ECONOMIC COSTS OF CARBON DIOXIDE REDUCTION STRATEGIES

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ECONOMIC COSTS OF CARBON DIOXIDE

REDUCTION STRATEGIES
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FOREWORD

This paper was prepared by London Economics (UK). Editorial revisions were made by Joseph Gilling, Ian Johnson, and Paul Wolman.
ABBREVIATIONS AND ACRONYMS

C  Carbon
CFCs  Chlorofluorocarbons (refrigerant)
CO₂  Carbon Dioxide
degree C  degree Celsius
GEF  Global Environment Facility
GHGs  Greenhouse Gases (CO₂, NH₄, CFC₃)
IPCC  Intergovernmental Panel on Climate Change
MAC  Marginal Abatement Cost
MB  Marginal Benefit
MC  Marginal Cost
NH₄  Methane (primary component of natural gas)
p.a.  per annum
TERI  Tata Energy Research Institute (India)

UNITS OF MEASURE

bbl  barrels (of oil)
billion  1,000 million (10⁹) or Giga
GJ  Gigajoules
k  kilo (thousand)
kg  kilogram
kWh  kilowatt hour
l  liters
M  mega (million)
t  metric tonne
TWh  terawatt (10¹²) hour
Greenhouse gas (GHG) equivalent  1 tonne carbon equals 3.67 tonnes CO₂

DIRECT GLOBAL WARMING POTENTIAL FOR 100-YEAR TIME HORIZON

<table>
<thead>
<tr>
<th>Gas</th>
<th>Global warming potential</th>
<th>Sign of the indirect component of the GWP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon dioxide</td>
<td>1</td>
<td>none</td>
</tr>
<tr>
<td>Methane</td>
<td>11</td>
<td>positive</td>
</tr>
<tr>
<td>Nitrous oxide</td>
<td>270</td>
<td>uncertain</td>
</tr>
<tr>
<td>CFC-11</td>
<td>3,400</td>
<td>negative</td>
</tr>
<tr>
<td>CFC-12</td>
<td>7,100</td>
<td>negative</td>
</tr>
<tr>
<td>HCFC-22</td>
<td>1,600</td>
<td>negative</td>
</tr>
<tr>
<td>HFC-134a</td>
<td>1,200</td>
<td>none</td>
</tr>
</tbody>
</table>

Note: The warming effect of an emission of 1 kg of each gas is noted relative to that of CO₂. The figures are best estimates projected from present-day atmospheric composition.

I. INTRODUCTION AND SUMMARY

Over the last five years, the problem of global warming has become one of the world's chief environmental priorities. The impact of, and risks caused by, the "greenhouse effect" are still controversial. However, a consensus is emerging that the long lead times for response mean that waiting until potential damage is proved and fully quantified may be a luxury that humankind cannot afford. A Framework Convention for Climate Change was recently negotiated through the United Nations Conference on Environment and Development (UNCED). Although the specific targets for abating greenhouse gas (GHG) emissions have not yet been agreed, the objective of reducing emissions has been endorsed. Table 1.1 summarizes current reduction targets. In 1990 and 1992 the Intergovernmental Panel on Climate Change (IPCC) presented a comprehensive report that verged on a consensus on the need for immediate action. Australia, New Zealand, and Denmark are seriously considering unilateral action, possibly including a tax on carbon emissions, and the European Community has just announced its intention to levy a carbon tax.

**TABLE 1.1 National Targets to Control Carbon Dioxide Emissions**

<table>
<thead>
<tr>
<th>Country</th>
<th>Million tonnes carbon emissions</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Former USSR</td>
<td>1,000</td>
<td>None.</td>
</tr>
<tr>
<td>China</td>
<td>550</td>
<td>None.</td>
</tr>
<tr>
<td>Japan</td>
<td>250</td>
<td>Stabilize per capita emissions by 2000.</td>
</tr>
<tr>
<td>UK</td>
<td>170</td>
<td>Stabilize emissions by 2000 if others do the same.</td>
</tr>
<tr>
<td>India</td>
<td>150</td>
<td>None.</td>
</tr>
<tr>
<td>Canada</td>
<td>100</td>
<td>Stabilize by 2000 as a first step.</td>
</tr>
<tr>
<td>France</td>
<td>100</td>
<td>Stabilize emissions by 2000 or 2003.</td>
</tr>
<tr>
<td>Italy</td>
<td>100</td>
<td>Stabilize by 2000, 20% cut by 2005.</td>
</tr>
<tr>
<td>Australia</td>
<td>60</td>
<td>Stabilize by 2000 (except CFCs), 20% cut by 2005.</td>
</tr>
<tr>
<td>Austria</td>
<td>15</td>
<td>20% cut by 2000.</td>
</tr>
</tbody>
</table>

*Notes:* Carbon emissions are for the year 1988; "stabilization target" means holding emissions at 1989/90 levels; New Zealand is committed to a 20 percent cut by 2000, and the following countries are targeted to stabilize by 2000: Belgium, Switzerland, Sweden, Finland, Norway, and Ireland.

Greenhouse gases—particularly carbon dioxide (CO₂) and methane (CH₄)—are the major contributors to global warming. CO₂ is produced in great volume in a variety of energy-using processes and accounts for more than 50 percent of the greenhouse effect. Because CO₂ is the major component of GHGs, this paper focuses on CO₂ abatement and the methodological issues in developing related strategies. The objective of CO₂ abatement is to reduce the rate of global warming, and the absolute level of warming, to levels justified by the costs and benefits of control. The degree of control must allow for uncertainty about environmental damage and for potential discontinuities or thresholds in the warming damage function. Action to control CO₂ should be cost-effective, allowing for different methods of control and for the costs of control versus the costs of adaptation.

Methane accounts for 15 to 20 percent of the greenhouse effect. Prospects for controlling methane emissions are mixed. For emissions from landfills, natural gas, and coal mining, technical fixes are well within reach. For emissions from livestock and rice paddies, however, the prospects for effective control are poor.

Finally, the role of CFCs as a greenhouse gas are not fully understood at this time. They are, in any case, being phased out by the end of the century, if not several years before.

**Purpose of this Paper**

One of the purposes for which the Global Environment Facility (GEF) has been established is to finance the incremental economic costs to developing countries of reducing greenhouse gas (GHG) emissions. The principal objectives of this paper, therefore, are as follows:

- Examine the economic issues of global warming and GHG emissions, particularly CO₂
- Identify possible economic policy options for their reduction
- Analyze the interrelation of policies and technologies that may affect abatement costs
- Relate these to the constraints that affect developing countries.

The issues addressed are complex, as they include problems related to joint products and interactive systems effects. All sources of GHGs must be considered—in particular, power systems, transport, commercial, industrial, and agricultural sources. The potential role of forests as "sinks" of CO₂ must also be part of the calculation.

**Policy Responses**

A number of instruments for the control of CO₂ as the primary GHG have been suggested. These may be divided broadly into two categories: *regulatory mechanisms*, where authorities set
standards and dictate actions; and *market-based mechanisms*, where economic incentives are relied upon to create the desired responses. The regulatory category can be *broad*—for example, maximum permitted emissions with fines or other penalties for excess emissions—or *specific*, where particular processes or procedures are mandatory. Market-based mechanisms vary principally in whether they act on prices—as with charges, taxes, or subsidies—or on quantities, as with tradable permits.

The choice of instruments will be constrained by circumstances in each country and, in particular, by the state of administrative abilities and the development of institutions. The use of taxes requires a well-developed tax administration. Tradable permits require a well-functioning market, and direct regulation assumes some belief that corruption and failures of implementation will not invalidate the approach. The potential for environmental taxes and other policy responses can, and should, form part of policy discussion with all countries.

The choice of regulatory or market-based policy instruments should be founded on economic principles to ensure that net benefits of CO\textsubscript{2} abatement are maximized or at least that total costs are minimized to meet a given CO\textsubscript{2} reduction target.

**Outline of Paper**

The paper considers the relevant economics of pollution control as applied to CO\textsubscript{2} abatement in section 2. The complexity of the policy framework is explored, and the strong interrelation between global CO\textsubscript{2} reduction and the "no regrets" policies (i.e., those that are in a country's best interests acting by itself) are highlighted. Policy choices and options may be altered if, as is often the case, "no regrets" policies have yet to be implemented.

Section 3 discusses the policy framework, including technological options, systems effects, and administrative and market instruments that could be used to control GHG emissions (Annex 1 provides further details on tradable permits as a potential market instrument).

Section 4 presents available empirical evidence on the costs of CO\textsubscript{2} abatement, including preliminary results from the empirical work described in this report. The illustrative examples developed in the report could usefully be extended and refined through a series of country case studies. Such studies would need to include both an analysis of technical options and appraisal of the strengths and weaknesses of different policy measures.

In Section 5, major subsectors such as electric power and transport are examined as well as the role of alternative fuels and renewable energies. Finally, the role of CO\textsubscript{2} sinks is considered as part of an overall strategy for CO\textsubscript{2} abatement.
Section 6 outlines an approach for developing a least-cost national strategy for CO₂ abatement, and guidance is provided that encompasses the following subjects:

- The technical options for reducing greenhouse gases (CO₂ in particular)
- The instruments by which these options can be implemented
- The feasibility of this implementation in each country context
- Criteria by which choices between feasible sets of instruments and options can be made.
2. THE ECONOMICS OF CO₂ EMISSIONS ABATEMENT

Although greenhouse gases include gases other than CO₂, the primary international concern is the reduction of CO₂ emissions, since CO₂ likely represents more than 60 percent of the total global warming potential over the next hundred years. This section discusses the economics of GHG emission abatement in terms of CO₂ abatement, although the concepts are equally applicable to the abatement of other GHGs.

Before addressing policy options and instruments to control global warming, it is sensible to look at the problem with some care. A useful summary is provided by Whalley (1991: 143-44):

Carbon dioxide concentrations are predicted to double from their current levels of about 350 parts per million (ppm) to 700 ppm by the years 2030 to 2075. This doubling probably will increase global mean temperatures by between 1.5 and 4.0 degrees Celsius; it will raise sea levels by 20 centimeters to 1 meter; it will increase the incidence of flooding, typhoons, hurricanes, and other extreme climatic events; and it will have microclimatic effects (such as local desertification or increased rainfall) that are hard to pinpoint accurately today.

There is evident uncertainty about the rate of growth of emissions, about their general effects, and about their local effects. Policy options, therefore, need to take account of this uncertainty.

The second feature to note is that CO₂ is a stock, rather than a flow pollutant. The importance of this point is that it is not essential for the policy to control the rate of emissions, year by year, as is the case, for example, with sulfur dioxide (SO₂). It is the cumulative volume of emissions that is important. This means that the control policy could allow polluters a choice as to the time path of emissions, based on the relative costs of controlling emissions in the near future, compared with the costs of controlling in the distant future, without jeopardizing the policy objective. This is not possible in the case of sulfur-related acid rain, however; the damage to forests would increase if emissions exceeded certain limits in any year.

Third, measures to abate CO₂ are often linked with the abatement of other pollutants such as SO₂ and particulates. The economics of GHG abatement will thus have to carefully take into account the benefits of "joint products."

Economic Principles of GHG Abatement

A first-principles comparison of alternative policy instruments requires a sketch of some basic ideas in environmental economics. These center around the concept of economic efficiency: whether resources are allocated within the economy in a way that delivers the most benefit. In
the context of global warming, an economically efficient policy would set an emission reduction target that maximizes the environmental benefits achieved by reducing global warming and the associated cost. The optimum condition would be attained when the marginal environmental benefits of reduced warming were equal to the marginal costs of reducing the emissions responsible for it. It is apparent that the cost of abatement can be determined more readily than the absolute value of benefits both at the national and global level. Conceptually, as with other economic systems, diminishing returns in benefits will occur with successive increments of CO$_2$ reduction, and costs will begin to rise rapidly as reduction targets are increased. These concepts are illustrated in Figure 2.1(a), wherein the total environmental benefits and the total control costs are seen to increase as emission control increases, and the warming effect is reduced. Figure 2.1(b) shows the marginal benefit and cost associated with these relationships. There is a level

**FIGURE 2.1 Total and Marginal Benefits and Costs of Emissions Reductions**
of CO\textsubscript{2} emission at which the marginal cost and marginal benefits just match. At emission rates higher than this, the benefits of tighter control would not justify the additional control costs. Beyond this level, the marginal costs outweigh the additional benefits.

The options that may be available both to implement CO\textsubscript{2} reduction strategies and to ensure that necessary adjustments are made are explored from a theoretical standpoint below. At the heart of the analysis is the concept of marginal abatement costs (MAC) and corresponding marginal benefits (MB). Economic theory indicates that an efficient solution will be found where MB equals MAC.

Figure 2.2 provides a diagnostic exposition of the situation facing a single country. The upward-sloping MAC curve shows, in a stylized way, the marginal cost of each new method of avoiding CO\textsubscript{2} emissions. Some of them—where MAC is below the x axis—have direct benefits that outweigh their costs. Examples might be the introduction of more efficient appliances or vehicles or the use of surplus energy in efficient industrial combined-heat-and-power schemes. But once these initial projects have been exhausted, projects have a positive cost and exhibit pronounced diminishing returns. Section 4 reviews the shape of the MAC curve, which will vary from country to country in response to local resource constraints and conditions.

As noted, the MB curves are more difficult to construct; however, conceptually, it is apparent that for an individual country, \(i\), the MB\(_i\) curve will slope downward to the right and that the global marginal benefit MB\(_g\) curve will be the aggregate of all the different MB\(_i\) curves. Even if the MB\(_g\) is fully defined, by implication there will be a variation in the optimum level of reductions between countries. The methodology developed in Section 6 therefore addresses the determination of the appropriate level of reduction for a particular country given that reductions in CO\textsubscript{2} emissions may have differing national and global marginal benefits.

As presented in Figure 2.2, the two downward-sloping curves show, first, the marginal benefits of reduced CO\textsubscript{2} to the country concerned, and second, the marginal benefits of CO\textsubscript{2} reduction to the world. The MB\(_i\) curve reflects two forms of domestic benefit: (a) reduced damage from global warming impact on the country in question and (b) joint benefits such as control of acid rain. Point A, where MB\(_i\) equals MAC, is the optimal control level for the country, whereas point B, where MB\(_g\) equals MAC, is the optimal world position. One of GEF's roles is to encourage movement from A to B through the financing of projects falling within this interval.

Policies that yield net positive benefits for the individual country are often dubbed "no regrets," although there is sometimes confusion about this term. Throughout this document "no regrets" policies are those where MB\(_i\) > MAC, although some commentators use the term to refer only to those cases where MAC < 0.
Within a country and globally, the cost of reducing any particular volume of emissions is minimized only by allocating the abatement responsibility across polluters in such a way that the marginal costs of abatement of each polluter are equalized. Figure 2.3 explains why. The marginal abatement costs of two polluting industries, A and B, are shown; the curves rise as each industry abates more, because the industries exploit the easiest options first. Industry A finds it more expensive than B to reduce emissions, perhaps because it operates on a smaller scale or because its production processes are more difficult to modify.

Consider the position at which the marginal abatement cost for both is the same ($200/tonne); Industry A abates by 200 tonnes a year, B by 800 tonnes a year. To understand why this allocation of control responsibility minimizes the combined costs of achieving a 1,000 tonne abatement, let us allocate the responsibility differently: 300 tonnes to A and 700 tonnes to B. The additional control costs incurred by A—the shaded area F—exceeds the savings in B's control costs—the shaded area G. Equalizing marginal abatement costs across polluters minimizes the total cost of achieving the policy objective.
Economic efficiency in pollution control involves two things: setting the control target appropriately, so that at the margin the additional benefits, however determined, are worth the additional costs of controlling emissions; and minimizing the costs of controlling emissions. If control targets are set as a matter of policy, there is nothing that market mechanisms can do to correct mistakes. It is then on their contribution to reducing costs that they should be judged.

Market mechanisms can help improve the economic efficiency of the overall solution. Suppose Industry A was obliged to reduce its emissions by 300 tonnes and Industry B by 700 tonnes. If a pollution tax was set at $200/tonne and neither were restrained by regulation, source A would prefer to pay a tax on 100 tonnes and abate 100 tonnes less. The savings in emission abatement costs on those 100 tonnes would be greater than the tax on those emissions. Conversely, source B would prefer to abate more, as the additional costs would be less than the tax it would avoid.

Similarly, if both sources were issued with tradable permits for their baseline emissions reduction requirements (300 tonnes by A, 700 tonnes by B), A and B would trade; source A would buy permits of 100 tonnes from B, and abate less. Either instrument—tax or tradable permit—could bring about the equalization of marginal control costs, thus minimizing total costs.

An efficient outcome requires that knowledge of the control costs of each polluter is known and acted upon. Have the regulators the means or the incentive to discover the costs and act upon them? The verdict of the literature, and experience of regulation, suggest that they have
not. Whereas each polluter has strong incentives to discover the costs of control, to minimize costs, the regulators have less incentive to minimize industry's cost of meeting an environmental target. Although numerous studies in the United States over the last 15 years testify that the control policies designed by regulators are indeed far from being least-cost solutions, environmental policy has responded slowly to these findings.

Prices or Quantities?

Is it better, in general, to control prices or quantities, in the context of global warming? The politics of the choice are predictable. Polluters have a natural preference for permits, if (as in the United States) they are distributed free, on the basis of historic emission levels. Their tradability enhances their value. Environmental lobbyists, on the other hand, are attracted to the principle that the polluter should pay a tax, in payment for the use of, and damage to, a common environmental asset, and they feel uneasy about conferring explicit rights to damage the environment that in addition confer financial advantage.

There is, of course, no practical difference, in terms of the environmental damage allowed, between regulations that permit pollution and the granting of permits to pollute. Nonetheless, the distinction between the two strategies must be taken into account, because a concern to play down the property-rights aspect of permits does appear to have restricted the development of permit markets in the United States.

The technical comparison of charges and permits turns on a rather different consideration. The regulator's concern has to do with the uncertainty about the responses of polluters to market signals and the cost of being wrong about this. The economist would advise that the regulator should weigh the risk of polluting too much (i.e., missing the emission-reduction target) against the risk of posing excessive-burdens on industry. Recalling the analysis in Figure 2.1, assume that the regulator has a clear idea about the position and shape of the marginal benefit curve but is uncertain about the position of the marginal cost curve.

An early contribution to this discussion was made by Weitzman (1974), who observed that from a strictly theoretical point of view, there is really nothing to recommend the control of quantities over the control of prices and vice versa: "generally speaking it is neither easier nor harder to name the right prices than to name the right quantities because in principle exactly the same information is needed to correctly specify either" (p. 478, italics in original). Weitzman concluded that the answer turns on the relative sensitivity of costs and benefits to the variable one is seeking to control and on the relative uncertainties surrounding them.

Two very different situations are compared in Figures 2.4(a) and 2.4(c). In the former, the pollutant has very damaging effects above certain threshold levels, so the marginal benefit curve is steep. The marginal cost curve, on the other hand, is relatively shallow. The regulator is advised that the marginal cost relationship could lie between Marginal Cost 1 (MC1) and
Marginal Cost 2 (MC2). In Figure 2.4(c) the situation is reversed; it does not matter so much in this case at what level emissions are controlled, so the marginal benefit relationship is relatively flat; however, the marginal costs of controlling pollution, uncertain as they still are, are known to rise quite sharply as more emissions are reduced.

In the first case, Figure 2.4(a), if the regulator elects to use a charge and sets it on the basis that the true marginal cost relationship (or whatever relationship it is that actually determines polluters' responses to the charge) lies midway between the two extremes, the area of uncertainty lies between emission reductions ER1 and ER2. In this case, it matters more to be nearly right about the emissions reduction, because the pollutant will be damaging above certain thresholds. The regulator cannot risk the uncertainty about the emissions reduction required: better, therefore, to regulate the quantity, by means of permits. An extreme example of the steep marginal benefit curve is shown in Figure 2.4(b), where it is vertical.

In the second case, Figure 2.4(c), the costs of being wrong about the quantity of emission reduction are much less; CO2 might be an example of this, since it is a pollutant whose stock has been accumulating since 1750, and the scientific understanding of the damage relationships is still vague. The costs of being wrong in this illustration have more to do with imposing excessive costs on industry and the economy. If the emission reduction is set at ER* by means of permits, and it turns out that emission control relationship is the more costly MC1, there would be substantial wasted expenditure by industry. The marginal costs of reducing emissions by the amount set by the regulator (ER*) would significantly exceed the marginal costs at the economically efficient reduction. Charges would be a better instrument in these circumstances; the range of error (in terms of marginal costs) would only be \( C_1 - C_2 \).

The first case might be said to characterize acid rain, the second, global warming. Since CO2 is a stock pollutant rather than a flow pollutant, there is greater toleration of getting the emissions target wrong than in the case of a flow pollutant such as acid rain. Note also that the marginal costs of abatement are likely to rise less sharply for SO2 than for CO2, since sulfur can be extracted from fuels relatively easily, whereas carbon cannot. These considerations suggest that permits are the more appropriate instrument for acid rain and that charges are more appropriate for CO2. The general consensus in favor of carbon taxes has, however, some theoretical support.
FIGURE 2.4 Uncertainty Effects Concerning Marginal Costs and Benefits of Emission Reductions
Financial Burdens on Polluters

A conventional observation is that market mechanisms impose additional burdens on polluters, inasmuch as the charges or permits are additional to the costs of pollution control, which are determined by the emission reduction objectives of the authorities. Furthermore, even if market mechanisms succeed in reducing the control costs, these savings are unlikely to offset the additional financial costs of the market mechanism. But how true are these claims?

Consider the polluter in Figure 2.5 who is required to reduce emissions by 50 percent. An emissions charge is imposed on all emissions at a level that would persuade this particular polluter to make the required reduction (because it is worth reducing emissions so long as doing so has a marginal cost less than the tax the polluter would save). In this case, the costs of the charge (on the emissions that remain) are double the costs of controlling the emissions (the shaded area under the marginal cost curve).

In this case, because of the way the marginal cost curve is drawn (as a straight line for simplicity), the polluter would avoid a quarter of the cost of the charge on the initial emissions by reducing emissions by 50 percent. The charges that are avoided are double the costs of controlling the emissions. The story is similar for permits. If the market price of permits is equal to the charge (as they would be if the permit market were well informed and not distorted), and the polluter were required to purchase permits, the polluter would reduce emissions by 50 percent and purchase permits for the remaining emissions.

Alternatively, the regulator might levy the charge only on those emissions in excess of the emissions target (i.e., 50 percent of the baseline), or issue permits free, in respect to the 50 percent of emissions that would remain once the polluter had complied with the target reduction. In either case, the compliant polluter avoids any costs other than those for controlling emissions.

If the polluter were issued with permits, again at no cost, in respect to the initial emissions, he would stand to profit by reducing emissions: the permits for the reduced emissions could be sold at double the cost of reducing the emissions. The question of whether or not market mechanisms add to industries' costs depends, then, on the baseline that is chosen for levying the charge, or selling permits. If permits are issued free, in respect to baseline emissions, they offer opportunities to polluters to make profits from being virtuous. Note that if more permits were to be sold throughout the market, the price would decrease.
Assessment of Policy Options

The economic policy options, broadly stated, involve either regulation or market mechanisms, as detailed below:

1. Regulation. Authorities would seek to limit emissions by direction, for example, in the following settings and cases:
   - The generating plants of power companies
   - Maximum number, usage, engine capacity, and speed limits of motor vehicles
   - Performance standards of energy-consuming equipment.

2. Market mechanisms. These fall into two categories:
   - Those acting on each tonne of emissions via prices, taxes, or charges-cum-subsidies
   - Those acting on the quantity of emissions, such as tradable emissions permits.
Charges could be levied in a variety of ways: on total emissions or on emissions in excess of some baseline. Because permits are assets, they could in principle be transacted, like any asset, in a variety of ways: traded, banked, offset against other emissions by the same company, leased, or even traded in futures markets. They could be acquired by potential users or by suppliers of the fossil fuels that give rise to CO₂. Because permits are assets, it is a matter of great interest to polluters whether they would be issued free, and if so on what basis, or whether they would need to be purchased.

In the context of the electric power sector—typically the largest source of CO₂ emissions—the choices of instrument center less on the question of regulation versus market mechanisms and shift to questions of how investment appraisal should be conducted. The economics that underlie the regulation/markets debate are no less relevant in that context.

Corresponding to the quantities or prices choice of instrument, two approaches could be taken to global warming:

1. Limit quantities of emissions to levels that the world’s ecology is thought capable of absorbing, and allow the cost of this policy to be determined by the market.

2. Decide on how much it is worth spending, or incurring for a marginal reduction (i.e., on the price of emission reduction), and see how much emission reduction materializes, while trying to organize markets and institutions to yield efficient cost reductions given the price.

The criteria by which these policy instruments might be assessed include ecological effectiveness, in the sense of being able to deliver the objective with reasonable predictability; economic efficiency, in the sense of minimizing the resource costs of the policy; economic predictability, in the sense of providing producers with stable guidelines for investment decisions; and administrative and political feasibility.

The Options

The general characteristics of policy options are discussed below and reviewed as to their applicability in developing countries.

Direct Regulation. The regulator’s problem is to acquire and make best use of relevant information. It is possible to imagine a world in which the regulator is omniscient, but why would taxpayers finance the research necessary for such a state of affairs? What is the penalty, to a public agency, associated with being less than 100 percent correct, especially when it is so difficult to establish the "correct" solution?
It should not be assumed, however, that market mechanisms are problem free. The imposition of charges has distinct informational requirements. Permit markets could be subject to market failures, in the sense that the players may fail to respond to market signals either because of lack of information or because they find it more profitable to act noncompetitively, or strategically (i.e., with an eye to gaining advantages over competitors). Furthermore, it must be decided as to how permits are to be issued and at what price.

Nonetheless, regulation is inefficient in two senses:

1. Since the regulator is unlikely to possess full information on abatement and operating costs, he is unlikely to be able to dictate which of the existing control technologies are able to minimize the cost of achieving a given emission reduction target, thereby leading to a static inefficiency.

2. For similar reasons, the regulator will be unable to predict the rate at which technological progress in emission abatement is possible; technical developments can neither be predicted nor commanded. The incentives to innovate are fewer under regulation than under market mechanisms, and it is difficult for the regulator to judge how the polluters could improve on what they are achieving under regulation. A dynamic inefficiency would then occur.

The advantages to the polluter from switching to a cheaper abatement technology are greater under a market regime than under regulation. Under regulation, the cheaper technology reduces the cost of controlling the emissions required by the regulator. But if a permit market existed, the polluter would abate more emissions than required by the regulator and then sell permits for the excess reductions. The polluter’s incentive to switch to the cheaper technology would be greater.

There is also a tactical dimension in the constant tension between regulator and regulated. The regulated will be aware that if they develop a cheaper abatement technology, the regulator will insist that it be applied. The main consequence of improvements in technology is to drive up the emission reduction target.

A more compelling reason for seeking a solution based on direct regulation is that in most countries national power systems (the main source of emissions) are monopolies whose responsiveness to price signals must be doubted. Competitive producers have to be responsive to prices for fear that they will be displaced by those who are. The fact that power companies are not in this position argues for regulation or supervision to ensure that they reduce CO\textsubscript{2} emissions.

The disadvantage of economic instruments is that monopolists can simply pass on their costs without modifying their behavior. If final consumers are limited in their ability to substitute
other, nonpolluting products, few reductions can be expected. In such circumstances, it may be better to regulate.

The phenomenon that is usually cited as an instance of market failure in the energy area is the fact that energy users require much higher rates of return (greater than 30 percent in real terms) to induce them to invest in energy conservation than is required of energy supply projects (about 10 to 15 percent in real terms). Hausman's (1979) study revealed that in the purchase of air conditioners, U.S. consumers revealed discount rates of 15 to 25 percent. Discount rates were a function of income: poorer consumers in the United States applied an implicit discount rate as high as 89 percent on purchases of energy-efficient goods, whereas wealthier consumers applied discount rates of only 5 percent. This suggests that consumers in developing countries may set demanding tests on investment in energy-saving investments.

One response to these findings is that consumers and firms are making "incorrect" decisions on energy-saving and need either to be subsidized or regulated. An alternative answer is that discount rates on energy saving are not too high but that discount rates on energy-producing projects are too low. Because electricity supply is usually a state-owned monopoly, with access to capital that is either supplied directly or underwritten by governments, energy projects are charged interest rates, or are evaluated at discount rates, that may be significantly below the social discount rate.

Ways of bringing energy saving and energy production into a better balance include:

- Cost-reflective electricity prices to consumers to encourage them economize on energy
- Removal of subsidies that state energy suppliers derive from access to cheap finance by setting interest rates of interest the same as those paid by other industries in the economy
- Adoption of a "least end use cost" philosophy by power utilities, whereby they act as energy service companies, seeking to minimize clients' costs rather than to maximize electricity sales.

Market Mechanisms. What lessons could the developing countries draw from the developed countries about the use of market mechanisms to control air pollution? In general, the application of market mechanisms is in its infancy. The United States has been experimenting with emissions trading for nearly a decade and is about to extend trading in \( \text{SO}_2 \) permits considerably.

As for the type of mechanism that has been preferred, the United States has chosen to rely on permits, whereas Europe has preferred charges. However, European experience to date has little guidance to offer on the relative effectiveness of the two modes of control, since the imposition of charges in Europe had been half-hearted—designed, it seems, more to raise revenues for investment in pollution control equipment than to meet stringent pollution standards.
Developing countries face conflicting pressures: globally, in terms of their role in the environment to reduce emissions and to slow or reverse deforestation and, domestically, to increase economic growth through industrialization. These objectives may appear to be conflicting; however, there is no rigid trade-off between environment and development. Eastern Europe furnishes cautionary examples of the way in which misconceived economic policies have delivered high rates of industrialization, at high environmental costs, but with mediocre economic performance. Eastern European countries in general consume more energy and produce more SO\textsubscript{2} and CO\textsubscript{2}, per tonne of steel, or dollar of GDP, than most other industrialized countries.

There is no iron law of economics that says that countries must pass through an energy-intensive phase of development, popular though that view is. Hong Kong and Singapore have not done so. The adoption of energy-intensive economic structures may, to some degree, be the result of a policy choice that may be misguided even within its own terms. Industrialization via import substitution, regardless of comparative advantage, encouraged by underpricing of energy and other resources, can be as inhibiting to growth as it is damaging to the environment.

Successful development is associated with policies that allow prices to reflect the cost of resources, be they foreign exchange, energy, or capital. The *World Development Report 1991* (World Bank 1991) indicated that investment projects supported by the World Bank earned higher returns in the countries that were least subject to economic distortions.

Carbon Taxes. These observations suggest that carbon taxes could be as effective in developing countries as in industrialized countries. A policy of using the price mechanism to control developing countries' pollution would be consistent with general macropolicy advice. The problem here, as with liberalization generally, is one of phasing: it may be difficult, or inefficient, to use market mechanisms to control pollution when other markets in the economy concerned are not functioning. For example, if a producer is not allowed to import control equipment, the only way to respond to a carbon tax would be to reduce output. This may impose an excessive political and economic cost, and the control policy could be the casualty.

The effectiveness of carbon taxes in sending appropriate signals to producers and consumers would be weakened by high inflation rates; these tend to swamp the messages transmitted by changes in relative prices.

The advantages of taxes underline the point that before such taxes are imposed, it is essential to establish a cost-reflective price structure for energy. Carbon taxes would be a step in the right direction, but they might not even manage to correct existing distortions.

India provides an example of a fuel price structure that is not only distorted but is distorted in a perverse way from the standpoint of CO\textsubscript{2} emissions, as shown in Table 2.1, where the economic cost of each fuel is expressed as an index of 100.
**TABLE 2.1** Example of Fuel Price Structure and Distortions

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Economic cost index</th>
<th>Actual price index</th>
<th>Economic cost plus 100% carbon tax</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>100</td>
<td>75</td>
<td>200</td>
</tr>
<tr>
<td>Oil</td>
<td>100</td>
<td>168</td>
<td>177</td>
</tr>
<tr>
<td>Gas</td>
<td>100</td>
<td>181</td>
<td>156</td>
</tr>
</tbody>
</table>

*Source: London Economics estimates.*

The differences in 1990 between actual prices and economic costs were significant: coal was 25 percent underpriced; gas was 80 percent overpriced. A carbon tax would suggest a very different price structure, inversely related to the 1990 structure.

A carbon tax on fossil fuels might, however, have unintended effects that would weaken the policy. Carbon taxes might induce greater recourse to untaxed fuels such as wood, charcoal, and crop residues. If the use of wood in place of kerosene reduced forested areas, it would reduce CO$_2$ sinks and lead to soil erosion. However, there is some evidence on fuel substitution that suggests that this is not a major problem. A study by Ruitenbeek (1990) of domestic fuel use in India indicated that households did not respond to changes in the relative price of fuelwood and kerosene by large substitutions of one for the other.

** Tradable Permits.** Tradable permits have the potential to be the most effective of the market instruments in promoting reduction of CO$_2$ emissions. In principle, permits are economically efficient, given a predetermined target level, if markets are perfect. In practice, however, they are bedeviled by problems of ambiguously defined property rights, high search and transaction costs, high administrative costs, and problems of enforcement. Furthermore, a permit authority would need to be established to create and monitor the emissions against permits.

The prices of permits for a flow pollutant such as SO$_2$ would be unstable and difficult to predict, but less so for a stock pollutant such as CO$_2$ because there is scope for substitution between years.

Tradable permits also have the attraction of enabling policymakers to avoid the political odium of taxes while sending the right market signals to polluters. If permits are issued on the basis of past emission levels ("grandfathering"), they cost existing industries nothing; their value in the aftermath would encourage polluters to control CO$_2$. However, they reduce potential competition by raising costs of entry relative to existing participants in the industry.
Permits could be traded internationally. Such a system requires that control policy should be defined in terms of emission targets for each country that would then need to be allocated (or auctioned) to CO₂ sources within each country. Countries that overachieved their targets could sell "spare" permits to others—that is, to those that had failed to achieve their targets. The efficiency gains from trade derive from the fact that countries for which the cost of controlling CO₂ emissions are relatively high might prefer to buy permits from those for which the cost of capital is relatively low.

Permits may be less feasible in some countries because they require a comprehensive administrative framework to provide an institutional setting for an efficient market and to monitor trading.

Anderson (1990) contrasts two applications of permits in both a developing and developed country—the first a success, the second a disaster. In 1976, Singapore successfully introduced permits for driving into the central business district, thus increasing government revenue and reducing traffic congestion. By contrast, many governments undercharge for logging licenses, discouraging loggers from putting a market value on the trees they chop down and from replacing the trees. For example, the United States subsidizes logging most heavily on land that is too arid and cold to reforest and in the Tongass rain forest in Alaska (Cairncross 1991).

Empirical studies suggest that relatively high rates of tax on fossil fuel use—between 50 and 150 percent—would be needed to reduce emissions by 20 percent below the business-as-usual scenario. (Rather lower levels might suffice if the introduction of such taxes signaled higher future tax rates.)

If carbon taxes are adopted, they should be applied to fuel inputs, however, not to products derived from them. Whereas taxes on fuels can closely reflect the carbon emitted by their combustion, the carbon emitted in the course of the production of items can vary considerably, not least because some producers are more efficient than others. The case for a general energy tax is therefore weak. Since the source of GHGs is carbon-based fuels, they should be taxed directly.

Carbon taxes would be relatively easy to collect, even in countries with weak administrative systems, because they can be collected from a manageable number of fossil-fuel suppliers and importers. The downside, as noted above, is that taxes are an additional burden on polluters; they could cost industry as much, if not more, than the cost of reducing pollution unless they are levied only on each polluter’s emissions in excess of some baseline level. On the positive side, however, carbon taxes could make a major contributions to revenue in countries where it is otherwise difficult to raise public revenues.

A politically attractive option is the charge-cum-subsidy approach, whereby the revenues from the charges are recycled to the charge-paying group to assist them with the investments in emission control that are required to meet the emission reduction target.
arrangement, the charge need not be as high as the tax because the spread of relative prices—between emissions and abatement—is increased by the subsidy. However, this is less efficient than a tax. The prices of carbon-intensive product prices rise less; consumers economize less on these products, and more investment on abatement is required to meet the target than is necessary or economically optimal.

Straight subsidies share this weakness, in that prices do not reflect environmental costs: consumers' ability to save energy, and to substitute between more and less energy-intensive products, is therefore not tapped. In short, although subsidies are invariably politically acceptable, whether on their own or as part of a charges-cum-subsidy scheme, they raise the economic costs of meeting the environmental target.

Conclusions Concerning Policy Options

The following general conclusions can be drawn from the foregoing discussion:

- The nature of the CO₂ as a pollutant, the uncertainty about its effects, and the steepness of the marginal cost of reducing it (because emissions are related to energy produced) all tend to favor a tax as the market-based instrument for controlling CO₂ emissions.

- Taxes are preferable to charges-cum-subsidies because taxes result in appropriate signals to the final goods markets, whereas the latter do not.

- On the question whether a tax would be appropriate to developing countries, a tax poses fewer administrative burdens than, for example, tradable permits.

- There are strong reasons, on general development grounds, for using market-based instruments.

- However, it must be doubtful whether electric power monopolies would respond to taxes alone; the latter may need to be reinforced by regulatory or command policies designed to restructure power systems in ways that reduce CO₂ emissions.

- Establishing energy prices that are related to long run marginal costs would be an effective step in reducing emissions in countries in which energy prices are below economic costs.
3. POLICY FRAMEWORK

This section discusses some of the practical considerations that must be addressed before an appropriate GHG reduction strategy can be identified are discussed.

**International Levels of CO₂ Emissions**

Emissions of CO₂ per head of population vary widely by region. European CO₂ production is currently about 2.2 tonnes per head per year, compared with more than 5 tonnes in the United States, 3.6 tonnes in the former Soviet Union (FSU) and Eastern Europe, and below 0.5 tonnes in the developing countries. About 23 percent of global CO₂ emissions are estimated to originate in the United States, 25 percent in Eastern Europe and the FSU, 13 percent in the European Community, and 5 percent in Japan. Recent estimates for the European Community indicate that 31 percent of CO₂ emissions are attributable to power generation, 25 percent to transport, 20 percent to industry, and 20 percent to residential and commercial energy use. Agriculture is responsible for substantial methane emissions. The development of nuclear power and steep oil price rises slowed the growth of emissions in the industrialized nations until 1985, but they are again increasing. CO₂ emissions have been rising at 5 percent per year since 1980 in developing countries. Table 3.1 summarizes recent estimates of CO₂ emissions.

The damage caused by GHGs is global, in contrast, say, to toxic waste, acid rain, or water pollution, where much of the environmental damage occurs in the polluting country or its immediate neighbors. Individual countries—particularly developing countries facing severe economic problems—may find it hard to achieve internal political consensus concerning the costs required to reduce GHGs because many of the benefits of controlling GHGs will accrue to other countries. A second problem is that many energy-intensive industries are internationally competitive; unilateral, or unbalanced, action by one country could damage the trading position of key industries. International consensus and cooperation are therefore essential. Any strategy for CO₂ control is likely to focus on stabilization as an initial goal (i.e., returning emissions in, say, 2000, to current levels). Consequently, reductions relative to the base year will have to be made if there is to be any significant impact on the rate and level of global warming.

One factor that may help in achieving an international consensus on CO₂ stabilization or reduction among countries with disparate regional and local priorities is that a joint benefit of efforts to reduce CO₂ emissions through lesser use of coal and heavy fuel oil will be reductions in primarily local or regional pollutants such as acid rain. The estimation of such joint benefits is complex; as more studies become available, however, estimates are emerging of "benefit per tonne CO₂ reduced," although in the developing countries, only impressionistic estimates of acid rain reductions can be made as yet. Nonetheless, it remains clear that in the electric power
sector, $\text{SO}_2$, $\text{NO}_x$, and $\text{CO}_2$ are all products of the same energy use and that policies aimed at controlling one will inevitably affect the others. Similarly, policies on $\text{CO}_2$ reduction in the transport sector may have significant benefits in the form of reduced local congestion, noise, and lead emissions.

**TABLE 3.1 Rankings of National and Regional $\text{CO}_2$ Emissions, Total and Per Capita**

<table>
<thead>
<tr>
<th>Country</th>
<th>Million Tonnes Carbon, 1988 (Total)</th>
<th>Country</th>
<th>Tonnes Carbon, 1988 (Per Capita)</th>
</tr>
</thead>
<tbody>
<tr>
<td>United States</td>
<td>1,310</td>
<td>Luxembourg</td>
<td>6.42</td>
</tr>
<tr>
<td>USSR</td>
<td>1,086</td>
<td>United States</td>
<td>5.34</td>
</tr>
<tr>
<td>China</td>
<td>610</td>
<td>East Germany</td>
<td>5.36</td>
</tr>
<tr>
<td>Japan</td>
<td>270</td>
<td>Canada</td>
<td>4.58</td>
</tr>
<tr>
<td>West Germany</td>
<td>183</td>
<td>Czechoslovakia</td>
<td>4.09</td>
</tr>
<tr>
<td>India</td>
<td>164</td>
<td>Australia</td>
<td>4.02</td>
</tr>
<tr>
<td>UK</td>
<td>153</td>
<td>USSR</td>
<td>3.83</td>
</tr>
<tr>
<td>Poland</td>
<td>125</td>
<td>Bulgaria</td>
<td>3.77</td>
</tr>
<tr>
<td>Canada</td>
<td>119</td>
<td>Poland</td>
<td>3.30</td>
</tr>
<tr>
<td>Italy</td>
<td>98</td>
<td>Denmark</td>
<td>3.03</td>
</tr>
<tr>
<td>East Germany</td>
<td>89</td>
<td>West Germany</td>
<td>3.01</td>
</tr>
<tr>
<td>France</td>
<td>87</td>
<td>Finland</td>
<td>2.79</td>
</tr>
<tr>
<td>Mexico</td>
<td>84</td>
<td>UK</td>
<td>2.66</td>
</tr>
<tr>
<td>South Africa</td>
<td>78</td>
<td>Romania</td>
<td>2.61</td>
</tr>
<tr>
<td>Australia</td>
<td>66</td>
<td>Netherlands</td>
<td>2.23</td>
</tr>
</tbody>
</table>

*Source: Oak Ridge National Laboratory, U.S. Department of Energy.*
Classification of GHG Abatement Options

Options for reducing GHGs that form the basis of abatement strategies can be classified as shown below.

**Energy Technology.** Measures fall into two categories: demand side and supply side measures. Under demand side measures (efficiency improvements), the following areas appear crucial to reducing GHGs:

- Industrial sector
- Transportation
- Residential and commercial
- Market response to demand for new products (e.g., CFC substitutes).

Supply side options include the following:

- Promotion of interfuel substitution
- Clean coal technology and repowering
- Cogeneration
- Gas-fired combustion
- Aeroderivative combustion turbines
- Noncarbon energy sources
- Renewable energy
- Reduction of losses during generation, distribution, and transmission
- Increased efficiency of motors and appliances.

**Forest Management.** Management of forests and biomass-related resources represents another basis for abatement strategies. Strategies here can focus on the following areas:

- Natural forest management techniques
- Sustaining natural forests
- Reduction of logging in forests and cattle ranching
- Efficient use of fuelwood
- Reforestation (e.g., offsetting CO₂ emissions).

**Agricultural Management.** Agriculture is a sink for CO₂, but it is a producer of a far more powerful GHG, methane. Management of methane emissions from agriculture may be one of the most challenging fields for abatement strategies because the principal sources—cultivation of rice and livestock—are so difficult to control. Note, however, that not all methane comes from agriculture: other sources include swamps, natural leakage from gas-bearing formations, emissions associated with production of gas and oil, and leakages during transmission of gas by pipeline.
The MAC and MB curves, and thus overall policy, are built up from the options noted above. It is important, therefore, before major steps are taken, to identify the relative effectiveness of policy options in each sector. The development of country case studies would provide considerable insights. These case studies would need a wide focus, and should cover, at a minimum:

- Energy and power systems; as energy supplier
- Transport; as an end-use sector dependent largely on liquid hydrocarbons
- Industry, commerce, and residential sectors
- Agriculture and forestry as CO₂ sinks.

Sectoral considerations as noted here are discussed in detail in section 5 below.

**Systems Effects and Dynamics**

One of the key issues that will need to be addressed is the interrelation between the options that exist to the left and right of the optimal point where MAC equals MB, for a given country (point A in Figure 2.2). Many of the options available require the existence of an infrastructure, such as adequate power transmission facilities, and there may be strong interrelations between the costs of initial and subsequent changes. For example, it may be that a large hydroelectric storage plant has costs per tonne of CO₂ avoided (compared with a fossil-fuel-fired alternative) that locate it in the region between optimal points A and B from the national and global perspectives, but its output cannot be used without development of the transmission system, which can be fully justified in terms of its local benefits. However, at the point at which policymakers are assessing policies to improve the global environment, this prerequisite does not exist, and the feasible set of options is therefore constrained. Similarly, it may be that the early development of a new technology can be justified by limited local benefits (i.e., it lies to the left of point A) but that its subsequent use in more difficult areas cannot. Use of this technology to satisfy global objectives will then, again, be constrained or increased in cost relative to the situation where all options to the left of point A have been implemented.

In developing countries, of course, this situation may exemplify a recurrent problem. This is one of the reasons for the focus in this paper on the analysis of policy options in a systems context and for the emphasis on the dynamics of the situation.

Neither the MAC nor the MB curves are known with certainty, although there is a much larger body of evidence on the MAC curve, and particularly on the direct costs of different technical options. An important factor in locating the MAC curve is its sensitivity to local conditions and to the state of development of other systems. If coal mines are located near large centers of population, then the use of coal-fired generation will be much more effective, and of lower cost, than if the coal must be transported, or the generated electricity transmitted, over long distances. If sites for hydroelectric storage are remote, then this will raise the overall cost
relative to nearer sites. Least-cost supply of rural communities may require very different technologies from those involved in the supply of metropolitan areas. Even in developed countries, site-specific factors can make for large differences in cost. It is therefore important to think of each technological option not as having a single cost but as having a range of costs depending on individual circumstances. These cost ranges may overlap with other technologies.

Similarly, the MB curves will vary considerably. Local conditions may mean that joint benefits from CO$_2$ control are large (e.g., where the location of coal stations near to population centers is causing air pollution damage or where the creation of an urban metro system reduces congestion significantly).

Both the MAC curve and the MB curves will be different for every country; that is, point B in Figure 2.2 is not the same for every country. The starting point of existing CO$_2$ emissions is very different, cost functions differ, and the local and global benefits from reduction will vary. Local conditions will mean that achievable options on the MAC curve have different costs, and some options may be infeasible. Achieving a least-cost abatement strategy for all countries requires some comparison of the feasibility and cost-effectiveness of each country’s strategy.

It is important to remember that both the MAC and MB curves are not static but dynamic. Both will change over time. Technological advances and interrelated developments in other areas will mean that the options reflected in the MAC curve will change both in feasibility and cost. An important aspect of this is the rapid development of renewable technologies, which is considered in chapter 5. The MB curves may also change substantially over time; the literature on critical loads provides considerable evidence that damage is much greater from, say, acid rain, if the levels of pollution exceed the level that can be absorbed by local ecosystems. Similarly, there has been considerable concern that there is some threshold beyond which the costs of global warming rise rapidly. In general, until serious environmental policies have been agreed and implemented, it is likely that both national and global MB curves will rise over time.

Policy responses to these observations are wide-ranging. First, the movement of the curves may be something that can be influenced. Policy choices therefore need to compare possibilities for the reduction of abatement cost (moving the MAC curve down) as well as enabling movement along the curve. A clear example is a technical assistance program that brings down the cost of implementing new technologies. Assistance in combating the effects of pollution may also be cost-effective, although it may be assumed that the possibilities for changing the balance of local damage are greater than for global.
Strategies for Reducing CO₂

The curves depicted in Figure 2.2 are illustrative of economy-wide abatement. They embrace the possibilities in all the main CO₂-producing sectors. The full range of abatement possibilities needs to be addressed before least-cost methods of reducing CO₂ can be identified.

It is helpful to focus on the five major areas that must be addressed if a policy and strategy are to be designed to address the major long-term effects from global warming:

- Energy production and use (CO₂, some methane, nitrous oxides) covering the power system, transport, and industrial energy use
- Industrial outputs of CO₂-emitting products, mainly cement
- Agriculture (principally methane)
- Burning of forested land, which contributes to CO₂
- Afforestation, which "fixes" the CO₂, at least in the short run.

However, notwithstanding the need for action in all sectors, it is apparent that the focus of early action will be on energy and, in particular, on power systems. Much of the existing literature has focused on this sector: This is the largest single source of CO₂, and abatement technologies in this area are the most developed. Strategies here focus on:

- Demand side measures
- Supply side measures
- Fuel substitution
- Technological advance
- Achieving an efficient demand and supply balance.

How Do Countries Differ?

As international discussion of appropriate GHG control policies develops beyond the Framework Convention for Climate Change, a key feature of the debate will be the ability of developing countries to apply environmental policies, and the time frame over which this might be possible. It will also be important to assess the costs of different policies in different countries.

In attempting to address these issues, and therefore to frame appropriate policy responses, differences between countries will be of particular importance. Possible country case studies will need to address, in the context of each country's specific situation, three questions:
In what respects, relevant to CO₂ control, are circumstances in the particular country different from other developing countries and different from those in developed countries?

How are these differences likely to affect the pros and cons of different options?

What time path for CO₂ reduction is feasible?

Much of the debate and analysis so far has occurred in the context of developed countries. The list of options for CO₂ control and the analytical methods for comparing them will in many respects be common for developed and developing countries. However, the circumstances of developing countries differ from those in developed countries in a number of ways that imply that the strength of the arguments for and against various options, and the balance between the arguments, may well be different. It is unreasonable, therefore, to expect one answer for all developed countries and another common answer for all developing countries. The following account highlights several key aspects of the circumstances that would have to be taken into account in an analysis of policy for a particular developing country.

**Income.** The global and national dimensions of income will influence a judgment of what is equitable for developing countries, in terms of bearing costs and receiving benefits, from CO₂ control. The control of an externality such as CO₂ should result in an increase in global income or welfare (broadly conceived). The costs will be incurred now in the sense that prices (implicit or explicit) will be raised above marginal cost (excluding global warming costs), while the benefits will come later in terms of improved environment.

All countries are likely to incur costs and receive benefits. Although the net benefit in an intertemporal sense should be positive from the global perspective, there is no guarantee that this will be true of individual countries unless measures are directed toward that end. Even if the net benefit is positive for a given developing country, it may find that the short-run costs cause considerable hardship. This may also be true of groups within a country. The lower level of income in developing countries, and similarly for groups within those countries, will be an important element in any distributional judgment of the costs and benefits of different schemes.

**History of CO₂ Emission.** This is also pertinent, since the relevant measure of the problem for policy purposes concerns the total net stock of CO₂ that has accumulated and is not simply given by the flow. Current and future policies can affect only current and future flows, and not past. From the point of view of allocative efficiency, bygones are bygones. Developing countries might, however, take the view that the greater costs should be borne by those with the greater responsibility for the creation of the problem. In this case, total past CO₂ emissions would become relevant, and this would point to greater costs for developed countries (energy-intensive countries such as China would have their burden increased relative to other developing countries if this criterion were applied). There is a generalized incentive argument of relevance here, too. If countries know that they may, at least in part, be called to account for the environmental consequences of their actions, they might take more care across the board.
**Energy Usage.** In developing countries, energy usage is generally lower (although recall again the case of China) per unit of income than in developed countries, and the mix of energy sources somewhat different. For example, households in developing countries would consume relatively more wood, cow dung, and kerosene in relation to electricity than in developed countries. This lower level of energy usage may affect the analysis in several ways:

- If it reflects a high income elasticity of demand for energy together with low income, then the problems created by growth in incomes may be severe. If it reflects poor infrastructure, then there may be an advantage in that infrastructural investments can be made with CO₂ criteria in mind. With a more developed infrastructure, some of the choices may have been made before such criteria were prominent.

- The different balance of energy sources and endowments will affect the kind of substitution analysis required—for example, between wood, coal, cow dung, solar heating, and kerosene for developing countries—whereas gas versus electricity might be relevant for the consumption of households in developed countries. Among the industrial users of energy, the differences may be less marked, but this is clearly a subject for research.

- The production of electricity is likely to involve much the same substitution possibilities in developed and developing countries, although the variation of endowments is likely to be important here. The two largest developing countries, China and India, are well endowed with coal and, given transport costs and low costs of labor, might have a considerable price advantage in using coal. Furthermore, any taxation of coal that reduces the world price of a resource in which a country is internationally competitive will reduce a country’s export earnings.

**Technological Choices.** All countries will have been influenced by past price and policy regimes and previous forecasts for the future. Changes in prices, taxes, and policies will affect technology choices for all countries. Those that have made the biggest investments in the areas subject to the highest price increases, and those that have made the least flexible choices, will be hit hardest. In some respects, being a later starter in the technology stakes is an advantage. Empirical research would be necessary here, but it may be that power stations in developing countries have been made less flexible, since, for example, the superiority of the coal option appeared more obvious when past decisions were taken.

**Industrial Structure.** Similar issues are posed by industrial structure. A question to be asked is whether the industrial structures in developing countries make them more or less flexible in response to price and policy changes. Some analysts have argued that developing countries are much less flexible than developed. This is far from obvious, however, and research on the relevant parameters would be of value.

**Institutional Structures.** In developing countries, institutions may alter responses to price incentives and regulation. These changes may not be of the kind predicted from simple models
of, for example, profit-maximizing privately owned firms with well-defined property rights. This would clearly be relevant to the control of forecasts, but it may also be relevant to the behavior of firms. For example, where firms are in the public sector, or are strongly regulated in the private sector, they may be expected to be compensated for cost increases. Or they may be tightly bound by administrative fiat or political pressure to particular suppliers. One must look carefully at institutional arrangements if the consequences of price changes and administrative policies are to be predicted appropriately.

**Administrative Arrangements, Information Resources, and Capabilities.** These factors may be much weaker in developing countries. In these circumstances, simple policies with low informational requirements may be called for. Corruption may be problematic in some countries. If so, policies that are easy to subvert, particularly by payment to officials, should be avoided, although of course no policy can be entirely cheatproof. Nevertheless, observability of contraventions will be an important criterion in policy choice.

**Policy Regimes and the Functioning of Markets.** This is the final factor influencing policy, and it is of special relevance to developing countries. Although there is substantial change toward freeing markets and reducing regulations, many developing countries still have distorted price systems and heavy regulation. The importance of well-functioning markets in the process of growth is increasingly recognized. However, given that many markets will stay distorted for some time, it will be important to ask how proposals for, say, a carbon tax policy will interact with other policy distortions. Would there be substitution toward commodities whose markets are still more distorted? Will regulatory controls prevent the responses that might be deemed desirable and so on?

The above key factors are reflected in the analysis that follows and in the identification of further research requirements. They are crucial in assessing the potential impacts of different policies, and, in particular, how they might differ for developed and developing countries.

In concluding this list of the potential sources of differences between developed and developing countries, two points must be stressed. First, each issue differs in application to a particular country, and there is an enormous heterogeneity in developing countries. For example, in 1982, China used twice as much energy to produce a unit of GDP as the Soviet Union and four times as much as Japan, whereas energy usage per unit of GDP in Singapore was very low. Second, some policy reforms that might lead to growth may also be consistent with better environmental conditions and CO₂ control. For example, excessive import substitution encouraged by the underpricing of energy may inhibit growth and damage the environment, through its influence on choice of industry and on choice of technique of production within an industry. Thus, one should not assume that the environmental contribution cannot be improved without damaging growth.
4. EMPIRICAL EVIDENCE

This section provides evidence from the literature on the level and shape of the marginal abatement cost (MAC) curve in particular countries. The literature is still in its infancy and stops some way short of providing authoritative guidance. There appears to be little rigorous empirical evidence that relates directly to developing countries.

Marginal Abatement Costs

Many analysts and commentators have investigated both the costs of CO$_2$ reduction and the carbon tax rates that are necessary in particular countries. They use varying methodologies and often produce conflicting results. In order to bring them together and provide guidance for subsequent work, eleven studies have been used to assemble an average estimate of a MAC curve. The curve, shown in Figure 4.1, is illustrative only and does not represent the MAC curve for any individual country. MACs have been estimated in constant 1989 prices for the period 1988-2005. Because most of the literature to date has focused on the United States or a world dominated by developed countries, the applicability of this information to developing countries may be limited.

![Figure 4.1: Marginal Cost of CO$_2$ Reduction, 1988-2005](image)

**FIGURE 4.1 Marginal Cost of CO$_2$ Reduction, 1988-2005**

1. The studies are Gerbers et al. (1990), Netherlands; Jorgenson and Wilcoxen (1990), United States; Nordhaus (1979), World; Edmonds and Barns (1990), World; Nordhaus (1990), World; Manne and Richels (1991b), United States; Congressional Budget Office (1990), United States; Morris et al. (1990), United States; Chandler and Nicholls (1990), United States; Chandler (1990b), Canada; and Manne and Richels (1991a), World.
An interesting finding of the literature is that there may exist a point on a country's cost versus CO$_2$ reduction curve where diminishing returns become very pronounced (i.e., the marginal cost of CO$_2$ reduction increases sharply for successive percentage point of reduction in emissions). This point will be matched by a "kink" in the curve associated with the need to use different and more expensive technologies that exhibit diminishing returns for rapidly rising costs. The "kinks" from individual studies are not evident in Figure 4.1, as they have been smoothed out by the averaging process.

Examples in the literature of this "kink" include:

- $300/tC (1989$US): Gerbers et al. (1990), Netherlands

From these results, the average "kink" is at a MAC of $225/tC. However, Nordhaus (1990) noted gradually diminishing returns.

The marginal cost of CO$_2$ reductions can also be interpreted as a tax required to produce those reductions. The tax may be seen as buying (at a fixed price) carbon reductions. Suppliers of carbon reductions who are profit-maximizing in the face of the tax will adjust their level of supply so that the reward to carbon reductions (the tax saving) is equal to the marginal cost of reduction. Hence, with the assumption that private and social costs are equal, the tax corresponding to a target level should be set at the marginal cost associated with this level. Thus, a curve that relates the tax to the reduction level will be a marginal cost curve.

**Constructing the MAC Curve**

Some MAC curves have been created for developed and developing countries. In this section, an example of each is considered: Jackson's (1991) study on United Kingdom supply curves for global warming abatement; and a study on India by the Tata Energy Research Institute (TERI), New Delhi (Grubb et al. 1989), on the incremental costs of CO$_2$ limitation strategies and their current potential for emissions abatement. Although both studies have empirical and theoretical problems, they are included here to indicated the process that has been followed in the existing literature.

**United Kingdom.** The methodology used in Jackson's (1991) study is that of integrated least-cost planning whereby end-use needs can be met in a variety of ways. Each way of meeting the demand or portion thereof will have a corresponding cost. A simple ranking system then prioritizes the various measures in terms of their cost-effectiveness.
A CO₂ abatement cost curve, as shown in Figure 4.2, has been derived by rank ordering the cost of individual measures per tonne of CO₂ saved. The height of the blocks in Figure 4.2 represents the cost in £/tonne of CO₂ saved, and the width of the blocks represents the potential contribution to saving CO₂ by a specified date (exchange rate, £1 = US$1.80). The curve then provides a direct comparison of the different abatement options in terms of their relative cost-effectiveness and their potential for reducing CO₂ emissions. Some of the costs may be negative because some of the measures are less expensive than the base case.

The most cost-effective route to reach a particular abatement target can be read from this schedule. An interesting feature of analysis is the apparent scope for cost savings associated with "below the line" options, even in a mature economy such as that of the UK. It is believable that such options can occur in developing countries, where skill shortages and other constraints prevent this emergence. However, in the UK, in the absence of market failure, either the market should develop or costs may be underestimated because other factors, such as transaction costs, have not been fully considered.

**FIGURE 4.2 Cost Curve for UK CO₂ Abatement Options**

(CHP = combined heat and power; PWR = pressurized water (nuclear) reactor cost of each measure based on life-cycle cost at 10 percent discount rate.)
**India.** Many options for reducing CO$_2$ emissions are desirable for India for reasons other than abatement of global warming. Three of the most important options are afforestation; enhancement of energy efficiency; and development and implementation of renewable energy technologies. However, each option would require substantial capital. The capital inflows could be linked to particular CO$_2$ reduction programs within a national CO$_2$ reduction framework. The TERI study (Grubb et al. 1989) considers the incremental costs of CO$_2$ reduction strategies and their current potential for emissions abatement—assuming the availability of funds.

Preliminary estimates from the study indicate reduction costs starting at about Rs600/tC (US$32) (for afforestation), rising to Rs 400,000/tC (US$23,500) (for enhanced rail freight transport). The total emissions reduction potential is estimated at about 90Mt carbon per annum. The cost curve is shown in Figure 4.3, where the vertical lines represent the cost in Rs/tonne of CO$_2$ saved, and the horizontal lines represent the potential contribution to saving CO$_2$ that the associated measure can achieve by a specified date. It is apparent that many measures such as enhanced rail transport would confer additional joint benefits that would reduce the effective cost to the economy of CO$_2$ reduction.

![Figure 4.3 Cost Curve for CO$_2$ Limitation Strategies in India](image-url)
5. SECTORAL CONSIDERATIONS

The choice of an effective GHG reduction strategy will require consideration of all major CO₂ emitting sectors. Some initial observations on the two most important sources, power systems and transport, on energy efficiency measures of a means of reducing emissions in industrial and commercial use, and on forestry as a possible "sink" are provided. These are not intended as a definitive treatment of any of these areas but more as preliminary observations to give the reader a flavor of some of the issues.

Electric Power Systems

The development of power systems varies widely among developing countries. Some have relatively well-developed systems that share many features with those of more developed countries, whereas others have less integrated supply with relatively rudimentary transmission systems.

In general, coal- and oil-fired generating plants form the backbone of the formal electricity systems; a large proportion of all generation capacity in developing countries is fired by these two fuels. A few developing countries have a limited nuclear capacity. The main alternative to coal and oil is hydroelectric generation. This can take the form of large or small storage or run-of-river plants. Recently, gas-fired power stations have become important in several countries; combined-cycle plant has substantial advantages both in terms of emissions and thermal efficiency.

The power systems of most developing countries can be improved considerably. The most endemic problems are the following:

- Low plant load factors
- Low thermal efficiencies
- Inappropriate pricing
- Lack of grid discipline
- Insufficient transmission and distribution operating information.

Most of these problems lead to higher CO₂ emissions than would occur with the same plant and supply of electricity under ideal conditions. Strategies to solve these problems are mostly of the "no regrets" type, independent of any CO₂ abatement objective, and their resolution often represents the least-cost method of reducing CO₂.

At present, relatively little use is being made of the newer renewable technologies such as solar voltaics, solar thermal, or wind power. Similarly, by-products from industrial processes (e.g., bagasse from sugar cane) have rarely been used extensively as fuels. A few geothermal power plants exist in developing countries, principally in the Philippines, Mexico, and Indonesia.
Opportunities for Change. Most developing countries seek rapid increases in GDP per capita and face rapid population growth during the coming decades, so that their power and transport systems will need to evolve rapidly to keep pace. This problem may be exacerbated by the expected increases in energy consumption per capita that generally accompanies development. In many countries, installed capacity is set to double, or more, over the next decade.

These developments, although they represent a severe problem of funding, also provide a great opportunity. It means that substantial changes in the fuel mix—and therefore in CO$_2$ emissions—of many countries’ power systems can be achieved by refocusing investment plans, and without the need for premature retirement of plants.

Alternative Fuels and Technologies. The fundamental issue in determining the costs of alternative power systems is the availability and price of alternative technologies and fuel mixes. The effective reduction of CO$_2$ in developing countries’ power systems relies on a shift away from coal and oil toward fuels that have lower CO$_2$ emissions, such as gas; toward hydroelectric or nuclear generation; or toward a new generation of renewable technologies, such as solar, biomass, wind, or wave power.

Unfortunately, each of the existing alternatives to coal and oil have some side effects. Gas is often seen as the most promising of the alternative fuels, principally because of the gains in thermal efficiency made possible by combined-cycle technology. However, methane leakage from inadequately specified or constructed pipelines may have harmful GHG effects that offset the gains from lower direct emissions, and most developing countries also do not have access to sufficient reserves of gas. Similarly, substantial reliance on nonpolluting hydroelectric power can result in the resettlement of populations and the destruction of forests and natural habitats, and the capital costs may also be prohibitive. Nuclear power creates problems of safety, linkages with arms production in politically unstable countries, and the storage of waste.

The Role of Renewables. Much effort has been put into the development of renewable technologies over the last decade, with considerable success. There is no doubt that these have a role to play in the future, although whether they can provide a major part of the solution remains an open question. They divide into technologies that harness natural forces and those that use fuels that can be regenerated. The most important technologies that harness natural forces are solar thermal, solar voltaic, wind–wave, and developments of hydroelectric power. These technologies require large land or sea areas for the capture of sunlight, wind, and wave power and involve substantial capital and construction costs. They also suffer from unreliability, in that wind and sun are unpredictable in many places. This means that more than 1 MW of plants using these technologies would be needed to substitute for 1 MW of, say, gas-fired steam plants.

A second group of renewable technologies involves the use of existing fuels or the use of fuels in a controlled way so that they can be regenerated. The general term "biomass" is applied to those fuels, which usually involve the subsequent use of by-products from agricultural
processes. Examples are bioethanol, produced by fermenting sugar cane; charcoal, produced when wood is burned in a confined space; and bagasse, the residue from the production of sugar cane. All can be used to fuel steam-raising for electricity generation. Their advantage in the present context is that burning the fuel creates less additional $CO_2$. If bagasse were left to rot, for example, methane would be produced, and if it were burned but not harnessed, $CO_2$ would be produced anyway.

Commentators have emphasized the need for sustainable energy production, where the fuels used are regenerated. If, for example, a specially cultivated area of forest were used as fuel but then replanted, the fixing of $CO_2$ would compensate for its initial production. However, an explicit link between forestry and electricity generation has yet to be formalized or implemented.

*Systems Effects.* As is well known, the simple comparison of costs between technologies will not provide clear guidance as to appropriate projects to include in the least-cost strategy. Instead, new projects need to be assessed within the context of the existing system and its expected development. That is, a total systems analytical approach must be used.

**Energy Efficiency**

Industrialized countries consume, at present, 70 percent of the world’s energy. However, it is not necessarily so that simply because developing countries use less energy, there are fewer possibilities for efficiency improvements. According to one report (USAID 1990), technically proven cost-effective energy conservation techniques and processes can save developing countries an estimated 10 to 30 percent of industrial sector energy costs and 10 to 25 percent of power sector energy consumption. The report states that in Pakistan alone, $9.7 million worth of energy savings have been identified through a series of energy audits. In Morocco, it has been estimated that the net present value of a national energy demand management program through 1996 may exceed $150 million. In India, a 10 percent reduction in industrial energy use would result in $1 billion in annual cost savings. In the Philippines, the overall conservation potential is estimated to be $500 million per year (USAID figures).

Examples of the inefficient use of energy in developing countries include Brazilian refrigerators, which are smaller (340-420 liters) than typical units in the United States (500 liters) but consume between 1,310 and 1,660 kWh per year (new U.S. units consume only 1,150 kWh per year). Ironically, the efficiency improvements obtained in the United States derive from a compressor imported from Brazil (Goldemberg et al. 1987).

Goldemberg's analysis indicates that the global population could roughly double, living standards could be improved far beyond satisfying basic needs in developing countries, and economic growth in developed countries could continue without increasing the level of global energy use in 2020 much above the present level.
Opportunities abound in both developing and developed countries for using energy more efficiently. Four areas that show promise for efficiency improvements are space heating, appliances, automobiles, and steel making, as detailed below:

- **Heating.** Heating accounts for 60 to 80 percent of final energy use in residential buildings in developed countries. Cost-effective energy reductions are possible by reducing heat losses and improving the efficiencies of heating systems. The lower-income groups in developing countries that use wood and other natural materials for heating and cooking consume three to ten times as much energy per capita as do consumers in developed countries, who generally have access to modern energy facilities. Efficiency gains with wood result from transferring from open fires to wood-burning stoves. Further efficiency gains would result from shifting to modern gaseous or liquid fuels.

- **Appliances.** Innovations in refrigeration technology are reducing the amount of electricity per liter size. The cost of potential savings from installing more efficient units are significant (Williams, Dutt, and Geller 1983), and the initial costs of the more efficient units may fall as the new technology becomes commonplace. An example of potential energy efficiency savings to developing countries is Indonesian electrical appliances: the majority of appliances currently being marketed in Indonesia incorporate levels of energy efficiency that are well below those justified on economic grounds. More efficient models are currently available to Indonesia, and their dissemination would allow households to reduce electricity consumption for key end-uses by at least 20 percent. By the year 2008, realistic improvements in electric appliances could reduce residential electricity use by 7 to 11 TWh for urban Java alone, thereby saving hundreds of millions of dollars in expenditures on new generating capacity (Schipper and Meyers 1991).

- **Automobiles.** In 1982, automobiles were responsible for one sixth of worldwide oil consumption. Four-fifths of the world's cars are in developed countries (Goldemberg et al. 1987), but the number of cars in developing countries is expanding rapidly and is projected to increase by 150 to 200 percent by the year 2000. This will result in a 1 percent annual increase of total oil use in developing countries between 1982 and 2000. Technological possibilities for improving fuel efficiency abound. It is doubtful, though, that market forces alone would lead manufacturers to produce, and consumers to buy, these highly efficient cars. Consumers would not receive great direct economic benefits, since fuel costs represent a tiny fraction of the total cost of owning and operating a car.

- **Steel Making.** About five-sixths of all steel is produced in industrialized countries, where it accounts for a significant fraction of manufacturing energy use. For example, it accounts for one-sixth in Sweden and one-seventh in the United States. New processes are evolving that decrease production costs; these are largely being generated in Sweden, where the small size of the industry requires it to exploit every cost advantage in order to remain competitive.
It seems clear that to improve end-use strategies some measure of government intervention is necessary. At present, government intervention in developing countries often discourages energy efficiency: the subsidizing of fuels is an important example. (One basic prerequisite of any improvements in energy efficiency is the pricing of fuels in accordance with the international markets; see Mulckhuysse 1990.) For example, in India, kerosene is subsidized to protect the lower-income groups. However, this requires extending the subsidy to diesel fuel as well, in order to keep diesel fuel consumers from switching to kerosene, which can be used in diesel engines. Extending the subsidy to diesel fuel then creates excess demand for diesel-based truck freight, heightening the country’s dependency on imported oil (Reddy 1981).

A further example of inefficient government intervention in many parts of the world is the setting of electricity prices below economically efficient marginal costs and basing them instead, at best, on average costs. In many developing countries, revenues are insufficient to cover total costs. A judicious mixture of government intervention and market mechanisms is thus required to provide increased energy efficiency.

The complexities of energy end-use decisionmaking generally can be dealt with far more effectively by those who know exactly what they need and how much they can afford (the consumers) and by those who know what the energy-using devices cost to produce (the sellers). Policy should be aimed at improving the market’s ability to allocate resources relating to energy end-use and intervening more actively only where the market mechanism is inherently weak or incapable of implementing social goals.

Transport

The transportation sector accounts for 15 to 20 percent of final energy use in OECD countries. In the United States, the transportation sector accounts for 28 percent of the fossil fuel and 63 percent of the petroleum consumed. Some 30 percent of U.S. CO₂ emissions arise from this sector (IEA 1984). Petroleum-fueled cars and light trucks account for 58 percent of all transportation energy use in the United States (Ross 1989) and thus the majority of transportation-related CO₂ emissions.

Notwithstanding the oil price shocks, transportation energy use in most OECD countries was considerably higher in 1987 than in 1973. Total travel, in passenger-km/capita, increased. The main reason was an increase in the number of cars. The share of travel occupied by air travel increased while that of rail and bus travel decreased. As a result of these shifts, the aggregate energy intensity of passenger travel increased. Automobiles dominate passenger travel in Europe and the United States, and their share is growing rapidly in Japan.

To reduce GHG emissions from the transport sector, three main alternative policies are available: increased vehicle efficiency, alternative transportation fuels, and improved transport system management. In the short run, transportation energy consumption can change rapidly as
consumers adjust their demands concerning when and how to travel. On a slightly longer time scale, higher vehicle and fuel prices, along with shifts in vehicle and transportation demand, will lead to changes in the types of vehicles in use. On a much longer time scale, investments can be made in alternative transportation fuels, new mass transit facilities, and high-occupancy travel lanes.

**Vehicle Efficiency.** International concern over energy efficiency has been cyclical, moving with oil prices. The trend in 1975-82 was a response to increased fuel prices. The vehicles manufactured in that period were, on average, 450 kg lighter and incorporated various fuel-efficiency technologies than did comparable models in the previous decade. Efficiency can also be increased by improving engine and transmission designs, reducing weight, and enhancing vehicle dynamics. Unfortunately, such improvements take time. For example, a new vehicle in the United States takes 4 to 5 years to go from prototype to product. Passenger car turnover is also slow, at 7 to 8 years, and rates for heavy trucks are even slower, at 12 to 15 years.

**Alternative Transportation Fuels.** A study by Deluchi et al. (1988) examines the impact of using alternative motor vehicle fuels on GHG emissions. The results are summarized in Table 5.1. The fuels can be divided into three categories relative to gasoline: those that will reduce GHGs by less than 25 percent, those that will increase GHGs, and those that will completely or nearly completely eliminate GHGs.

Fuels that will reduce GHGs by less than 25 percent:

- Diesel fuel
- Natural gas
- Methanol from natural gas
- Electricity from natural gas
- Electricity from current mix.

Fuels that could result in increased GHG emissions:

- Methanol from coal
- Electricity from coal
- Ethanol from biomass (if produced and transported using fossil fuels).

Fuels that eliminate or nearly eliminate GHG emissions:

- Methanol from wood
- Ethanol from biomass (using biomass to produce and transport the fuel)
- Hydrogen from nonfossil-fuel-generated electricity
- Electricity from nonfossil fuels.
Each of the alternative fuels is problematic. Biomass fuels require production systems and infrastructures not currently available. In addition, it is unlikely that there is sufficient land available to grow corn to convert to ethanol or biomass for methanol or ethanol. For hydrogen, the production systems and infrastructure would have to be created. There are storage and safety concerns to be resolved for vehicles having on-board reservoirs of hydrogen. If hydrogen is to be used to reduce GHGs, it must be made by using nonfossil-fuel-generated energy.

Electric vehicles are only a viable option if the electricity is produced from nonfossil fuels. Further technological advances, particularly with batteries, are needed to produce electric vehicles that are as convenient to use as today's fossil-fuel-powered vehicles.

**TABLE 5.1 Relative Emissions by Fuel Type**

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Relative Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline</td>
<td>100</td>
</tr>
<tr>
<td>Diesel</td>
<td>81</td>
</tr>
<tr>
<td>Natural gas</td>
<td>81</td>
</tr>
<tr>
<td>Methanol from natural gas</td>
<td>97</td>
</tr>
<tr>
<td>Methanol from coal</td>
<td>198</td>
</tr>
<tr>
<td>Methanol from wood</td>
<td>0</td>
</tr>
<tr>
<td>Ethanol from biomass</td>
<td>0</td>
</tr>
<tr>
<td>Hydrogen from nonfossil sources</td>
<td>0</td>
</tr>
<tr>
<td>Electricity from nonfossil sources</td>
<td>0</td>
</tr>
<tr>
<td>Electricity from natural gas</td>
<td>82</td>
</tr>
<tr>
<td>Electricity from current mix</td>
<td>99</td>
</tr>
<tr>
<td>Electricity from coal</td>
<td>126</td>
</tr>
</tbody>
</table>

*Source: Deluchi et al. (1988)*

The prospects for continued energy savings in transportation include the new, more efficient aircraft that the world's airlines are adding to their fleets, which reduce the average energy use per kilometer of travel. There is potential, too, within the automobile industry, but efficiency improvements have been decreasing rather than increasing. The 1990 auto fleets in Europe average about 9 liters/100 km, and those in North America average about 11.5 liters/100 km. These figures could be improved to about 5.9 liters/100 km at less than a 10 percent increase in vehicle cost, if saving energy were the only consideration. Such improvements are unlikely,
since consumers are not solely interested in fuel efficiency, and manufacturers are unwilling to raise prices on that basis alone.

Transport System Management. A number of options for the management of transport systems can be used to reduce GHG emissions. These include altering demand through more accurate pricing mechanisms (taxing gasoline, road tolls, automobile taxes, and registration fees); through parking and transportation demand management; and by increasing the number of high-occupancy vehicle lanes and the availability of mass transit.

Improved technology is not the only input to saving energy in automobiles. The number of people per vehicle has fallen steadily since 1970 in Europe, the United States, and Japan. This has increased the energy intensity of automobile travel by about 10 percent. As a result, the intensity of automobile travel in 1987 was higher than in 1970 in some countries and only marginally lower in most others.

The fuel intensity of almost all trucks has improved. However, the nature of truck use has changed; more light and medium-weight trucks are being driven in congested urban areas. As a result, the intensities of truck freight (in energy/tonne-km) have increased in almost every European country, Japan, and the United States.

Transportation energy use is a serious concern in developing countries. The largest component of the dramatic increase in oil use in developing countries during the last decade has been in the transportation sector. From 1973 to 1986, oil use in developing countries increased by 60 percent. During the same period, oil used by OECD countries declined by 13 percent (USAID 1990). Recent projections by the U.S. Department of Energy (1989) indicate that the overwhelming majority (80 percent) of growth in world oil consumption through to the year 2010 could come from developing countries. For fifteen of the largest developing countries, about 50 percent of the growth in oil consumption in the 1970-84 period has been in transportation.

The approaches that have been effective in reducing the growth of energy use in transportation in developed countries may not be effective in developing countries. Industrialized countries have been able to reduce the average consumption of fuel per highway mile significantly by replacing existing vehicles with more efficient models and developing or expanding mass transit in urban areas. The potential for such improvements in developing countries is limited because of the slower turnover of vehicles and the lack of capital to invest in infrastructure improvements.

Forestry and Global Warming: The Role of CO₂ "Sinks"

Afforestation. Investment in afforestation as a method to ameliorate global warming is a temporary and limited solution because trees absorb carbon only as long as they are growing. That is, they only absorb more carbon if their incremental growth exceeds their incremental
decay. Carbon released by dying trees offsets carbon sequestered by younger stands. Therefore, a stand of trees in its steady state (i.e., when the incremental growth and decay are in balance) does not influence the amount of carbon withdrawal regardless of its size.

However, afforestation will provide a more lasting contribution when the trees are harvested sustainably and then used for renewable energy purposes to replace fossil fuel energy sources. The process of using the biomass for energy purposes cancels out the carbon absorbed during the growing period, but it also displaces the carbon emissions that would have been emitted otherwise.

The previous sections describe elements of the least-cost process by which the options available to mitigate global warming are determined. It is important to recognize that afforestation should undergo the same analysis (i.e., it should be included in the least-cost ranking process). It is possible that reducing existing deforestation in developing countries may actually be one of the lowest cost options available to these countries. Although afforestation is a temporary measure in terms of reducing global warming, the time until the steady state is reached (at which point the stand does not absorb further carbon) provides an extended period in which technological change in noncarbon energy may produce additional methods to mitigate global warming.

**TABLE 5.2 Afforestation Costs in the United States**

<table>
<thead>
<tr>
<th>Annual carbon sequestration (million tons)</th>
<th>Cost per metric ton ($)</th>
<th>Sequestration rate (tC/ha/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-100</td>
<td>12.2</td>
<td>5.4</td>
</tr>
<tr>
<td>100-200</td>
<td>18.2</td>
<td>4.5</td>
</tr>
<tr>
<td>200-300</td>
<td>22.9</td>
<td>5.8</td>
</tr>
<tr>
<td>300-400</td>
<td>24.6</td>
<td>5.6</td>
</tr>
<tr>
<td>400-500</td>
<td>26.0</td>
<td>7.1</td>
</tr>
<tr>
<td>500-600</td>
<td>31.2</td>
<td>5.6</td>
</tr>
<tr>
<td>600-700</td>
<td>38.6</td>
<td>6.7</td>
</tr>
<tr>
<td>700-800</td>
<td>40.7</td>
<td>6.2</td>
</tr>
</tbody>
</table>

*Source:* Cline (1991), calculated from Moulton and Richards (1990), Table 1a.
The cost range for carbon removal through afforestation is thought to be fairly large and higher than that for deforestation (see below). Cline (1991) reports that estimates of the cost of carbon removal through afforestation are far lower than the $100-300/tC provided by existing macroeconomic models. Moulton and Richards (1990) provide the most reliable estimates of the cost of avoiding carbon through afforestation in the United States. These range, for the first 60 million tonnes of carbon sequestered annually, on the first 25 million acres, from $5 to $10/tC. As the total annual sequestration rises from 700 to 800 million tons (land area 300 to 340 million acres), the cost rises to $35/tC. Table 5.2 above reports Moulton and Richards's results for afforestation costs in the United States at various sequestration rates.

The central finding of Moulton and Richards (1990) is that the United States could sequester up to 30 percent of annual U.S. carbon emissions at a cost of just under $201 per metric tonne. The land requirement for this amount of carbon storage would be 197.6 million acres.

Lower cost estimates have been estimated by Sedjo and Solomon (1989). Under their higher land acquisition price, and for a fully mature afforested area, the cost of sequestering carbon by a fully matured forest amounts to $7.50/tC. This calculation is based on the premise that "tree-pickling" will occur; this involves greater carbon removal, as no carbon is released from dying trees to offset the absorption of carbon by new growth. Darmstadter and Plantinga (1991) note that under the option of afforestation, ignoring the option of permanent carbon storage, the cost of carbon sequestration could more than triple, as account must be taken of harvesting costs at maturity.

Vital to the cost estimate of carbon sequestration is the price of land acquisition. Andrasko, Heaton, and Witten (1991) estimate that afforestation projects in Guatemala and Costa Rica to offset carbon emissions from a new power plant in the United States suggest carbon sequestration costs in the region of $0.82 to $1.37/tC. Sedjo and Solomon (1989) estimate carbon sequestration in the tropics of $4.30/tC. Nordhaus (1990), however, estimates that carbon sequestration through reforestation would cost in the region of $100/tC. A possible reason behind extreme variations in the cost estimates is the different sequestration rates used. Nordhaus assumes a rate an order of magnitude smaller than the other studies indicated. Nordhaus based his calculations on early EPA carbon sequestration rate estimates that have since been criticized. Therefore, the conclusion to be derived from these studies is that carbon sequestration through afforestation would cost no more than $5/tC in the tropics and $20/tC in more temperate and developed regions.

The potential for afforestation in the United States is perhaps 80 million hectares, a possible 30 million hectares in temperate developed countries, and a further 150 million hectares in tropical developing regions. On this basis Cline (1991) indicates that 260 million hectares would be available globally for carbon sequestration, which could possibly sequester 1.6 million hectares of carbon annually. Although afforestation is a temporary solution to global warming, it could reduce global carbon emissions by an average of 18 percent over the next 35 years.
Afforestation as an option for ameliorating global warming is very attractive not simply for the reasons indicated above. Carbon sequestered by forestry is twice as effective as emissions avoided through fuel switching to lower-carbon-content fuels and to nonfossil fuel energy options. Typically, only one-half of annual carbon emissions remain in the atmosphere. Therefore, a ton of carbon sequestered from the atmosphere effectively absorbs two tonnes of carbon emitted. Thus the contribution that afforestation can make to global warming should not be understated.

**Deforestation.** Darmstadter and Plantinga (1991) estimate that the cost of avoiding carbon emissions from deforestation amounts to $2.30 per tonne of carbon in Brazil, $15/tC in Indonesia and $8/tC in Côte d'Ivoire. The variation between the three countries’ cost estimates reflects the significant value of logging activities in Indonesia and Côte d'Ivoire compared with cattle ranching in Brazil.

Using figures on the level of carbon emissions from deforestation in Brazil, Cline has produced more detailed estimates of the cost of avoiding carbon emissions in Brazil. The cost of eliminating all the agricultural land in the Amazon to avoid deforestation would only be $4/tC annually. To eliminate 25 percent of the agricultural land, the cost falls to $1/tC annually. The estimates by Darmstadter and Plantinga (1991) and Cline (1991) imply that 690 million tonnes of carbon could be avoided annually at an average cost of $6.35/tC in Indonesia, Brazil, and Côte d'Ivoire.
6. A SIMPLIFIED METHODOLOGY FOR A CO₂ ABATEMENT STRATEGY

Least-cost reduction of GHGs will require a combination of approaches and will need to encompass all GHG-producing sectors. It will also need to involve changes at all stages in the fuel cycle, from fuel switching and generation technologies to improved energy efficiency at both the conversion and end-use stages. It is important to recognize the breadth of the problem and the interrelation between sectors and activities within sectors.

This section brings together the analysis from the paper to develop a framework for subsequent country case studies and practical guidance for policymakers and practitioners advising on appropriate development strategies. Where relevant, some quantitative information to act as a starting point is provided; however, the creation of a detailed database is beyond the scope of the present study. The methodology is designed to be equally applicable to all sectors. However, quantitative data is largely limited to the electric power sector.

Ten Steps to Defining Least-cost Abatement Strategies

The following steps summarize the wide-ranging analyses that will be necessary before least-cost and feasible abatement strategies can be established. Figure 6.1 relates these steps to each other and shows that some iteration between them is needed before a final answer can be reached. The preceding sections and the annexes provide a starting point for each step, but substantial country-specific analysis is also needed.

Step 1. Establish the basic structure of demands, supplies and possible policies to identify priorities for analysis. This step includes the following substeps:

a. Assembling data on the structure of the energy system at present, and plans for its least-cost expansion. These substeps are necessary to provide a base case to which subsequent environmental policies can be compared. Items requiring attention in the power system context include capacity mix, including planned retirement, maintenance, and any necessary upgrading; problems with organization and management, including grid discipline; fuel supply and costs, including transportation and any likely future developments; development of the transmission system; and existing plans for future expansion.

b. Establishing "Baseline" Future Demand. In most developing countries, this will be rising steeply. The key determinants are population growth and likely increase in consumption per capita. The World Energy Conference published projections in 1989 suggesting that global primary energy demand would grow by 76 percent by the year 2000, and that associated CO₂ emissions would grow by 69 percent despite a (now optimistic) assumption of a three-and-a-half-fold increase in nuclear power. A consistent set of population growth estimates, and likely changes in consumption in each of the key sectors of energy, transport, commerce/industry, and agriculture/forestry for each country will be required.
FIGURE 6.1 Ten Steps to an Abatement Strategy
c. Identifying appropriate instruments and implementation methodology in industry. This includes the following steps and questions:

- Financing of new plant construction. Are some technologies easier/more appropriate for private sector involvement? Are there planning or institutional advantages to particular approaches?

- Are some approaches precluded by a lack of expertise in the country concerned?

- Is there scope for encouraging particular changes through the use of taxes (or permits)? If so, are the relevant administrative mechanisms in place?

- Are particular types of methods and technologies more or less susceptible to corruption or lack of appropriate control mechanisms?

Step 2. Review and compile, on a country basis, data on specific measures to reduce CO₂ emissions. This involves the following substeps:

a. Establishing which technological options are feasible for development of the system in the particular country. Key issues for power systems include the availability and reserves of different fuels; possibilities for import of new/enhanced fuel supply (e.g., gas); land area available for wind/solar generation; nonutilized water catchment and river flow; and existing industrial and agricultural processes, for generation based on bagasse, for example.

b. Exploring the extent to which existing energy use and production can be improved. These are usually items that lie in the "no regrets" part of Figure 2.2, but establishing whether all possible options have been implemented is a necessary step in deciding on a global abatement strategy. Important elements include:

- End-use efficiency measures, including demand management (which in turn requires analysis of a cost-reflective pricing policy), improvements in efficiency, changes in appliance and lighting technologies, and a switch to biomass-based fuels.

- Improvements in generation efficiency by upgrading existing generation capacity or changing fuel use.

- The possible use of combined-heat-and-power (CHP) schemes, where, for example, existing generation is extended to provide heated water or steam or existing steam-raising capacity is extended to provide generation.
There are also numerous examples in the transport field, for example the upgrading of vehicles to achieve much greater fuel efficiency, as has been discussed in a number of countries.

c. *Adapting existing estimates of the costs of the feasible options to allow for local conditions.*

In the power system, this is not simple. The costs of each kWh generated are determined by:

- Capital costs of plant and construction, including local labor and other specific costs.
- Fuel costs, which depend on location and resources, plus transport or pipeline costs.
- Operation and maintenance costs, including the requisition of spare parts, and possibly the need to employ expatriate skilled technicians. In addition, costs for kWh depend on the length of time for that each plant runs. In fully developed power systems a variety of plant with different capital and operating cost characteristics are used to cover peak, shoulder, and base load periods. Some may run for as long as 7,500 hours in a year, while others run only for a few hundred.

Many renewables have the characteristics of only being usable for some of the time, because of dependence on sun, wind or rain. So their use requires additional cost, which often takes the form of back-up diesel generators or battery storage.

Table 6.1 summarizes the estimated range of costs accumulated during the present study.

**Step 3.** *Estimate the net impact on CO₂ emissions of the different measures.* Figure 6.2 indicates the relative emissions of different commercially available power systems. It shows that even within fossil fuels, technologies exhibit wide differences. Emissions from an "average" conventional coal-fired steam turbine are three times those from the best available combined cycle gas turbine. The choice of plant will be affected by the imposition of carbon taxes.

The cost per kWh for each technology has been calculated on a stand-alone basis without consideration of system effects that could lower cost, particularly in systems with hydro and solar generation. Possible fully developed costs have been estimated for technologies under development and will show declining average costs over time. For proven technologies, the fully developed cost is an average or reflects possible technological improvement.
### TABLE 6.1 Summary of Indicative Cost Ranges for Conventional and Alternative Technologies

<table>
<thead>
<tr>
<th>Technology</th>
<th>Present cost (U.S. cents/kWh)</th>
<th>Possible fully developed cost (U.S. cents/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large coal</td>
<td>4 - 6</td>
<td>4</td>
</tr>
<tr>
<td>Oil</td>
<td>7 - 9</td>
<td>7</td>
</tr>
<tr>
<td>Nuclear</td>
<td>6 - 15</td>
<td>4</td>
</tr>
<tr>
<td>Single cycle gas turbine</td>
<td>9 - 12</td>
<td>7</td>
</tr>
<tr>
<td>Combined cycle gas turbine</td>
<td>7 - 10</td>
<td>6</td>
</tr>
<tr>
<td>Large storage hydro</td>
<td>6 - 20</td>
<td>5</td>
</tr>
<tr>
<td>Small storage hydro</td>
<td>10 - 30</td>
<td>15</td>
</tr>
<tr>
<td>Run of river hydro</td>
<td>10 - 30</td>
<td>15</td>
</tr>
<tr>
<td>Solar thermal</td>
<td>11 - 12</td>
<td>4</td>
</tr>
<tr>
<td>Solar photovoltaic</td>
<td>23 - 35</td>
<td>4</td>
</tr>
<tr>
<td>Wind</td>
<td>6 - 20</td>
<td>3</td>
</tr>
<tr>
<td>Wave</td>
<td>8 - 25</td>
<td>5</td>
</tr>
<tr>
<td>Geothermal</td>
<td>7 - 20</td>
<td>6</td>
</tr>
<tr>
<td>Landfill gas</td>
<td>4 - 10</td>
<td>3</td>
</tr>
<tr>
<td>Industrial waste</td>
<td>8 - 15</td>
<td>7</td>
</tr>
<tr>
<td>Municipal solid waste</td>
<td>5 - 12</td>
<td>5</td>
</tr>
<tr>
<td>Biomass: forestry</td>
<td>7 - 20</td>
<td>5</td>
</tr>
</tbody>
</table>

*Note:* Indicative estimates of current costs (U.S. cents/kWh) and possible costs following further research and development. Some of the above technologies—for example, solar photovoltaics and wind—require additional storage facilities if they are to supply electricity for the full load curve.

*Source:* London Economics estimates.
FIGURE 6.2 Greenhouse Gas Emissions from Commercially Available Power Plants

1. Average conventional steam turbine (coal, Eff 34 percent); 2. Best available steam turbine (coal, Eff 39 percent); 3. Pressurized fluidized bed combustion (PFBC) (coal, Eff 42 percent); 4. Average conventional steam turbine (oil, Eff 38 percent); 5. Best available combined-cycle gas turbine (oil, Eff 48 percent); 6. Cogeneration: average conventional steam turbine (coal, Eff 78 percent, E/H = 0.50); 7. Average combined cycle gas turbine (natural gas, Eff 36 percent); 8. Cogeneration: best available steam turbine (coal, Eff 83 percent, E/H = 0.60); 9. Best available combined cycle gas turbine (natural gas Eff 45 percent); 10. Cogeneration: pressurized fluidized bed combustion (coal, Eff 86 percent, E/H = 0.65); 11. Cogeneration: best available steam turbine (oil, Eff 81 percent, E/H = 0.60); 12. Cogeneration: steam-injected gas turbine (natural gas, Eff 75 percent, E/H = 0.80); 13. Cogeneration: best available combined cycle gas turbine (natural gas, Eff 77 percent, E/H = 1.0)

*Cogeneration. GHG emissions vary substantially among commercially available technologies for producing heat and power. Central-station power plants are compared with cogeneration plants providing both useful heat and power. The energy requirement for electricity production using cogeneration technologies is taken as the total energy supplied minus that which would have been required to produce the heat independently (assuming a boiler efficiency corresponding to a lower-heating value of 90 percent). All power plant efficiencies (Eff) are based on higher heating values. For the cogeneration system, the energy-to-heat ratios are given as E/H. The greenhouse gases are expressed as an equivalent amount of carbon dioxide (CO₂eq/kWh). Methane and methane-related fuel-cycle emissions from coal, oil, and natural gas consumption are taken into account.

Step 4. Estimate the net costs of reducing emissions using the different measures. This step requires the comparison of CO₂ emissions from any chosen technology with a "base case" of continued use of the existing technology and draws on the cost estimates prepared for (1B) above. An illustration in the power system context is as follows:

- Table 6.2 provides an example of the type of analysis that will be necessary for the specific case of the power sector (although in the particular country context, only a subset of the technologies listed here will be relevant).

- The first column of Table 6.2 shows a broad range of typical costs for each technology, and the second column a recent estimate of typical CO₂ emissions. The third column shows an "add-on" cost required to make this technology fully equivalent to the base technology (e.g., the cost of back-up diesel generators or battery storage).

- In the final column, these estimates are combined to create a "price per tonne of CO₂ saved," relative in this case to large coal stations.

It should be emphasized that an analysis such as that in Table 6.2 is only a starting point, in that the systems effects and inter-relations have not been covered (and indeed that few of the figures in this version are known with certainty). The appropriate method of bringing this information together is covered below. Nevertheless, the ranking provided by an analysis of this kind is helpful as a starting point for analysis.

The preliminary identification of costs per tonne CO₂ saved should act as a method of screening technological options and ranking them in order of priority. It should also be carried out for the other main CO₂-producing sectors, again to establish where priorities should lie.
**TABLE 6.2 Cost of CO₂ Abatement Using Different Technologies**

<table>
<thead>
<tr>
<th>Technology</th>
<th>Cost (1990) U.S. cents/KWh</th>
<th>Emissions CO₂ Kg/KWh</th>
<th>Add-on cost to cover load curve</th>
<th>Cost of CO₂ abatement relative to large coal ($/tonne CO₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large coal</td>
<td>5</td>
<td>1.13</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Oil</td>
<td>7 - 9</td>
<td>0.68</td>
<td>NA</td>
<td>45 - 89</td>
</tr>
<tr>
<td>Nuclear</td>
<td>10 - 15</td>
<td>0</td>
<td>NA</td>
<td>44 - 89</td>
</tr>
<tr>
<td>Single cycle gas turbine</td>
<td>9 - 12</td>
<td>0.59</td>
<td>NA</td>
<td>74 - 130</td>
</tr>
<tr>
<td>Combined cycle gas turbine</td>
<td>7 - 10</td>
<td>0.41</td>
<td>NA</td>
<td>28 - 69</td>
</tr>
<tr>
<td>Large storage hydro</td>
<td>6 - 20</td>
<td>0.003</td>
<td>NA</td>
<td>9 - 133</td>
</tr>
<tr>
<td>Small storage hydro</td>
<td>10 - 30</td>
<td>0.01</td>
<td>NA</td>
<td>45 - 223</td>
</tr>
<tr>
<td>Run of river hydro</td>
<td>10 - 30</td>
<td>0.003</td>
<td>NA</td>
<td>44 - 222</td>
</tr>
<tr>
<td>Solar thermal</td>
<td>8 - 12</td>
<td>0</td>
<td>10</td>
<td>115 - 150</td>
</tr>
<tr>
<td>Solar voltaic</td>
<td>20 - 35</td>
<td>0</td>
<td>10</td>
<td>221 - 354</td>
</tr>
<tr>
<td>Wind</td>
<td>8 - 20</td>
<td>0.007</td>
<td>10</td>
<td>116 - 223</td>
</tr>
<tr>
<td>Wave</td>
<td>8 - 25</td>
<td>0</td>
<td>10</td>
<td>115 - 266</td>
</tr>
<tr>
<td>Geothermal</td>
<td>7 - 20</td>
<td>0.05 - 0.07</td>
<td>10</td>
<td>112 - 234</td>
</tr>
<tr>
<td>Landfill gas</td>
<td>4 - 10</td>
<td>0.50</td>
<td>NA</td>
<td>-16 - 79</td>
</tr>
<tr>
<td>Industrial waste</td>
<td>8 - 15</td>
<td>NA</td>
<td>10</td>
<td>115 - 177</td>
</tr>
<tr>
<td>Municipal solid waste</td>
<td>5 - 12</td>
<td>NA</td>
<td>10</td>
<td>89 - 150</td>
</tr>
<tr>
<td>Biomass: forestry (sustainable)</td>
<td>7 - 20</td>
<td>-0.16</td>
<td>NA</td>
<td>16 - 116</td>
</tr>
</tbody>
</table>

Source: London Economics estimates.
Step 5. Establish the constraints faced by the country that will define the feasible combination of CO₂ abatement measures and instruments. This background data will need to cover a mix of economic, geographic, political and administrative factors. They will include the following:

- Constraints on capital and financial flows.
- Likely availability of private finance, and the cost penalties that the credit rating of the country may impose.
- Administrative systems for enforcing regulations or administering taxes.
- The operational details of the energy and power system (and transport system).
- Natural resources, exploitation and possibilities for availability of fuels, including imports. This will also need to cover any constraints on foreign exchange where the local currency is nonconvertible.
- Geographic details over land area available for renewable technologies, and, for example, hydrological, sunshine, and other climatic information.

Step 6. Identify and quantify possible joint benefits or costs. Before attempting any analysis of CO₂ reduction costs and benefits, it is necessary to establish whether the policies that might be followed, or the technologies that might be used, have other effects that would change their appropriateness. There are a wide range of such effects, but the following is a preliminary list of the more important ones:

- SO₂, NOₓ, and particulate emissions from power plants and other combustion plants.
- Methane emissions from, for example, natural gas pipelines (it should be noted that, because methane has a GHG damage potential more than 20 times that of CO₂, quite small gas leakages can cause environmental problems, and this could lead to a reversal of the appropriateness of a switch to gas technology in some power systems).
- The extent to which other environmental damage should change a view of renewables. Large storage hydroelectric schemes, for example, have considerable effects on forests, flora and fauna, as well as possible dislocation of populations. Wind farms are unsightly and noisy.
- The saving in running costs of energy efficiency schemes—as opposed to any environmental savings—must be taken into account in assessing their applicability.
- The need to treat emissions, and costs, in a total fuel cycle context. Appropriate definition of costs therefore includes all other incremental costs associated with the change.
- In the transport sector, reduced congestion, noise, accidents, and so on must be considered.
**Step 7.** Combine the global benefit of CO₂ reduction with any local joint benefits and compare with the MAC curve to establish the target level of CO₂ reduction. This is one of the hardest parts of the task. It involves the use of all the above data to create both the two MB curves of Figure 2.2 and the MAC curve. It is probable that the basis will be as follows:

- The MBₜ curve will be predominately the result of local valuation put on joint benefits, such as reduced congestion and air pollution.
- The MBₜ curve is likely to be the result of studies, such as Cline (1991) and Nordhaus's (1991) benefit estimations, and it may take the form of a single price (in terms of $/tonne CO₂ removed), or it will be a target set that is consistent with the conventions.
- The MAC curve for each country will be built up, as indicated in section 3, from a sequence of technological and other methods of ascending cost per tonne CO₂ saved. Note that systems effects may change the relative ranking and implied costs of each item.

**Step 8.** Assess the appropriate combinations of options to establish feasible implementation and estimate overall costs. Once the data described in steps 1-7 have been assembled, the options that will satisfy both the environmental goals and the constraints must be identified. Evidence to date, however, suggests that the feasible options may be few and, indeed, that even stabilization of CO₂ emissions may be different in the context of some developing countries.

**Step 9.** Explore the wider macroeconomic effects of the chosen option and the ability of the country to respond. This is crucial in determining the impact of a set of policies. Although this report has focused on the direct, or first-round, costs of options to reduce CO₂ emissions, general equilibrium, or second-round, effects may also be important in the long run. Losses faced by each country will be crucially dependent on how long it takes to adjust to the new equilibrium.

**Step 10.** Refine the analysis to reduce the costs of implementation and establish the appropriate timing for actions. As already noted, none of the parameters on which the set of feasible options is based is fixed. All the constraints that define the feasible set are in principle capable of relaxation, technologies and costs will change, and both supply and demand conditions can be adjusted by appropriate policies. It is important, therefore, to identify and prioritize actions that may be taken to provide a lower-cost path to the required level of CO₂ reductions (and, if necessary, to redefine the target level for abatement). A checklist of possible methods of reducing the overall cost includes the following:

a. **Relaxing constraints.**

- The difference in cost between a capital-constrained and an unconstrained CO₂ abatement strategy is important.
- The relaxation of other constraints may also be important. For example, the availability of new fuel supplies (e.g., by the construction of a new gas pipeline) may turn out to provide lower costs.
b. Reducing abatement costs by encouraging new technologies.

- This is more of an international strategy than for any particular country, though it may be relevant for the larger developing countries. If, for example, solar thermal power is found to be a promising alternative, but is marginally too expensive to be "least cost," then an appropriate route for technical assistance might be in the development of this specific technology.

- In general, the encouragement of promising technologies that are only marginally too expensive or where technical options are precluded by specific impediments will be an important part of the solution.

c. Solving administrative and systems problems that are limiting the feasible set of options. There are a number of preconditions for the least-cost implementation of abatement policies that have been identified in previous sections. In the power system context, they include:

- Tax administration
- Cost-reflective pricing
- Sufficient transmission and distribution infrastructure
- Grid and financial discipline.

d. Steps to reduce losses by making factor substitution possible. These include:

- Training schemes
- Transitional subsidies
- Encouragement of new enterprises
- Technical assistance programs.

The appropriate timing pattern for least-cost adjustment will involve a mixture of these items. For example, if it is believed that renewable technologies can be made to fall steeply in cost, and that it will take five years for sufficient administrative and financial structures to be developed, then it will be least-cost to wait before making major changes.
REFERENCES


Ross, M. 1989. "Improving the Efficiency of Electricity Use in Manufacturing." Science 244.


ANNEX: INTERNATIONAL TRADABLE PERMITS

The differences between countries identified above suggest that abatement costs and appropriate rates of adjustment may vary widely. A possible mechanism for allocating policies in a global least-cost manner may be international tradable permits. There are, however, two main technical problems: (1) administrative practicality; and (2) the allocation problem. But permits could be allocated in such a way as to enable developing countries to participate in global initiatives.

Administrative Issues

A trading system requires a supranational authority, supported by reporting and monitoring procedures that would reassure all participants that all other countries' emissions corresponded to their holdings of permits. The regulator of any permit market needs to perform the basic functions of a clearing bank—to establish that those who draw checks (the sellers of permits) have funds in their account (surplus permits), and to keep track of transactions.

It would not be essential for the international authority actually to manage the trade in permits, but the need to manage the allocation of permits (see below) and to verify the authenticity of the permits which would be offered for sale argues for such an arrangement. However, the sums involved, and the associated power, would be considerable—greater, perhaps, than nations would wish to entrust to an international authority.

Because emissions of CO₂ can be calculated reasonably accurately from the consumption of fuels, internationally tradable permits would not require recording procedures within each country that were any more detailed or onerous than would be required for a carbon tax. The problem would not be one of mechanisms but of the credibility of the arrangements. The large quantities of foreign currency that some countries could secure by selling permits might offer too great a temptation to "print money." The international authority would need powers of inspection that many governments might regard as unacceptably intrusive; but, as we shall see, the attractions of this scheme may outweigh objections to this requirement.

How Should Permits be Allocated?

A major problem in designing an internationally tradable permits system concerns the initial allocation of permits. The major emitters of CO₂ were shown in Table 1.1 in the main text. This table reveals the enormous differences in annual per capita emissions (North America, 1,200

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1. Centralized control would probably be exercised within countries. Some countries would probably seek to control the trade in permits, or at least to channel the trade through a central agency, to ensure that the foreign exchange proceeds are repatriated and lodged in the central bank.
Mtonnes; India, 150 Mtonnes). The two main drivers of global CO\textsubscript{2} are population and per capita GDP, but energy-intensity and the energy mix in each economy are also important. In developing countries, the first three factors conspire to generate rates of growth in CO\textsubscript{2} emission three times the world average.

The problem for developing countries is that they face constraints of external financing. Pollution control would require additional imports of equipment, but the reduction in CO\textsubscript{2} would not generate this foreign exchange to cover these costs unless CO\textsubscript{2} reduction earned foreign exchange. Tradable permits would provide a mechanism for earning this foreign exchange.

Establishing the baseline distribution of internationally tradable permits would be key to their launching. A variety of plausible rules have been proposed for doing so, but each would have its objectors:

- If permits were allocated on the basis of emissions, they would reward the heaviest polluters and the developed countries, and penalize poor countries, which tend to use more energy per dollar of GDP.

- If they were allocated on the basis of GNP, they would reward the developed countries, as well as running into the familiar problems of how to measure GDP.

- If they were made on the basis of equiproportional reductions in emissions, they would penalize countries that expect to grow rapidly as well as the energy-efficient countries that have already exploited the cheaper abatement options.

Grubb (1989) has argued in favor of a per capita entitlement to emit carbon, as being morally defensible (equal rights to every citizen of the world to a global atmospheric resource), and less open to disputes about data than a GDP-based allocation, as well as being redistributive in a way which many might support.

None of these rules are likely to win universal support. A distribution rule that might stand a better chance of doing so would use countries' projected GDP as the basis, adjusted for energy efficiency gains that are associated with economic growth. This allocation might persuade developing countries to participate; developed countries might be persuaded that it made due allowance for "catching up." With such an initial allocation, developing countries would almost certainly be net sellers of permits, and hence net beneficiaries of the trading system, since the permits would be free.

There may need to be constraints on the rate at which developing countries sold them. If a country cashed in a quantity of internationally tradable permits that called into question its ability to sustain its economic growth, and hence its future commitment to the internationally tradable permits system, the international community might wish to impose some constraints.

The attraction of this scheme is that if developing countries were awarded permits on the basis of future GDP, or on some population-weighted basis, they would cash some of them and thereby release the external financing constraints. The sums that might be involved in permit
trades could be very significant. About 5 billion tonnes of carbon were emitted in 1987. If the permit price were $100/tonne carbon—a representative calculation from econometric modeling—the total value of just one year’s stock of permits would be $500 billion. If only 20 percent were traded each year, the annual transactions would be $100 billion.

The significance of a population-weighted distribution is that if developing countries used all their permits, their marginal cost of abatement would be lower than for developed countries. Some developing countries would choose to abate more, by selling their permits; the foreign exchange proceeds of the sales would finance the imported equipment necessary to do this. Moreover, by selling the permits to private sector buyers, developing countries could tap into new sources of external funding.

Market distortions would be expected. On whatever basis permits were allocated, major players in the permit market (e.g., the United States, Russia, China, India) would each have some power to influence the permit price. Would this undermine the efficiency of the permit market? The analysis carried out so far on the effects of dominant positions on permit prices suggests that market imperfections would be one of the lesser problems confronting a permit market.

Conclusions

A proposal for internationally traded permits would encounter two principal difficulties:

- An effective international authority would be needed, and this would imply a greater transfer of economic power, and some intrusion.

- The allocation problem is likely to prove contentious.

But the attraction of internationally tradable permits is that they equalize the costs of controlling CO$_2$ across countries and could be allocated in ways that redistributed income to the benefit of developing countries, as a price of their support for a global initiative. In doing so, they would provide developing countries with the means to cover the foreign exchange cost of abatement.