several key issues relating to discount rates. The topic is dealt with more fully in Chapter 4.

Compared with most other economic investment decisions, the time perspective of measures aimed at mitigation of climate change is considerably longer. Cline (1992) suggests a 200-300-year time horizon for climate policy decisions, whereas investments in economic activities seldom need more than a 25-year horizon. This longer time horizon makes assumptions about how the economic and the environmental systems will develop and the discounting of future values critical to the evaluation of measures.

The discount rate denotes the social opportunity cost of capital. It reflects the net impact on total social benefits if one unit of present output is withdrawn from consumption and instead is invested elsewhere (for instance, in production or abatement). The criterion for optimal social and economic development is that the marginal total benefits from the different investments should be equal regardless of what the investments are aiming at. In other words, the social discount rate should be equal for all investments. If not, it would be possible to reallocate resources and attain a higher social benefit without any cost. Thus, the discount rate expresses a condition for dynamic (or intertemporal) efficiency.

The discount rate also provides a signal to decision makers who evaluate single projects or measures to take decisions in accordance with dynamic efficiency (over time). Even if one accepts the requirement to apply the same discount rate for marginal projects within a given time period, there are many potential optimal levels of the discount rate. This level depends, *inter alia*, on the social preferences about present versus future consumption that may be reflected in an intertemporal welfare function. The formulation of this function has been the subject of an extended debate in which questions about intertemporal comparisons as well as the current distribution of welfare have been raised.

It is worth emphasizing that, although externalities related to climate change will affect the social rate of discount, it is not sufficient merely to adjust this discount rate to take full account of climate change in a CBA. One must include also the "price" of the environment, which may increase substantially over time. As a consequence, future impacts from climate change may be quite important to present day decisions, even in "discounted terms": A 5% increase in the price of the environment will fully counteract the effect of a 5% discount rate.

To conclude, discounting is necessary in order to compare costs and benefits at different time periods. Attempts to avoid discounting or to apply a different discount rate for climate measures than for other investments will inevitably result in an inefficient policy. However, it is difficult to pick out the correct social discount rate, as there are no practical observations of such a rate. Furthermore, discount rates may depend on the future scenario that is assumed, and could vary over time – in particular, very long-term discount rates may be lower as economic growth rates saturate and decline (see Munasinghe, 1993).

5.5.2.2 *CBA and equity*

The benefits and costs of climate change mitigation strategies may accrue to different countries (and to different regions within larger countries) in different ways and at different times. How one reconciles these differences is therefore one of the central dilemmas facing policymakers, and it involves some crucial equity issues (see Chapter 3).

Thus, although CBA can provide answers on who should engage in how much abatement based solely on the criterion of maximizing economic efficiency, it must be recognized that some deviation from the global least-cost solution as obtained by CBA may have to be accepted to get international agreement. As indicated earlier in Figure 5.1, there will likely be a trade-off between equity objectives and economic efficiency. CBA can help define the trade-off curve, but it cannot provide an answer to what combination of economic efficiency and equity is necessary to get international agreement. However, whether there is a trade-off between equity and efficiency, and what the properties of this trade-off are, depend on what policy instruments are available. For example, if one permits side payments (in lump sum form) between countries, the efficient allocation of emissions across countries could be achieved independently of the equity issue.

Several concerns shape equity perceptions and the ability to obtain international agreements. Effective action to control climate change depends on a degree of international agreement. Therefore, a first obstacle to whatever mechanism might be agreed on is national sovereignty – to what extent will sovereign nations subject themselves to enforcement actions by others? Even simple agreements for joint implementation of projects involving two countries have run into difficulties (as discussed later in this section).

The second obstacle is the heterogeneous nature of the effects of greenhouse warming. Although the most widely cited measure of climate change is the average increase in global temperature, climate change affects different countries differently. In addition, the costs or response measures and their economic implications vary greatly among countries, particularly as a function of the level of development. Therefore, perceptions of the benefits of global cooperation will differ greatly.

A third obstacle is posed by strategic incentives. If some countries take the lead and set up a greenhouse gas control agreement, others have an incentive to free-ride and abstain from joining, as they cannot be excluded from the benefits such an agreement creates. If countries act selfishly in this way, few will become party to an agreement. Instead, most countries will not cooperate, and no general agreement will be reached even if all countries were to benefit from it. (This is the well-known prisoner's dilemma from game theory.[65]) Some argue that the overwhelming historical contribution to the build-up of greenhouse gases from developed countries constitutes an "environmental debt," that cannot be conveniently ignored using the traditional "sunk cost" approach. If past contributions to greenhouse gas emissions are considered from an equity viewpoint, establishment of appropriate side payment mechanisms from developed to developing countries, including financial assistance and technology transfer, could facilitate more enthusiastic cooperation by developing countries in efforts to mitigate climate change.

The question of joint implementation illustrates the limits of CBA in this regard. The motivation for joint implementation is a straightforward result of CBA. If a country – say the U.S. – decides to make an effort to reduce greenhouse gas emissions, and if reductions can be obtained at lower costs abroad, then the U.S. should initiate projects in other countries to minimize overall costs (Aaheim, 1993). The receiving country has nothing to lose if the additional cost of such a joint implementation project is covered by the investing nation. Yet many countries and organizations have reacted with skepticism to such an approach, for reasons that are political and based on equity concerns rather than on economic efficiency. The reasons include mistrust of the true willingness of the industrial countries to mitigate climate change, the belief that the ultimate reduction in greenhouse gases under such a regime would be negligible, and the suspicion that joint implementation gives industrial countries an opportunity to "buy themselves out of their problems" at the expense of the developing countries.[66] Indeed, some developing countries fear that joint implementation investment might partly substitute for traditional forms of financial and donor assistance, and that such agreements might preclude the right of their own future generations to emit greenhouse gases.

Table 5.4. *Criteria for choosing a strategy*

1. Flexibility
2. Urgency
3. Low cost
4. Irreversibility
5. Consistency
6. Economic efficiency
7. Profitability
8. Political feasibility
9. Health and safety
10. Legal and administrative feasibility
11. Equity
12. Environmental quality
13. Private vs. public sector
14. Unique or critical resources

Source: EPA (1989).

Brazil and other countries have advanced a further reason for host country skepticism of joint implementation projects, namely that Annex I countries to the Framework Convention on Climate Change would invest in all the low-cost/high-return projects, and thus when non-Annex I countries were eventually required to curb emissions they would find the cheapest and best options already taken up.

5.5.3 Multicriteria analysis

Even the staunchest advocates of cost-benefit analysis would concede that economic efficiency (or economic value) is not the sole criterion in setting public policy, and that policymakers rightfully need to consider a broader set of objectives. Unfortunately, there is much confusion about what constitutes a coherent set of objectives. Table 5.4, taken from a major United States Environmental Protection Agency (EPA) study, lists the criteria suggested as constituting the basis for selecting public policy. The authors point out that the first four criteria listed – flexibility, urgency, irreversibility, and low cost – "would generally be given the highest priority." Note that many of these criteria overlap each other, and economic efficiency is among them!

Simple applications of CBA tend to focus only on economic efficiency. However, in more recent extensions, traditional CBA concepts are embedded in MCA, which expressly allows more than one objective and expressly addresses risk and uncertainty, thereby providing an integrating mechanism for most of the criteria listed. Multicriteria analysis techniques first gained prominence in the 1970s, when the intangible environmental externalities lying outside conventional cost-benefit analysis (CBA) methodologies were increasingly recognized. It also met one objective of modern decision makers, who preferred to be presented with a range of feasible alternatives, as opposed to one "best" solution. MCA also allows for the appraisal of alternatives with differing objectives and varied costs and benefits, which are often assessed in differing units of measurement.

Of the criteria listed in Table 5.4, criteria 1, 2, 3, 4, 5, and 6 can all be treated by modern decision analysis. Indeed, questions of timing (urgency), flexibility (or robustness), capital constraints ("low cost") are all central elements of the approach. Also, criterion 13 is really part of 6. (In the text, the authors of the EPA report amplify the criterion as follows: "Does the strategy minimize governmental interference with decisions best made by the private sector?") Furthermore, modern valuation techniques permit substantial parts of criteria 9 and 12 to be included in the economic analysis as well. As conceded by the EPA report (p. 393), "if the principal costs and benefits can be quantified in monetary terms, economic theory provides a rigorous procedure for making trade-offs between present and future costs, and for considering uncertainty, profitability, and most of the other criteria."

There is also a need to separate the basic goals of public policy – such as economic efficiency and equity – which surely have primacy, from implementation issues such as legal and administrative feasibility, which are generally secondary. The premise of CBA analysis is that one looks first at the primary objectives and then asks how many of the primary objectives one may have to sacrifice to achieve practical implementation. This principle has become accepted in many areas of policymaking. For example, the starting point for setting electric utility rates is to calculate the economically efficient tariff (based on marginal costs) and then make adjustments to protect low income groups (through lifeline rates, special provisions for disconnection in the event of nonpayment, etc.). The essence of the approach is not that noneconomic issues are ignored, but that the trade-offs between economic efficiency and equity (or indeed other objectives not readily monetized) are explicitly quantified and displayed in such a manner that decision makers are made aware of how much of one objective is traded off in the interests of the other.

Indeed, one of the advantages of MCA is that it forces political decision makers to look at the trade-offs between their major objectives rather than attempting to boil down everything into a single number, particularly where valuation techniques may be controversial. Nowhere is this more important than in the valuation of risk to human life.[67]

The application of MCA methods involves the following steps:

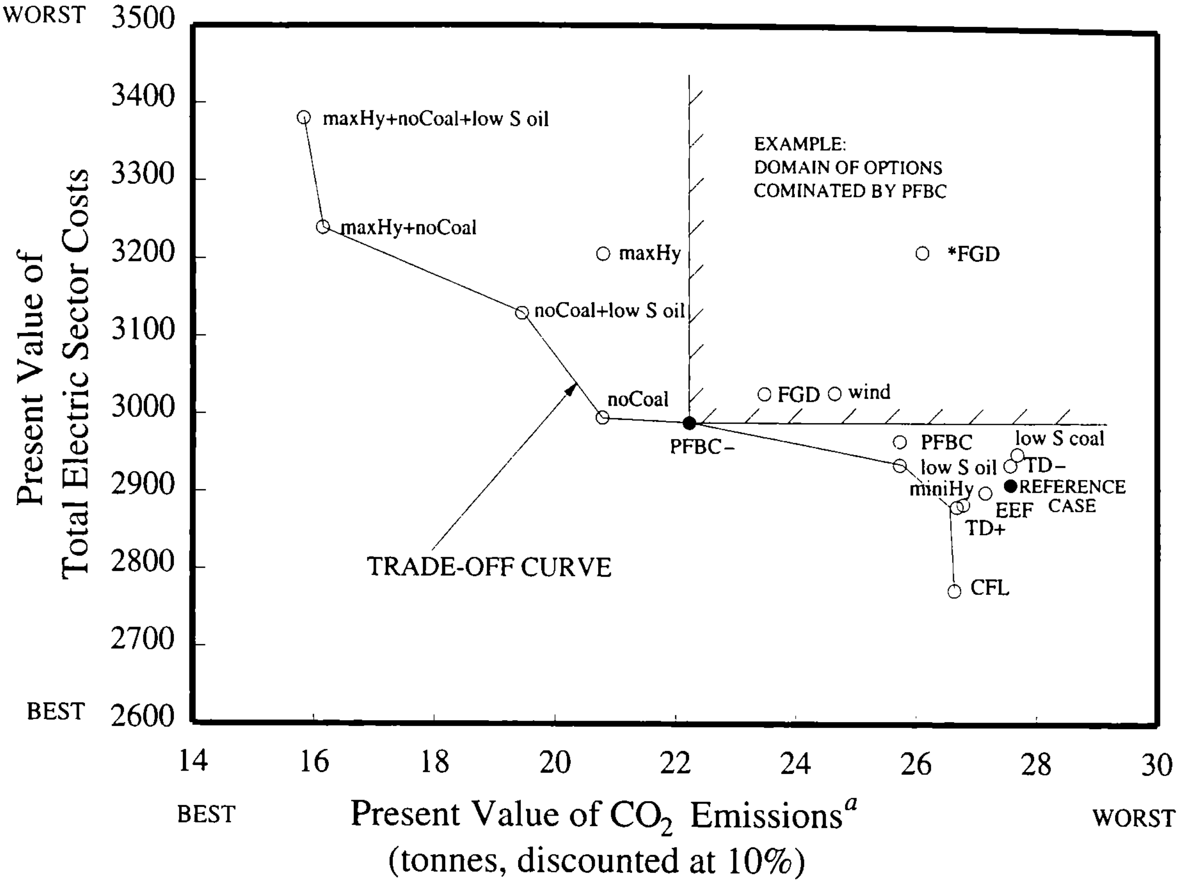
(1) Selection and definition of attributes, say A_i, $i = 1, \ldots n$, selected to reflect important planning objectives. Although the two major relevant attributes in the context of the global climate change problem are cost and greenhouse gas emission reductions, we have already noted that strategies to control emissions may have other side effects, some positive and some negative, that may also be difficult to value and that might therefore require consideration of additional attributes (such as biodiversity and equity).

(2) Quantification of the levels A_{ij} of the i attributes estimated for each of the j alternatives. In this quantification, full consideration must be given to discounting issues, for noneconomic and economic attributes alike. At this stage of the analysis, trade-off curves are powerful tools for communicating with decision makers. They are particularly relevant in a situation, such as the climate change problem, where the quantification of benefits may be difficult and where decision makers must act largely on the basis of trading-off short-term costs against certain levels of greenhouse gas emission reduction.

(3) Determination and application of a decision rule, which amalgamates the information into a single overall value or ranking of the available options or which reduces the number of options for further consideration to a smaller number of candidate plans. Where amalgamation is contemplated, attribute levels are first translated into a measure of value, $v_i(A_{ij})$ (also known as the attribute value function).[68] This is sometimes combined with a normalization procedure, usually on a scale of 0 to 1 (in which the lowest value of the attribute value function is assigned 0, the highest 1). Subsequently, weights w_i for each attribute must be determined to arrive at the overall amalgamation.

Table 5.5. *Technology interventions for greenhouse gas emission reductions*

Option	Comments	Symbol
Wind energy	305 MW total	**wind**
Minihydro		**miniHy**
DSM: energy efficient refrigerators		**EEF**
DSM: compact fluorescents		**CFL**
Transmission & distribution loss reduction	10% T&D loss goal (in place of 12%) by 2000	**TD+**
	12% goal delayed to 2003	**TD–**
Max hydro	Builds both reservoirs in the Upper Kotmale project; 144 MW high dam version of Kukule	**maxHy**
Clean coal technology	Pressurized fluidized bed combustion-combined cycle units; assumed for all coal units after 2000	**PFBC**
	With pessimistic capital cost assumptions	**PFBC–**
Clean fuels	Use imported low-sulphur residual oil for diesels (0.5% S by weight rather than 2.5% S)	**low S oil**
	Use low sulphur (0.5%) coal (rather than 1% S coal)	**low S coal**
FGD systems	Model free to choose optimal generation mix; coal plants must have FGD systems	**FGD**
	FGD systems forced onto basecase solution	***FGD**
No coal	Model free to choose least-cost combination of diesels + hydro	**noCoal**



[a] Calculating the present value of tonnes of CO_2 emissions over the life of each measure is equivalent to assuming that the damage due to a tonne of CO_2 remains constant over this period. It is not necessary to know the monetary value of the damage due to CO_2 emissions since the analysis only involves a comparison of options.

Figure 5.12: The trade-off curve.

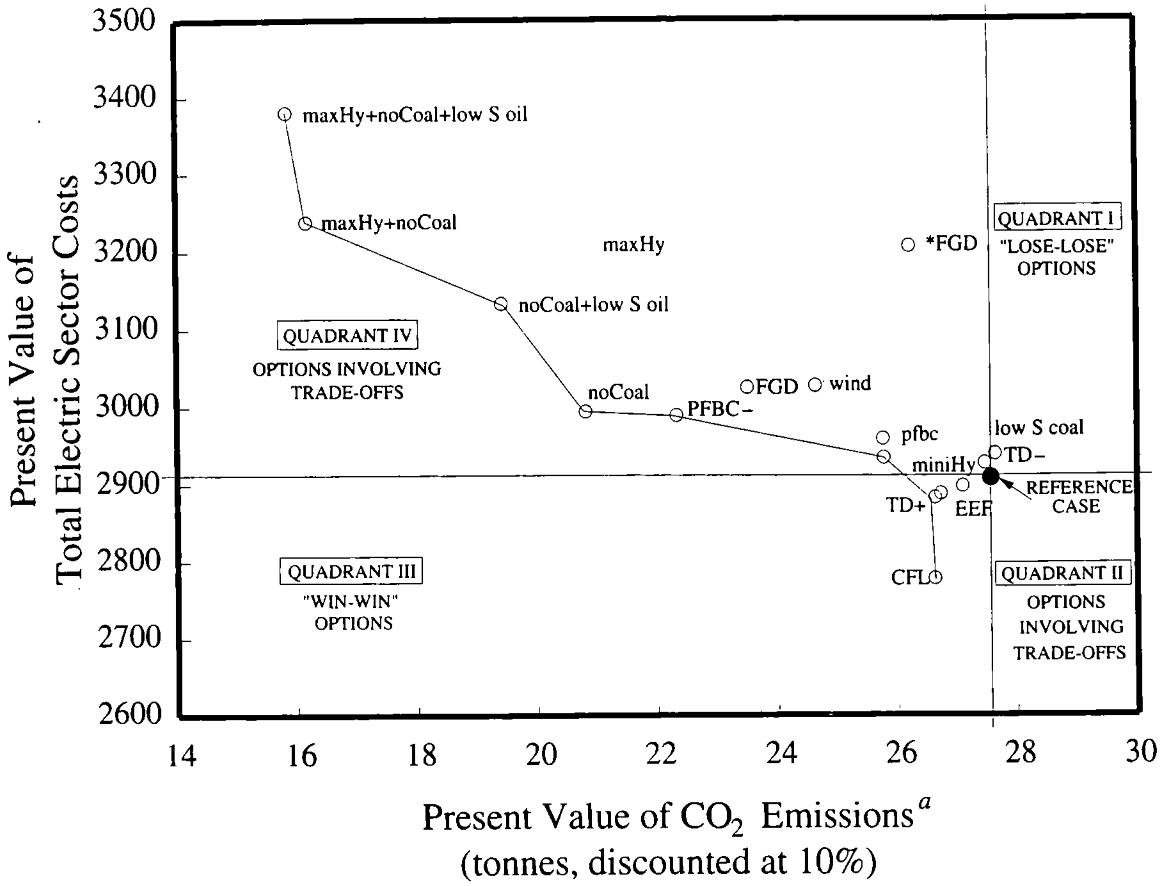
Trade-off curves are a particularly useful tool for the analysis of energy-environmental policy options. Figure 5.12, taken from a recent study of options for greenhouse gas emission reductions in Sri Lanka (Meier *et al.*, 1993), illustrates the essential concepts. The figure is a plot of two attributes – greenhouse gas emissions and total system costs – for the technology options identified in Table 5.5. Each point represents a perturbation of the reference case, defined as the official 1993 basecase capacity expansion plan of the national power company, the Ceylon Electricity Board (CEB).

The *trade-off curve* is the set of options that are not dominated by others (sometimes referred to as the "noninferior set"). These are the options that are "closest" to the origin, and therefore represent the "best" set of options that merit further attention.[69]

Several useful concepts arise here. First is the concept of *dominance*.[70] Pressurized fluidized bed combustion (PFBC – a clean coal technology) is said to dominate the options in the sector shown, namely flue gas desulphurization (FGD) and wind. PFBC has better costs and better (i.e., lower) greenhouse gas emissions, and is thus preferred over the other options under both criteria. If only these two attributes mattered, there would be no reason to select any of the dominated options in place of PFBC.

Another perspective is gained by dividing the solution space into quadrants with respect to the reference case (Figure 5.13). The options that fall into quadrant III are the "win-win" options, which are better than the reference case in *both* attributes. In this case, minihydro, energy-efficient refrigerators, transmission and distribution system loss reduction, and compact fluorescents all fall into this quadrant, providing both cost and emission gains. Such win-win solutions were mentioned earlier, in Section 4, in connection with the empirical estimates of the MAC curves (e.g., Figure 5.4). These "below-the-line" options in the MAC curves are equivalent to the options in quadrant III of a multiattribute analysis.[71]

Finally one should note that MCA leads to *implicit* valuations whenever two options are compared. For example, in the case of Figure 5.13, a decision maker who prefers option Y (maximum hydro + no coal) to option X (no coal + low sulphur oil) makes an implicit valuation of the concomitant re-



[a] Calculating the present value of tonnes of CO_2 emissions over the life of each measure is equivalent to assuming that the damage due to a tonne of CO_2 remains constant over this period. It is not necessary to know the monetary value of the damage due to CO_2 emissions since the analysis only involves a comparison of options.

Source: Meier *et al.* (1993).

Figure 5.13: "Win-win" options.

duction of greenhouse gas emissions in terms of the increased costs (i.e., equal to the slope of the trade-off curve between X and Y or about 200\$/ton of CO_2).[72]

It must also be noted that the choice of criteria in an MCA will depend on each country's short- and long-term development plans. Despite a common global objective of stabilizing atmospheric concentrations of greenhouse gases, developing countries may use different criteria because of immediate or urgent needs to ensure food supplies and service debt requirements. Consequently different countries may place different weights on the attributes.

5.6 Conclusion

Cost-benefit analysis has many advocates but also many detractors. Certainly the rather narrowly defined traditional approaches to CBA, developed originally for project-level decision making with planning horizons typically no more than 20 years, clearly have difficulty in dealing with the very long time frames and high levels of uncertainty encountered in the climate change context. This chapter has interpreted modern CBA more broadly to encompass a family of decision-analysis techniques that includes cost-effectiveness analysis, multicriteria analysis, and decision analysis, in addition to traditional cost-benefit analysis.

Despite the current limitations of these various techniques, modern CBA (broadly defined) remains the best framework for identifying the essential questions that policymakers must face when dealing with climate change. The CBA approach forces decision makers to compare the consequences of alternative actions, including that of no action, on a quantitative basis. To the extent that some impacts and measures cannot be valued monetarily (e.g., biodiversity), extensions of the traditional CBA approach, such as multicriteria analysis, permit some quantitative expression of the trade-offs to be made.

Decision analysis also provides many insights for dealing with uncertainty. Flexible policies are essential when faced with large uncertainties. Increased knowledge may narrow uncertainty, but the range of options may not necessarily increase.

Finally, the most important benefit of applying CBA is not necessarily the predicted outcome (which always depends on assumptions and the particular technique used) but the *process itself* (which establishes a framework for gathering information and forces an approach to decision making that is based on rigorous and quantitative reasoning).

Endnotes

1. However, it is not universally accepted that cost-benefit analysis is appropriate to the analysis of policy options to address global climate change. A major report recently issued by the U.S. Office of Technology Assessment (OTA, 1993) contains an extensive discussion of how adaptation strategies should be chosen, yet manages to avoid all mention of cost-benefit analysis *per se*. It talks about how one might minimize vulnerability to climate change and about insurance strategies, but avoids the central question of how one might determine the amount of insurance one wishes to buy. Similarly, priorities may be set on noneconomic grounds, and CBA could be used in a secondary role (see e.g., Turner, 1991).

2. Although this needs a bit of modification in the presence of capital constraints, which may limit selection of the "best" single project.

3. However, as we shall see later, extensions of CBA *can* help in identifying the *trade-offs* between economic efficiency and equity.

4. The degree of emission abatement is reported in such studies in two rather different ways. The first is as a reduction from some baseline – itself defined as the trajectory of greenhouse gas emissions for some postulated business-as-usual scenario. The second is in terms of reductions from some reference year (e.g., "reduce greenhouse emissions to 80% of their 1990 levels by 2010").

5. The ethical and epistemological aspects of the climate change problem are not addressed here. For further discussion, see, for example, Brown (1992).

6. A recent survey of economists and scientists knowledgeable about the climate change problem elicited typical views at the extremes of this spectrum (Nordhaus, 1994a). One respondent argued, "the existence value of species is irrelevant – I don't care about ants except for drugs," while another cautioned that "loss of genetic potential might lower the income of the tropical regions substantially." In Section 5.5 we address the different types of values – use, option, existence – in more detail.

7. But see below for a discussion of the difficulties of making cross-country comparisons of costs.

8. There may also be some outcomes that are inefficient, namely those that lie inside the frontier of efficient points shown in Figure 5.1. Such an inefficient point is represented by option 6. This is discussed further in the presentation of multicriteria analysis, below.

9. It should be noted that the algebra of cost-benefit analysis can be expressed in many different ways: the cost-benefit ratio, net present value, or the internal rate of return are all different ways of doing the arithmetic. However, particularly in situations involving portfolios of potential actions, and where shortages of capital may constrain the choice, great care must be paid to rigorous application of the principles; otherwise, different methods may yield different decisions. Maximizing net present value subject to applicable resource constraints is the most useful approach for climate change analysis.

10. Perhaps the simplest and most intuitive example of why the marginal cost of emission reduction increases with increasing levels of reduction is the removal of pollutants from wastewater. The first 60% can be easily removed by a settling basin: Large particles simply settle by gravity, and all that is required is a structure in which the process can take place. The next 30%, however, requires biological treatment. This involves not just a physical structure, but pumps to aerate the water to promote the growth of aerobic bacteria. The next 5-6% requires chemical treatment, with high operating costs arising from the use of chemical agents. Although 100% removal is theoretically possible, it would require complete distillation, which is extremely expensive.

11. Although we show the marginal cost and benefits of emission reduction as linear in Figure 5.2, this need not be so. For example, where abatement costs are subject to economies of scale, there might be sections of the MAC curve that have a form other than that shown in Figure 5.2. But as noted elsewhere (e.g., Figure 5.4), empirical studies of the marginal cost curves frequently do exhibit the stylized shapes shown in Figure 5.2.

12. The acidity of precipitation is influenced by complex interactions between sulphur oxides, related oxidation products, and NO_x.

13. For example, the presence of CFCs could affect climate change not only directly through their global warming potentials, but also indirectly through the impact of stratospheric ozone depletion on biota-like nanoplankton – which in turn influence oceanic CO_2 uptake. Similarly, the degree of reliance on fossil fuels would affect CO_2 emissions directly and CO_2 absorption indirectly – via the effects of acid rain on forests and biomass.

14. There are some exceptions, notably for radioactive wastes, which also have extremely long lifetimes. Thus the total environmental risk, and the scale of the disposal problem at any one time, is not so much dependent on current rates of production of nuclear wastes as on the total stock.

15. IPCC (1995) estimates the lifetime of methane at 14.5 ± 2.5 years.

16. See, for example, Hoel and Isaksen (1993, 1994) for a further discussion and numerical calculations.

17. There are exceptions here as well, most notably the phenomenon of acid rain, which is largely a long-range phenomenon often involving emissions in one country and acid rain damage in another. However, to the extent that lake acidification completely destroys aquatic ecosystems, one could argue that at least some of the impacts are irreversible, although even here the impacts are generally of a fairly local nature. Long time periods may also elapse between the onset of acid rainfall and actual visible damage.

18. For new data on emissions and acid deposition rates in Asia, see World Bank (1993).

19. To be sure, there are exceptions. Even the richer countries of Europe are affected by mutual pollution problems (e.g., acid rain in Scandinavia from the UK, or the severe water pollution problems in the Rhine Basin involving Switzerland, Germany, France, and the Netherlands, or the dumping of wastes in the North Sea). However, in most cases where international pollution issues involve richer countries, much better institutional mechanisms exist for addressing these problems (e.g., the EU in Europe) than are available for resolving environmental disputes between rich and poor.

20. For a discussion of the relationship between economic assistance for restructuring in Eastern Europe and assistance to guarantee desired environmental standards, see, for example, Amman *et al.* (1992).

21. However, the indirect impacts (for example, large-scale immigration from Mexico that might follow from agricultural devastation in that country) may ultimately prove to be much more serious for the U.S. than the direct consequences of sea level rise or higher energy bills for air conditioning, but such impacts are also very difficult to quantify and many regard them as speculative. Proper CBA analysis would correct for such distorted perspectives.

22. In some cases laboratory experiments – such as growing plants in CO_2-enriched atmospheres – do provide some actual data for predictions.

23. A recent UNEP review of greenhouse gas abatement costing studies concluded that "the state of abatement costing studies in developing countries is wholly inadequate even to draw preliminary conclusions concerning possible costs and the impact of different abatement options. It is a body of analysis which is only just beginning, and which may take many years to mature towards consensus even on very rough estimates and understanding of the key issues" (UNEP, 1992).

24. See, for example, the review of eleven studies by London Economics (1992).

25. See, for example, Moreira *et al.* (1992) for Brazil; Sitnicki *et al.* (1991) for Poland; or Meier *et al.* (1993) for Sri Lanka.

26. Unfortunately, there is some confusion in terminology with respect to this point. Some (e.g., London Economics, 1992) use the term "no regrets" to describe policies for which MB > MAC, that is, for which the marginal benefits exceed the marginal costs. Others use the term only where MAC < 0, that is, for those options that are "below the line" in the empirical cost curves of the type shown in Figure 5.5. However, since on both the cost and the benefit side there will be some netting out (e.g., to account for joint costs and benefits), the criterion MAC< 0 is arbitrary, whereas MAC< MB is well defined.

27. The fact that such "no-regrets options" are in fact observed is much debated. What may be calculated as monetary benefits need not necessarily be regarded as benefits by decision makers – there may be other, nonmonetary costs involved. The huge subsidies given to European agriculture illustrate the point that more than monetary benefits might affect decisions. In the case of developing countries, the unavailability of finance may constrain the ability to implement some of these options. For example, until recently, obtaining finance through export credits for power generation expansion has been much easier than financing energy efficiency measures.

28. These methodological problems have been recognized by the GEF, which has initiated a research programme to find an operational approach for measuring and agreeing on full incremental costs within the context of the Framework Convention on Climate Change. This is the so-called PRINCE study (Programme for Measuring Incremental Costs for the Environment); see King (1993).

29. Another problem here is that the concept of "least cost," as well as the integrated planning process to achieve it, may be quite complex (see, for example, Munasinghe, 1990; Meier, 1990; Crousillat, 1989). Such a solution, typically obtained by fairly sophisticated optimization models, may be "least-cost" only for a very narrow band of input assumptions; and if these assumptions prove to be different, then an investment programme predicated on the "least-cost" plan may ultimately be distinctly nonoptimal.

30. In the words of King (1993),

> How can the adoption of apparent win-win solutions be stimulated? Such solutions are sometimes referred to as negative incremental cost projects because they are economically viable in their own right. The dilemma arises because these projects are often not being funded. On the one hand, if the GEF restricts itself to those projects that have positive incremental cost while the bulk of negative incremental cost options remains unfunded, it risks becoming irrelevant to the main solution to the global environmental problem. On the other hand, providing grant finance for economically viable projects effectively makes a net transfer to the country, which is not the purpose of new and additional funding; worse, it provides a perverse incentive to potential recipient countries to delay economic reform.

31. This is likely to be true even though higher CO_2 concentration itself may promote plant growth.

32. For further discussion, see, for example, IPCC (1990) or Lave and Vickland (1989). However, as also noted by Nordhaus (1994b), the fertilizing effect of atmospheric CO_2 is a particularly strong mitigating factor for agricultural nations, particularly where water is a limiting factor. Although the extent and quantitative importance of CO_2 as a fertilization agent are controversial, the balance of the evidence is positive.

33. See, for example, Glieck (1989) or Pachauri (1991).

34. This report identifies thirty-nine studies (or elements of studies) focussed on inventories of greenhouse gases, forty-eight studies of effects, and forty-six studies of mitigation.

35. For example, in a report prepared by the Tata Energy Research Institute for the India Ministry of Environment and Forests (TERI, 1991), the chapter "Adaptive Strategies for India in the Perspective of Climate Change," which elaborated on the impacts associated with given levels of sea level rise and mean temperature, was entirely qualitative in nature, and no cost estimates were attempted. Similarly, neither the volume on climate change published by the Asian Energy Institute (Pachauri and Behi, 1991) nor the country studies conducted by UNEP (reported in UNEP, 1992) contains any country-specific estimate of costs associated with specific levels of greenhouse gas accumulation in the atmosphere. The Asian Development Bank is currently sponsoring a multicountry project in Asia that is attempting to establish costs of potential effects.

36. There are several related issues. For example, should one use nominal exchange rates, trade-weighted rates, or purchasing power parity rates in making cross-country comparisons of costs or impacts?

37. The question of "green accounting" is one of valuing and aggregating marketable and nonmarketable goods (see, for example, United Nations, 1993, or Munasinghe *et al.*, 1995). The many different proposals for "green accounting" reflect the difficulties involved. Rather than speculate about valuation or poorly founded proxies for nonmarketable goods, MCA provides an alternative approach.

38. These results are for studies that estimate both emission reductions and GDP impacts relative to some baseline, i.e., relative to the trajectory of emissions in the absence of the policies followed. For many countries, particularly the developing nations, even significant reductions from such baselines may still imply increases in the absolute quantity of greenhouse gases emitted. Other studies report results in terms of greenhouse gas emissions in some future target year, relative to emissions in some prior year (e.g., 2010 emissions 10% less than 1990 emissions).

39. For further discussion see UNEP (1992), p.72. Studies that have examined the question of unilateral vs. multilateral approaches include Proost and van Regemorter (1990), Edmonds and Reilly (1985), and Rutherford (1992).

40. Additionally one might note that, although the environmental risks of current technologies are fairly well established, those that apply to new technologies – including some (such as fusion or new nuclear reactor cycles) that are sometimes proposed as solutions to the climate change problem – are less certain.

41. See Chapter 6 (Section 6.7) for a more extensive discussion of the secondary benefits of reducing greenhouse gas emissions. Results reported there range from \$2/tonne of carbon abated to over \$500/tC.

42. For example, in one alternative (the "Treaty Alternative"), Alfsen *et al.* (1992) estimated the loss in GDP at 3.1 billion Kroner and the loss of private consumption at 2.6 billion. However, joint product benefits were estimated at 2.4 billion (with a range of 1.0-3.8 billion).

43. For purposes of clarity, we have drawn only a single marginal cost curve (MAC) in Figure 5.7. It is quite possible, however, that different countries will also have different marginal cost curves (although the differences in costs are likely to be smaller than the differences in benefits).

44. For example, studies by Burgess (1990) and Larsen (1993) address the impact of eliminating price subsidies. They estimate the level of reduction in greenhouse gas emissions by applying assumed price elasticities to the difference between the subsidized and unsubsidized prices. Burgess, using the difference between the actual average cost of electricity and the estimated long-run marginal cost (LRMC) and applying an assumed long-run price elasticity of -1, estimates the reduction in greenhouse gas emissions for eleven countries, including the U.S., China, India, and some small developing countries such as Tanzania and Peru. Not surprisingly, the bulk of the total carbon emission savings of 124 million tons/year (mtpy) comes from coal fuel savings, of which India accounts for 11.9 mtpy, China 26.6 mtpy, and the U.S. 85.4 mtpy. Larsen, performing the same analysis but from the perspective of *fuel* prices, applies estimated own- and cross-price elasticities for the different fossil fuels to the difference between an appropriately adjusted border price and the domestic subsidized fuel price, and, more significantly, includes the countries of the former USSR and Eastern Europe. In this analysis, the former USSR (917 mtpy) and Poland (105.2 mtpy) dominate the results; indeed, the combined estimated impact of India (54 mtpy) and China (45.4 mtpy) together is less than that for Poland.

45. The GEF has recently introduced the term "type I project" for those which operate in the range AC (i.e., for which national economic benefits are greater than national costs) and "type II project" for those in the range CD (i.e., for which national economic benefits are less than national economic costs, but global benefits are such that the project is justified under GEF criteria). For further discussion, and arguments for why the GEF should give priority to type II projects, see, for example, Anderson and Williams (1993).

46. This is a partial list. Other problems include the assumption that noncarbon-based materials are benign with respect to the greenhouse gas problem, uncertainty concerning natural sources, and uncertainty over the spatial distribution of physical impacts.

47. See IPCC (1995), Chapter 6, for further discussion of uncertainty in future emissions.

48. One need only remember how dramatically growth rates and energy/GDP ratios fluctuated in the decade following the 1973 oil crisis to recognize the hazards of such forecasts.

49. This issue is made more complicated by the fact that much deforestation is presently driven by the need to expand pasture land, which in turn implies higher methane emissions from livestock.

50. For a full discussion of uncertainty in emissions, see, for example, Ebert and Karmali (1992).

51. See note 45.

52. The U.S. Nuclear Regulatory Commission has made repeated attempts to establish probabilities for specific kinds of accidents through a technique known as fault tree analysis. Despite the appearance of scientific rigour, the resultant probability estimates remain highly controversial. For examples of the use of cost-benefit analysis by the U.S. NRC, see, for example, Mubayi *et al.* (1991) or Abrahamson *et al.* (1989).

53. Precautionary expenditures may also be influenced by aversion to catastrophic risks. A recent example is the hundreds of billions of dollars per year spent in the U.S. to avert nuclear attack.

54. Perhaps there is a possible role for financial markets in insuring (and pricing) environmental risks (just as utilities can insure or self-insure against environmental damages caused by accidents at plant sites), but since the damage estimates related to climate change are very difficult to assess, the opportunities for such an approach seem limited, even if occurrence probabilities for various damages could be estimated more accurately.

55. If prices of marketed goods are distorted (e.g., due to arbitrary taxes and subsidies), it will be necessary to use shadow prices – usually the set of economic opportunity costs or efficiency prices – to determine their correct economic value (for details, see Dasgupta *et al.*, 1972; Little and Mirrlees, 1974).

56. It should be noted that the distinction between a mitigation measure and an adaptation measure may not always be clear cut.

57. "Preliminary results suggest that although U.S. crop production could decline, supplies would be adequate to meet domestic needs" (EPA, 1989). It might well be pointed out, however, that this reflects the very narrow perspective of the study: U.S. grain exports represent a significant supply of food for developing countries, and were the U.S. surplus to decline, developing countries might well be concerned about the use of food exports as a political weapon.

58. Particularly difficult to value is the cost of forced adaptation and population movements – a problem already encountered in cost-benefit analyses of the impact resulting from the creation of large reservoirs where significant numbers of individuals must be forcibly relocated (World Bank, 1994).

59. For further details, see Munasinghe (1993) and Pearce and Warford (1993).

60. The issue of option values and irreversibility in CBA has received increasing attention in the literature, starting with Arrow and Fischer (1974) and continuing more recently with Chichilnisky and Heal (1993).

61. For a recent overview of techniques suitable for valuing environmental costs and benefits, especially in developing countries, see Munasinghe (1993).

62. The theoretically correct measure of WTP is the area under the Hicksian demand curve, which describes the relationship between the price and quantity demanded of the environmental resource, keeping the level of consumer utility intact. Problems of measurement may arise because the commonly estimated demand function is the Marshallian one, which indicates how demand varies with the price of an environmental good, while keeping the user's income level constant. In practice, it has been shown that the Marshallian and Hicksian estimates of WTP are in good agreement for a variety of conditions, and in a few cases the Hicksian function may be derived once the Marshallian demand function has been determined (Willig, 1976; Braden and Kolstad, 1991). What people are willing to accept (WTA) in the way of compensation for environmental damage is another measure of economic value that is related to WTP. WTA and WTP could diverge (Cropper and Oates, 1992). In practice, either or both measures are used for valuation.

63. Contingent valuation methods in particular are somewhat controversial and need great care in their application to produce credible results.

64. One also needs to take note of the fact that this principle is also not universally accepted, particularly by political leaders. The principle that "past sacrifices ought not to be in vain" is frequently invoked as relevant to present decisions. Indeed, in the climate change debate, developing countries correctly note that it is the developed countries that are largely responsible for the present levels of greenhouse gases in the atmosphere and that this past behaviour *is* relevant in the search for equitable solutions in the future. However, these observations point to the *equity* dimension of the problem and do not affect how one ought to seek the economically efficient options.

65. However, for a criticism of this argument, see Brown (1992), who points out that some European countries have already taken unilateral action to reduce greenhouse gases in the hope that others will follow. Moreover, other game-theory paradigms have been proposed for modelling international environmental negotiations. For example, Carraro and Siniscalo (1992, 1993) propose a "chicken game" framework belonging to the class of coordination games.

66. For a discussion of these issues, and a discussion of how CBA can make a contribution to the evaluation of such projects, see Aaheim (1993). Concerns about "market justice" and related considerations are outlined in Rose (1990).

67. Differential valuation of human lives is strenuously opposed by some: if a U.S. life is worth $1.5 million, then so is everyone else's. On the other hand, when making comparisons of per capita GDP, economists are increasingly turning to purchasing power parity adjustments in an attempt to make more valid comparisons of economic level. MCA avoids these difficulties by moving judgments about the value of human life from the domain of technical assessment into the domain of political decision making, where such judgments properly belong.

68. MCA deals with attitudes towards risk and uncertainty at this stage by the use of multiattribute utility functions, which explicitly capture attitudes towards risk. See Keeney and Raiffa (1976) for an application in water resource planning, or Keeney and von Winterfeldt (1987) for application to electric utility planning.

69. We note also that the trade-off analysis and surfaces will be much more complex as the number of attributes increases.

70. Decision analysis distinguishes among several types of dominance – such as strict dominance and significant dominance. See, for example, Meier and Munasinghe (1994) for an application of these concepts to environmental decision making.

71. In general, the trade-off curve may extend into quadrant II, and quadrant III may contain fewer solutions or none at all.

72. However, because of the presence of joint products – each represented by a different dimension in the multidimensional trade-off space – valuations that look only at two dimensions need to be interpreted with some caution.

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THE WHITE HOUSE

WASHINGTON

October 18, 1996

MEMORANDUM FOR DISTRIBUTION

FROM: Michael Warren, Executive Director
National Economic Council

SUBJECT: Climate Change Deputies Meeting

There will be a joint NEC-CEA Deputies meeting on climate change on Wednesday, October 23 at 10:30 a.m. in room 231 OEOB. This meeting will be chaired by Dan Tarullo and Kathleen McGinty.

An agenda will be sent to you next week. Please call Kristen Panerali at the NEC at 456-5353 with your clearance information. Thanks.

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United States Department of State

Assistant Secretary of State for Oceans and International Environmental and Scientific Affairs

Washington, D.C. 20520

October 17, 1996

MEMORANDUM

TO: Distribution

FROM: OES - Rafe Pomerance, Acting

SUBJECT: Submission to Secretariat of the UN Framework Convention on Climate Change

Attached is a revised draft of the proposed United States submission to the Secretariat of the UN Framework Convention on Climate Change. This draft has been revised to reflect comments and suggestions raised by several agencies. In order to ensure that agencies have an opportunity to review the final draft before submission to the Secretariat, I am sending the document for your final clearance.

As background, you should know that this submission is designed to outline in broad terms the key elements of a final agreement that are important for further discussion and consideration. More detailed policies and positions will be developed by the USG in the months ahead with your participation. Our submission at this time is intended to help maintain the momentum we have established in defining the negotiations on terms that are consistent with our interests. In order to ensure that our views are fully reflected in the documentation prepared for the next round of negotiations in December, it is essential that we provide our suggestions for key negotiating elements at this time. The U.S. submission will be compiled along with those of other nations by the Secretariat and will be circulated publicly.

To comply with the Secretariat's deadlines, we would appreciate your clearance by noon, Friday, October 18, 1996. Please fax or phone your comments to me on (o)647-2232 or (f)647-0217.

Thank you for your assistance.

Attachment:
As stated.

Draft Rev. 3 -- 10/17/96

U.S. Submission on Elements of a New Legal Instrument

(October 15, 1996)

General

In the U.S. view, the new legal instrument should respond effectively to the threat posed by global climate change; should reflect outcomes that are real and achievable; should be consistent with economic prosperity; should allow for maximum flexibility and cost-effectiveness in its implementation; and should lay the foundation for continuing progress by all countries.

Meeting the ultimate objective of the Convention will require concerted, long-term efforts by all Parties. While it is important for developed countries to take the lead, it is also essential that the Kyoto agreement recognize the growing contribution of developing country emissions and begin to plan for appropriate, cost-effective ways to address these emissions in a sustainable manner. In this connection, at COP-2 the United States called for continued work toward a longer-term concentration goal (e.g. for the next 50-100 years), recognizing that scientific understanding and technology will improve over time.

In putting forward these suggestions for a new legal instrument, the United States has rejected proposals by some countries calling for short-term targets that we believe could not be realistically achieved. We have also rejected the use of inflexible, harmonized policies and measures. In the spirit of providing individual countries greater flexibility in meeting any agreed upon limitations, we believe that it is critical that flexibility in implementation be accorded all countries, including through emissions trading and joint implementation among nations.

We believe that the following elements would serve as a useful basis for the consideration of topics that would need to be included in a new legal instrument. Given the continuing uncertainties surrounding the form of such an instrument, we have noted particular aspects of these issues that may differ depending on whether the Parties choose a protocol or an amendment to the FCCC to codify their agreement.

Preamble

If the legal instrument takes the form of a protocol, it might include a preamble. If it takes the form of an amendment, it would not, although the decision adopting the amendment could.

Definitions

A protocol would need to incorporate some or all of the definitions in Article 1 of the Convention, include its own definitions, or some combination of the two. An amendment, to the extent it introduces new terms, might also require amendment of Article 1.

Objective

An amendment would, and a protocol should incorporate the objective in the Convention; we do not believe it is either necessary or desirable to develop a separate objective for this legal instrument.

Level and Structure of the Target

The Geneva Declaration calls for a legally-binding target and timetable, consistent with the U.S. call at COP-2, to shift the negotiations away from unrealistic, near-term proposals to medium-term targets that are both realistic and achievable.

The Berlin Mandate calls for adoption of the protocol/other legal instrument at COP-3, making calls to date for differentiated commitments in this timeframe impracticable. Therefore, it will be important that the target/timetable be sufficiently specific (to facilitate compliance), flexible in terms of its implementation (to encourage broad participation) and straight-forward (to ensure negotiation and adoption by COP-3). As we noted at COP-2, the United States opposes efforts to develop inflexible, harmonized policies and measures.

A number of ideas and approaches have been suggested thus far in the discussions within the Ad Hoc Group on the Berlin Mandate (AGBM). Many of these ideas and approaches have focused on a single-year target, but we believe it will be important to consider a broader range of possibilities (e.g., cumulative or aggregate targets, multiple-year rolling average targets, flexibility over time through banking or borrowing, etc.) We anticipate that more such ideas and approaches will be tabled and considered as we work toward a new legal instrument for adoption at COP-3.

The United States is continuing its domestic analysis and assessment efforts so as to contribute to this discussion in upcoming negotiating sessions.

Advancing Article 4.1 Commitments

"Continuing to advance the implementation of Article 4.1 commitments" will be a critical component of next steps and must be reflected in the Kyoto agreement. Given the global nature of this problem, we must work together toward a global solution, recognizing our common but differentiated responsibilities and capabilities. A number of assumptions underlie U.S. views on next steps:

- Article 4.1:
  - -- Applies to all Parties;
  - -- Speaks to issues ranging from inventorying emissions, to reporting, to adopting policies and measures;
  - -- Speaks to the requirement to promote the development and diffusion of technologies;
- The Convention anticipates that the status of countries will evolve over time (e.g., Article 4.2(f))
- Paragraph 2.b of the Berlin Mandate governs what will be included on this issue in the Kyoto agreement

Bearing in mind these assumptions, there are a number of approaches that can be taken through a new legal instrument. For example, the Parties could agree to:

- continued and more systematic support for efforts to develop national action plans (particularly in developing countries) following the revised Annex I Guidelines for National Communications and the newly adopted Non-Annex I Guidelines for Initial Communications
- redoubled efforts to adopt and implement "no-regrets" measures
- expanded programs aimed at developing, diffusing and deploying climate-friendly technologies (including through

systematic efforts to identify and remove barriers to technology diffusion and to enhance the role of international financial institutions in responding to the threat of global climate change)

- further consideration of thresholds at which the status of countries would change, and the process involved in such a change in status

- further consideration of future steps (post-Kyoto) toward the objective of the Convention

International Emissions Trading/Joint Implementation

In the U.S. view, emissions trading/joint implementation will be an essential element of the Kyoto agreement; it will therefore be a priority task to establish the guidelines for a credible emissions trading/joint implementation regime by December 1997.

We believe that emissions trading and joint implementation regimes will motivate parties to achieve and strengthen national commitments to reduce or limit greenhouse gas emissions because the cost savings potential in these types of programs can achieve more environmental protection than less flexible, less cost-effective regimes.

Various design questions will need to be resolved by the Kyoto Conference, including, for example, whether inter-gas trading will be allowed; how trades would most effectively be monitored and reviewed; what distinctions might be drawn with respect to participation in an emissions trading/joint implementation regime (e.g., absent national targets, could project-specific baselines be used?)

A number of principles must underlie an emissions trading/joint implementation regime. At a minimum, such a regime must be efficient, transparent and verifiable.

Institutions

For reasons of administrative efficiency and in light of budgetary constraints, a new legal instrument should utilize existing institutions to the maximum extent practicable.

A protocol would need to specify its institutions. In the case of an amendment, the institutions established under the Convention would apply. (Note: We do not believe it would be appropriate for non-Parties to a protocol to be officers of an institution serving the protocol.)

Compliance

The term "compliance" is used in this context to refer to the cluster of processes/mechanisms that provide incentives for the Parties to abide by their legal commitments.

Ensuring effective compliance will be critical for environmental as well as economic reasons. Unless parties comply, there will be little incentive to act and we will not achieve our environmental objectives. Uneven compliance will undermine confidence in the new legal instrument and encourage "free-riding."

A key means of promoting compliance will be to ensure that commitments are realistic and achievable (as noted above). In addition, it will be important to consider supplementary means for promoting compliance, including ways to ascertain whether Parties are meeting their obligations and ways to encourage them to do so. In this context, we will need to consider elaborating existing reporting and review mechanisms.

Unless otherwise provided, an amendment to the Convention would be covered by the Convention's reporting requirements, as well as dispute settlement provisions and any multilateral consultative process that might be established. A protocol would need to specify whether any of these Convention mechanisms would apply, as well as any additional compliance-related provisions.

Decision-Making

Only the Parties to the protocol or amendment should have decision-making authority with respect to that instrument.

Final Clauses

A protocol would need to contain several final clauses, including, for example, provisions on entry into force and amendment. An amendment's final clauses are already set forth in the Convention.

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Journal of Economic Perspectives—Volume 7, Number 4—Fall 1993—Pages 11–25

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Reflections on the Economics of Climate Change

William D. Nordhaus

Albert Einstein's reaction to quantum mechanics was "God does not play dice with the universe." Yet mankind *is* playing dice with the natural environment through a multitude of interventions—injecting into the atmosphere trace gases like the greenhouse gases or ozone-depleting chemicals, engineering massive land-use changes such as deforestation, depleting multitudes of species in their natural habitats even while creating transgenic ones in the laboratory, and accumulating sufficient nuclear weapons to destroy human civilizations. As natural or social scientists, we need to understand the human sources of these global changes, the potential damage they cause to natural and economic systems, and the most efficient ways of alleviating or removing the dangers. Just as towns in times past decided on the management of their grazing or water resources, so must we today and in the future learn to use wisely and to protect economically our common geophysical and biological resources. This task of understanding and controlling interventions on a global scale can be called managing the global commons.

The issue analyzed in this symposium is the threat of greenhouse warming. Climatologists and other scientists warn that the accumulation of carbon dioxide (CO_2) and other greenhouse gases is likely to lead to global warming and other significant climatic changes over the next century. Many scientific bodies, along with a growing chorus of environmental groups and governments, are calling for severe curbs on the emissions of greenhouse gases. In response, governments have recently approved a framework treaty on climate change to

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monitor trends and natural efforts, and this treaty formed the centerpiece of the Earth Summit held in Rio in June 1992.[1]

Natural scientists have pondered the question of greenhouse warming for a century. Only recently have economists begun to tackle the issue, studying the impacts of climate change, the costs of slowing climate change, and alternative approaches for implementing policies. The intellectual challenge here is daunting for those who take policy analysis seriously, raising formidable issues of data, modeling, uncertainty, international coordination, and institutional design. In addition, the economic stakes are enormous, involving investments on the order of hundreds of billions of dollars a year to slow or prevent climate change.

My purpose here is to provide a non-technical introduction to the economics of climate change. I will sketch the scientific background and uncertainties, survey the results of existing studies of the impacts of climate change, present a summary of a study of efficient policies to slow global warming, and end with the uncertainties that haunt the entire field.

The Scientific Background

What is the greenhouse effect? It is the process by which radiatively active gases like CO_2 selectively absorb radiation at different points of the spectrum and thereby warm the surface of the earth. The greenhouse gases are transparent to incoming solar radiation but absorb significant amounts of outgoing radiation. There is no debate about the importance of the greenhouse effect, without which the Earth's climate would resemble the moon's.[2]

Concern about the greenhouse effect arises because human activities are currently raising atmospheric concentrations of greenhouse gases. The major anthropogenic greenhouse gases are carbon dioxide (emitted primarily from the combustion of fossil fuels), methane, and chlorofluorocarbons (CFCs)—but of these CO_2 is likely to be the most significant over the coming decades. Scientific monitoring has firmly established the buildup of the major greenhouse gases over the last century. Using the standard but problematical metric of the "CO_2 equivalent" of greenhouse gases,[3] atmospheric concentrations of greenhouse gases have risen by over half of the preindustrial level of CO_2.

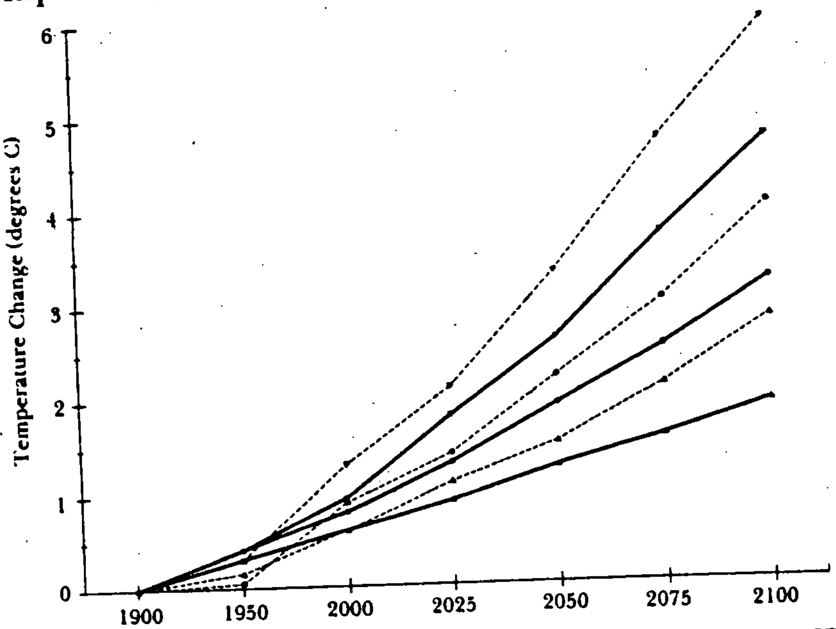
While the historical record is well established, there is great uncertainty about the potential for future climate change. On the basis of climate models,

[1]Formally known as the United Nations Conference on Environment and Development (UNCED), the Earth Summit was the culmination of an effort to reach international agreements on climate, forest, biodiversity and biotechnology, as well as to develop principles for environmentally sound economic development.

[2]A non-technical description of the science underlying the greenhouse effect is contained in National Academy of Sciences (1992). A thorough survey, full of interesting figures and background, is contained in IPCC (1990).

[3]Because greenhouse gases have differing lifetimes, combining them into a single index of their "CO_2 equivalent" poses complex scientific and economic questions, as Schmalensee (1993) shows.

Figure 1
Projections of Global Temperature Increase: IPCC Report and DICE Model



Note: IPCC Report is from Intergovernmental Panel on Climate Change (1990), while DICE model is from Nordhaus (1993). The dashed lines are from IPCC Report and represent, from top to bottom, high estimate, best estimate, and low estimate. The solid lines are from the DICE model and represent, from top to bottom, the 90th, 50th, and 10th percentiles of calculated temperature increases from 500 Monte Carlo runs. In both cases, the changes represent temperature increases from 1900.

scientists project that a doubling of the atmospheric concentrations of CO_2 will in equilibrium lead to a warming of the earth's surface of 1 to 5 degree Celsius; other projected and equally uncertain effects include an increase in precipitation and evaporation, a small rise in sea level over the next century, and the potential for hotter and drier weather in mid-continential regions such as the U.S. midwest. Atmospheric scientists have engaged in a spirited debate about the climatic impact of increasing greenhouse-gas concentrations, but it is unlikely that the uncertainties will be resolved until this vast geophysical experiment has run its course.

To translate these equilibrium results into a projection of future climate change requires a scenario for emissions and concentrations. Using rudimentary economic modeling, the Intergovernmental Panel on Climate Change (or IPCC), an international panel of distinguished scientists, projected that "business as usual" would produce a 3 to 6 degree C warming in 2100 (relative to 1900) with the best guess being 4 degrees C. The dashed lines in Figure 1 show the high, best, and low estimates from the IPCC.

I have recently used a dynamic optimization model (the DICE model, described more fully later in this paper) to develop a distribution of future temperature increases. Figure 1 shows as solid lines the 10th, 50th, and 90th percentiles of the temperature-increase distribution from the DICE model. In general, economic models project rising relative energy prices and slowing economic growth in the coming decades; as a result, they tend to show lower emissions and temperature trends than the extrapolative approaches often used in the scientific community and exemplified by the IPCC projections. However, virtually all projections are worrisome because climate appears to be heading out of the historical range of temperatures witnessed during the span of human civilizations.

Climate models resemble large macroeconomic models in their ability to answer virtually any question that modelers care to ask. However, the reliability of climate models for global climate changes is unproven, and climate modelers do not expect to be able to forecast regional climates accurately in the foreseeable future. Some believe that there may be "regime changes" in which the climate flips from one locally stable equilibrium to another, say because of changes in ocean circulation. Elaborating bigger and better models will provide fruitful full employment for climatologists well into the next century.

Impacts of Climate Change

What are the likely impacts of projected climate changes over the next century? To begin, we should recognize that in the long march of economic development, technology has increasingly insulated humans and economic activity from the vagaries of climate. Two centuries ago, work and recreation were dictated by the cycles of daylight, the seasons, and the agricultural growing season.

Today, thanks to modern technology, humans live and thrive in virtually every climate on earth. For the bulk of economic activity, variables like wages, unionization, labor-force skills, and political factors swamp climatic considerations. When a manufacturing firm decides between investing in Hong Kong and Moscow, climate will probably not even be on the list of factors considered. Moreover, the process of economic development and technological change tend progressively to reduce climate sensitivity as the share of agriculture in output and employment declines and as capital-intensive space heating and cooling, enclosed shopping malls, artificial snow, and accurate weather or hurricane forecasting reduces the vulnerability of economic activity to weather.

In thinking about the impact of climate change, one must recognize that the variable focussed on in most analyses—globally averaged surface temperature—has little salience for impacts. Rather, variables that accompany or are the result of temperature changes—precipitation, water levels, extremes of droughts or freezes, and thresholds like the freezing point or the level of dikes and levees—will drive the socioeconomic impacts. Mean temperature is chosen because it is a useful *index* of climate change that is highly correlated with or determines the more important variables. Moreover, it must be emphasized that impact studies are in their infancy and that studies of low-income regions are virtually non-existent.

Existing research uses a wide variety of approaches including time-series analysis, engineering studies, and historical analogs. Climate change is likely to have different effects on different sectors and in different countries.[4] In general, those sectors of the economy that depend heavily on unmanaged ecosystems—that is, are heavily dependent upon naturally occurring rainfall, runoff, or temperatures—will be most sensitive to climate change. Agriculture, forestry, outdoor recreation, and coastal activities fall in this category. Countries like Japan or the United States are relatively insulated from climate change while developing countries like India are more vulnerable.

This survey of impacts will concentrate primarily upon the United States, because that is where the evidence is most abundant. In reality, most of the U.S. economy has little direct interaction with climate. For example, cardiovascular surgery and parallel supercomputing are undertaken in carefully controlled environments and are unlikely to be directly affected by climate change. More generally, underground mining, most services, communications, and manufacturing are sectors likely to be largely unaffected by climate change—sectors that comprise around 85 percent of GDP.

A few studies have estimated the impact of an equilibrium CO_2 doubling (2.5 to 3 degrees C) on the United States, and the results of three such surveys are shown in Table 1. The first column of Table 1 shows the results of Nordhaus (1991) updated to 1988 prices. The other two comprehensive studies by Cline (1992) and Fankhauser (1993) use largely the same data base but extend the Nordhaus analysis to other sectors. The convention used in most damage studies is to calculate impacts in terms of today's level and composition of output. Hence, the \$53 billion estimate of damage from CO_2 doubling estimated by Cline and shown in Table 1 superimposes the estimated impacts that would occur roughly a century from now upon today's economy.

Cline has performed the most detailed economic analysis of the potential impact of climate change on a number of market and non-market sectors, and the overall results are shown in the second column of Table 1. While Cline examined a wide variety of possible impacts, many of the estimates are extremely tenuous and may lean toward overestimating the impacts. For example, Cline's estimates of the impact of losses from storms assume that storms become more severe, whereas both the IPCC and the National Academy studies concluded that the effect of warming on storm intensity is ambiguous. Another example is leisure activities, where he includes only losses to skiing but excludes any gains from the much larger warm-weather industries such as camping,

[4]An early review, emphasizing the potential costs of climate change, is contained in EPA (1989). A more balanced approach, emphasizing the potential for adaptation, is contained in National Academy of Sciences (1992).

Table 1

Comparison of Estimates of Impact of Global Warming on the United States: Impact on Incomes of CO_2 Doubling
(in billions of 1988 U.S. dollars per year)

	Nordhaus	Cline	Fankhauser
Heavily affected sectors			
Agriculture	1	15.2	7.4
Coastal areas	10.7	2.5	2.3
Energy	0.5	9	0
Other sectors	38.1		
Wetland and species loss	[b]	7.1	14.8
Health and amenity	[b]	8.4	30.3
Other	[b]	11.2	12.1
Total: billions of $	50.3	53.4	66.9
(Percent of output)	*1.0*	*1.1*	*1.3*

[a]References are Nordhaus (1991), Cline (1992), Fankhauser (1993).
[b]These are included in the total for "other sectors."

boating, and swimming. In agriculture, Cline relies on estimates that involve little or no adaptation. For health effects, Cline bases his estimates on a study that virtually ignores adaptation. For species loss, Cline takes a very costly decision (that of the Northern spotted owl) and uses that as the basis for valuation. Even with this tendency to see the pessimistic side of global warming, Cline's estimates of impacts are only marginally above those found in other studies (1.1 percent of GNP for a 2.5 degree C warming in Cline, as opposed to 1 percent of GNP for a 3 degree warming in Nordhaus).

A third approach is a compilation by Fankhauser (1993). This study employs much the same methodology as Nordhaus and Cline but uses additional studies and extends the analysis to the OECD countries and to the world. Fankhauser's results are very close to those in earlier studies, finding a 1.3 percent impact of a 3 degree warming for the United States.

A full assessment of the impact of greenhouse warming must, of course, include regions outside the United States. To date, studies for other countries are fragmentary, and it is not possible to make any general conclusions at this time. A preliminary reading is that other advanced industrial countries will experience modest impacts similar to those of the United States, and some may even have net economic benefits; for example, Fankhauser (1993) extends his analysis and estimates losses from CO_2 doubling of 1.4 percent to OECD countries and 1.5 for the world. Another estimate, more qualitative in nature, is an intensive survey of experts on the economic impacts of climate change

(Nordhaus, 1993b). For a 3 degree C warming in 2090, the median response was an economic loss of 1.8 percent of world output. However, there is great uncertainty: the median estimate of the 10th percentile of outcomes is for no impact, while the median estimate of the 90th percentile of outcomes is for a 5.5 percent loss of world output.

All these studies indicate the great uncertainty about the impact of climate change. More recent analysis suggests that the studies reported in Table 1 may well overestimate the impact of climate change because they ignore many ways in which economies can adapt to changing climate. One kind of adaptation ignored in most studies is the buffering of shocks by trade. A study by Reilly and Hohmann (1993) begins with the results of agricultural production-function studies such as those used in Table 1; these studies estimate the impact of climate change on crop yields in individual regions. These yield estimates are then imbedded in a model of international trade. Reilly and Hohmann find that trade tends to reduce the economic impacts by a factor of from five to ten as reactions of supply and demand buffer production shocks. For example, the estimated impact of a substantial (30 percent) yield shock in temperate regions, buffered by the adaptive response in markets, produces a negligible impact on incomes: 0.06 percent of income for the U.S. and 0.08 percent loss for the world over a period of nearly a century. This careful study is a good lesson on how impact estimates often tend to exaggerate losses while ignoring gains and adaptations.[5]

Another approach to measuring impacts is a "Ricardian" analysis that estimates the rents to climate in particular climate zones and then uses these to estimate the impact of climate change on income. The Ricardian approach is useful because it allows all forms of adaptation, whereas the production-function approaches omit all but a few forms of adaptation to changing climate. A study by Mendelsohn, Nordhaus, and Shaw (1993a, b) developed such an approach by examining the impact of climate on U.S. agriculture. This study uses cross-sectional data on climate, farm-land prices, and other economic and geophysical data for almost 3000 counties in the United States.

Applying the model to a global-warming scenario found a range of impacts. The traditional analysis of global warming analyzes the impact upon the

[5]One might suspect that there is often an unconscious impulse to find costs and ignore benefits of climate change. A comparison of two sets of studies is instructive in this respect. Almost two decades ago, a series of studies was undertaken to investigate the impact of flights in the stratosphere on global *cooling*. Studies by d'Arge and others (summarized in National Research Council, 1979) found that global cooling of 1° C would impose costs in a number of areas. Of the nine areas of costs identified in the global cooling studies (agriculture, forest products, marine resources, health, locational preferences, fuel demand, housing, public expenditures, and aesthetics), only two were examined in the 1989 EPA study of global warming and *none* were calculated by the EPA to produce benefits. The largest estimated cost in the global cooling studies was the amenity effect of cooling, determined through regional wage differentials. This topic was completely ignored in the EPA studies. One is tempted to say that environmental impact studies can find the cloud behind every silver lining.

grains. Under this approach, the Ricardian model finds annual losses ranging from $6 to $8 billion annually (without CO_2 fertilization in 1988 prices at 1988 levels of farm income). This can be related to gross farm income in 1982 of $175 billion. Strikingly different results emerge if we use a broader approach which includes all agricultural crops. For these, the net impact of warming is slightly positive, ranging from a loss of $0.7 billion to a *gain* of $2 billion per year. The differing results arise because the broader approach weights relatively more heavily the irrigated lands of the American West and South that thrive in a Mediterranean and subtropical climate, a climate that will become relatively more abundant with a warmer climate.

The one area where our information is particularly sparse is for developing countries. Small and poor countries, particularly ones with low population mobility in narrowly restricted climatic zone, may be severely affected. Much more work on the potential impact of climate change on developing countries needs to be done.

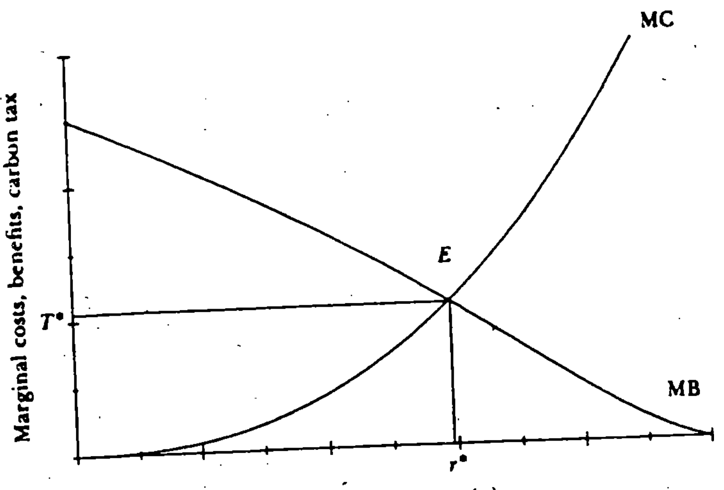
The Balancing Act in Climate Change Policies

The greenhouse effect is the granddaddy of public goods problems—emissions affect climate globally for centuries to come. Because of the climate externality, individuals will not produce the efficient quantity of greenhouse gases. An important goal of economic research is to examine policies that will find the right balance, on the margin, of costs of action to slow climate change and the benefits of reducing future damages from climate change.

The benefits of emissions reductions come when lower emissions reduce future climate-induced damages. To translate these into a marginal benefit function, it is necessary to follow the emissions through greenhouse-gas concentrations to economic impacts, and then take the present value of the impact of an emission of an additional unit. Graphically, we can depict the marginal damages averted per unit of emissions reduction as the downward-sloping marginal benefit (MB) curve in Figure 2.

The second relationship is the marginal cost of emissions reduction, which portrays the costs that the economy undertakes to reduce a unit of greenhouse-gas emissions (or the equivalent in other policies that would slow greenhouse warming). A wide variety of approaches are available to slow climate change. Most policy discussion has focussed on reducing CO_2 emissions by reducing the consumption of fossil fuels through energy conservation, alternative energy sources (some would even contemplate nuclear power), and other measures. Such policies could be implemented through carbon taxes of the kind James Poterba analyzes in this symposium, while some prefer regulations such as tradable emissions permits. Other approaches include reforestation to remove CO_2 from the atmosphere and putting even more stringent controls on CFCs.

Figure 2
Marginal Costs and Benefits of Greenhouse-Gas Emissions Controls



Note: Efficient policy comes at point *E*, where marginal cost of further emissions reduction (MC) equals marginal benefit of emissions reductions in slowing climate change (MB). T^* is the efficient carbon tax while r^* is the efficient reduction rate.

Another option, definitely not in the environmentally correct package, would be to offset greenhouse warming through climatic engineering, primarily through measures to change the albedo (reflectivity) of the earth. Such options include injecting particles that would increase the backscattering or reflecting of incoming sunlight or stimulate absorption of carbon. Two particularly interesting proposals include shooting smart mirrors into space with 16-inch naval rifles or seeding the oceans with iron to accelerate carbon sequestration.[6] Whatever the approach, economists emphasize the importance of cost-effectiveness—structuring policies to get the maximal reduction in harmful climatic change for a given level of expenditure. Figure 2 shows schematically the marginal cost of cost-effective emissions reductions as MC.

The shape of the cost function for reducing CO_2 emissions has been thoroughly studied, and the effort discussed by John Weyant in this symposium represents the most careful comparative examination of the results of different models. In addition, policies should include other cost-effective measures, and a recent National Academy of Sciences Panel (1992) has compared the costs of a wide variety of measures, including rough estimates of the costs of climate engineering.

From an economic point of view, efficient policies are ones in which the marginal costs are balanced with the marginal benefits of emissions reductions. Figure 2 shows schematically how the efficient rate of emissions reduction and

[6] The issues of geoengineering are discussed in National Academy of Sciences (1992, Chapter 28).

the optimal carbon tax are determined. The pure market solution comes with emissions reductions at 0, where MB is far above the zero MC. Point E represents the efficient point at which marginal abatement costs equal marginal benefits from slowing climate change. The policy can be represented by the efficient fractional reduction in emissions, r^* on the horizontal axis, or by the optimal carbon tax, T^* on the vertical axis.

Empirical Modeling of Optimal Policies

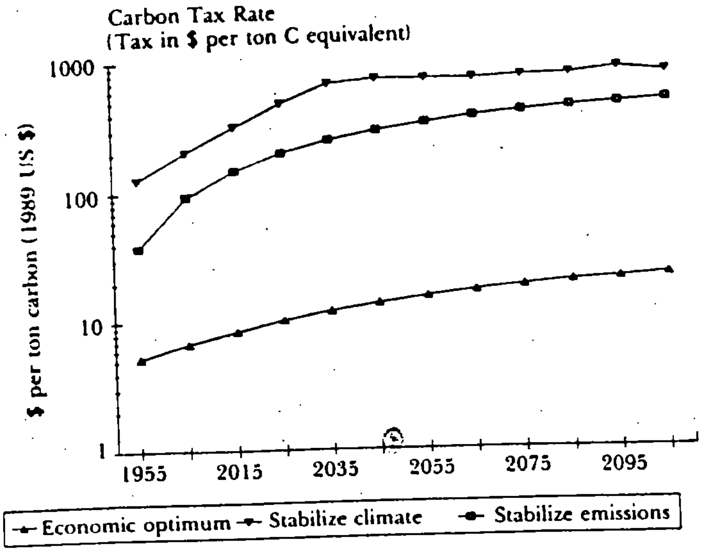
Sketching the optimal policy in Figure 2 demands little more than pencil, paper, and a rudimentary understanding of economics. To move from theory to useful empirical models requires understanding a wide variety of empirical economic and geophysical relationships. Work has progressed to the point where the economics and natural science can be integrated to estimate optimal control strategies. In one study, I developed a simple cost-benefit analysis for determining the optimal steady-state control of CO_2 and other greenhouse gases based on the comparative statics framework shown in Figure 2 (Nordhaus, 1991). This earlier study came to a middle-of-the-road conclusion that the threat of greenhouse warming was sufficient to justify low-cost steps to slow the pace of climate change.

A more complete elaboration has been made using an approach I call the "DICE model," shorthand for a Dynamic Integrated Model of Climate and the Economy.[7] The DICE model is a global dynamic optimization model for estimating the optimal path of reductions of greenhouse-gas emissions. The basic approach is to calculate the optimal path for both capital accumulation and reductions of greenhouse-gas emissions in the framework of the Ramsey (1928) model of intertemporal choice. The resulting trajectory can be interpreted as the most efficient path for slowing climate change given inputs and technologies; an alternative interpretation is as a competitive market equilibrium in which externalities or spillover effects are corrected using the appropriate social prices for greenhouse-gas emissions.

The DICE model asks whether to consume goods and services, invest in productive capital, or slow climate change via reducing greenhouse-gas emissions. The optimal path chosen is one that maximizes an objective function that is the discounted sum of the utilities of per capita consumption. Consumption and investment are constrained by a conventional set of economic relationships (Cobb-Douglas production function, capital-balance equation, and so forth) and by a newly developed set of aggregate geophysical constraints (interrelating economic activity, greenhouse gas emissions and concentrations, climate change, costs of abatement, and impacts from climate change).

[7]The basic model and results are presented in Nordhaus (1992a, b), while complete documentation and analysis are forthcoming in Nordhaus (1993a)

Figure 3
Calculated Carbon Taxes for Three Policies



To give the flavor of the results from the DICE model, consider the economic optimum and compare it to two alternative policies that have been proposed by governments or by the environmental community. The three options are (1) economic optimization as described in the previous paragraph; (2) stabilizing greenhouse-gas emissions at 1990 levels, a target that was endorsed at the Rio Earth Summit by the United States and other governments; and (3) stabilizing climate so that the change in global average temperature is limited to no more than 0.2 degrees C per decade with an ultimate limitation of 1.5 degrees C (compare this with the projections in Figure 1).

Solving the DICE model for the three policies just described produces a time sequence of consumption, investment, greenhouse-gas emissions, and carbon taxes. The carbon taxes can be interpreted as the taxes on greenhouse-gas emissions (or the regulatory equivalent, say in auctionable emissions rights) that would lead to the emissions that would attain the policy objectives just described.

Figure 3 shows the resulting carbon taxes. For calibration purposes, in the United States, a carbon tax of $100 per ton would raise coal prices by about $70 per ton, or 300 percent; would increase oil prices by about $8 per barrel; and would raise around $200 billion of revenues (before taking account of emissions reductions). The economic optimum produces relatively modest carbon taxes, rising from around $5 per ton carbon to around $20 per ton by the end of the next century. The stabilization scenarios require much more stringent restraints. For emissions stabilization, the carbon tax would rise from around $40 per ton of carbon currently to around $500 per ton late in the next century;

climate stabilization involves current carbon taxes over $100 per ton carbon today rising to nearly $1000 per ton by the end of the next century.

The DICE model can also be used to inquire into the estimated net economic impact of alternative policies. For the global economy, the economic optimum has a net benefit over no controls for the global economy (in terms of the discounted present value measured in 1990 consumption units) of $270 billion. On the other hand, stabilizing emissions or climate imposes major net economic costs. Stabilizing emissions leads to a net present-value loss of around $7 trillion relative to the optimum, while attempting to stabilize climate would have a net present-value cost of around $41 trillion. If these present value figures are converted into consumption annuities using an annuity rate of 4 percent per annum, these strategies represent, respectively, a gain of 0.05 percent and losses of 1.4 and 8.2 percent of today's annual gross world output. It would take a major misestimate of either the costs of emissions reductions or of climate-change damages to make the stabilization options economically advantageous.

Several other economic studies have also calculated efficient approaches to slowing global warming. The studies of Manne and Richels (1990, 1992), Peck and Teisberg (1992), and Kolstad (1993) find conclusions roughly similar to those reported here. Other studies—those of Kolstad (1993) as well as earlier studies by the present author (1979, 1991)—also determine the optimal emissions control rates and carbon taxes and show optimal policies in the general range of those determined here.

Two studies derive quite different results, one more optimistic, one more pessimistic. The studies by Jorgenson and Wilcoxen (1991, most strikingly) show a lower set of carbon taxes needed to stabilize greenhouse-gas emissions than those shown here; the reason for the lower carbon taxes seems to reside largely in the slow projected economic growth. By contrast, the study by Cline (1992) proposes much higher control rates. The more stringent controls in the Cline study are due to a number of features—primarily because the Cline result is not grounded in explicit intertemporal optimization and assumes a rate of time preference that is lower than would be consistent with observed real interest rates. Clearly, if we arbitrarily assume a near-zero discount rate (as Cline does), society will undertake massive investments in tangible, human, and environmental capital; who will do all this saving is an unanswered question.

Uncertainties and Anxieties

Most economic studies of the impacts and policies concerning climate change are based on scenarios like the smooth and gradual warming depicted in Figure 1. And, as indicated in the last section, the conclusion that emerges from most economic studies is to impose modest restraints, pack up our tools, and concentrate on more pressing problems. Given the high costs of controls and the modest projected impacts of a 1 to 3 degree C warming over the next half century, how high should global warming be on an international agenda that includes exploding population in the South, nuclear proliferation in the Middle East, collapsing economies in eastern Europe, increasing cycles of poverty and drug use along with stagnating incomes in the West, and sporadic outbreaks of violence and civil war just about everywhere? Given the modest estimated impact of climate change along with these other urgent concerns, we might conclude that global warming should be demoted to a second-tier issue.

Yet, even for those who downplay the urgency of the most likely scenarios for climate change, a deeper anxiety remains about future uncertainties and surprises. Scientists raise the specter of shifting currents turning Europe into Alaska, of mid-continental drying transforming grain belts into deserts, of great rivers drying up as snow packs disappear, of severe storms wiping out whole populations of low-lying regions, of surging ice sheets raising ocean levels by 20 to 50 feet, of northward migration of old or new tropical pests and diseases decimating the temperature regions, of environmentally induced migration overrunning borders in search of livable land. Given the potential for catastrophic surprises, perhaps we should conclude that the major concern lies in the uncertainties and imponderable impacts of climate change rather than in the smooth changes foreseen by the global models.

At present, we do not have the scientific basis for making a firm judgment of the likelihood of one of these catastrophic outcomes. In the survey discussed above (Nordhaus, 1993b), experts were asked about the probability of a 25 percent sustained loss in global income from a 3-degree C warming in 2090 (scenario A) and a 6-degree warming in 2175 (scenario B). The median estimated probability of this catastrophic outcome was 0.5 percent for scenario A and 3 percent for scenario B. On the other hand, the assessment of the catastrophic scenarios varied greatly across respondents and particularly across disciplines. For scenario B, according to the most pessimistic quartile of respondents, the mean probability of this catastrophic outcome was 40 percent. The more pessimistic assessments generally came from natural scientists while the more sanguine views were held by mainstream economists.

Once the door is open to consider catastrophic changes, a whole new debate is engaged. If we do not know how human activities will affect the thin layer of life-supporting activities that gave birth to and nurture human civilization, and if we cannot reliably judge how potential geophysical changes will affect civilization or the world around us, can we use the plain vanilla cost-benefit analysis (or even the Häagen-Dazs variety in dynamic optimization models)? Should we be ultraconservative and tilt toward preserving the natural world at the expense of economic growth and development? Do we dare put human betterment before the preservation of natural systems and trust that human ingenuity will bail us out should Nature deal us a nasty hand?

Faced with this dilemma, we might be tempted to say that such questions are beyond the capability of rational analysis and turn the decisions over to philosophers and politicians. Rather, I believe that natural and social sciences have a central role to play in analyzing potential future outcomes and delineating potential responses. Society often requires that decisions be made in the absence of complete information, whether the decisions be military strategy, oil drilling, or research and development. In each case, a reasoned decision process involves listing the events that may occur, estimating the consequences of the events, judging the probabilities that each of the events will occur, weighing the expected value of the consequences against the expected costs under different courses of action, and choosing the action that maximizes the expected value or utility of the outcome.

Reasoned decision-making under uncertainty is no different for climate-change policy than for other areas, although it may be more complex and require crossing traditional disciplinary boundaries more often. In thinking through the appropriate treatment of future surprises, to the natural scientists falls the crucial task of sorting through the apocalyptic scenarios and obtaining rough judgments as to the likelihood of different geophysical outcomes so as to distinguish between the likely, plausible, possible, and virtually impossible. To the social scientists falls the issue of assessing the probabilities, determining the values of different outcomes, and devising sensible strategies in the face of such massive uncertainties. To our leaders falls the burden of ultimately deciding how to balance future perils against present costs. For all, this is a fruitful use of our collective talents, full of intellectual challenges and practical payoffs.

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Journal of Economic Perspectives—Volume 7, Number 4—Fall 1993—Pages 27–46

Costs of Reducing Global Carbon Emissions

John P. Weyant

Projecting the costs of reducing carbon emissions is extremely important, and exceedingly difficult. Such projections are an integral component of cost-benefit analyses of alternative policies; for example, for the global climate policy analysis described by William Nordhaus in this symposium. Moreover, the nature of the climate change problem dictates that costs be incurred long before benefits can be realized or accurately measured. Consequently, the political spotlight predictably focuses on the cost estimates whenever specific policy options are contemplated.

Projecting the costs of reducing carbon emissions is difficult because many assumptions must be made about how the world will evolve over a very long period of time with and without a control program. Typically, some of these assumptions, like population growth, are taken from outside sources. Other factors, like the response of energy demand to changes in economic output or energy prices, are the result of modeling the behavior of economic actors in response to exogenous stimuli. Considerable uncertainty exists about both the exogenous factors and the best way to model the behavioral responses.

The global nature of the climate change problem adds yet another complication to the cost analysis. Scientists have concluded that it is the global concentration of carbon in the atmosphere that influences climate. Moreover, since carbon in the atmosphere gets mixed more or less uniformly, emissions anywhere change concentrations everywhere, but with a long lead time. Current global carbon emissions are estimated to be only about 4 percent of the stock of CO_2 in the atmosphere attributable to human activity (and about

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1 percent of total atmospheric carbon). Thus, the cost of reducing global carbon concentrations depends on the collective emissions of all the countries of the world over long periods of time. This makes an analysis of the costs of controlling emissions in any one country or region at any point in time an important guide to appropriate policies for that particular country, but an incomplete one.

For the purposes of surveying a number of assumptions and models, the recently completed Energy Modeling Forum 12 study entitled "Controlling Global Carbon Emissions; Costs and Policy Options," which included a comparison of results from 14 models for 13 standardized scenarios, is helpful in this endeavor (Gaskins and Weyant, 1993a, b). A number of more specialized study groups were also organized during EMF 12 to study dimensions of emissions control policy not considered in the original study design. In total, results from 16 models were included in EMF 12, and over two dozen control scenarios were considered. In addition, several other major studies completed over the last three years are relied upon in developing our conclusions here, in particular the excellent surveys by Nordhaus (1991), Congressional Budget Office (1990), Beoro, Clarke, and Winters (1991), Cline (1992), and Dean et al. (1993).

An important limitation of the existing studies, including those represented in EMF 12, is that they focus almost exclusively on reducing carbon dioxide emissions, and include very little detail on the developing countries. Although carbon dioxide is the most important greenhouse gas, reductions in emissions of other greenhouse gases like methane may ultimately prove more cost effective (Blitzer et al., 1992; Schmalensee, 1993).

Many models are now available for studying emissions reductions in the United States and other OECD countries, and a growing number of global analyses offer some regional detail. In the global studies, however, developing countries are typically treated in a simplistic fashion, or aggregated together because of lack of appropriate data and institutional information for the countries involved, or computational limits on model size. A number of developing countries (including China, India, Brazil, Egypt, Nigeria, Indonesia, and others) have substantial emissions at present and/or emissions levels that are likely to grow rapidly during the first half of the next century. This has led to the development of models that can provide a more realistic picture of the potential for emission reductions in these individual countries (Blitzer et al., 1992, 1993; Pachauri and Khanna, 1992), and valuable insights for the global models.

The next section of this paper discusses the key dimensions of any projection of the cost of reducing carbon emissions. The paper then discusses the projections that have been made, including long-, medium- and short-range time horizons. Finally, the conclusion summarizes what we know and don't know about the costs of controlling carbon emissions and recommends an agenda for future research.

Key Determinants of Cost of Control Projections

Hundreds of projections of the cost of reducing carbon emissions have been published over the past decade, a pace that seems likely to continue. Each projection has four key elements: (1) the baseline input assumptions to the analysis; (2) the specification of the control scenario being considered; (3) the structure of the model employed to make the projection; and (4) the cost measure(s) reported. Knowing a few basics about how these elements are handled in a particular study can go a long way towards helping one understand how its results relate to other available projections.

Baseline Input Assumptions

The assumptions included in the baseline scenario are important because the incremental cost of carbon emission controls are measured relative to them. Any analysis of the cost of reducing carbon emissions must rely on input assumptions in three areas: population and economic activity; energy resource availability and prices; and technology availabilities and costs.

Most of the groups projecting the costs of reducing carbon emissions have relied on population and economic assumptions from other groups. The worldwide population growth projections are commonly from demographic models of the World Bank or the United Nations. For economic assumptions, such studies generally rely on economic growth projections made by others, or on external assumptions about labor force participation, and productivity growth. For either population or economic growth, there is less uncertainty about projections for the developed countries than for the developing countries. Birdsall (1992) offers a discussion of the dependence of the results of global warming analyses on population projections.

A second key set of input assumptions to the models concerns the price and/or availability of energy resources. The prices of fossil fuels like oil, natural gas, and coal tend to be important because they are what generally need to be substituted away from when carbon emissions are restricted. Since gas combustion produces about 60 percent of the carbon produced by coal combustion and 80 percent of the carbon produced by oil combustion per unit of energy consumed, optimistic assumptions about natural gas availability can make carbon emissions targets easier to achieve in the short run. Another key dimension of the energy supply picture is the assumption made about the response of the oil exporters to the imposition of a carbon tax or other policies that reduce the demand for oil imports.

A final set of key assumptions about inputs are those made about the costs and efficiencies of current and future technologies, both for energy supply and energy use. Most analysts use a combination of statistical analysis of historical data on the demand for individual fuels, and a process analysis of individual technologies in use or under development to represent trends in energy technologies. At some point these two approaches tend to look quite similar though, as the end-use process analysis usually runs out of new technology concepts after a couple of decades, and it is then assumed that the efficiency of the most efficient technologies for which there is an actual proposed design will continue to improve as time goes on. Particularly important, but difficult, here is projecting technological progress. Attempts to estimate empirically the dependence of future trends in productivity on factor prices, including energy, are rare. Jorgenson and Wilcoxen (1991) present one prominent attempt to do so.

In the long run, the assumptions made about the cost of substitutes for conventional oil and gas determine the cost of controlling carbon emissions. It is generally assumed that the long-run carbon-based fuel alternatives (for example, coal generated electricity and coal-based liquid synthetic fuels) will be less expensive than non-carbon alternatives (like solar-generated electricity, and liquid fuels made from biomass). If this were not the case, there would be no projected long-run costs of controlling carbon emissions.

Existing emissions controls on fossil fuel combustion, like those on sulfur dioxide included in the U.S. Clean Air Act and its amendments, are represented in the models via their projected impact of fuel choice trends, or by using higher costs for technologies that emit sulfur dioxide in the process analysis approach. Representing these costs can be an important element of the baseline scenario because coal use generally leads to high sulfur *and* carbon emissions. Thus, restricting sulfur emissions can lead to some reductions in coal use and, hence, carbon emissions.

Control Scenario

A control scenario translates a carbon emission control program into model inputs. Several dimensions of the control scenario considered are important. First, the control program must specify a goal, which can be an annual carbon emissions target, an atmospheric CO_2 concentration limit, a rate of carbon taxation, or some combination of these elements. The goal must also include a rate at which the objective is to be achieved—because of the time required to replace energy-producing and -consuming capital equipment, it may be easier to reach a more stringent annual emissions target over a longer period of time than a less stringent one over a shorter period of time.

The instrument to be used to achieve the objective must also be specified. For example, an emissions target may be met via a carbon tax, an emissions permit trading system, energy efficiency standards, or a variety of other policies. For control scenarios involving carbon taxation, some assumption needs to be made about the use of the revenues generated, and about the tax treatment of imports of energy and energy intensive products.

A final crucial element of the control program is the allocation of the allowable emissions among countries or regions. Since developing countries are poorer to begin with and likely to grow faster than the developed countries, they will probably not agree to proportional cuts in emissions by all countries.

The paper by James Poterba in this symposium offers an excellent discussion of "North-South" negotiations.[1]

Model Structure

The models considered here can be classified into six distinct classes, depending on the way the relevant markets are represented. The first three categories are *energy-economy models*: the distinguishing feature of such models is that they treat the energy sector in a more aggregate fashion than the energy models, and instead contain much more detail on markets and/or agents in the rest of the economy or economies. The other three categories are *energy models*, which focus on the various markets for energy—fossil fuels, renewables, electric power, and refined fuels—and on specific energy conversion and/or end-use technologies. They treat the rest of the economy in a more aggregated fashion. (See Beaver, 1992, for a more detailed structural comparison of the EMF 12 models.)

The salient characteristics of each class of model are summarized in Table 1, along with examples of models that are included in each class, the time horizon considered, the amount of foresight assumed, and whether the behavioral parameters included in the model are empirically or judgmentally determined. None of the models considered here incorporates uncertainty about future events in representing decision-making by individual participants in the economy.

One distinction of importance in the three energy-economy approaches lies in the level of disaggregation of the non-energy sectors. Both disaggregated and aggregated economic equilibrium models allow investment levels to be chosen endogenously. However, the disaggregated equilibrium models consider markets by industry category, and allow GDP to be determined, in part, by these interindustry interactions. The aggregate equilibrium models, on the other hand, usually include markets for broad sectors like capital, labor, and energy, and determine GDP with an aggregate production function. The main advantage of the disaggregated approach is that it allows a closer look at non-energy markets; the main advantage of the aggregate approach is that it allows more detail in looking at energy markets.

The disaggregated energy-economy models can be further subdivided into long-run growth and short-run macroeconomic adjustment variants. The macroeconomic adjustment models include multiple sectors and explicitly represent the processes by which unemployment and inflation are created and influence the level of economic output.

In the three classes of energy models—energy-sector equilibrium, optimization, and energy demand simulation models—the major distinction is the manner of modeling prices in the energy sector. An energy-sector equilibrium model examines simultaneous equilibria in all energy sector markets: fossil fuel, renewable energy, electricity, and so on. Contrary to the first three model

[1] See also Chichilnisky (1993).

Table 1
Model Types and Distinguishing Characteristics

Market Representation	*Model Author(s)*	*Scope*	*Time Horizon*	*Fore-sight*	*Param*
Disaggregated Economic Equilibrium	CRTM (Carbon Rights Trade Model) Rutherford (1992)	World	2100	M	J
	DGEM (Dynamic General Equilibrium Model) Jorgenson/Wilcoxen (1991)	U.S.	2050	P	E
	GOULDER Goulder (1993)	U.S.	2030	P	J
	GREEN (General Equilibrium Environmental) Burniaux/Martin/Nicoletti/ Oliveira-Martins (1991)	World	2050	M	J
Disaggregated MacroEmetric Adjustment	DRI McGraw-Hill Brinner, Shelby, Yanchar, Christofaro (1992)	U.S.	2010	M	E
	LINK Kaufman/Li/Pauly/Thompson (1991)	World	2010	M	E
Aggregate Economic Equilibrium	CETA (Carbon Emissions Trajectory Assessment Model) Peck/Teisberg (1992a)	World	2100	P	J
	GLOBAL 2100 Manne/Richels (1992a)	World	2100	P	J
Energy-sector Equilibrium	GEMINI Decision Focus, Inc. (1990)	U.S.	2030	P	J
	FOSSIL2 AES Corporation (1990)	U.S.	2030	M	J
	GLOBAL MACRO ICF, Inc. (1988)	World	2100	M	J
	ERM (Edmonds-Reilly Model) Edmonds/Reilly (1985); Edmonds and Barns (1991)	World	2095	M	J
	MWC (Model of Warming Commitment) Mintzer/Schaper (1992)	World	2095	M	J
	EDS (IEA Energy Demand System) International Energy Agency (1991)	World	2005	M	E
Energy-sector Optimization	MARKAL (MARket ALlocation Model) Morris/Solomon/Hill/Goldstein (1990)	U.S.	2025	P	J
Energy Demand Simulation	T-GAS (Trace Gas Accounting System) Piccot, et al. (1990)	World	2010	M	E

Key: M is myopic; P is perfect; J is judgmental; E is econometrically estimated.

types, this type of model does not include any markets for non-energy goods. These models generally offer a regional analysis of the nation or globe, along with great detail on energy technology.

The objective of an energy-sector optimization model is minimization of total U.S. energy sector costs, given the demands for energy services from the rest of the economy. Although this optimization approach contains within it an implicit equilibrium, it does not actually use explicit market prices. This approach usually allows energy use to be reduced only through the introduction of more efficient technologies, and employs a great deal of detail about such technology. However, it does not examine economic effects outside the energy sector—even questions like what effect higher energy prices would have on the quantity of energy demanded.

The energy demand simulation approach uses projections of energy prices and economic activity, together with econometrically estimated parameters representing the behavioral response of industry and consumers to these factors, to estimate how much energy will be consumed. This approach has no explicit representation of supply, and thus does not model an explicit equilibrium in energy markets.

Two other features of the models are important in understanding and assessing differences in model projections: the assumption made about the foresight employed by economic agents in making decisions, and the source of key parameters employed in representing economic behavior. In some models it is assumed that economic agents base current consumption, production, and investment decisions on current prices only (myopic expectations), while others assume that they base these decisions on perfect information about the price projections produced by the model.

The substitution parameters used in the models are either judgmental (although generally calibrated to the available empirical literature in some way) or econometrically estimated with historical data. Reflecting the typical practice of including only a limited number of aggregate parameters whose values can easily be changed in sensitivity analyses in them, the models with judgmentally determined parameters are sometimes also referred to as "parametric" models.

Cost Measure

The cost of carbon emission reductions are reported using at least four alternative cost measures: (1) the *carbon tax* required, which measures the marginal cost of the last ton of emissions reduced; (2) the *total direct cost*, which measures the marginal cost of the reductions integrated over all emissions reductions; (3) the loss in *gross domestic product* (GDP), which measures the reduction in the total goods and services produced by the economy, and thus may include the impact of the carbon emission reductions on capital accumulation and technological progress, and (4) *compensated income variation*, which measures how much consumers would have to be compensated to make them as well off in terms of their own utility after the imposition of the emissions reduction program as in the baseline scenario. Not all models can produce results for all cost measures, which further complicates comparisons. For example, energy sector models cannot produce compensated income variation results (since they do not examine the broader economy in that way), and the total direct cost is generally not reported by general equilibrium modelers. These measures tend to move together, but departures from this general rule can be significant. For example, general equilibrium models may project lower carbon taxes required to achieve an emissions target, but greater GDP losses than energy sector models if they include a strong negative influence of higher energy prices on economic growth. This lowers baseline emissions, but increases the share of emissions reductions that comes from lower economic growth rates rather than reductions in energy intensity or fuel switching.

Along with the problem of measuring the cost of emissions reductions along different dimensions, cost measures are often discussed according to their time frame. The next section of this paper discusses "long-run" costs, defined as those costs which remain after a transition to primary reliance on non-fossil fuel sources of energy can be completed. The following section will address "short-to-intermediate-run" costs, which occur until that transition is completed. Both sorts of costs are likely to be important to policy-makers. Although the total annual costs of carbon emission reductions are generally projected to be higher in the long run, the marginal costs of control can be higher in the short run. In addition, the relative importance of short- and long-run costs depends on the rate at which future costs are discounted, which is an ongoing debate as mentioned by Richard Schmalensee in his introduction to this symposium. Throughout the discussion here, the goal is to describe results that appear to be robust across all sets of input assumptions and models, and when the results differ, to figure out why.

Long-Run Cost Projections

The transition period to a low-carbon world is likely to take 40 to 60 years, even if it started today. This results from the long life of energy-producing and -consuming capital stock, and the long lead time required to develop, refine, and phase in new carbon-free technologies. Every carbon emission control study must come to grips with this fact.

Common Conclusions

Three major general conclusions can be drawn about the cost of controlling carbon emissions in the existing long-run economic studies, defined here as those extending beyond 2040: controlling global carbon emissions over this time horizon will require a significant amount of international cooperation; if such cooperation can be achieved, a control program that is phased in gradually need not slow world economic growth appreciably, but will be expensive in absolute terms; and a system of international emissions trading can improve the efficiency of a global control program and significantly reduce its cost. Each of these points is explored in turn.

A significant amount of international cooperation will be required to control carbon emissions in the long run. Manne and Richels (1992a) observe that it will probably be impossible to limit global carbon emissions to 1990 levels by the middle of the next century if China does not participate in the control program—even if *all* other countries reduce their emissions to zero! Although China is responsible for only about 11 percent of global carbon emissions today (650 million tons out of world total of 6 billion tons) that percentage is expected to grow as the Chinese economy develops and uses its substantial coal reserves as part of that development process. If carbon emissions in China grow at 4 percent per year, which is not a particularly high baseline projection, in 56 years the emissions in China alone will equal total world emissions today. Efforts to limit global carbon emissions may start with the developed countries, but they cannot end there.

The costs of stabilizing global carbon emissions appear likely to be in the range of about 4 percent of GDP per year by the year 2100. For example, consider four key control scenarios from the EMF 12 study. Each includes participation by all major carbon emitters. In the "Stabilize Global Emissions" scenario, the countries of the OECD and the former Soviet Union are assumed to reduce emissions by 20 percent relative to 1990 levels by 2010 and maintain them at that level through 2100, while the rest of the world is restricted to increasing their emissions by no more than 50 percent relative to 1990 levels through 2100. This allocation of emissions rights leads to global emissions in 2010 and thereafter that are no greater than those in 1990. In the "Reduce Global Emissions" scenario the OECD and former USSR reduce emissions by 50 percent relative to 1990 by 2050, and the rest of the world is again limited to no more than a 50 percent increase relative to 1990 levels; this leads ultimately to about a 15 percent reduction in global carbon emissions. In the "Slower Growth in Global Emissions" scenario, the developed countries limit emissions to 1990 levels by 2000 and the developing countries are again limited to no more than 50 percent more than today's emissions levels, resulting in about an 18 percent increase in global emissions relative to 1990. Finally, the "Phased-In Tax" scenario includes a carbon tax imposed by all countries that increases from $15 per metric ton of carbon in 1990 at 5 percent per year. This is approximately the tax trajectory that would result from limiting *cumulative* world emissions over the next 50 years to 50 times 1990 emissions.

By the year 2040, all four scenarios would cause the world GDP on average to drop by about 2 percent of GDP per year, plus or minus half a percent. By 2100, they would reduce global GDP by 4 percent per year, plus or minus 1 percent. However, all of these scenarios represent a significant departure from the historical trend in carbon emissions. The baseline projection, without any of these policy changes, is that carbon dioxide emissions will have doubled by 2040, and increased by a factor of nearly six-fold by 2100. The "Phased-In Tax" scenario would reduce emissions rather sharply by the year 2100, while the other three scenarios would keep carbon emissions within about 20 percent of their present level over the next century.

The cost of a long-run global carbon emissions control program designed to limit emissions to their 1990 level (about 6 billion metric tons), is projected to be about 2.5 percent of world GDP by the year 2043, plus or minus 1 percent. If world GDP were projected to grow at 2.3 percent per year over the next 50 years in the absence of a control program, a control program phased in over that period would only lower that growth rate to 2.25 percent per year. Thus, if climate change turns out to be a very serious problem, it can be controlled without eliminating or even noticeably reducing long-run economic growth. On the other hand, 2.5 percent of the almost $90 trillion dollar world economy in 2043 (in 1990 dollars) would amount to about $2.25 trillion dollars per year (2.5 percent of current world GDP is over half a trillion dollars). Given other pressing world problems, this sum represents a substantial long-run commitment of societal resources.

These cost estimates have so far generally assumed that the emissions reductions are achieved efficiently in each region as, for example, through the use of a tax on the carbon content of fossil fuels. Given institutional constraints in both the developed and developing countries, this assumption may ultimately turn out to be overly optimistic, but the results obtained for the carbon tax cases provide useful benchmarks on what might be achievable.

A growing number of analysts have studied the potential for international trading of emissions rights to reduce the cost of a global carbon emissions control program. In such a program, one country can pay for emissions reductions in another country, if that is less expensive than the available domestic options. In EMF 12, an emissions trading program was considered relative to the global emissions stabilization scenario, where the initial allocation of emissions rights is 20 percent lower than current emissions for the developed countries and 50 percent more than current emissions levels for the developing countries. Results from four models show that this strategy can reduce the costs of control by one-third or more, by equalizing the marginal cost of control across all nations.[2] Allocation of emissions rights by population or GDP per capita would lead to even greater benefits from international emissions trading (Yamaji and Okada, 1992; Edmonds et al., 1993). At some point, the technology of energy production and use may become homogeneous enough to eliminate these advantages, but until that point an international emissions trading program will be worth serious negotiating efforts; in fact, it may be the only way to solve the participation problem noted above.

[2]For example, the four models included in EMF 12 that attempted the International Emissions Trading Scenario—ERM, OECD-GREEN, Global 2100, and CRTM—project a decrease of 30 percent to 40 percent in the initial cost of Stabilize Global Emissions scenario with trading with respect to the no trading case.

Significant Differences in Assumptions and Models

Although the long-run cost of controlling carbon emissions seems fairly similar in many published studies, there are some differences as well. First, the estimated cost of reducing emissions to achieve any CO_2 emission or concentration target depends on the baseline emissions projection of carbon emissions, which in turn depends on the projected rates of economic growth, income elasticities for energy demand, and rates of non-price induced shifts in energy efficiency. Second, the degree to which "backstop" technology assumptions—advanced technologies with high cost and unlimited supply—are employed has a large impact on the cost of control estimates. Third, in lieu of backstops, some analysts use resource supply curves with large flat segments at higher prices, and differences in these assumptions can be significant. Again, each of these three points will be examined in turn.

Most long-run projections of the costs of controlling carbon emissions foresee a major role for coal in the future baseline energy mix, and since coal is abundant on a global basis, this assumption limits future energy price increases. As a result, the major determinants of long-run energy demand turn out to be population growth, economic growth, the income elasticity of demand for energy, and the non-price-induced rate of change in energy demand per unit of economic output. Very few modelers make their own projections of long-term worldwide economic growth, worldwide income elasticities, or long-term energy efficiency trends. Thus, most researchers rely on the few estimates that are available, most of which are for just the United States or the other members of the Organization for Economic Cooperation and Development (OECD).

Even when the assumptions about GDP growth rates are standardized, a wide range of reference case emissions projections are produced by the models. By the year 2100, projections of world CO_2 emissions from eight different models range all the way from a tripling to a seven-fold increase over 1990 levels.[3] The reason for this variation is simple enough: relatively small differences in model parameters lead to large differences when their effects are compounded over more than a century. Much of the difference in projections from the models for 2100 can be explained by differences in the assumed rate of decrease in energy use per unit of economic output independent of energy price changes. The Global 2100 model uses a value of .5 percent per year for this parameter, while the Edmonds-Reilly model employs 1.0 percent per year assumption. This single difference explains virtually all of the nearly factor of two difference in the baseline emissions projections from these two models in 2090 (Dean et al., 1993; Gaskins and Weyant, 1993b). The more disaggregated assumptions made in the Global Macro model imply about a 1.25 percent rate of decrease in energy use (per unit of output). Estimates of this aggregate parameter based on historical data range from a rate of decrease of about .5 percent per year to an *increase* at about that rate (Jorgenson and Wilcoxen,

[3]The eight models are ERM, Glob-Macro, Global 2100, OECD, IEA, CETA, MWC, and CRTM.

1991; Manne and Richels, 1992a). Researchers who have attempted to extrapolate the types and efficiencies of energy-using equipment into the future have argued that the potential exists for a rate of decrease in energy use per unit of economic output from 1 percent per year to over 2 percent per year without any increase in energy prices.

Some analysts use the backstop technology concept (introduced by Nordhaus, 1973) to represent the idea that at a high enough price for energy, one or more technologies will combine to provide a virtually unlimited supply of energy. The inclusion of such technologies puts a cap on the ultimate cost of carbon emissions reductions. In fact, Manne and Richels (1990), who include both a carbon-based backstop (like synthetic oil from coal) and a carbon-free energy backstop (like synthetic oil from biomass) in their analysis, have observed that the long-run carbon tax in such a set-up can be calculated on the back of an envelope, as the difference between the costs of the carbon-free and carbon-based backstops divided by the carbon emissions rate of the carbon-based backstop.[4]

Analyses that do not include backstop technologies per se generally include long-run supply curves for carbon free resources that become very flat at high cost levels. The resources included and extent of high-cost carbon-free resource availability vary from one analysis to another, but each serves to limit the long-run cost of carbon emission reductions.

Short-to-Intermediate Run Costs

In the short-to-intermediate run, the economy must face the costs of transition away from primary reliance on carbon-based energy. Again, some commonalities among the results of these transition studies are reviewed, and then some differences.

Common Results

Several common themes emerge from a review of the cost of control projections for the short-to-intermediate term. First, if the emissions target requires moving faster than the natural rate of capital stock turnover and technology development, significant additional adjustment costs are likely to be incurred. Second, recycling the revenues obtained from carbon taxation in a way that reduces less efficient ways of raising government revenues can significantly reduce the net cost of the control program. Third, if some major carbon emitters fail to participate in the control program, the downward pressure on oil prices and the supply of carbon-intensive goods in the participating coun-

[4] For example, in EMF 12 a carbon-based non-electric backstop costing $50/BBL, a non-carbon non-electric backstop at $100/BBL, and a carbon emission for the carbon-based backstop of .24 metric tons carbon/barrel oil were specified. Thus, the long-run carbon tax produced by the Global 2100 model is ($100-$50)/.24 = $208/metric ton carbon.

tries will cause increases in carbon emissions by non-participants relative to their baseline levels, somewhat offsetting any gains.

Studies of the cost of controlling carbon emissions show that incremental reductions in allowable emissions cost more as the absolute level of allowed emissions in any particular year is reduced. This finding is especially true in the short- and intermediate-run, up to about 2040, before old fossil-fuel based energy producing and consuming equipment can be fully retired and new carbon-free technologies can be fully introduced. For example, in EMF 12 the cost of stabilizing U.S. carbon emissions (reducing them an average of 30 percent relative to the no control baseline) ranged from .2–.75 percent of GDP in 2010, while the cost of reducing emissions by 20 percent in that year (or an additional 15 percent relative to baseline emissions on average) range from .9–1.7 percent of GDP. In other words, a 20 percent additional reduction in emissions relative to 1990 levels (and, on average, a 15 percent reduction relative to 2010 baseline emissions) could more than double the cost.

Existing studies also demonstrate that trying to reach fixed emissions targets faster—say by 2010 rather than 2040—imposes significant additional adjustment costs. Short- to intermediate-run carbon tax projections from the models that significantly exceed their long-run levels provide the most dramatic evidence of situations where these additional adjustment costs are likely to be incurred.[5] This result is observed in results from models that take a long-term perspective; it is still larger in the medium-term models that try to track year by year energy-using and energy-producing capital stock adjustments over the next 20–40 years; and amplified still further in the short-run econometrically estimated demand models that focus primarily on projecting energy demand over the next 5–15 years. These adjustment costs result from a combination of empirically and judgmentally estimated adjustment rate parameters, as well as actual data on existing technologies and capital equipment in place. Despite the heterogeneity in modeling approach adopted, each leads to a projection that substantial adjustment costs are likely to be incurred in this scenario. Extensive sensitivity analyses by Petersen et al. (1992) show that even a ten-year delay in the date by which the global stabilization target must be achieved can reduce the peak in the carbon tax projections dramatically. In addition, Manne and Richels (1992b) show that the peak is virtually eliminated in Global 2100 model by limiting total emissions over a 50-year time period to fifty times the 1990 levels, and letting the model decide when the emissions should occur to maximize the discounted utility of consumers. This optimization results in more emissions than required to stabilize annual emissions in the short run, and less emissions than required to stabilize annual emissions in the long run.

[5] In EMF 12, the average carbon tax required to reduce U.S. carbon emissions in 2010 to 20 percent below their 1990 level is about $350 per metric ton, while the same goal can be achieved in 2050 with an average carbon tax of slightly over $200 per metric ton.

If a carbon tax is used to reduce emissions, the way in which revenues from that tax are used has an important impact on the projected GDP loss. Models that do not explicitly represent the tax system often assume tacitly that the revenues simply accrue to the government, with no particular incentive affects, like the revenue from a lump sum tax. However, carbon tax revenues could be used to reduce existing taxes that discourage economic activity, particularly capital formation. This is not a prescription to overhaul fiscal policy to minimize the impact of a carbon tax on the economy, but a more general observation regarding the relationship between taxation and economic growth. It emerges in the carbon emission control context because it helps explain differences in model results and identifies the way in which carbon tax revenues are recycled as an important consideration in evaluating them as a potential policy instrument. As part of the EMF 12 study, simulations with four models of the U.S. economy (DRI McGraw-Hill, LINK, DGEM, and Goulder) indicate that from 35 percent to as much as 100 percent of the U.S. GDP losses for the phased-in carbon tax could ultimately be offset by recycling revenues through cuts in existing taxes (Shackleton et al., 1992). On the other hand, if the revenues are used to fund low return government projects, the cost of achieving the carbon emission reductions could be substantially *greater* than when they are recycled in lump sum fashion (Nordhaus, 1993).

If the OECD or any other group of countries unilaterally implements a carbon reduction program, resulting changes in international energy prices will cause carbon emissions in other countries to increase relative to baseline levels (Rutherford, 1992; Nicoletti and Oliviera-Martins, 1992; Horton, Rollow, and Ulph, 1992; Rutherford et al., 1992). Increased carbon emissions by non-participating regions occur both as a result of increased energy intensity of economic activity domestically (that is, through the use of more energy intensive production processes and demands for more energy intensive products) and through the migration of energy-intensive production into unconstrained regions. Carbon restrictions place countries who control at a competitive disadvantage in energy-intensive industries. Thus, the cost to countries who control emissions increases with the level of cutback, but the impact on global emissions may drop off sharply if large groups of countries fail to cooperate. In comparing model results, we will generally assume universal participation because that is what most existing studies have assumed. Edmonds et al. (1993) and Nicoletti and Oliviera-Martins (1992) also consider some of the implications of partial participation on control costs.

Significant Differences

The most significant differences in short-to-intermediate term cost projections result from differences in the rate of achieving emission targets, introduction rates for new technologies, and retirement rates for existing facilities; economic growth projections; the treatment of pre-existing taxes on energy and on other inputs to the economy; and assumptions about natural gas availability and price.

If a fixed annual emissions rate target is specified, cumulative costs can be reduced with some increase in short-term emissions either by allowing more time for reaching the target, or by phasing in more gradually the instrument(s) used to achieve the target (like a carbon tax). The cost reduction can be particularly significant if the target date and rate of implementation are set to allow new carbon-free technologies to be phased in smoothly. The timing issue has been explored through extensive sensitivity analysis by Petersen et al. (1992) and Manne and Richels (1992b). Similar issues involving the rates of technology introduction and retirement have also been explored through sensitivity analysis by Petersen et al. (1992).

Different projections of economic growth can lead to different estimates of carbon control costs. The EMF 12 study design includes a 2.2 percent growth rate in GDP for the U.S. over the next 30 years. However, one of the models included in the study (DGEM) produced an independent GDP projection of 1.4 percent per year over that time frame (for a description of the methodology employed see Jorgenson and Wilcoxen, 1991, 1992). The lower growth rates result in lower carbon taxes being required to meet any particular emissions target. Interestingly, though, the computed GDP losses from such carbon taxes are not significantly less than in the other models, because higher carbon taxes lead to higher energy prices, which significantly diminish capital accumulation and productivity growth.[6]

Models that include preexisting energy taxes generally require a larger increase in energy prices and, therefore, a higher carbon tax to reach a fixed emissions target (for example, Kaufman, 1992). In countries with higher existing energy taxes, a larger carbon tax must be utilized to achieve a given percentage increase in retail energy price levels. Moreover, most models exhibit increasing marginal costs of energy demand reductions with respect to decreases in the level of energy demand. In addition, Goulder (1993) has observed that general equilibrium models can include preexisting taxes on all factors of production which results in carbon taxes being more costly to the economy. Carbon taxes lead to less energy use which makes other factors less productive, but if these factors are already taxed, the marginal productivity loss will be greater than if there were no preexisting taxes on the other factors. In effect, a carbon tax operates as an implicit factor tax; higher preexisting taxes elsewhere increase the propensity of the carbon tax to generate further distortions in factor markets. This effect also serves to blunt the effectiveness of

[6]The lower GDP growth rate was adopted for a "Low GDP Growth" sensitivity scenario. This scenario does lead to a significant reduction in the cost of control because it directly reduces the reference level of emissions projected by each model. In addition, when all the models are run with the low GDP growth rate assumptions, they produce carbon taxes that are more closely consistent with those projected by the lower growth models.

revenue recycling as a means of reducing the net costs of imposing a carbon tax to reduce carbon emissions.

Finally, the cost of the transition to the non-carbon-based energy technologies can be significantly affected by the availability of natural gas resources. Since natural gas has a lower carbon emissions rate than oil or gas, more fossil energy can be consumed within any emissions constraint if the use of natural gas can be increased. The "High Natural Gas Resources" scenario included in EMF 12 postulates a quadrupling of natural gas resources in each region, an optimistic assumption that thus gives an upper bound on the importance of this factor. In any event, this assumption does lead to a 30 to 40 percent reduction in the discounted cost of stabilizing emissions over the next 20 years.

Conclusions and Directions for Future Research

Regardless of one's view on the magnitude of the global climate change problem and preferred carbon emissions control objective, two things appear to be paramount in any attempt to minimize the cost of any control program—international cooperation and time for existing energy-related facilities to be retired and for new technologies to be phased in. A carefully designed revenue recycling program and set of trade policies can also reduce the costs of the control program significantly. The long-run cost of stabilizing global carbon emissions at 1990 levels appears to be about 4 percent of world GDP per year (plus or minus 1 percent). Although this cost is very high in absolute terms, it implies only a minor reduction in the rate of economic growth if the control program is phased in gradually. On the other hand, if policy were to focus on some convenient but arbitrary earlier goal—like stabilizing or decreasing emissions rates by 2000 or 2010 relative to 1990 levels—the increase in costs could be substantial.

Given the timing and coordination issues discussed here (involving coordination with fiscal and trade policies, as well as with control programs in other nations), a look at the cost side of the equation suggests the advantages of a more gradual control policy, unless the damages resulting from the small amount of additional emissions over the next half century can be argued to be worth the relatively large incremental cost of eliminating them. Reducing the growth rate of emissions might not only be beneficial itself, but also put us in a better position to control emissions more aggressively in the future, if that should become necessary.

Additional research in several areas could significantly improve our ability to understand the costs of reducing carbon emissions, and thus to evaluate alternative policy options.

1. Information about the potential for technologies that improve energy efficiency is incomplete and often inconsistent, and there is little conclusive analysis regarding their likely rate of adoption. However, this factor is a major

determinant of baseline emissions levels, a major source of differences in emissions projections between the models, and a major determinant of the cost of achieving any emissions target. Particularly important here are assessments of market imperfections or distortions that impede the introduction of more efficient technologies. For example, energy pricing in China, the developing countries, and the former Soviet Union has been far below world market levels.

2. The existing long-run population and economic projections display some considerable differences. In particular, relatively little is known about likely economic and population growth in the future in such important and diverse countries as China, India, Brazil, Nigeria, and the independent states of the former Soviet Union.

3. The adjustment costs that result from any control strategy depend on the availability and cost of energy sources that do not emit carbon. Many of these are "renewable" resources like solar or wind power. Such technologies are not currently cost-effective, but they could easily become competitive in the future—say, if carbon taxes reach $100 per metric ton. The models included in this study all represent these adjustment costs in one way or another, but often the approaches lead to markedly different results. This suggests the value of additional work on data and models of new technology availability dates and introduction rates, as well as of technology transfer to the developing countries.

4. Some possible offsets to carbon emissions are not directly part of energy production or use; for example, tree planting or slowing deforestation, or reducing other greenhouse gas emissions like methane from natural gas system leaks, coal bed seams, or ruminants. These approaches might be as effective as carbon emissions reductions in slowing climate change.[7]

5. The value of additional work on the linkages between environmental policies and international trade in energy and non-energy goods is high. See McKibbin and Wilcoxen (1992) and Manne and Rutherford (1992) for promising new work in this direction.

■ *I am grateful for research support to the U.S. Department of Energy, the U.S. Environmental Protection Agency, and the National Science Foundation and for valuable comments to Darius Gaskins, Jim McMahon, Don Rosenthal, Richard Schmalensee, Bob Shackleton, Carl Shapiro, Jim Sweeney, and Timothy Taylor.*

[7]Herzog et al. (1993) argue that a large scale *long-run* program of carbon sequestration may not ultimately prove feasible. A small interim program could, however, provide much needed time for the world's economies to make the adjustments necessary to transition to non-carbon based energy fuels. See, for example, Callaway et al. (1993) and Richards et al. (1993).

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Journal of Economic Perspectives—Volume 7, Number 4—Fall 1993—Pages 47–63

Global Warming Policy: A Public Finance Perspective

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The scientific evidence on how man-made emissions of greenhouse gases affect global climate is not yet conclusive, but in spite of this, many policy-makers have proposed various policies to reduce these emissions. Carbon dioxide is the single most significant man-made greenhouse gas. One of the most common policy prescriptions for slowing greenhouse gas emissions is a carbon tax: a tax on fossil fuels in proportion to the amount of atmospheric carbon dioxide that is released when they are burned. It differs from other broad-based energy tax proposals, such as President Clinton's recent proposal for a BTU tax, in the relative burdens that it places on coal, oil, and natural gas.

Enacting a carbon tax is only one of many possible policy responses to the possibility of global warming. Such responses can be divided, following Nordhaus (1991), into three broad categories: amelioration, abatement, and prevention. Ameliorative actions focus on offsetting the effects of a warmer climate if and when they occur. They include migration, increased use of air conditioning in regions that are affected by global warming, and shifting patterns of industry and land use in particular areas. The second group of policies, which focus on abating the effects of global warming as they occur, might include painting roof-tops and highways white, to reflect more incoming sunlight back into space, or chemical modifications to the oceans to encourage CO_2 absorption. Finally, the third group of policies focus on preventing the build-up of greenhouse gases before they can affect global climate. The carbon tax is an example of such a preventive policy.

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Global climate change is a slow process, at least relative to many other phenomena studied in economics. Most of the consequences of global warming occur in the middle of the next century, at the earliest. This time profile of benefits has an important implication for comparisons of the three classes of policy responses described above. Since the benefits of all three types of policies accrue in the distant future, but the costs of preventive policies are incurred now, the benefit-cost ratio for prevention policies is more sensitive to the discount rate than the benefit-cost ratio for either abatement or amelioration policies. At high discount rates, prevention policies look relatively unattractive. Nevertheless, preventive policies have received nearly all of the attention in global warming policy discussions. Part of their appeal derives from a concern with worst-case scenarios. Because atmospheric carbon dioxide has a long half-life, reducing emissions today provides a margin of insurance against future discoveries of adverse effects. Part of the preventive policies' appeal is clearly political, however. Enacting an environmental tax increase enables politicians to claim that they have taken immediate action on the global warming "problem."

The possibility of global climate change raises a host of new research questions for economists. Many are more novel, and some might say more interesting, than the analysis of the taxes and subsidies that are aimed at preventing greenhouse gas emissions. Yet in the last few years, a substantial volume of research has considered the design of taxes to slow greenhouse gas emissions and the economic effects of such policies. In this paper, I summarize the insights that have emerged from this work.

The paper begins by explaining that while efficiency considerations create a presumption for using coordinated international policies to alter greenhouse gas emissions, the prospects for such action are bleak. It then focuses on the public finance of carbon taxes at the *national* level, considering the design of such taxes as well as their incidence across and within nations. The next part of the paper focuses on greenhouse gas emission policies that could be enacted in less developed countries, such as the elimination of fossil fuel subsidies and other policies to slow deforestation. A brief conclusion suggests several promising directions for future study.

Prospects for Coordinated International Action

There is a strong theoretical, if not practical, presumption that actions concerned with global climate change should be taken at a supranational level. National emission abatement policies are likely to select inefficient emission targets for several reasons. First, and most important, they neglect the benefits from emission reduction that accrue to other nations, and therefore tend to select too little emission control. Second, no single nation acting alone can stabilize greenhouse gas emissions; this makes it difficult to marshall support for any action at all. Third, international competition can undermine environmental policy-making. If one nation enacts a policy to reduce a particular class of emissions, polluters with high abatement costs may move to other nations with less stringent emissions standards. As nations compete with each other to retain internationally mobile factors, they may be caught in a "race to the bottom" with respect to environmental policy. Finally, unilateral national policies are unlikely to achieve the least-cost method of reducing emissions, since they do not trade off opportunities for emissions reduction in different countries. Hoel (1993) discusses the gains from multilateral environmental action, and Martin et al. (1992) present empirical evidence on the cost savings from multilateral rather than unilateral policies to reduce greenhouse gas emissions, with a focus on the European case.

In spite of these efficiency arguments, coordinated international action is difficult to achieve. Without a system of international property rights, nor any associated mechanism for enforcing property claims or adjudicating disputes, it is difficult to develop market-based solutions for global environmental problems. International coalitions for environmental action are fundamentally *voluntary* associations which function only when all nations benefit from participation. There is wide disparity in the costs and benefits of different policies across nations on many environmental problems, including global climate change. The central task of designing a successful environmental accord is therefore to find compensation mechanisms, such as aid or other transfers, that will draw the "losers" from environmental policies into the coalition. If wealthy nations with the resources to make transfers that convince other nations to participate in an agreement are not committed to a global environmental accord, or if they choose to free-ride on the actions of other nations, the prospects for success are limited.

Measuring the costs and benefits of global climate change for an individual nation, and even the world, involves substantial uncertainties. In this issue, Nordhaus surveys much of the work to date. One finding is that currently developing nations, which tend to derive higher shares of GDP from agriculture than their developed neighbors, are more sensitive to climate change than currently developed nations. Developing nations are also more likely to be affected by some of the other aspects of global climate change. For example, Cline (1992) lists the 50 nations with the highest predicted costs as a share of GNP of adapting to rising sea levels, one of the consequences of global warming. New Zealand is the only developed nation in his list. For some nations, such as Canada and Russia, global warming might actually prove beneficial and raise agricultural yields. Nordhaus (1991) concludes that the potential costs to the United States of a warming earth will be modest, at least over the next century.

One of the key challenges in forging any cooperative agreement on climate change is the poor alignment between the burdens of reducing current CO_2 emissions, which fall on a small group of nations, and the benefits of such actions, which are distributed more widely. Since developed nations account for most current greenhouse gas emissions, they would bear a disproportionate share of the costs of policies to lower these emissions. The United States and Canada currently account for 25 percent of world CO_2 emissions. Europe and the former Soviet Union account for 40 percent of the total, and Japan for another 5 percent (World Resources Institute, 1991). The emission shares of currently-developed nations diminish as one looks further into the future. The most rapid growth in CO_2 emissions over the next century is projected to occur in China, the former Soviet Union, and other developing nations. These are the nations that bear the heaviest burdens of long-term slow-growth policies.

Some optimists argue that the problems of achieving coordinated international action can be solved, and they point to the 1987 Montreal Protocol, which established a timetable for phasing out production of chlorofluorocarbons (CFCs), as a model of concerted international environmental action. Ninety-three nations signed the Montreal Protocol, which set targets for the reduction of global CFC production. The lessons of this case therefore warrant some elaboration.[1]

The Montreal Protocol specifies CFC production targets based on a nation's 1986 production of CFCs, with some allowance for production capacity under contract but not yet operational in 1986. Developing nations are permitted to expand their CFC use between 1986 and 1996, and to begin reduction after 1996. The Protocol also provides for transfers to less developed countries to facilitate the adoption of substitute products. This provision helped build global consensus for the agreement by defusing the argument of the less developed countries that their growth would be stunted if they were forced to rely on expensive alternatives to CFCs. The Protocol has no explicit enforcement mechanism, but experience since 1986 has been encouraging: global CFC production has declined faster than the Protocol targets.

There are several reasons why the CFC experience may not generalize to other international environmental problems, such as global climate change. First, there was greater scientific consensus on the nature and the immediacy of the "ozone problem" than on the link between greenhouse gas emissions and global warming. A substantial body of research suggested that CFC emissions were reducing stratospheric ozone levels, and the discovery of a "hole" in the ozone layer above the Antarctic in the early 1980s catalyzed world action to stop ozone depletion.

Second, CFCs are economically much less important than fossil fuels. Chlorofluorocarbon consumption accounted for a trivial share of world GDP prior to the Montreal accord, while fossil fuel consumption is a major economic activity in many nations. Production of CFCs was concentrated among a small

[1]Benedick (1991) provides a detailed summary of the political negotiations leading up to the Montreal Accord.

set of multinational chemical companies who were also the natural suppliers of CFC substitutes. Some have even suggested that some CFC producers *supported* a ban because they expected to exercise greater market power if current CFC users were forced to switch to substitutes (UNEP, 1991). In contrast, there is wide dispersion in the suppliers of fossil fuels and possible alternatives.

Third, the ozone depletion problem appeared immediate when the Montreal Protocol was signed, in marked contrast to the long horizons involved in the current policy debate regarding greenhouse gases. After the discovery of the ozone hole, CFC emissions were linked with the rising incidence of skin cancer cases. It was therefore possible to identify a near-term gain that could be weighed against the cost of phasing out CFC production. In contrast, policies to reduce greenhouse gases burden current generations for the benefit of future generations.

Even though there were fewer obstacles to reaching international agreement on CFCs than on greenhouse gas emissions, negotiations leading to the Montreal Protocol took several years and frequently threatened to unravel. The Protocol's fund for technology transfer has not been fully funded, a pattern that underscores the difficulty of convincing developed nations to commit resources to international organizations focused on global environmental improvement.

The experience with other attempts to achieve multinational environmental cooperation is less encouraging than the case of CFCs. For example, 13 nations, including the United Kingdom and Poland, have not signed the 1985 Helsinki Protocol on sulfur oxides (acid rain) in Europe. Sulfur oxides are economically more significant than CFCs, and the inter-country differences in the net benefits of Protocol participation are larger than for CFCs. The failure of the Helsinki negotiations may therefore provide a better indication of the prospect for a global warming accord than the success in Montreal. Recent proposals for a carbon tax in the European Community, which are explicitly conditioned on similar actions by other nations, also suggest that CO_2 reduction will be more difficult than CFC reduction.

Although coordinated international action to adopt a carbon tax or similar policy currently seems unlikely, many nations appear committed to unilateral action to reduce greenhouse gases. Finland, Sweden and the Netherlands have already adopted carbon taxes, even though unilateral action by these nations can exert only a trivial effect on the growth rate of global greenhouse gas emissions.[2] I now consider several aspects of unilateral carbon tax design and incidence, as well as the potential difficulties that arise in implementing unilateral taxes in a global economy.

[2]Haugland, Lunde, and Roland (1992) describe the structure of carbon tax policies that have been adopted in Scandinavian countries. Many of the institutional details have important effects on the effects of these taxes. In Sweden, for example, there is a cap on the share of a firm's sales that can be collected; this effectively results in a zero marginal tax rate for many firms.

Table 1
Alternative Taxes on Fossil Fuels

	Coal	*Oil*	*Natural Gas*
Unit of Measure	Ton	Barrel	10^3 cu. ft.
Tons of Carbon/ Unit of Fuel	.605	.130	.016
Carbon Emissions/ Billion BTUs	.025	.020	.015
BTU Content	24.2	6.5	1.07
Average Mine-Mouth or Wellhead Price, 1989	\$23.02	\$17.70	\$1.78
$5/ton Carbon Tax:			
Absolute Tax	3.17	0.65	0.08
Percentage of Price	13%	4%	5%
BTU Tax:			
Percentage of Price	13%	5%	7%

Notes: Poterba (1991) with new calculations relating to fuel BTU content.

The Anatomy of a Carbon Tax

The carbon tax on each fossil fuel is proportional to the amount of carbon dioxide emitted when it is burned.[3] Coal produces more carbon dioxide per unit of energy than either oil or natural gas, so it faces the highest carbon tax rate. If the combustion of each fuel is assumed to affect the environment only through its effect on carbon emissions, then the optimal Pigouvian tax on each fuel will be proportional to its CO_2 emissions.[4]

Table 1 describes the carbon tax in more detail. The first few rows offer information on carbon emissions, energy content measured in BTUs (British Thermal Units), and recent prices of the various fuels.[5] The next two rows show the impact of a $5/ton carbon tax. It would raise coal prices by 13 percent, and increase the consumer prices of oil and natural gas by 4 percent and 5 percent respectively. The table also compares the tax rates on different fuels from a carbon tax with those from a BTU tax, a tax on the energy content

[3]Greenhouse gas tax policy should not be limited simply to taxing CO_2. Emissions of all gases that contribute to global warming, such as methane and nitrous oxides, should be taxed at the same rate per unit of "global warming potential." Nordhaus (1990) and Schmalensee (1993) discuss how to measure global warming potential.

[4]When the government can raise revenue through lump-sum taxes, then the optimal tax on each good equals the externality imposed by its consumption. Diamond (1973), Sandmo (1975), and Poterba (1993) develop this point and consider the effect of restricting the government's set of tax instruments.

[5]Tax rates are sometimes specified per ton of carbon, and other times per ton of carbon dioxide emitted. Since the atomic weights of carbon and oxygen are 12 and 16 respectively, a ton of carbon corresponds to 3.67 tons of CO_2. Tax rates can be translated accordingly.

Table 2
Implicit Carbon Taxes, Dollars / Ton of Carbon, G-7 Nations, 1988

	Coal	*Oil & Oil Products*	*Natural Gas*
United States	0	$65	0
Japan	−17	130	2
Germany	−77	212	23
France	0	351	38
Italy	0	317	80
United Kingdom	−46	297	0
Canada	0	108	0

Source: Hoeller and Coppel (1992).

of each fuel, set for coal at the same level as the $5/ton carbon tax. The BTU tax places a higher relative burden on natural gas than on the other fuels. Because externalities are associated with end-products of combustion, not with energy use *per se*, there is a strong rationale for basing Pigouvian taxes on emissions rather than other fuel characteristics such as BTU content.

It is difficult to translate Table 1 into practice for two reasons. First, fossil fuel combustion creates many potential externalities other than global climate change. In this case, the optimal taxes on various fossil fuels can differ from those prescribed by a simple analysis of relative CO_2 output. Various studies, described in Viscusi (1992), have evaluated the local air pollution and other externalities associated with fossil fuel use. These studies generally suggest that the negative externalities associated with coal combustion exceed those from other fossil fuels, implying that the extra tax burden on coal should exceed that on other fuels.

The second problem in implementing the tax rates in Table 1 is that most developed nations already tax fossil fuels. Many of the existing taxes are justified by revenue needs rather than externality correction. In the United States, for example, the current tax rate on gasoline is just over 30 percent of the producer price, while in Britain, Sweden, and other European nations the tax rate often exceeds 60 percent of the producer price. Table 2 shows the existing implicit taxes on each of the three major fossil fuels in the G-7 nations; negative signs imply that a fuel is subsidized. The table confirms the widely known pattern that energy tax burdens in the United States are low relative to those in other nations, but also shows the disparity of the net tax treatment of coal across industrial countries. Germany, Britain, and Japan all provide subsidies to their coal industries. How should the carbon tax be combined with pre-existing taxes? In the unlikely case where existing fossil fuel taxes have been set optimally for Ramsey and Pigouvian reasons, and if the potential effect of fossil fuels on global climate can be viewed as a previously-ignored externality, then the carbon tax should be added to the existing tax. Failing this case, it is difficult to make strong statements about the combination of the carbon tax and other levies.

The International Incidence of a Carbon Tax

If enacted in the United States today, a tax of $5/ton on carbon such as that considered in Table 1 would slow, but not stabilize, the growth of CO_2 emissions. It would raise between $10 and $15 billion annually. A carbon tax of $100/ton, which could result in U.S. emissions of CO_2 in the early part of the next century *below* levels in the late 1980s (Congressional Budget Office, 1990), would raise approximately $200 billion, or more than 3 percent of GNP. Even in Japan, where energy consumption per dollar of GNP is lower than in the United States, revenues from such a tax would be more than 1 percent of GNP. Schelling (1992) observes that the sheer magnitude of these revenue flows represent an important obstacle to any coordinated international action that involves revenue collection by a supranational organization. Few developed countries are likely to cede control over revenues of this magnitude to an international organization.

Practical analyses of carbon taxes must therefore focus on unilateral tax policies without revenue transfers across countries. Whalley and Wigle (1991) use a computable general equilibrium model to evaluate the effect of enacting similar carbon taxes in all countries, with each country keeping the revenue it collects. Their findings underscore the difference in incidence between a carbon tax levied on consumption of fossil fuels, and a similar tax levied on production. When nations are permitted to keep the revenue they collect, a consumption-based tax places a much higher burden on oil-producing countries than a production-based tax. A consumption-based carbon tax that would reduce CO_2 emissions by 50 percent would reduce GDP by 4 percent in North America, 1 percent in Europe, and by 19 percent in oil exporting countries. This contrasts with an equal-value tax on production, which *raises* GDP by 5 percent in oil-producing countries, and reduces GDP by 4 percent in both Europe and North America. The key difference between these policies is that with the production tax, fossil fuel exporters receive the revenue from the tax.

Whalley and Wigle's (1991) estimates, and those from other computable general equilibrium models, reflect the loss in output that results from higher fossil fuel prices.[6] Further analysis with these models suggests that these output losses are sensitive to the structure of pre-existing taxes, on both fossil fuels and other goods. Goulder (1992) and Bovenberg and de Mooij (1992), for example, show that carbon fuel taxes interact in important ways with labor income taxes.

[6]Dean and Hoeller (1992) survey long-run results from six general equilibrium models, and emphasize the substantial difference in their results. Joskow's (1992) discussion of the results from the Jorgenson-Slesnick-Wilcoxen (1992) model illustrates some of the difficulties associated with the use of computable general equilibrium models for assessing greenhouse gas policy.

Labor supply depends on the real after-tax wage measured in terms of consumer prices. Since carbon taxes are indirect taxes, they reduce the real after-tax wage.[7]

Enacting a carbon tax affects the government's budget as well as relative prices. Because substantial tax increases are likely to have contractionary macroeconomic effects, some proposals call for coupling a carbon tax increase with other tax cuts to generate a revenue-neutral policy. In European countries that rely on indirect taxes for significant revenues, a natural policy would involve reducing the value-added tax or other excise tax rates. For the United States, it would be possible to reduce income taxes to offset carbon tax revenues. The possibility of using carbon tax revenues to cut other tax rates has spawned a recent debate on "revenue recycling," with several studies claiming that adopting a carbon tax could yield efficiency gains rather than deadweight losses. Goulder (1993) shows that the efficiency cost of a carbon tax is much attenuated if the tax proceeds finance other tax cuts, such as reductions in the personal income tax. Shackleton et al. (1992) claim still more, arguing that if carbon tax revenues are used to reduce capital tax burdens, for example by instituting an investment tax credit, then the carbon tax can actually *raise* national output.

Initially, the revenue-recycling argument seems fallacious. If the status quo includes some extremely inefficient taxes, then almost *any* new tax can generate an efficiency improvement. Simply demonstrating that raising the carbon tax and reducing other onerous taxes would lead to an efficiency gain does not imply that carbon taxes should be adopted. Rather, one must compare the carbon tax policy with the set of all feasible policies that could reduce the onerous taxes and achieve a balanced budget. On reflection, however, the revenue-recycling argument may make more sense. If there is a causal link between enacting a carbon tax and cutting particular other taxes, perhaps because of political constraints on raising existing taxes, and if there are no other ways to enact changes in these other taxes, then it is appropriate to consider how the funds are used in evaluating the net benefit from a carbon tax. Absent a strong basis for linking enactment of a carbon tax to other particular tax changes, a plausible assumption is that carbon taxes would be paired with a proportionate reduction in all existing revenue sources.

In addition to the uncertainty about how carbon tax revenue would be used, which has an important effect on how the carbon tax affects output, there is some disagreement about whether higher fossil fuel prices affect the rate of economic growth. Because growth rate effects compound from year to year, they have the potential to dwarf many of the other effects of changing fossil fuel taxes. However, the available empirical evidence about these effects is not

[7]The after-tax wage is $(1 - t)w/p(1 + s)$, where w denotes the nominal wage, p the producer price level, t the marginal income tax rate, and s the average indirect tax rate. Carbon taxes raise s. This distorts labor supply. The cost of this distortion depends on the pre-existing level of $(1 - t)/(1 + s)$, the initial tax wedge.

conclusive (Jorgenson and Wilcoxen, forthcoming 1993; Weyant, in this journal). The rate of productivity growth in many developed countries declined at roughly the same time as the 1973 oil price shock. Whether these two developments are causally related, however, is an open question, and warrants further analysis.

The computational models described above yield results on the long-run output reduction that might accompany higher taxes on fossil fuels. These output reductions can not be viewed in the same light, however, as output reductions from traditional distortionary taxes that are enacted to raise revenue. Since carbon taxes are *Pigouvian* taxes, at the optimal tax rate the present value of the marginal output losses associated with the tax would precisely equal the present value of the marginal gains from reducing greenhouse gas emissions. Even if the taxes are not set optimally, if there is some social value to reducing greenhouse gas emissions, the foregone output associated with a carbon tax overstates the net social cost of these policies.

Are Carbon Taxes Regressive?

One of the most frequent objections to raising fossil fuel taxes in most developed countries is that such taxes fall most heavily on low-income households. This regressivity argument has been a central component of opposition to higher gasoline taxes in the United States. The underlying basis for the argument is simply that the ratio of consumption to income declines as one moves up the income distribution (Poterba, 1989).

There are now several studies of the distributional burdens of carbon taxes in the United States and other nations: Smith (1992) provides evidence for Europe, and Jorgenson, Slesnick, and Wilcoxen (1992) and Poterba (1991) for the United States. These studies suggest that simple analyses of the ratio of expenditures on fossil fuels relative to income substantially overstate the regressivity of such taxes. If tax burdens are analyzed relative to lifetime income, the fossil fuel taxes appear less regressive than when compared with current income. In addition, most developed nations have a variety of auxiliary fiscal policies that reduce, or could be used to reduce, any adverse distributional effects of carbon taxes. For example, many transfer programs are already indexed for price changes. Transfer recipients are therefore partly insured against tax-induced changes in consumer prices. Carbon tax proposals could also be coupled with modifications in income tax schedules to redistribute purchasing power to low-income households.

The possibility of coupling carbon taxes with other policy changes, whether to achieve distributional ends or for other reasons, highlights an important limitation of most existing models of these taxes. Modellers usually evaluate "pure" policies, such as carbon taxes levied on all fossil fuels. In practice, policies will inevitably be enacted with exemptions and other special provisions that both reduce their power to limit greenhouse gas emissions, and magnify their adverse effect on the amount of output lost per unit of emissions abatement. The revealed preference of policy-makers in many countries for command-and-control, rather than efficient, market-based pollution control policies, underscores the potential divergence between actual and theoretical policies.

While most discussions of the economic effects of carbon taxes focus on long-term output effects, a word should be added about the possible short-term macroeconomic effects. Even a balanced-budget carbon tax can have adverse short-run effects on output if nominal wages and prices respond slowly to higher taxes. To illustrate this possibility, consider a carbon tax that is coupled with a reduction in labor income tax rates. The carbon tax represents an increase in the overall indirect tax rate, and for a fixed set of producer prices, it will raise the consumer price level. If the nominal money supply is constant—that is, if the monetary authority does not accommodate the carbon tax—then higher consumer prices will translate into a smaller *real* money stock. This amounts to a monetary contraction, a "self inflicted wound" in macroeconomic terms, and to lower aggregate output.[8] Slow phase-in of a carbon tax would blunt these effects.

Implementation Issues in an Open Economy

One additional theoretical argument for supranational rather than unilateral actions to curb greenhouse gas emissions involves the difficulties of implementing policies such as carbon taxes in open economies. Most national-level carbon tax proposals call for taxing imports of fossil fuels in the same way as domestic production. This does not completely solve the problem of equal treatment of foreign and domestic production of fossil-fuel intensive goods, however. If imports of such goods are not taxed, there will be production inefficiencies as production of these intermediate goods will be diverted from domestic locations. Poterba (1991) argues that border taxes on a few classes of imports—for example, steel, autos, and chemicals—could avoid most of these problems. In practice, however, it might be difficult to adopt such "environmental tariffs" under current GATT rules.

Nations with unilateral carbon taxes might also choose to provide tax rebates to exporters of goods with high fossil fuel content, to avoid adverse competitive effects in international trade. Such export rebates and related provisions have been enacted in some of the Nordic countries' carbon taxes,

[8]Poterba, Rotemberg, and Summers (1986) suggest that a 3 percent of GNP shift from direct to indirect taxation, for example, from an income tax to a carbon tax, would reduce real GNP by .6 percent in the quarter when the tax change took effect and cumulatively by 3 percent of annual GNP over the policy's first three years. The Congressional Budget Office (1990) presents more specific results on the macroeconomic effects of carbon taxes with various assumptions about other policy responses.

with the result that these taxes provide no marginal disincentive for CO_2 emissions for large firms engaged in export trade (Haugland, Lunde, and Roland, 1992).

Reducing Greenhouse Gas Emissions in Less Developed Nations

The discussion so far has concentrated on unilateral policies to reduce greenhouse gas emissions in developed countries. Efficient policies to slow greenhouse gas emissions, however, are likely to involve some reductions in emissions from less developed countries (LDCs) as well. Mors (1991) estimates that the costs of reducing CO_2 emissions in less developed countries may be only one-fourth of the cost in developed nations, mainly because many LDCs have relatively inefficient energy utilization systems. There are important differences between analyzing policies for controlling greenhouse gas emissions from LDCs and developed countries. These differences arise because the same policies that could be used in developed nations, such as carbon taxes, might have different effects in LDCs, and because there are new policy options, such as programs to slow deforestation, that must be considered.

The effects of raising fossil fuel prices in LDCs has received less research attention than the comparable problem for developed countries. The work that has been done suggests important heterogeneity in the likely effects of such policies on different LDCs. Blitzer et al. (1992), for example, contrast the effect of a carbon tax on India and Egypt, and recognize that differences in the relative use of coal and other fossil fuels, as well as differences in economic structure, play an important role in determining the effects of such taxes on individual nations.

Less developed countries also differ from developed countries in their current tax treatment of fossil fuels. While most industrial nations tax these fuels, many LDCs currently subsidize the direct consumption of fossil fuels, and the indirect consumption through electricity. Table 3 presents suggestive information on these subsidies, drawn from Shah and Larsen (1991). The World Bank (1992) estimates that eliminating fossil fuel subsidies could reduce carbon dioxide emissions by 29 percent in the former Soviet Union and Eastern Europe, and by 11 percent in currently developing nations. Combined, these reductions would yield an 11 percent reduction in current global emissions of carbon dioxide. Eliminating these subsidies would also confront consumers in the subsidizing nations with world market prices for their fuels, thereby improving the efficiency of global energy consumption.[9]

[9] Just as introducing new carbon taxes would have adjustment costs, removing current subsidies would result in economic dislocation. Again, these could be minimized by gradual phase-out.

Table 3
Subsidies to Fossil Fuel Consumption
(measured by ratio of domestic to border price)

Country	*Coal*	*Oil*	*Natural Gas*
China	.84	.48	.40
Former USSR (1991)	.50	.49	.35
Poland	.31	.77	.50
India	.86	.90	—
United Kingdom	.90	—	—
South Africa	.50	—	—
Czechoslovakia	.40	.85	—
Mexico	—	.48	—

Source: Shah and Larsen (1991), Table B1.

While existing energy subsidies may be difficult to justify on efficiency grounds, they may serve distributional objectives within countries. This makes the claim that subsidy removal provides a "free lunch" overly optimistic. Viewed from the perspective of a social planner with distributional as well as efficiency objectives, eliminating the subsidies may have real costs. This is supported by a cursory analysis of fossil fuel subsidies in the developed world, where these subsidies are invariably the result of domestic political pressures. In the United Kingdom, for example, subsidies to coal use sustain mine employment in particularly depressed regions. In the United States, despite overwhelming evidence that scrubbing high-sulfur coal is not a cost-effective way to reduce sulfur oxide emissions, clean air policy for more than a decade required scrubbers on some power plants. This was largely due to the political influence of high-sulfur coal miners.

The political economy of fossil fuel subsidies in LDCs poses an important impediment to efficient global action to reduce greenhouse gas emissions. A cost-effective way to surmount these internal political problems could involve resource transfers from some developed nations to some LDCs, explicitly targetted at compensation for the "losers" from policy reforms. Finding an institutional structure for such transfers, however, confronts the problems of coordinated international action that were described earlier.

The importance of deforestation in contributing to greenhouse gas emissions from less developed countries raises a second set of differences between global climate policies in developed and developing nations. Forest-burning currently accounts for approximately one-fifth of anthropogenic emissions of carbon dioxide (World Resources Institute, 1991). In Brazil, deforestation is three times as important as fossil fuel consumption as a source of CO_2 emissions (Shunker, Salles, and Rios-Velilla, 1992). Some forecasts call for rapid increases in the rate of deforestation, particularly in Amazonia, in the early part of the next century. Most rain forest burning occurs as the forest is converted to agricultural use by new settlers, so policies to slow this settlement are candidates for reducing the level of greenhouse gas emissions.

Before examining the role of taxes and other government policies that affect the rate of deforestation, it is essential to recognize that not all deforestation creates greenhouse gases. Living forests are an important carbon *sink*: photosynthesis draws CO_2 out of the atmosphere. Cutting tropical hardwoods for furniture construction, and replacing the felled trees with new growth, therefore has the potential to absorb greenhouse gases. *Burning* tropical forests either to clear land or for firewood, or failing to replace forest that is cut for lumber, *does* contribute to the ambient level of greenhouse gases.

Governments in LDCs can employ several different policy instruments to affect forest utilization. The first and probably most important set of policies concern incentives for settlement and agricultural expansion in currently-forested areas. In Brazil, for example, the national government has historically encouraged settlement in rain forest regions. Binswanger (1989) and Reis and Margulis (1991) explain that credit policies, infrastructure development, and other government subsidies played a key role in the rise of cattle-ranching in Amazonia. They further argue that given Amazonia's soil, such ranching would not be economically attractive *without* the government subsidies.

Removing existing subsidies that encourage deforestation parallels removing fossil fuel subsidies in promising an efficiency-enhancing means to slow greenhouse gas emissions. They are likely to be particularly cost-effective policies. Cline (1992) concludes that the cost of reducing global carbon emissions by removing government incentives to deforest are only several dollars per ton. This is substantially less than most estimates of emission-reduction costs in developed nations.

A second set of policy instruments that affect forest clearing are taxes on logging and other related activities. Panayotou and Sungsuwan (1989) study deforestation in Thailand, and conclude that taxes on resource rents would have significant effects in discouraging logging in environmentally sensitive areas. Empirical analysis of such policy proposals depends on a set of elasticities, such as that for logging activity with respect to net log prices, that in many cases are known with very little precision. The prospective importance of carbon dioxide emissions from the Third World suggests that estimating these parameters is an important research priority.

Finally, land tenure rules have important effects on the utilization of tropical forests. One of the central problems in Amazonia, for example, where land claims are difficult to enforce, is that land users do not take a long-term perspective in making land use decisions. Imperfect property rights reduce the cost of obtaining land, and lead tenants to maximize short-run returns, often by burning the forest and exploiting the resulting land for only brief periods. Weak property rights discourage replanting of forest. The reform of land tenure rules in LDCs is a complex problem, and one that has many potential effects other than those concerned with global climate change. Nevertheless, this is a type of policy that could significantly affect greenhouse gas emissions.

Conclusion

This paper has sidestepped the single most important question in designing a carbon tax: what is the optimal tax rate? In principle, this question is simple to answer: the optimal carbon tax equates the present discounted value of the net externalities from a ton of carbon emitted today with the marginal cost of emission reduction, making appropriate correction for distributional differences in the incidence of benefits and costs. Even after several years of intense research activity on carbon taxes and global warming, however, there is great uncertainty concerning the optimal carbon tax rate. While such uncertainty is not unprecedented in tax policy discussions (what is the optimal tax rate on capital gains?), the *sources* of this uncertainty suggest promising directions for future research. Two aspects of this uncertainty deserve comment.

One source of uncertainty about optimal carbon taxes concerns the appropriate discounting for time and risk in considering the policy's costs and benefits. In this journal, Chichilnisky and Heal survey many of the issues related to this question. Cline (1992) has emphasized that policies to reduce greenhouse gas emissions are more attractive at low discount rates and when the policy analysis involves a longer time horizon. Yet there is little agreement on what discount rate is appropriate for such calculations.

A second source of uncertainty concerns the economic consequences of a given level of greenhouse gas accumulation. The efforts by Nordhaus (1991) and Cline (1992) to estimate how the U.S. would be affected by global warming suggest the immensity of the calibration exercise. The task is complicated further by the sensitivity of the loss estimates to events that occur with low probability. Even if the mean and median outcomes are not particularly costly, outcomes with one chance in ten may be very costly to the United States and other nations. It is difficult enough to estimate the *mean* effects of various levels of greenhouse gas emissions; trying to specify the entire distribution of such outcomes, as well as the probability of remote outcomes such as shifts in the Gulf Stream, is an extraordinary research challenge for physical scientists. Economics must be ready, however, to help evaluate such forecasts as they become available, and to focus attention on areas where uncertainty reduction is most valuable.

Given the significant cost uncertainties associated with policies to slow greenhouse gas emissions, *caution* is likely to be a key characteristic of optimal policies. Low carbon taxes, enacted on a nation-by-nation basis, can establish the mechanism for revenue collection and provide some evidence on how these taxes affect economic activity. Immediate enactment of a high-rate carbon tax would entail substantial policy risk, and is best done (if ever) after experience with more modest tax levels.

■ *I am grateful to Lawrence Goulder, Ron Promboin, Carl Shapiro, Richard Stroup, Timothy Taylor, and especially Richard Schmalensee for helpful comments. This research was supported by the Institute for Policy Reform, the NSF, and the MIT Center for Energy and Environmental Policy Research.*

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October 17, 1996

Dr. Joseph Stiglitz
Chairman
Council of Economic Advisers
Old Executive Office Building
Washington, D.C.

Dear Joe:

Rumor has it that in addition to all your other responsibilities you will be a major architect of the administration's analytic framework for climate change policy analysis (I first heard about this when I testified before the Senate Energy and Resources Committee on September 17th in a hearing that started with testimony by Under Secretary of State Tim Wirth). As you may know,
I have spent a great deal of my time during the last six years on studies, reviews, and model comparisons on a broad range of climate change policy issues. If you need any input from me or any of our various working groups (which include most of the analysts working on these issues) at any time do not hesitate to call on me. In fact, I met with Larry Lau today on some projects we are doing together, and told him what was going on in the administration and he said he would also be willing to serve as an external reviewer if that would be helpful to you. Unfortunately, I will not be in Washington again until November 12-15, but hope to see you at the discount rate workshop Paul Portney and I have put together at RFF on the 14th and 15th of November (I was at a brunch with Kenneth Arrow on Saturday and he convinced me he has yet another round of new ideas on that subject).

Sincerely yours,

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Meeting on Climate Change Litigattion
4:00 p.m., Thursday, October 17, 1996

Attendees:

Dr. Dale Jorgenson
Chairman
Department of Economics
Harvard University

Dr. Florentin Krause
Staff Scientist
Lawrence Berkeley Laboratory

Philip E. Clapp
Executive Director
Environmental Information Center

Dr. Daniel Lashof
Senior Scientist
Natural Resources Defense Council

BIOGRAPHY: DALE W. JORGENSON

Dale W. Jorgenson is currently Chairman of the Department of Economics and Frederic Eaton Abbe Professor of Economics at Harvard University. He has been a Professor in the Department of Economics at Harvard since 1969 and Director of the Program on Technology and Economic Policy at the Kennedy School of Government since 1984. Jorgenson received his Ph.D. degree in economics from Harvard in 1959 and his B.A. in economics from Reed College in Portland, Oregon, in 1955.

Jorgenson was elected to membership in the National Academy of Sciences in 1978 and the American Academy of Arts and Sciences in 1969. He was elected to be a Foreign Member of the Royal Swedish Academy of Sciences in 1989. He was elected to Fellowship in the American Association for the Advancement of Science in 1982, the American Statistical Association in 1965, and the Econometric Society in 1964. He served as President of the Econometric Society in 1987. He was awarded honorary doctorates by Uppsala University and the University of Oslo in 1991.

Jorgenson received the prestigious John Bates Clark Medal of the American Economic Association in 1971. This Medal is awarded every two years to an economist under forty for excellence in economic research. The citation for this award reads in part:

> Dale Jorgenson has left his mark with great distinction on pure economic theory (with, for example, his work on the growth of a dual economy); and equally on statistical method (with, for example, his development of estimation methods for rational distributed lags). But he is preeminently a master of the territory between economics and statistics, where both have to be applied to the study of concrete problems. His prolonged exploration of the determinants of investment spending, whatever its ultimate lessons, will certainly long stand as one of the finest examples in the marriage of theory and practice in economics.

Jorgenson is the author and co-author of more than two hundred journal articles, contributions to books, and books in economics. His most recent books, POSTWAR U.S. ECONOMIC GROWTH and INTERNATIONAL COMPARISONS OF ECONOMIC GROWTH, were published by The MIT Press in 1995. He is the Managing Editor of the monograph series, CONTRIBUTIONS TO ECONOMIC ANALYSIS, published by the North-Holland Publishing Company in Amsterdam.

Prior to Jorgenson's appointment at Harvard he was Professor of Economics at the University of California, Berkeley, where he taught from 1959 to 1969. He has been Visiting Professor of Economics at Stanford University and the Hebrew University of Jerusalem and Visiting Professor of Statistics at Oxford University. He has also served as Ford Foundation Research Professor of Economics at the University of Chicago.

An important feature of Jorgenson's research program has been collaboration with students in economics at Berkeley and Harvard, mainly through the supervision of doctoral research. Collaboration has often been an outgrowth of a student's doctoral dissertation and has lead to subsequent joint publications. Thirty-eight economists have collaborated with Jorgenson on published research. Many of his former students are now professors at leading academic institutions in the United States and abroad.

Jorgenson was born in Bozeman, Montana, in 1933 and attended public schools in Helena, Montana. He is married to Linda Ann Mabus Jorgenson, who is an attorney in Cambridge, Massachusetts. Professor and Mrs. Jorgenson reside in Cambridge with their children, Kari, age 20, and Eric, age 22. Kari is a student at Harvard College and Eric is a recent graduate of Duke University.

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BRIEF CURRICULUM VITAE

Dr. Florentin Krause is the Director of the International Project for Sustainable Energy Paths (IPSEP), a private energy policy research group located in El Cerrito, California. A native of Germany, Mr. Krause received his Ph. D. from the University of California in Berkeley and has been serving as a staff energy analyst at the Energy and Environment Division of Lawrence Berkeley National Laboratory. In 1981, Dr. Krause co-authored with Amory Lovins the first prevention-oriented energy policy book on global warming. Subsequently, the Dutch government commissioned him to carry out a major bottom-up analysis on the economics of mitigating carbon emissions in Western Europe. He is the lead author of a number of books on alternative energy futures and energy policies, and has published many dozens of technical reports and papers in his field. Several of his publications have been translated into foreign languages including German, French, Italian, Spanish, Russian, Polish, and Czech.

During 1994-1995, he served as a lead author of the scientific assessment report (Working Group III) by the Intergovernmental Panel on Climate Change (IPCC) of the UN. In other activities, he has written and testified on the economics and environmental implications of alternative energy strategies and policy options for a number of national and international organizations. They include the UN Intergovernmental Negotiating Committee (INC), the Organization for Economic Cooperation and Development (OECD), the Commission of the European Communities (CEC), the UN Economic Commission for Europe, the Joint Economic Committee of the U.S. Senate, the National Association of Regulatory Utility Commissioners (NARUC), and the Special Commissions on Climate Change of the German and Dutch parliaments.

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PHILIP E. CLAPP

Philip E. Clapp is Executive Director of the Environmental Information Center, a non-profit environmental advocacy organization established in 1994.

In 15 years as a Congressional staff member on environmental issues, as chief lobbyist for a large membership environmental organization, and as an environmental consultant to major domestic and foreign corporations, Mr. Clapp has developed an extensive background in U.S. environmental policy in areas from clean air to solid waste disposal. In addition, he held a leading staff role in Congressional debates on national energy policy.

Mr. Clapp served six years as Legislative Director to Senator (now Undersecretary of State) Timothy E. Wirth (D-Colorado) when he served in the House. In that position he played a major part in drafting environmental legislation within the jurisdiction of the Energy and Commerce Committee, including all energy legislation, the Clean Air Act, the Superfund hazardous waste cleanup law, and nuclear and solid waste disposal statutes.

Mr. Clapp also served as an Associate Staff Member of the House Budget Committee for five years and directed the staff of its Task Force on Energy and the Environment from 1981 to 1985, which had budget jurisdiction over the Department of Energy and all federal environmental programs.

Mr. Clapp was National Program and Legislative Director of Clean Water Action, Inc., Washington, D.C., where he directed federal legislative activities. Mr. Clapp played a role in the environmental community's legislative activities on reauthorization of RCRA (solid and hazardous waste disposal), the Clean Water Act, and CERCLA (Superfund hazardous waste program). He developed national media and grassroots organization campaigns, and worked with members of Congress, Congressional leadership, and committee staffs in development of legislative proposals and strategy.

Mr. Clapp was a member of the national steering committee of Environmentalists for Clinton/Gore, the environmental issues arm of the Clinton/Gore campaign.

Mr. Clapp was also Vice President of National Strategies, Inc., Washington, D.C. At National Strategies, he was a consultant on environmental issues for major U.S. securities firms and for Latin America's largest international engineering and construction company. He also developed comprehensive government and media relations programs for top securities and communications industry clients. He directed and represented a 100-member trade association of the CEO's of Fortune 1000-sized corporations with interests in tax, securities and banking issues. Mr. Clapp also represented influential labor unions on corporate boards and as a principle negotiator and public spokesperson in bankruptcy reorganization and hostile takeover situations. As representative of management and labor, Mr. Clapp organized the team that successfully lead Frontier Airlines' 1985 fight against a hostile takeover attempt by Continental Airlines. In addition, he represented financier Michael Milken in a variety of transactions from 1985 to 1988, as his liaison with labor organizations. Mr. Clapp facilitated the successful employee buyout of a large Seattle shipbuilding firm, coordinating 18 months of negotiations with creditors of the $200 million company.

Before coming to the Environmental Information Center, Mr. Clapp was the Government Affairs Director at Spiegel & McDiarmid, Washington, D.C. In that position, he coordinated the firm's government affairs practice and monitored legislative matters for the firm's clients.

Mr. Clapp is a 1975 graduate of Harvard University.

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Biographical Sketch——Daniel A. Lashof

Dr. Daniel Lashof is a Senior Scientist with the Natural Resources Defense Council, specializing in global climate change science and policy. Dr. Lashof has written extensively on many aspects of the global warming problem and is frequently asked to testify before Congressional Committees considering the issue. Dr. Lashof was a member of the Presidentially appointed Federal Advisory Committee on Greenhouse Gas Emissions from Personal Motor Vehicles, and has participated as an observer in the deliberations of the Intergovernmental Panel on Climate Change and the negotiations of the United Nations Framework Convention on Climate Change.

Dr. Lashof's publications include "Global Climate Change: The Dangers Are Real" (*The Electricity Journal*, 1994), *America's Energy Choices: Investing in a Strong Economy and a Clean Environment* (Union of Concerned Scientists, 1991), and *The Statehouse Effect: State Policies to Cool the Greenhouse* (NRDC, 1990). Before joining NRDC, Dr. Lashof served on the staff of the Environmental Protection Agency where he was the lead author and editor of the report to Congress *Policy Options for Stabilizing Global Climate*. Dr. Lashof has also written on the role of biogeochemical feedbacks in global warming, the contribution of agriculture and biomass burning to greenhouse gas emissions, the relative global warming potential of different greenhouse gases, and the structure of an international agreement to curb greenhouse gas emissions.

Dr. Lashof obtained his A.B. *magna cum laude* in Physics and Mathematics from Harvard University. He obtained his Ph.D. from the interdisciplinary Energy and Resources Group at the University of California, Berkeley.

The Natural Resources Defense Council is a leading national environmental research and advocacy organization, supported by 235,000 members.

EUROPEAN STUDIES ON THE COSTS OF MITIGATING CARBON EMISSIONS: A REVIEW OF METHODS AND FINDINGS

by

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Final draft, forthcoming in *Energy Policy*

ABSTRACT

Conventional wisdom has it that top-down studies of mitigation costs are too pessimistic while bottom-up studies are too optimistic. In examining mitigation cost studies for Western Europe, this paper finds this interpretation to be seriously flawed. The paper expands the analytical framework for interpreting mitigation cost studies, evaluates the treatment of no regrets options and other input assumptions in the various studies, and includes findings from recent integrated top-down/bottom-up modeling assessments not covered in the IPCC report. Based on these new elements, it is found that mitigation costs tend to be overestimated not only in top-down studies, but also in bottom-up studies. Given this pervasive bias toward pessimism, the body of existing mitigation cost assessments for Western Europe can be read as follows: Over the next three to four decades, a combination of tax shifts, market transformation instruments and policies to reform subsidies and internalize non-climatic externalities could cut carbon emissions in Western Europe by 40-50 percent relative to the base year, at no loss or at a gain in gdp. Averaged over the medium-term and including a phase-in period, an economically optimal rate of implementing Western Europe's no regrets potentials is found to be in the neighborhood of 2 percent per year relative to base year levels.

Acknowledgements/disclaimer:

The author is with the International Project for Sustainable Energy Paths and with the Energy and Environment Division of Lawrence Berkeley National Laboratory. The presentation in this paper expresses the personal views of the author alone and not those of Lawrence Berkeley National Laboratory or the IPCC. The author wishes to thank his European collegues Carlo Carraro, Kora Cristof, Dominique Finon, Kirstin Halsnaes, Peter Hennicke, Jean-Charles Hourcade, Thomas Johannson, Leo Schrattenholzer, and Angela Tudini, as well as all other IPCC coauthors who helped assemble and interpret the mitigation cost studies reviewed in Chapters 8 and 9 and in this paper.

Artical title abbreviated as: European studies

Keywords: Mitigation costs; no regrets potentials; carbon emission reductions.

INTRODUCTION

As in the case of the North American studies, mitigation cost estimates[1] for Western Europe vary widely. For any given reduction target between stabilization of carbon emissions and a 50 percent reduction, and for time horizons between now and 2030, the highest estimates indicate significantly positive costs while the lowest estimates indicate significantly negative costs (i.e., a net economic gain from mitigation efforts, or an opportunity cost from not pursuing such measures). Moreover, though the median results from top-down studies are distinctly higher than those from bottom-up studies, there is significant overlap between their ranges: estimates from net costs to net benefits are found within both bodies of research.

This wide range of results poses a challenge. To obtain useful policy guidance, reported findings have to be further interpreted. First, it is necessary to understand how the paradigmatic differences between top-down and bottom-up studies contribute to these divergent results. Second, it is necessary to explain the differences in findings within each category of studies. Third, one has to consider possible shortcomings and biases that are common to all mitigation cost assessments, whether top-down or bottom-up.

Working Group III of the IPCC has made a first attempt to provide such interpretation and review (IPCC 1996: Chapters 8&9). This paper builds on Chapters 8 and 9 of the IPCC report but also augments it in significant ways. The paper expands the analytical framework for interpreting mitigation cost studies, offers a more detailed and comprehensive critique of bottom-up procedures, including recent empirical evidence on the economics of market transformation options, and more carefully correlates the findings of individual studies with the treatment of no regrets options and other key input assumptions. It also examines recent integrated bottom-up/top-down studies of combined fiscal and non-fiscal policy packages that were not covered in the IPCC report. These expansions not only provide a fresh view of the cost biases in top-down and bottom-up studies, but also allow considerably more definite conclusions regarding the "no regrets" potential for carbon reductions in Western Europe and by implication, in the OECD in general.

Pessimism versus optimism in mitigation cost estimates

Elsewhere in this issue, Hourcade and Robinson present the conventional wisdom, according to which top-down studies may be too pessimistic (i.e., mitigation cost estimates may be too high), while bottom-up studies may be too optimistic. This line of reasoning, which is mainly driven by alternative interpretations of the energy efficiency gap, suggests that actual mitigation costs fall somewhere in between. Symbolic of such a compromise, the Executive Summary of Working Group III arrives at a minimum consensus estimate, according to which the no regrets potential for reducing carbon emissions in OECD countries is 10-30 percent below baseline projections over the next several decades.

The present review arrives at a different assessment. It finds that both top-down studies and bottom-up studies are overly pessimistic, i.e., that *both* tend to significantly overstate mitigation costs. This alternative interpretation arises from consideration of four factors:

- A range of no regrets options that are omitted not only in top-down studies but also in bottom-up studies;

— The pessimistic estimating bias created by the omission of macroeconomic feedbacks in bottom-up studies;

— Empirical evidence from market and policy evaluation research substantiating the interpretation of the energy efficiency gap as an economic efficiency gap;

— A net bias toward pessimism created by various approximation procedures within engineering-economic life cycle cost analyses themselves.

The conventional wisdom on the supposed optimism of bottom-up studies ignores these factors.

The following paper is divided into three sections. In the first section, we review a range of generic factors that may create, individually or in combination, a bias toward optimism or pessimism in mitigation cost studies. The focus here is on bottom-up studies since these give the lowest mitigation cost estimates. In a second section, we review and interpret the results of various Western European bottom-up studies, with emphasis on multi-country analyses that put national differences into a larger perspective. In a third section, we review and interpret Western European macroeconomic studies. Here, the emphasis is on integrated bottom-up/top-down assessments, which overcome one of the main difficulties in comparing the two types of modeling analyses.

RANGE OF ZERO OR NEGATIVE-COST POLICY OPTIONS

The pivotal role of no regrets options in mitigation cost analysis arises from the fact that benefits from negative-cost measures may offset all or a portion of the impacts from measures with positive costs. If no regrets measures are not just cost-neutral but produce sizable benefits (other than climate change mitigation), even a limited supply of negative-cost emission reduction measures can generate sufficient savings to offset large emission reductions with slightly positive costs. The level of emission reductions that can be achieved at a zero total cost to the economy at large may thus be significantly greater than the reductions that can be obtained from no regrets measures alone.

Indeed, it then becomes conceivable that the entire transition to a climatically neutral level of carbon emissions could be possible at a net economic benefit to society. Such a net transition benefit could arise if savings from zero and negative cost measures over the next several decades are large enough to exceed the costs of accelerating the development and advancing the market diffusion of cheap low-carbon supplies.

Range of no regrets options

The principal energy-related policies that could reduce carbon emissions while improving economic efficiency are the following:

1) Energy or carbon taxes, coupled with shifts in the tax structure that reduce the overall deadweight losses of the tax system

2) Removal or reform of various subsidies for energy sources and technologies

3) Internalization of environmental externalities not related to climate change

4) Market transformation policies

   a) Utility regulatory reforms that eliminate barriers to entry for generators using cogeneration and renewables-based technologies

   b) Market transformation policies that eliminate barriers other than entry to investments in cost-effective cogeneration and other low-carbon energy supply technologies

   c) Utility regulatory reforms and other market transformation policies that eliminate barriers to cost-effective investments in energy-efficient end-use technologies

   d) Utility regulatory reforms and other market transformation policies that eliminate barriers to economically efficient substitutions of lower-carbon natural gas or district heat with higher carbon electricity or vice versa

5) Accelerated research and development (R&D) and commercialization programs for new energy efficiency and low-carbon supply technologies.

The term energy tax is used in this paper as a generic concept that may or may not include taxes differentiated by carbon content.

The term market transformation (option 4) is used here to broadly describe policy measures that reduce market failures through instruments other than changes in energy prices. The major non-price instruments include energy efficiency incentives for energy users provided by utilities and/or governments; procurement incentives for manufacturers provided by utilities and/or governments; voluntary agreements or standards between governments, professional societies, and manufacturers; and legally mandated minimum efficiency standards. Three of these four major policy instruments rely on voluntary participation by consumers and/or manufacturers.

Option 5 addresses the well-recognized pattern of private under investment in R&D, and the inability of markets to optimize the time path for the development and commercialization of competing new technologies.

THE ECONOMIC PESSIMISM OF TOP-DOWN STUDIES

It is widely agreed that top-down studies tend to overestimate mitigation costs. This bias is partly due to pervasive deficits in the analysis of no regrets options based on subsidy removal, incorporation of environmental externalities, and tax shifts, as illustrated in Table 1. The non-climatic environmental benefits of a carbon tax alone may be of the same order of magnitude as the gdp losses calculated in various top-down studies.[2] Similarly, the removal and reform of subsidies could produce significant emission reductions at negative net cost, especially in the context of a climate protection strategy.[3]

Shortcomings of top-down studies in these areas can reinforce each other. For example, non-consideration of environmental externalities, subsidies, and market transformation options may lead to grossly excessive estimates of required carbon taxes and erroneous assessments of the gdp and welfare effects of tax shifts (see the section on top-down studies below).

Table 1 here.

In addition, the modeling procedures of top-down studies introduce several other biases toward overestimating mitigation costs, and so can the choice of model type itself.[4] The key factors involved are inadequate treatment of saturation effects and associated structural changes in final energy demand (Swisher and Wilson 1993), omission of cost-reducing feedback effects between carbon constraints and the rate of technological innovation (Carraro 1994, Gerstenberger 1992);[5] and implicit use of private discount rates rather than lower discount rates that may be appropriate for policy analysis (Krause et al. 1993).

Some of the differences between bottom-up and top-down analyses can be overcome by integrating the two modeling methods, as has been done in several recent Western European studies (see the last section of this paper). Such an integrated modeling approach allows the analysis of tax shift options in combination with non-fiscal measures while at the same time capturing the all-economy feedback effects of non-fiscal programs. However, the results of such integrated studies are still centrally driven by the bottom-up analysis of alternative energy systems. Thus, a central task in interpreting the existing literature on mitigation costs is the clarification of estimating biases associated with bottom-up methods.

THE ECONOMIC PESSIMISM OF BOTTOM-UP STUDIES

The view that bottom-up studies are inherently optimistic is based mainly on two assertions:

- That the economy-wide feedback effects omitted in bottom-up studies have the effect of increasing mitigation costs.
- That many of the observed market barriers to the adoption of energy efficiency technologies may not in fact represent market failures; and/or, that the implementation costs of correcting these problems would exceed the benefits of improved markets.

It is argued below that this assessment is fundamentally flawed. First, it assessment fails to consider all relevant factors that need to be taken into account in determining the net pessimism or optimism of bottom-up studies. Second, it fails to consider pertinent theoretical research and empirical research on those cost factors that are taken into account.

Pessimism due to omission of important no regrets options

For the above assessment to be conclusive, bottom-up studies would need to exhaustively cover all no regrets options. Simple inspection of available studies for Western Europe and other OECD countries shows that this is not the case. In particular, bottom-up studies routinely omit the economic benefits from three important no regrets options:

- economically advantageous tax shifts;[6]
- subsidy removal; and
- incorporation of non-climatic externalities.

As already discussed, the last two options are routinely omitted in top-down studies as well. The omission of these no regrets options represents a significant bias toward pessimism. These deficits are by themselves sufficient to put into question the claim that bottom-up studies underestimate the costs of mitigation.

Pessimism due to omission of feedback effects

Bottom-up studies represent incomplete, partial equilibrium analyses covering only the energy sector. As such, they cannot capture the impacts from substitutions of fossil fuels that occur outside the energy sector. These impacts include changes in prices, in disposable income, in trade and in the sectoral composition of gross domestic product, all of which lead to secondary changes in final energy demand. Because of these limitations, estimates from bottom-up studies are necessarily approximate. However, as discussed below and as further demonstrated by the results of integrated bottom-up/top-down studies, the net bias introduced by these limitations is toward overestimating mitigation costs.

The rebound effect

Basic economic considerations suggest that the implementation of money-saving energy efficiency options will generate a feedback effect. Provided that no compensating energy or carbon tax increases are introduced, cost-effective market transformation policies may raise the demand for energy services relative to the fixed business-as-usual level assumed in bottom-up studies, and may somewhat[7] raise final energy demand. This rebound effect would then make somewhat larger emission reduction efforts necessary to achieve a given reduction target. In that sense, bottom-up studies could underestimate mitigation costs.

Bias toward pessimism in the context of climate protection strategies

This line of reasoning fails to account for the suppressive impact of climate stabilization strategies on the rebound effect. It also fails to take into account other feedback mechanisms that arise in this policy context and that tent to bring major reductions of mitigation costs. The net effect is an overestimation of mitigation costs.

First, as shown in theoretical research (CEC 1992, Howarth and Winslow 1994), a least-cost strategy for reducing emissions would consist of energy taxes and market transformation programs in combination. Under such a strategy, the after-tax prices of energy and fossil fuels are likely to rise significantly. These higher after-tax energy prices will tend to direct additional disposable income from cost-effective energy savings into less energy-intensive forms of consumption than found in the business-as-usual case. This will tend to suppress rebound effects.[8]

Second, even as *after-tax* energy prices rise beyond those in the reference case, the economy at large will still benefit from reduced *pre-tax* fossil fuel prices as the use of fossil fuels declines. This potentially large secondary economic benefit of emission reduction measures is not endogenously captured in bottom-up studies, which adds a systematic bias toward pessimism.[9]

Third, most bottom-up studies fail to account for the reduction in the cost of energy efficiency technologies that occurs when market transformation policies move these products from niche markets with high mark-ups into mass markets with low mark-ups. Evidence from market research suggests that this policy effect can greatly reduce the first-cost premium of energy efficiency technologies (GEA 1994). In favorable cases, it may entirely eliminate this premium, as illustrated by the experience with refrigerator efficiency standards in the U.S. (Greening et al. 1996). By contrast, bottom-up studies typically rely on data derived from current market prices, which include the high first cost premiums found under status quo conditions of limited market share.[10] The use of current market prices or implausibly high mark-ups in engineering-economic analyses of mass manufacturing again creates a bias toward overestimating mitigation costs.

Finally, bottom-up models suffer from the same lack of endogenous mechanisms as top-down models when it comes to capturing the feedback effects of aggressive climate protection policies on the rate of innovation in the area of energy efficiency and low carbon supply technologies. As a result, bottom-up studies may at once underestimate the future-year resource potentials of energy efficiency and other low-carbon technology measures and overestimate the costs of these technologies.[11]

Correcting the energy efficiency gap: adjustment costs and implementation costs

Bottom-up and top-down analysts agree that the phenomenon of the energy efficiency gap can in principle be explained by information failures, principal/agent conflicts, losses of consumer surplus, high transaction costs, bounded economic rationality, uncertainty regarding ex post performance, and a variety of combinations thereof (Jaffe and Stavins 1994, Krause et al. 1994, Sanstad and Howarth 1994).

Furthermore, it is widely agreed that policy action aimed at facilitating the adoption of technologies with lower life cycle costs can only result in net economic benefits when such action succeeds in reducing the sum of all direct plus indirect costs associated with adopting life cycle cost minimizing technologies, without creating implementation costs that exceed the benefits of such action.

Expanded empirical basis of bottom-up analysis

Many top-down analysts believe that bottom-up research overlooks or ignores the indirect and intangible cost factors not captured by life cycle cost analysis. This perception, and related claims that current markets for energy efficiency may already be economically efficient, have their origin, in part, in the failure of most bottom-up studies to connect their empirical data to a rigorous theoretical economic framework. This gap has been closed in recent work by Sanstad and Howarth (1994), who conclude that a wide range of market barriers identified in bottom-up research constitute market failures in the standard economic sense.[12]

Another outdated preconception is that bottom-up research is purely engineering-economic and thus devoid of behavioral and other data. Over the last decade, bottom-up analysis has expanded to include applied research on consumer behavior, marketing patterns and institutional conditions, and on the effectiveness of utility and government sponsored market transformation programs. This broadened body of empirical research provides persuasive and unrefuted evidence that most energy efficiency technologies and well-designed policy programs preserve or increase consumer surplus. The same evidence shows that such programs can cost-effectively reduce or eliminate transaction costs and other adjustment costs that now prevent the adoption of economically optimal technologies (Krause et al. 1994).

Consumer surplus and preferences

Technical analysis shows that in many end-use applications, energy-efficient technologies are identical to standard versions in every respect except energy use (Koomey and Sanstad 1994). Moreover, such analysis demonstrates that many of these technologies increase utility and comfort, not diminish it. These findings are complemented by market research showing, for example, that adoption rates for energy-efficient technologies in new commercial buildings differ greatly based on whether firms owned or rented these buildings (Hines 1990). If a loss of utility, productivity, or comfort were the decisive factor in technology choice, — rather than the landlord/tenant agency problem — one would have expected the same adoption rates among both groups.

In addition, voluntary market transformation programs based on incentives and procurement competition provide a market-based testing ground in which consumer preferences and other indirect cost factors fully come to play. The high participation rates achieved in many U.S. and Western European utility demand-side management programs (Nadel 1990, Mills 1993) show that consumers and firms readily embrace energy-efficient technologies when programs are well-designed, i.e., when they effectively reduce transaction costs for testing and obtaining these devices.

Even regulatory policies based on minimum efficiency standards for buildings, vehicles, and component equipment can incorporate market-based mechanisms that safeguard against losses of consumer surplus.[13] Such regulatory standards also are routinely subject to cost/benefit tests. A comparison with command and control regulations in the field of classical pollution control is therefore misleading.

Costs of policy implementation

The omission of program administrative costs in many bottom-up studies represents a bias toward optimism. The quantitative significance of this omission depends, in part, on the assumed mix of policies. A major portion of energy-efficiency technology options can be implemented using voluntary agreements and/or mandatory efficiency standards, for which implementation costs are typically negligible.[14]

Where more expensive incentive-based programs are used, administration costs have been found to add less than 15 percent on average to engineering-economic technology costs.[15] The growing use of systematic process and impact evaluations has led to a falling trend as utilities and energy service companies have gained experience. More recent, third generation procurement-based programs and voluntary agreements have still lower administration costs and can approach those for regulatory standards. Overall, these findings from evaluation research suggest that for a coordinated package of voluntary and regulatory instruments, average implementation costs across all end-uses can be limited to less than five percent of technology costs. This cost correction represents at best a minor fraction of life cycle cost savings and will not substantially change the cost-effectiveness of energy efficiency options.

Biases created by other input assumptions and modeling procedures

Even if bottom-up studies were significantly optimistic in their treatment of indirect costs, this would be an insufficient basis for concluding that their mitigation cost estimates are optimistic. Rather, it is necessary to comprehensively examine the various bottom-up input assumptions and modeling procedures for additional factors that might create a bias toward pessimism or optimism. Factors that result in overestimation of mitigation costs include the following:

— Incomplete analysis of end-uses and sectors

— Incomplete or dated analysis of technology and policy options

— Neglect of demonstrated near-commercial and advanced technologies

— Omission of capital cost savings from downsizing of downstream or upstream equipment and from lower maintenance and replacement costs for such equipment

— Omission of cost savings due to changes in non-energy process requirements (labor, water, materials)

— Omission of secondary benefits due to increased consumer amenity or productivity

— Omission of credits for avoided transmission and distribution investments and O&M costs in utility systems

— Use of prototype-based costs rather than mass market costs for near-commercial technologies

— Use of discount rates higher than the social discount rate

Factors that create a bias toward optimism (i.e., underestimation of mitigation costs) are:

— Omission of policy implementation costs (see above)

— Omission of losses of consumer amenity and other indirect costs that are not offset by gains in utility and that cannot be reduced or eliminated by market transformation policies

— Overestimation of energy savings that can be achieved in practice due to inaccurate baseline data and lack of field measurements

— Insufficiently disaggregated analysis of technology cost-effectiveness by equipment type, size, intensity of utilization, and geographic location

In an in-depth analysis covering 21 costing factors including the above list, Krause et al. (1995b) find that purely engineering-economic life cycle cost estimates for efficiency improvements in Western European electricity use tend to be significantly biased toward overestimating the costs of saved energy, and thus the cost of mitigating carbon emissions.

Uncertainties about policy adoption in the political process

From a purely economic point of view, the timing of technology shifts in bottom-up scenarios is conservative in that no premature retirement of end-use equipment is assumed[16] and shifts occur over two or more replacement cycles for many end-uses. The implied or assumed phase-in periods broadly match experience with introducing utility demand-side management programs and government efficiency standards in a range of end-uses. Bottom-up scenarios simply assume a much more widespread and synchronized application of these instruments.

Though the institutional capabilities for carrying out major market transformation programs have been demonstrated, scenarios based on complete economy-wide implementation of technical-economic potentials can be questioned from the point of view of political feasibility. For a given reduction target and time table, mitigation costs may rise if only a fraction of replacement investments are in fact shifted to cost-minimizing high-efficiency technologies.

This potential source of cost assessment optimism is difficult to quantify since it depends in large measure on political judgment. Furthermore, the political feasibility argument can be raised about other proposals for climate stabilizing policy action as well, such as high carbon taxes or tradeable permit systems. As discussed below, most existing bottom-up estimates are based on significantly less than the full implementation of technical-economic resource potentials.

More fundamentally, mitigation cost studies are to inform the societal policy-making process, not prejudge it. The purpose of economic assessments may be defeated when technical-economic calculations are strongly altered by assumptions about political feasibility. In a properly agnostic approach to this issue, the implementation fraction would be treated as an explicit scenario variable (see the review of individual studies below).

REVIEW OF WESTERN EUROPEAN BOTTOM-UP STUDIES

The time horizons used in the key bottom-up studies for Western Europe range from the year 2010 to 2030. Three major multi-country projects were conducted. These are the Coherence study for the Joule program of the European Commission (Coherence/CEC 1991), which covered ten European Union countries ; the ETSAP study for the IEA (Kram and Okken 1993), which covered Belgium, Italy, the Netherlands, Norway, Sweden, and Switzerland in addition to several non-European OECD countries; and the IPSEP study for the Dutch government (IPSEP 1993/1996, Krause 1995), which covered France, Germany, Italy, the Netherlands, and the United Kingdom.

In addition, a number of national bottom-up studies were undertaken. Among these, by far the most comprehensive is that of the Enquete Commission on Climate Protection of the German parliament (Enquete Commission 1995). The Enquete Commission's bottom-up scenarios were also used in an integrated bottom-up/top-down macroeconomic modeling assessments for that country (see the section below on top-down and integrated studies). Two national bottom-up studies were performed for Denmark (Morthorst 1993) and for the Netherlands (Ybema et al. 1993) as part of the UNEP country studies program (UNEP/Risø 1994). A number of further important contributions were made in sectoral bottom-up studies such as the Swedish study of the heat and power sector (Bodlund et al. 1989, Mills et al. 1991).

The energy sector baseline: business-as-usual versus least-cost energy system

In most of the Western European bottom-up studies (i.e., in the Danish UNEP, FRG Enquete Commission, Coherence/CEC and IPSEP studies), mitigation costs are calculated relative to business-as-usual scenarios for the demand for final energy and the mix of supply sources. These business-as-usual projections not only omit most cost-effective demand-side efficiency resources but typically also fail to reflect a least-cost mix of energy supply sources.[17]

Despite these shortcomings — or, rather, because of them — these "conventional wisdom" scenarios arguably provide the most meaningful baseline for determining the incremental costs or benefits of alternative carbon reduction strategies. They broadly represent official energy planning and policy as pursued during the 1980s, before climate change became an important concern. The policy initiatives in the fields of energy efficiency and renewable energy that have been undertaken since then are far from sufficient to implement available technical-economic potentials. Therefore, business-as-usual projections best approximate the costs of energy services Western European nations might have incurred and/or were prepared to bear in the absence climate-oriented policy changes.

An alternative baseline definition is used in the ETSAP studies and in the Dutch UNEP study.[18] Here, the reference scenario is, at least nominally, a least-cost mix obtained from a strictly economic integration of the various resource options using a linear propgramming model. Implicit in this least-cost baseline are technology shifts that produce substantial economic savings relative to a business-as-usual case. The substantial changes in existing energy policies that are required to bring about a least-cost baseline are, however, not detailed. These changes are reserved for the policy case in the other studies.

Economic indices for comparing study results

In exploring mitigation costs, both total costs and marginal costs of emission reductions are of interest, but the usefulness of each in comparing studies and countries depend on the type of baseline. When an optimized energy system is taken as the baseline, both the marginal and total costs of mitigation are by definition positive for all levels of emission reductions. However, when the reference case is a business-as-usual scenario, total costs may be negative or positive, depending on the reduction target and the size of negative-cost and zero-cost resource potentials. Each group of studies therefore needs to be considered separately.

Quantitative results: zero net cost reduction potential and time path

Results from the Western European bottom-up studies using a business-as-usual baseline are given in Table 2. Findings are reported in terms of the maximum analyzed percentage reduction relative to base year emissions that was found to produce a zero or negative net change in the cost of energy services relative to the baseline.[19]

Table 2 here.

costs enter the resource mix only when considering reductions in excess of 20-40 percent relative to base year levels.

Regardless of their magnitude, these differences in marginal costs point to the potential economic advantage of a tradable emission rights system within the European Union. However, top-down assessments also show that national differences in the energy or carbon intensity of gdp are an unreliable predictor for the relative macroeconomic impacts of carbon constraints (CEC 1992).

Analytical and data differences

The wide range of the above study results can be narrowed considerably, and thus yield more precise policy guidance, if important differences in input assumptions are taken into account. These are: incomplete coverage of end-uses and sectors, only partial policy implementation of economic resource potentials, incomplete portfolios of technology measures for the covered end-uses and sectors, and various differences in cost definitions and data.[21]

Coverage of end-uses and implementation of technical-economic potentials

The degree to which demand-side efficiency potentials were considered in each study is indicated in Table 2. The percentages represent the combined effect of the scope of the end-use analysis and of the assumed implementation of technical-economic potentials. The Coherence/CEC study covered only about a quarter of final energy consumption.[22] In the Danish UNEP and FRG Enquete Commission studies, energy efficiency options for the transport sector beyond those incorporated in the baseline were neglected or their costs were not analyzed and simply assumed to be zero. The IPSEP study developed cost curves for efficiency improvements in all sectors including the transport sector.

Different assumptions were also made regarding the feasible implementation fraction. For example, the Danish UNEP study assumed close to 100 percent implementation of supply-side no regrets potentials, but only a roughly 60 percent implementation of analyzed demand-side potentials.[23] In the IPSEP study, the mobilization of efficiency and other unconventional resources was made an explicit variable. Mitigation costs were calculated assuming, respectively, 25%, 50%, 75%, and 100% mobilization of the technical-economic potentials of energy efficiency, cogeneration, and renewable resources.

Technology and cost data

Not all studies succeeded equally in developing internally consistent technology, cost, and program implementation data. The most detailed substudies on these input assumptions are found in the FRG Enquete Commission and IPSEP reports.[24] Comparison with the IPSEP and FRG Enquete Commission substudies suggests that the Coherence/CEC study understated cost-effective percentage efficiency improvements in the major end-uses by a factor of two or more.[25] The "low" and "high" sensitivity cases in the IPSEP study illustrate that feedback effects of climate policies on technology costs and fuel prices can decisively reduce total mitigation costs.[26]

Inconsistencies in "optimized" baselines

The figures in Table 2 not only provide the absolute emission reductions that can be achieved at zero or negative net cost, but also an approximate indication of the adjustment periods needed for realizing these targets in a least-cost fashion. The following reduction ranges were obtained for the countries covered in these studies:

By about 2005-2010: 10 - >36 percent (median of 23 percent)

By about 2015-2020: >23 - 58 percent (median of 41 percent)

By about 2025-2030: >45 - >60 percent (median of >53 percent)

Averaged over the time horizon of each study, annual no regrets reduction rates are found to be a compounded 1-3 percent per year relative to the base year and 3-6 percent per year relative to the business-as-usual baselines.

The studies shown in the table were not or only partially normalized regarding economic growth, structural change, fuel prices, technology costs, policy effectiveness, etc. Despite these variations, the figures show a consistent pattern:

— Within the year 2000-2030 time frame, larger reductions become feasible at zero net cost as time horizons grow longer, despite continued economic growth.

— For any given target within the range of zero-cost reductions, mitigation costs decline as longer adjustment periods are allowed for reaching the target.

This pattern reflects the fact that all of the above bottom-up studies identify significant energy efficiency, fuel switching and cogeneration potentials that are not exploited in the reference case. Because most of these no regrets resources are introduced in the course of normal capital stock turnover, cost-effective carbon reductions "keep coming."

Quantitative results: marginal costs

Given the wide range of carbon intensities found in the status quo and baseline energy supply systems of Western European countries,[20] a significant range of marginal costs is to be expected. This is borne out by the results of the three multi-country projects:

— In the Coherence/CEC study, the range across nine countries is 0-40$/ton of CO_2 for stabilization at base year levels (time horizon 2010). For a ten percent reduction, the range becomes much wider at 6-1560$/ton of CO_2.

— In the ETSAP study, the marginal cost of limiting year 2020 emissions to 1990 levels ranges from a low of about zero (Belgium) to a high of about 700 $/ton of CO_2 (Sweden).

— In the IPSEP study, the marginal costs of limiting year 2020 emissions to base year levels or of reducing them by 10 percent is small or negative in all five countries analyzed.

Here as elsewhere, the degree of detail and comprehensiveness in the analysis of no regrets options plays a decisive role. The negative marginal costs found in the IPSEP study arise mainly from cost-effective energy efficiency improvements and cogeneration investments not considered in the other multi-country studies. For modest targets, these negative-cost options dominate mitigation costs. Technology options of high marginal

In the ETSAP and Dutch UNEP studies, incomplete coverage of end-uses and technology and cost input data are reflected in the baseline. The "optimized" baseline projections in these studies showed flat to significantly rising final energy demand levels that really are quite close to the business-as-usual projections used in the studies summarized in Table 2. This pattern is inconsistent with a least-cost optimization of the energy system. Inspection of assumed energy efficiency potentials and costs, and comparison with the FRG Enquete Commission, Danish UNEP, and IPSEP studies indicates that with more comprehensive assessments of no regrets options, economically optimal levels of year 2020 final energy demand would have been significantly below base year levels. As a result, the ETSAP and Dutch UNEP studies are inconclusive regarding total mitigation costs.

Analysis of energy supply options

The relative contributions from demand-side efficiency and low-carbon supply options vary significantly among Western European bottom-up studies. Table 2 shows two proxy indicators, the coefficient of improvement in the average energy intensity of gdp (AEII), and assumptions regarding the future deployment of nuclear power. The AEII coefficient implied in the bottom-up studies of Table 2 is 2-5%/yr, compared to a range of 0-1%/yr assumed in most top-down studies.[27]

The difference between the AEII coefficient and the rate of carbon reductions below the baseline indicates the extent to which shifts toward lower-carbon energy supplies augment emission reductions from energy efficiency improvements.[28] Here, the treatment of nuclear power is important (see Table 2). The ETSAP and Coherence/CEC studies were based on scenarios in which nuclear power was retained. The FRG Enquete Commission and IPSEP studies included scenarios in which nuclear power was phased out.[29]

Discussion: overall results

In light of the above review of input assumptions, the zero net cost potential for reducing carbon emissions in Western Europe is probably best characterized by the higher estimates in Table 2. In view of the previously-discussed generic bias toward economic pessimism in bottom-up studies in general, even these results are likely to be conservative. Using just the median figures in Table 2, average no regrets emission reduction rates over the next three decades would be about 2 percent per year relative to the base year. Carbon emissions in 2020-2030 could be cut by about 50-60 percent relative to baseline projections at zero or negative net cost. This figure is two to five times larger than the minimum (consensus) range of the IPCC report, which suggested an OECD-wide no regrets potential of 10-30 percent relative to the business-as-usual baseline.

The above findings imply growing opportunity costs if mitigation strategies should be limited to a mere stabilization of emissions rather than progressive reductions below base year levels. Finally, several Western European bottom-up studies suggest that the region could achieve significant reductions in carbon emissions at zero or negative net cost even while phasing out nuclear power. Overall, bottom-up research indicates that Western European governments may have significantly more economic degrees of freedom in pursuing carbon reduction strategies than has been recognized to date.

REVIEW OF WESTERN EUROPEAN TOP-DOWN STUDIES

Among others, Western European top-down studies have made unique contributions in three areas. One is the early recognition and modeling of a range of tax shift options for minimizing or offsetting undesirable economic effects of energy or carbon taxes. The second is the modeling of integrated energy tax/market transformation/tax shift policies using linked bottom-up and top-down models. The third is the comparative analysis of groups of countries using one and the same modeling system.

Tax shift studies

The results of various Western European tax shift studies are reviewed in CEC (1992) and Bossier and Bréchet (1995), as well as by Hourcade and Robinson in this issue. Like corresponding work in the U.S., these studies examined modest energy or carbon taxes of typically less than 50$/ton C that resulted in only limited emission reductions below the baseline.[30] They found that under these conditions, tax shifts could partially or fully offset the deadweight losses induced by the energy tax. Several modeling exercises even found a net gain in gdp for certain tax shifts and countries (IPCC 1996).

In recent U.S. theoretical work, Goulder (1994) has suggested that for larger emission reductions below the baseline, tax shifts would no longer produce economic efficiency gains. The author assumes that a much higher tax would be needed to induce larger emission reductions. He argues that revenues from such a much higher tax would exceed opportunities for offsetting highly distortionary taxes, and would create bigger deadweight losses than the existing taxes on capital and labor they would displace.

This line of reasoning overlooks four factors that are key in interpreting Western European tax shift studies. For one, climate change mitigation helps abate a number of non-climatic externalities (footnote 2 above). Second, current fossil fuel consumption, as well as energy use in general, is significantly subsidized (footnote 3 above). Third, current differences in the taxation of coal, oil, and gas bear little relationship to differences in associated externalities, and could themselves be reformed at a possible gain in welfare while reducing carbon emissions (Hoeller and Coppel 1992).

As a result of these three factors, the imposition of carbon taxes may function, in part, as a welfare and efficiency-enhancing reduction in price distortions that impede economic efficiency. Well-designed tax shifts that include subsidy removal and reform thus are likely to offer robust reductions in deadweight losses over a much wider range of tax levels than suggested by Goulder.[31]

The fourth factor is that several Western European studies analyze a range of combined fiscal and non-fiscal policy packages not modeled in U.S. tax shift exercises. Here, the non-fiscal components include market transformation programs that require no tax revenue at all (such as energy efficiency standards), as well as the direct recycling of revenues into cost-effective energy efficiency and low-carbon supply investments through an energy efficiency fund or equivalent "ear-marking." The combination of non-fiscal instruments with ear-marking of all or a portion of carbon/energy tax revenues reduces the required tax level for achieving a given reduction target (Goto 1995) and opens the possibility for large emission reductions at zero or negative net cost even when applying only a low tax (Krause et al. 1995a).

Integrated bottom-up/top-down studies

Recent theoretical economic research suggests that a combination of fiscal and market transformation policies is economically more efficient than the use of tax instruments or market transformation programs alone (CEC 1992, Howarth and Winslow 1994). This insight is reflected in various Western European policy actions or proposals, notably those of the Danish government, the European Commission, and the FRG Enquete Commission on Climate Protection, all of which emphasize packages of taxes, tax shifts, and market transformation policies. These and other policy proposals have been evaluated in a number of integrated studies[32] that link bottom-up scenarios and top-down models (Bossier et al. 1995, Danish Ministry of Finance 1995, DRI 1991, Enquete Commission 1995, Godard and Beaumais 1994, Koeppl et al. 1995).

The FRG Enquete Commission study

Among the linked studies, the modeling work of the FRG Enquete Commission is particularly informative in that it was based on a detailed, well-researched bottom-up scenario and covered an extended time horizon (1987-2020). The integrated modeling work was co-authored by two institutes specializing in bottom-up research (IKE and ISI) and two macroeconomic research institutes (DIW and EWI).

Modeling methodology

The policy scenario in the FRG Enquete Commission study consisted of a linked energy tax/market transformation/tax shift approach. The energy tax was a low tax equivalent to the proposal of the European Commission. In the bottom-up assessment, two main energy sector scenarios were developed. One kept nuclear capacity constant (R1), while the other included a nuclear phase-out (R2). In both cases, year 2020 emissions were cut by 45 percent relative to 1987 (35 percent relative to 1993).

The principal modeling procedure, which is representative of other integrated studies, is illustrated in Figure 1. The bottom-up energy scenarios were translated into economic stimuli and structural changes by economic sector, using input-output methods. A neo-keynesian macro model was used to determine gdp, structural changes, employment and other macroeconomic impacts (Walz et al. 1994). Modeling uncertainties in this procedure were explored through sensitivity analyses.[33] In a separate analysis, a general equilibrium model was used to assess trade effects.

Figure 1 here.

Results

The results are summarized in Table 3. In all cases, average gdp increased, and so did employment. In most branches, production increased by 2-6 percent. Output in the fossil fuel industries declined by 3-10 percent. The electricity sector was little affected.

Table 3 here.

In the unfavorable variant, gross domestic product rose by 0.2-0.3 percent, and employment also increased by 0.2-0.3 percent, equivalent to about 100 000 jobs (averaged over the 1987-2020 period). However, measures to reduce carbon emissions were in effect being financed through a 0.6-0.7 percent reduction in private consumption.

In the favorable variant, gdp gains were larger at 0.5-0.7 percent on average, partly because the induced modernization of production facilities led to a permanent rise in productivity. Here, both private consumption and employment rose. However, the productivity gains also meant that employment impacts were no greater than under unfavorable input assumptions.

The Enquete Commission assessment also found that alternative power sector scenarios based on the phase-out, maintenance, or expansion of nuclear power had a negligible impact on gdp (Table 3). The general equilibrium modeling of the trade effects of an energy tax suggested that differences in gdp impacts for the unilateral versus coordinated EU-wide implementation of the energy tax were small, with the unilateral tax being slightly more favorable.

Short-term studies

Among integrated assessments with a short-term focus, several Western European studies analyzed how alternative energy tax exemptions for industry might affect achievable emissions and total macroeconomic costs. We briefly summarize the findings from the WIFO study, which are broadly representative.[34] In this modeling work, a portion of tax revenues was recycled through a fund for cost-effective energy efficiency improvements and cogeneration investments.[35]

It was found that whenever the energy efficiency fund was part of the policy package, both gdp and employment effects were positive. If the energy efficiency programs were replaced by other forms of tax recycling or by budgetary deficit reductions, gdp and employment impacts were always negative.

A strategy that purely relied on payroll tax cuts and did not employ energy efficiency incentive programs was found to be inferior to the combined application of payroll tax cuts and an energy efficiency fund, both in emission reductions (20 percent lower) and in gdp and employment (losses rather than gains).

The study further found that a negative net cost of carbon reductions was maintained when industry exemptions from the energy tax were paired with market transformation programs. Overall emission reductions appeared more sensitive to the abandonment of the energy efficiency fund than to industry exemptions.

Discussion

These integrated studies suggest that gdp and employment impacts can be neutral or positive even when large emission reductions are pursued and over a wide range of policy combinations involving only modest energy taxes. In both studies, market transformation programs plus tax shifts resulted in macroeconomic efficiency advantages, even though the policy measures of the bottom-up scenario had the effect of somewhat *increasing* the total cost of energy services relative to the reference case.[36] This outcome again illustrates the importance of tax shifts, and underlines the economic pessimism of bottom-up studies, which do not incorporate tax shifts.

Given significant non-climatic externalities and inefficient subsidies, the welfare benefits of reducing carbon emissions have almost certainly been underestimated in these studies. Further enhancements of macroeconomic benefits can be expected from the modeling of bottom-up scenarios in which energy service bills show a significant decline. The trade-offs between exemptions from energy taxes and compensatory market transformation programs should be modeled in greater detail and for a larger number of countries.

SUMMARY

Conventional wisdom has it that top-down studies overestimate mitigation costs while bottom-up studies underestimate them. The analysis of relevant methods and input data in this paper indicates that this interpretation is flawed: both types of studies tend to *over*estimate mitigation costs, with studies based on detailed bottom-up scenarios closer to the mark.

First, virtually all mitigation cost studies for Western Europe and for the OECD in general neglect the no regrets options related to environmental double dividends and subsidy removal. Second, this pervasive no regrets deficit is compounded in bottom-up studies by the omission of tax shift options. Third, technical analysis, market research, and experience with market transformation instruments in a number of OECD countries shows the practical feasibility of improving energy efficiency and supply markets at a substantial net economic benefit, even after fully accounting for all indirect costs. Finally, the cost and technology inputs for bottom-up studies contain a wide range of conservatisms that overshadow other procedures with effects in the opposite direction. In particular, the failure of bottom-up analysis to capture a number of feedback effects tends to result in a net bias toward cost pessimism.

Given these limitations, the closest approximation to the costs of mitigating carbon emissions in Western Europe is found in the more comprehensive bottom-up studies and in recent integrated bottom-up/top-down analyses. In quantitative terms, a careful and informed reading of the entire body of existing studies leads to the following conclusions: In a well-designed policy approach, carbon emissions in Western Europe could be cost-effectively reduced by a compounded 3-6 percent per year below the business-as-usual baseline, or by about 1-3 percent per year below base year levels.

With proper attention to all no regrets options, the zero net cost potential for cutting carbon emissions can be conservatively represented by the median of these ranges. For the 2020-2030 time horizons, this median corresponds to a reduction of more than 50-60 percent relative to the business-as-usual baseline. This no regrets range is at least twice as large (and significantly more narrow than) the minimum consensus figure of 10-30 percent given in the IPCC report.

This discrepancy suggests that Western Europe would incur significant opportunity costs if it should limit its mitigation efforts to a mere stabilization of emissions rather than progressive reductions below base year levels. This indication of growing opportunity costs from overly modest reduction targets clashes with recent top-down studies (Wigley et al. 1996), which suggest that a go-slow approach in early years, followed by more aggressive action in later decades, could be economically beneficial.

In summary, the wide and seemingly inconclusive range of mitigation costs found in the IPCC report transforms into a significantly more definite sign post for fashioning economically sound quantified emission reduction targets: Close examination of available studies suggests that with a combination of fiscal reforms and aggressive market transformation policies, the European Union could cut its carbon emissions over the next 30 years or so by roughly 2 percent per year relative to 1990 levels without adverse economic impacts, and possibly at a net benefit.

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1 In this paper, the term mitigation costs always refers to the net economic or welfare cost of reducing fossil carbon emissions after considering various double dividends but *before* considering the benefit of avoided climate changes.

2 See, for example, Barker (1993) and Ekins (1994), who finds non-climatic externality values of $20-212 per metric ton of C for the UK and other European countries, and the review of 10 studies by Statistics Norway (1995), which finds a range of $52-1426/tC for non-climatic environmental benefits and $74-1630/tC for benefits from reduced traffic in that country. The latter review indicates benefits ranging from about 5 percent to more than 100 percent of gdp losses calculated for various carbon tax scenarios.

3 In such a context, subsidy removal and reform would be accompanied by the imposition of carbon/energy taxes. These ensure that the removal of supports for domestic producers, and the attendant reductions in energy prices, do not translate into increased fossil fuel consumption and emissions. Removing global subsidies to fossil fuel consumers has been estimated to be equivalent to imposing a carbon tax of 50-90$/tC and to emission reductions below the baseline of 5-18 percent in 2010 at a net economic benefit (Larsen and Shah 1992, Burnieaux et al. 1992). Though OECD energy prices are generally above world market prices, major subsidies are found even there in the form of a range of price and budgetary supports, notably for coal. Recent OECD case studies indicate that removal and reform of about $100 billion of subsidies (defined there to include some non-climatic externalities) could yield reductions in year 2010 OECD carbon emissions of several percent below the baseline, along with positive gdp and welfare effects (Michaelis 1996).

4 Neo-keynesian macro models result in higher mitigation cost estimates than general equilibrium models, which assume greater adjustment speeds for capital stocks.

5 In the global studies reviewed by Richels and Sturm in this issue, an additional source of pessimism is the neglect of spillage effects (Krause et al. 1993), i.e., the penetration in the developing world of new low-carbon technologies first introduced in the the OECD in response to the unilateral adoption of emission constraints.

6 For a discussion of the conditions under which tax shifts can reduce deadweight losses and result in economic efficiency gains, see the section on top-down studies at the end of this paper.

7 Because any additional energy services would be provided with more efficient technologies as well, the percentage increase in final energy demand would be less than the underlying percentage increase in energy service demand.

8 A macroeconomic analysis of this suppressive effect is found in Goto (1995). See also the discussion of integrated top-down/bottom-up studies at the end of this paper.

9 For example, Reinsch and Considine (1992) estimate that even the OECD-wide adoption of the mild carbon/energy tax proposed by the European Commission (1991) would reduce pre-tax oil prices by more than 10 percent in 2007,

equivalent to a 47 billion dollar annual saving for the OECD nations, and 90 billion dollars worldwide. Though oil producing nations might attempt to defend their revenue streams through new cartel agreements, their ability to do so is questionable (CEC 1992), and would likely decrease in the face of stronger carbon constraints. Some bottom-up studies examine this effect through sensitivity tests based on lower energy price assumptions without, however, venturing beyond the range of fossil fuel price forecasts made for various rates of *growth* in fossil fuel consumption.

10 See the critique of this procedure in Krause et al. (1995b). Where allowance is made for economies of scale under changed market conditions, as in government-sponsored cost-effectiveness analyses of energy efficiency standards, the typical practice is to use "ideal" manufacturer mark-ups. These are often far in excess of what equipment producers end up being able to charge in mass market competition. See the market research in GEA (1994), and the empirical ex-post evaluation of U.S. appliance standards in Greening et al. (1996)).

11 See Gerstenberger (1992) for an empirical analysis of the effects of higher energy prices on the rate of innovation in the area of energy efficiency. Most bottom-up studies with longer time horizons (30-40 years) do capture some technology innovation effects by explicitly taking into consideration a range of advanced technologies. However, assumptions in this regard may be quite cautious and in any event, do not capture those techniques that are not yet known. Thus, bottom-up studies are likely to contain a significant bias toward cost pessimism even in this area.

12 While most economists readily concede that problems of uncertainty and high information and transaction costs are universal characteristics of 'normal' markets, some argue that these do not constitute market failures. In an in-depth theoretical economic critique of this view, Sanstad and Howarth (1994) show that the equation of 'normal' markets with economically efficient markets is a fallacy based on tautological arguments.

13 Recently proposed or enacted standards are generally formulated on a performance basis, i.e., they do not prescribe the use of any one particular technique or design. Performance-based standards give manufacturers incentives for technological creativity while providing wide latitude for preserving non-energy attributes important to consumers. Issues of consumer surplus can be, and often are, empirically assessed before standards are promulgated by first conducting voluntary incentive programs. In many cases, standards are merely used to accelerate the completion of the technology diffusion process after a technology has already been adopted by a sizable fraction of consumers and firms. Furthermore, the tandem application of incentives and standards can be used to accelerate innovation, which increases consumer surplus. Finally, market research can be used to evaluate issues of product attributes after standards have taken effect. Recent empirical work of this kind on U.S. appliance efficiency standards found no measurable negative effects on product selection and attributes (Greening et al. 1996).

14 For example, the cumulative cost of developing and implementing federal energy efficiency standards for U.S. appliances and other products amounted to 50 million dollars, equivalent to one tenth of one percent of the estimated net present value benefits of these standards in the period till 2015 (McMahon et al. 1990).

15 This figure is based on measured savings from several billion dollars of U.S. utility spending on demand-side management programs and comprehensive cost data including savings verification, free rider costs, profit incentives for utility shareholders, and program evaluation (Eto et al. 1995). Similar proportions are reported in Western European evaluation studies (Mills 1993). Earlier estimates by Joskow and Maron (1993) were based on incomplete data and have proven far too high. The costs of saved energy are reduced further when accounting for the secondary market transformation effects of incentive programs, such as 'free drivers' (Levine and Sonnenblick 1994), secondary equipment and maintenance savings, and accelerated product improvements.

16 The conservatism of this procedure is enhanced by the fact that in a number of end-uses, early replacement can be economically justified because of a favorable ratio between potential annual energy savings and the total replacement cost of the device. As discussed above, climate stabilization policies may also trigger accelerated innovation that could make some early retirement of existing end-use equipment attractive.

17 The business-as-usual supply mix typically reflects existing barriers to market entry for independent generators as well as some or all of a range of other politically determined factors that have shaped official energy planning in Western Europe. These include limitations on gas imports (all of the EU during the cold war period), preferences for use of domestic coal (e.g., Germany), and industrial strategies based on nuclear electrification (France).

18 Least-cost configurations for the energy system are also developed in the Coherence/CEC, IPSEP, and FRG Enquete Commission studies.

19 In several cases, the shown emission reductions were associated with significant net economic benefits, but no measures to obtain further emission reductions were analyzed. Here, reductions are shown with a "greater than" sign.

20 For example, in the Coherence/CEC study, year 2010 emissions correspond to a stabilization at 1988 levels for Germany (pre-1990 borders), a 5% increase for France, 12% for the UK, 24% for Italy, 30% for Spain, and 72% and 86% for the less developed countries of Greece and Portugal, respectively. For the EU-12 as a whole, the business-as-usual increase is 14% by 2010.

21 Gdp growth rates, energy demand, and fuel price projections are relatively similar across studies. For example, both the Coherence/CEC study, the FRG Enquete Commission study, and the IPSEP study derive these inputs from the projections of the European Commission.

22 Excluded from the analysis were all of industry, most of the tertiary sector, and all vehicle efficiency improvements in transport except certain modest improvements in cars.

23 Baseline energy efficiency improvements in the transport sector excluded a significant range of cost-effective or cost-neutral options, and because some other efficiency options were not analyzed, Table 2 indicates that less than half of the available cost-effective energy efficiency potential was incorporated in the mitigation cost analysis.

24 The latter study employed a number of data refinements not or only partially applied in other European bottom-up studies. These included feedback effects of climate policies on technology costs; program administration costs; credits for energy efficiency investments from secondary capital savings in upstream or downstream end-use equipment; credits for avoided transmission and distribution costs; and alternative assumptions regarding the effectiveness of policy efforts in mobilizing unconventional resources.

25 The Coherence/CEC and IPSEP studies are directly comparable in so far as both use the "Energy for the Next Century" study of the European Commission (CEC 1990) as the business-as-usual baseline. With assumed efficiency improvements relative to the baseline in the Coherence/CEC study averaging about 20 percent, and only about 25 percent of final consumption investigated, the study yields a roughly 5 percent reduction in final energy requirements below the rising projection of the business-as-usual reference case. Extrapolating the analysis to all end-uses would raise this percentage to about 20 percent. Across all end-uses, the more comprehensive and up-to-date technology cost and performance data of the IPSEP study indicate a cost-effective savings potential of 40-60 percent on a weighted average basis. Adjusted to the shorter (year 2010) time horizon of the Coherence/CEC study, this percentage is about 25-35 percent. Overall savings of 5% rather than 25-35% indicate a less than 20 percent capture of the total cost-effective potential.

26 In the study, high and low estimates were developed not only for fuel prices, but also for technology costs. Low cost assumptions were used to reflect plausible cost reductions from feedback effects of carbon constraints, while high assumptions illustrated outcomes in absence of these feedbacks.

27 See IPCC (1996), Chapter 9. The AEII coefficient is functionally identical to the coefficient of average energy efficiency improvement (AEEI) referred to in top-down studies. However, the latter name ignores that this coefficient includes both energy efficiency improvements in the technological sense and structural changes.

28 In all studies, differences also exist in the definition of the costs and potentials of low-carbon energy supply options and in the degree to which the multi-country studies succeeded in using consistent input assumptions across countries. The ETSAP and IPSEP projects used cost data that were consistently defined across countries, while the input assumptions in the national substudies of the Coherence/CEC project were determined by national teams. This led to significant differences in technology portfolios and cost estimates and to the much wider range of marginal cost estimates found in that study.

29 Zero net cost scenarios for reducing carbon emissions while phasing out nuclear power were also identified by Bodlund et al. (1989) for Sweden. The FRG Enquete Commission examined a rapid phase-out by 2005, while the IPSEP study assumed a gradual phase-out by 2020.

30 The carbon tax as originally proposed by the European Commission (CEC 1992) was to start at $14 per metric ton of carbon in 1993 and gradually rise to $46 per metric ton by 2000.

31 The greater recognition of externality issues related to fossil and nuclear energy explains why many of the Western European top-down studies model an energy or combined energy/carbon tax in addition to a pure carbon tax (see, e.g., Standaert 1992). While a carbon tax might be more effective in reducing CO_2 emissions than an energy tax, this advantage in the area of climate change is widely viewed as economically less important than policies that reduce risks and externalities from both fossil and nuclear energy production (CEC 1992, Enquete Commission 1995: 755, WIFO 1995).

32 The term integrated study is reserved here for macroeconomic studies in which energy sector impulses are derived from bottom-up assessments using a business-as-usual baseline.

33 Under unfavorable assumptions, energy efficiency investments were financed through reductions in private consumption. Also, energy efficiency investments were assumed to displace investments in production facilities. Furthermore, it was assumed that half the revenue from the energy/carbon tax would be used to reduce government budget deficits (without, however, lowering interest rates) and to finance government energy efficiency programs. The other half of the tax revenue was used to reduce payroll taxes. In the favorable variant, energy efficiency investments by consumers and firms were financed through increased borrowing and use of savings. This way, a reduction in private consumption was avoided. Also, energy efficiency investments in this variant did not displace investments in production. On the contrary, they were assumed to induce broader modernization investments in production facilities. Energy tax revenues were completely recycled through lower payroll taxes.

34 Of the five short-term studies referenced above, all but the DRI report arrive at a zero to slightly positive gdp impacts. The comprehensiveness and detail of underlying bottom-up scenarios vary greatly in these studies.

35 Two other studies examined programs in which some of the carbon/energy tax revenue is used to provide energy efficiency investment subsidies for industry (Bossier et al. 1995 for six EU countries and Ministry of Finance 1995 for Denmark). Various practical issues associated with "ear-marking" are discussed in OECD (1996).

36 In the near-term studies such as WIFO (1996), this increase is mainly due to the short time horizons used (as little as 5-8 years). When cost-effective investments are modeled on a year-by-year basis, much of the savings that occur after amortization are not captured. In the work of the FRG Enquete Commission, which covered a longer time horizon (1987-2020), the national energy service bill in 2020 increased due to the use of bottom-up scenarios based on the lower of the two implementation fractions shown in Table 2. For this input assumption, a reduction target of 45 percent relative to 1987 (35 percent relative to 1993) exceeds the zero net cost point, which is only 23 percent for scenario R2 (see Table 2 above).

Table 1: Scope of European top-down and integrated top-down/bottom-up mitigation cost studies: range of policy options analyzed

	0	1	2	3	4a	4b	4c	4d	5	6	7a	7b
	Energy and/or carbon tax		**Price corrections**		**"NO REGRETS" OPTIONS Market transformation incl. utility regulatory reform**				**Accel.R&D/ Commercial.**	**Higher-cost/ backstop technologies**	**Integrated assessment tax shifts + "no regrets" partial**	**full**
	Lump-sum or revenue raising	Tax shift or mixed recycling	Subsidy removal /shifts	Incorporation of environm. externalities	Barriers to Market entry	Other barriers cogeneration & renewables	End-use barriers energy efficiency	fuel switching	Efficiency, low-carbon supplies	Efficiency, low-carbon supplies	Options 0-1 with any of 4 and 5	Options 0-1 with all of 2-6
Multi-country studies												
Non-US OECD	Yes	-	-	-	-	-	-	-	-	(Yes)	No	No
EU multi-member studies	Yes	Yes			(Yes)	(Yes)	(Yes)	-	-	-	(Yes)	No
National studies												
Austria	Yes	Yes	-	-	(Yes)	(Yes)	(Yes)	(Yes)	-	-	(Yes)	No
Belgium	Yes	Yes	-	-					-	-	No	No
Denmark	Yes	Yes			(Yes)	(Yes)	(Yes)	(Yes)			(Yes)	
Finland	Yes	-	-	-	-	-	-	-	-	-	No	No
France	Yes	Yes	-	-	-	-	(Yes)	-	-	-	(Yes)	No
FRG	Yes	Yes	(Yes)	-	Yes	Yes	Yes	(Yes)		-	Yes	No
Italy	Yes	Yes		-	-	-	-	-	-	-	No	No
Netherlands	Yes	Yes	-	-	-	-	-	-	-	-	No	No
Norway	Yes	Yes	-	(Yes)	-	-	-	-	-	-	No	No
Portugal	Yes	-	-	-	-	-	-	-	-	-	No	No
Spain	Yes	-	-	-	-	-	-	-	-	-	No	No
Sweden	Yes	Yes	-	-	-	-	-	-	-	-	No	No
Switzerland	Yes	Yes	-	-	-	-	-	-	-	-	No	No
UK	Yes	Yes	-	-	-	-	-	-	-	-	No	No

Notes:

Yes in parentheses indicates that the option was only partially considered (e.g., based on only one or a few programs, technologies, end-uses, or sectors).

Sample of studies based on Grubb, et. al. (1993); IPCC (1996), ch. 9; and individual studies referenced in this paper.

Table 2: Zero or negative net cost carbon reduction potentials in Western European bottom-up studies

STUDY	COUNTRY	INPUT ASSUMPTIONS				Zero cost reduction in carbon emissions			AEII	Avg. rate of C reduction	
		Time horizon	C-growth factor in BAU baseline	Implementation of DSE potentials	Phase-out of nuclear power?	2005/2010	2015/2020	2025/2030	final energy /gdp	below base year	below baseline
						% below base year			%/yr	%/yr	%/yr
EU-5 Coherence/CEC	F, G, I, NL, UK	2010	*1.09*	*<25%*	*No*	23			2.7%	1.3%	4.5%
Country-by-country			*1.00 - 1.24*			10-36					
EU-5 IPSEP	F, G, I, NL, UK	2020/30	*1.22*	*50%*	*Yes*		>26		4.2%	1.0%	4.2%
				100%	*Yes*		>58	>60	5.1%	2.9%	6.2%
FRG Enquete Commission	Germany	2020	*0.99*	*50%*	*Yes*	14	23		3.1%	1.0%	3.0%
				75%	*No*		>39		3.5%	1.8%	3.9%
Risø/UNEP	Denmark	2030	*1.16*	*<0.45*	*not applicable*	>21		>45	2.1%	1.5%	3.2%
Range						10-36	23- >58	>45- >60	2.1% -5.1%	1% - 2.9%	3% -6.2%
Median						**18**	**>41**	**>53**	**3.6%**	**2.0%**	**4.6%**

(1) BAU = Business-as-usual scenario. Table excludes studies using an optimized energy system as the reference case.
(2) DSE = Demand-side efficiency. Defined here as potentials beyond those already implemented in the business-as-usual scenario, based on IPSEP estimates.
(3) AEII = Average rate of energy intensity improvement, based on energy consumption per unit of gdp. Includes both energy efficiency gains and structural change.
(4) Enquete Commission study refers to Germany after reunification. 1993 base year eliminates post-1990 "wall-fall" contraction of baseline emissions.
(5) Implementation fractions for Coherence/CEC, Danish and FRG study accounts for efficiency potentials not incorporated into baseline or policy case.
(6) High implementation fraction for FRG study assumes some modal shifts and more vehicle efficiency improvements at zero net cost (R1V scenario).
(7) Coherence/CEC results shown for EU-5 only to facilitate comparison with IPSEP study. EU-5 represents about three quarters of total EU carbon emissions.

Table 3: Macroeconomic impacts of reducing German carbon emissions by 35 percent below the 1993 baseline

		1995		2005		2020		Average	
		(R 1)	(R 2)	(R 1)	(R 2)	(R 1)	(R 2)	(R 1)	(R 2)
GDP	favorable	1.3%	2.0%	0.7%	0.9%	0.3%	0.1%	0.5%	0.7%
	unfavorable	0.9%	1.3%	0.2%	0.4%	0.1%	0.1%	0.2%	0.3%
Private consumption	favorable	1.2%	1.9%	0.3%	0.5%	0.1%	0.1%	0.4%	0.5%
	unfavorable	-0.1%	-0.1%	-1.0%	-1.0%	-0.6%	-0.5%	-0.7%	-0.6%
Employment	favorable	0.5%	0.7%	0.1%	0.7%	-0.1%	0.0%	0.2%	0.3%
	unfavorable	0.3%	0.5%	0.1%	0.2%	0.1%	0.2%	0.2%	0.3%

R1= with nuclear power constant
R2= with nuclear power phased out by 2005

Source: Enquete Commission (1995), p. 871-876.

Figure 1: Modelling approach in integrated bottom-up/top-down studies