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THE COSTS OF LIMITING FOSSIL-FUEL CO_2 EMISSIONS: A Survey and Analysis[1]

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1. INTRODUCTION

In the late 1980s, interest flourished in the issue of global climate change. Many studies focussed on the options for limiting anthropogenic emissions of greenhouse-related gases and managing the consequences of global warming and climate change. Making appropriate policy choices requires information on both the costs and benefits, as they occur over time, of policy interventions, and an increasing number of studies have sought to quantify the costs especially of limiting CO_2 emissions, as the dominant anthropogenic source. Such analyses now form an important part of overall policy assessments and influence international negotiations on policy responses. However, these studies are not well understood. In this paper we seek to analyze the literature on the costs of CO_2 abatement.

The majority of work in estimating the costs of reducing greenhouse gas emissions has occurred since 1988, but interest in the issue of costing emissions reductions began more than a decade earlier with the work of Nordhaus (1, 2). Nordhaus's early work focussed on the issue of reducing fossil-fuel CO_2 emissions, as did that of Edmonds & Reilly (3, 4), Kosobud et al (5), Seidel & Keyes (6), Rose et al (7), Lovins et al (8), Williams et al (9), Manne (10), Perry et al (11), Nordhaus & Yohe (12), and Mintzer (13), among others. Only Seidel & Keyes, Perry et al, and Mintzer examined non-CO_2 emissions, and these studies treated them separately and in an ad hoc manner; none of the studies took land-use change into account explicitly.

While not the primary focus of their analysis, some of the studies conducted prior to 1988 analyzed the cost of emissions reductions. The results of these studies foreshadow the current debate. Edmonds & Reilly (14) noted in their 1985 literature assessment:

> The economic costs of CO_2 abatement policies have only been partially analyzed at this time. Edmonds and Reilly, Kosobud et al, and Nordhaus, each using a different model, indicate that the reduction in aggregate GNP associated with even stringent punitive strategies is not large, usually only a few percentage points. Lovins et al argued that the costs might actually be negative.

This assessment explores the subsequent development, deepening, and broadening of these research veins, focussing on the past five years of research on the costs of limiting CO_2 emissions. While other gases are relevant (15),[2] as invited by Annual Reviews we focus on fossil CO_2 because this forms the bulk of projected radiative change over the next century, because debates about the economic impact of limiting greenhouse gas emissions have focussed on fossil-fuel CO_2 as potentially the most expensive, and because data concerning fossil CO_2 sources are good and the relevant research base is rich and deep. We recognize the potential role of forests as a "sink" for CO_2 emissions as a significant but currently separate issue which is beyond the scope of this paper.

The purpose of this paper is fourfold. First, we seek to give a broad and accessible guide to the main studies reported over the past five years.[3] Second, we seek to clarify the issues involved in estimating abatement costs through a systematic study and classification of the relevant concepts. Third, through critical analysis of reported results, we suggest ranges of plausible estimates. Finally, we highlight the most important areas of uncertainty or confusion and suggest areas on which future research needs to concentrate.

To this end, we start (Section 2) by noting differing uses of the term "costs" and the way in which scope and definition of analysis affects results.

[2]Note that the list of relevant emitted gases differs importantly from the list of greenhouse gases. The list of relevant greenhouse gases, that is, those gases that are effectively transparent to incoming sunlight but that absorb in the infrared spectrum, includes CO_2, CH_4, N_2O, O_3, H_2O, CFCs, and CFC substitutes. Greenhouse-related emitted gases are linked to greenhouse gases through natural processes such as atmospheric chemistry and albedo.

[3]In finalizing this review, we have sought to reference the most accessible, relevant, and general sources, rather than obscure or superseded ones. In particular, the series of papers by Cline, and by Manne & Richels, have each been brought together in books; various studies for the European Commission have been brought together in a two-volume edition of the *European Economy*; and many of the reports by the Organization for Economic Cooperation and Development (OECD) Economics Department have been reproduced in a special issue of *OECD Economic Studies*. All these volumes were published during 1992, and to the extent possible we reference the books rather than the many separate research papers.

We clarify the way in which we use the term in this paper so that results are to the extent possible comparable.

Sections 3 and 4 then review abatement cost estimates. Section 3 summarizes estimates derived directly from studies of the technologies available for limiting emissions, and ways of interpreting them. Section 4 summarizes the results of studies that have sought to model the impact of CO_2 abatement on whole energy systems.

Sections 5 and 6 then explore the modelling and assumption differences that affect cost estimates. Section 5 explains and classifies the different kinds of models that have been applied, and Section 6 reviews the impact of variations in key numerical parameters. Sections 2–6 draw heavily on the review of literature performed for Phase 1 of the United Nations Environment Programme (UNEP) Greenhouse Gas Abatement Costing Studies (16).

The paper then draws together the material in sections 2–6, to examine critically the nature and relative importance of these various sources of cost difference, and the implications that follow from this. Section 7 analyzes the economic and engineering perspectives, the differences between which are a major source of cost differences; the discussion includes the role of energy-efficiency and of low-carbon supply technologies, as well as resolution of these perspectives. Section 8 then examines issues relating to the strategy of abatement and scope of analysis. Finally, Section 9 draws general conclusions from the study, and suggests some implications for future research.

2. MODELLING AND COSTING DEFINITIONS AND PARADIGMS

The cost of emissions reductions is always computed as a difference in a given measure of performance between a reference scenario and a scenario that involves lower emissions. By far the most commonly used measures of performance are the net direct financial costs to the energy sector assessed at a specified discount rate; and the estimated impact on gross national product (GNP), or its close cousin GDP. GNP is the monetary value of new final goods and services produced in a given year, and it provides a measure of the scale of human activities that pass through markets, plus imputed values of some nonmarket activities. It is generally assumed that financial costs in the energy sector can be closely related to impacts on GNP, though as noted below this is not always the case.

Neither direct financial costs nor GNP provide direct measures of human welfare. One factor is that human welfare does not necessarily increase linearly with the degree of consumption; a given loss of income will likely matter far more to poor people, or poor countries, than to richer ones, for example. Some studies attempt to capture this through "equivalent welfare" measures, but these still rely centrally on a marketed-products basis. A broader limitation is revealed by the fact that there are many examples where GNP moves in the opposite direction to human well-being. For example, a disease that increases the sale of medicine may boost GNP but make individuals worse off; environmental disasters can stimulate economic activity, but the environment (and human enjoyment of it) is diminished.

This reflects the fact that GNP does not incorporate many nonmarket factors that affect welfare. Some studies have sought to examine explicitly the impact of abatement on various external costs, and concluded that these can be very significant (Section 8.4). However, in general, studies focus on financial costs or GNP impact. In the broader literature, other welfare indices have been attempted (such as the United Nations Development Programme's (UNDP) Human Development Index), but data are rarely adequate to quantify impacts in such terms in abatement-costing studies. At present, for quantifying results there is little practical alternative to working with monetary cost and GNP impacts, but the caveats about these as measures of welfare impacts need to be borne in mind.

Nor is GNP necessarily a good measure of consumption. For example, some forms of carbon taxation can move resources from consumption to investment, which can boost GNP but for many years may lower consumption. It is unclear whether welfare has improved or declined. Alternatively, tax revenues might be returned to households, which could raise household consumption but depress long-term GNP.

This also raises the issue of comparing costs in different periods. Results concerning abatement costs are sensitive to the assumed discount rate. This is particularly important with respect to evaluating the importance of the potential impacts from climate change, where the appropriate discount rate is both crucially important (because of the long timescales) and very uncertain (because of the timescales and because it is an attempt to make an explicit valuation of long-term public welfare); for a discussion see Cline (17). For assessing abatement costs, the timescales are less and the discount rate has to be related to the actual rates revealed or set by government for the sector in which the abatement investments are being made, so this is a less central (though still significant) issue. In this study we simply report results as estimated by the studies concerned, given the discount rates they assume (which, for the major energy investments considered in this study, are typically about 5–8% real discount rate).

Almost since the beginning of costing studies, a clear division has existed between those that fundamentally use an economic approach, which relies on observed market behavior and which generally assume that markets operate equally efficiently in the reference and abatement case; and those that use a technology-engineering approach, which emphasizes a technically optimal abatement scenario (which may be contrasted with a reference case that is by implication not optimal). The choice of "cost paradigm" in this sense is a fundamental determinant of results—including often the sign of abatement costs—and these differences form an important theme of this paper.

Economic studies use "top-down" models, which analyze aggregated behavior based on economic indices of prices and elasticities, and focus implicitly or explicitly on the use of carbon taxes to limit emissions. These studies have mostly concluded that relatively large carbon taxes (e.g. that could much more than double the mine-mouth cost of coal) would be required to achieve goals such as the stabilization of fossil-fuel carbon emissions.

Technology-oriented studies use "bottom-up" engineering models, which focus on the integration of technology cost and performance data. Many such studies have concluded conversely that emission reductions could be achieved with net cost savings.

The division between the "economic paradigm" and the "engineering paradigm" is closely related—but not identical—to the division between "top-down" and "bottom-up" models, as it has emerged in the literature. These differences, as a major source of differing estimates, form a strong theme in this paper: the formal modelling differences are clarified in Section 5.1, and the underlying "paradigmatic" issues are explored in Section 7.

There are also many modelling differences within each category. Most notably, since 1990 an important general division has become evident between the application of top-down models that have been developed for long-run "equilibrium" analysis of energy and abatement costs (reflecting an idealized economy with optimal allocation of resources), and conventional macro-economic models designed for shorter-run analysis of the dynamic responses of economies (which reflect many existing imperfections). Long-run equilibrium models generally estimate the costs of reducing emissions to be positive and high by the standards of most environmental measures implemented to date. Macro-economic models indicate a far more complex pattern of responses and cost indicators, which may move in different directions and vary over time. The distinctions are explored further in Section 5.2.

Rather than initiate our survey with a detailed analysis of models, however, we start by summarizing the results that have been presented, with a review and interpretation of technology cost curves (Section 3) and then a summary of general results from system modelling studies (Section 4).

3. ABATEMENT TECHNOLOGIES AND TECHNOLOGY COST CURVES

3.1 Technology Cost-Curve Results

Clearly a major determinant of CO_2 abatement costs will be the costs and adequacy of technologies that can reduce emissions. Many studies of the technologies that could help to limit greenhouse gas emissions have been conducted; major reviews are given in IPCC (18), Fulkerson et al (19), IEA/OECD (20), Grubb (21), and Goldemberg et al (22). In addition, many international databases with information on energy technologies have now been established; the UNEP study (16, Appendix 1) lists no less than 13 technology databases now available.

Technology cost curves provide a useful way of summarizing the technical potential for limiting emissions as identified in such studies. The simplest approach is to stack up different technologies in order of the cost of emission reductions or energy displaced, though cost curves can be used to represent the output for almost any degree of sophistication in modelling. There are various ways of generating cost curves of successively greater sophistication and consistency, as discussed in UNEP (16).

Discrete technology cost curves for various developed countries are presented by Lovins & Lovins (23), Mills et al (24), Jackson (25), and Krause et al (26). An EPRI (27) study examined potential savings in the US electricity sector and concluded that "if by the year 2000 the entire stock of electrical end-use stock were to be replaced with the most efficient end-use technologies (nearly all of them estimated to be cheaper than equivalent supply), the maximum savings could range from 24% to 44% of electricity supply." Lovins & Lovins (23, 27) suggest much higher potential savings still. The cost curves associated with these two analyses are shown in Figure 1, which demonstrates that a good database does not necessarily ensure comparable results; the potential estimated by EPRI (the upper curve) is clearly very much smaller than that estimated by Lovins (the lower curve). Compared against typical US electricity prices of at least 6–7 cents per kWh, however, both illustrate that substantial emission reductions appear to be available at net cost savings.

Technology cost curves have by no means been confined to developed countries. A number are presented in studies of the Asian Energy Institute network summarized in (16); Figure 2 shows a discrete technology cost curve estimated for CO_2 savings available by 2000 in Brazil. Figure 3 shows a continuous version of a technology cost curve for Poland.

A consistent set of national abatement cost curves, derived by aggregating technology studies, is presented by COHERENCE for the Commission of

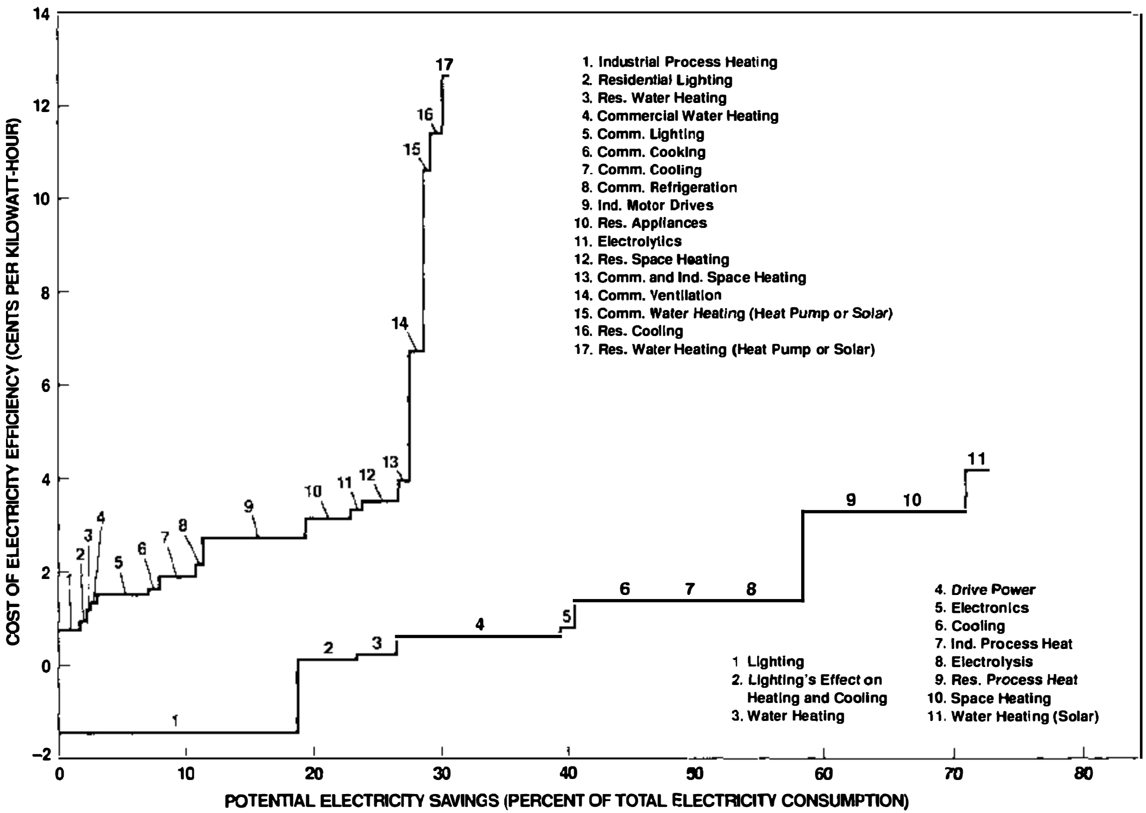


Figure 1 Discrete energy-efficient technology cost curves for the United States. The figure shows two estimates of the potential savings of electricity (as a percentage of system demand) available by using various more efficient technologies, in order of increasing cost per unit saved. These costs compare with typical US electricity prices of 6–8 cents per kWh; all costs below this thus involve net economic savings for the user at the discount rates employed for the analysis. The upper curve is an estimate by the US Electric Power Research Institute; the lower curve is by the Rocky Mountain Institute of Amory Lovins et al. Source: *Scientific American*, September 1990.

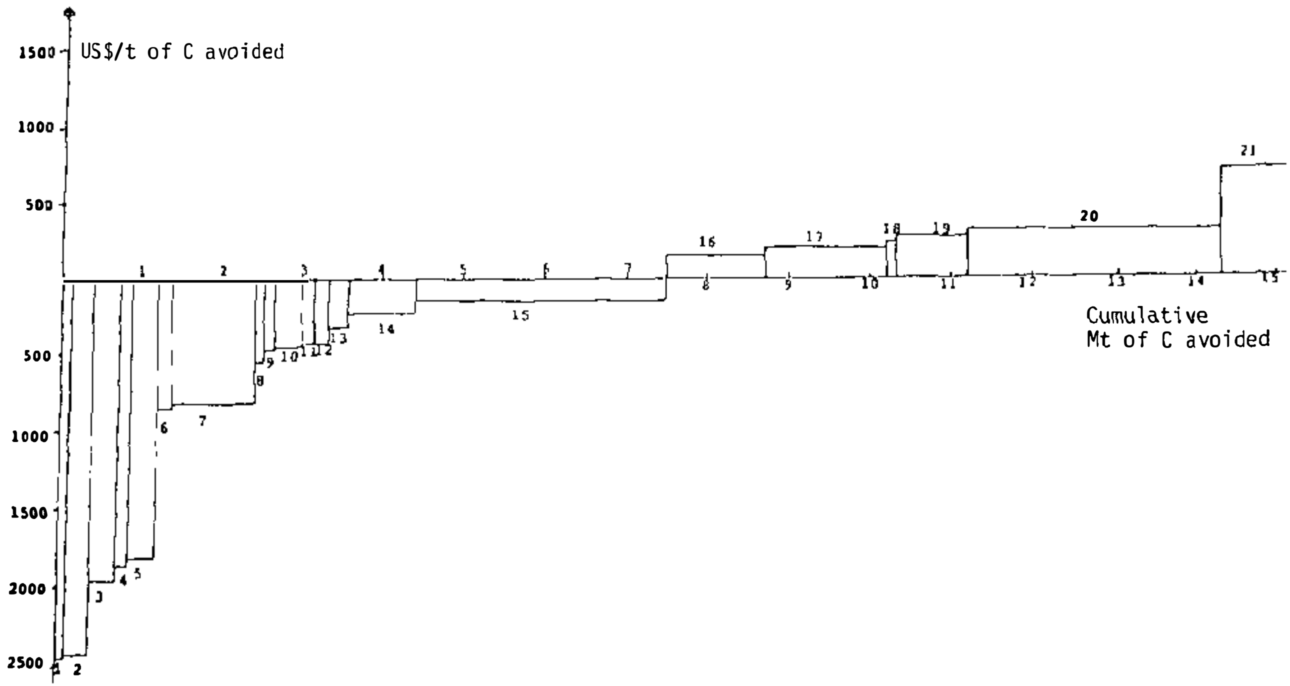


Figure 2 Discrete CO_2 abatement technology cost curve: Brazil. Cumulative amount of C avoided by the year 2000 for several technological improvements. 1—Incandescent (incand.) efficient (eff.) × incand. standard (std.)—commercial sector. 2—Fluorescent (fluor.) std. × incand. std.—commercial sector. 3—Fluor. eff. × fluor. std.—commercial sector. 4—Compact fluor. × incand. std.—commercial sector. 5—Incand. eff. × incand. std.—residential sector. 6—Fluor. eff. × fluor. std.—industrial sector. 7—fluor. std. × incand. std.—residential sector. 8—Improved electric ovens—industrial sector. 9—High eff. motors—industrial sector. 10—Housekeeping measures—industrial sector. 11—Variable-speed motors—industrial sector. 12—Better electrolytic processes—industrial sector. 13—Improved air-conditioners—residential sector. 14—Compact fluor. × incand. std.—residential sector. 15—More eff. vehicles—transport sector. 16—More efficient refrigerators—residential sector. 17—Alternative fuel alcohol—transport sector. 18—More eff. public illumination—public sector. 19—Highway improvements—transport sector. 20—Solar water heating—residential sector. 21—Eff. diesel engine—transport sector.

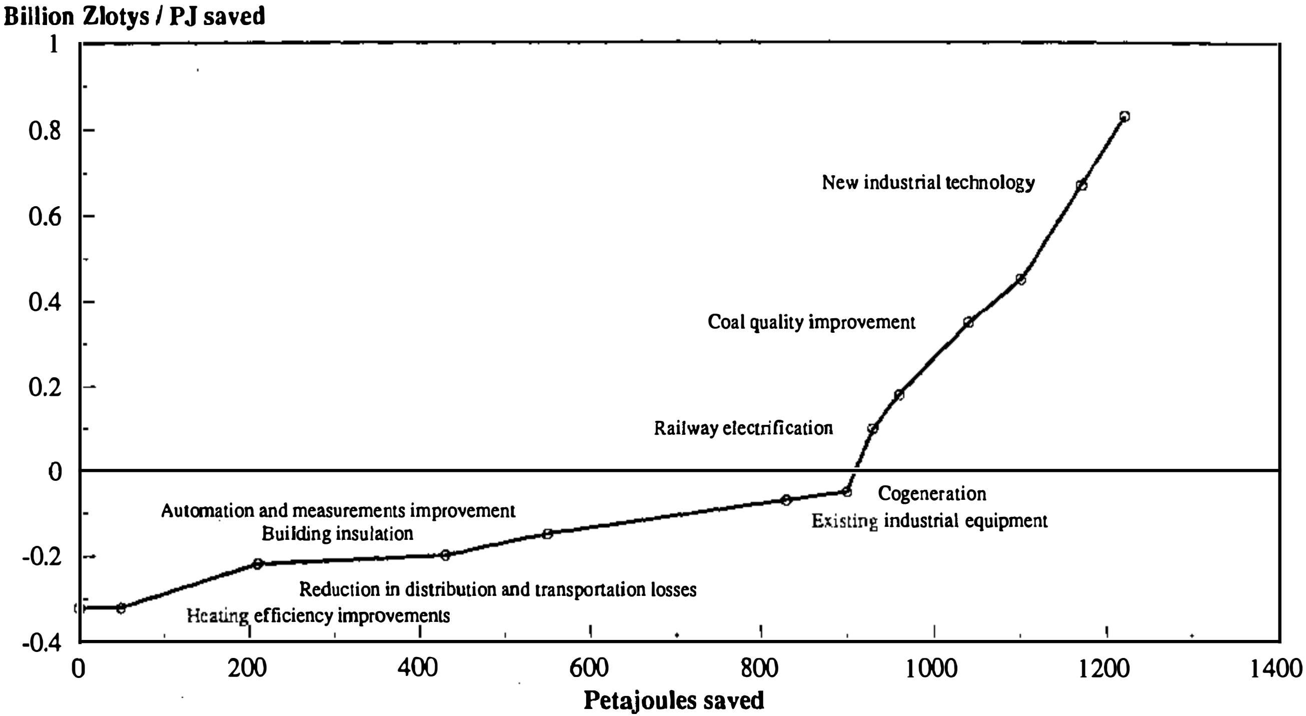
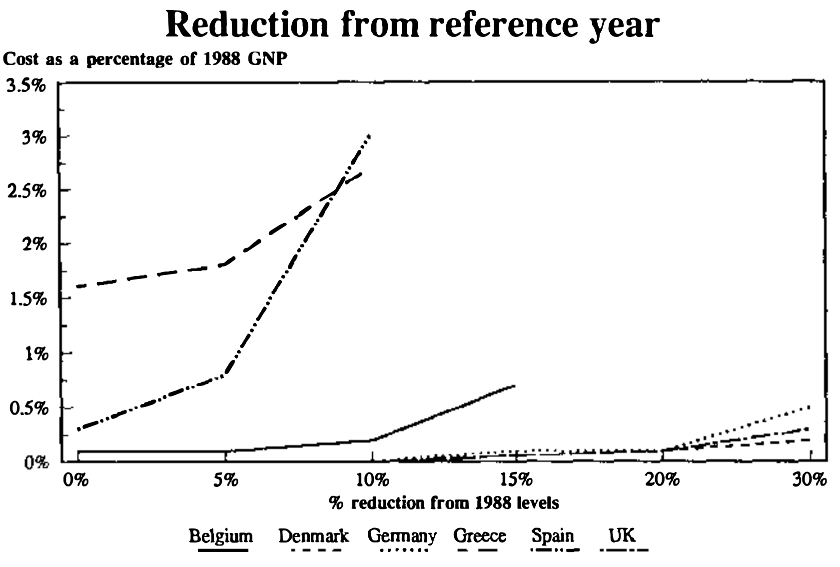


Figure 3 Continuous energy-efficient technology cost curve: Poland. Source: Sitnicki (51)



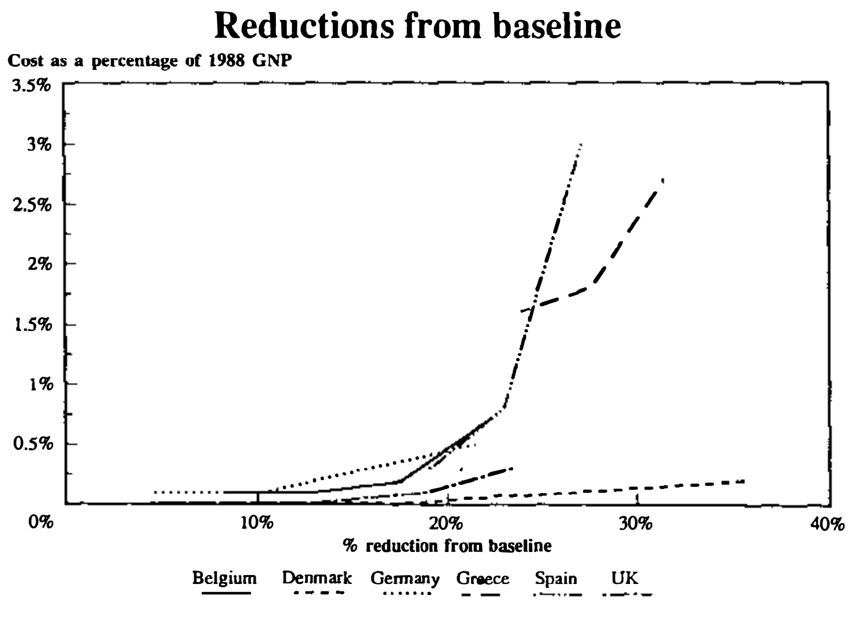


Figure 4 Abatement technology cost curves for selected EC countries. Source: COHERENCE/CEC (29)

the European Communities (29). Figure 4 summarizes the results, which indicate considerable variation between countries and highlight the dependence on the baseline projections; the technologies identified offer stabilization of emissions relative to a base year (1988) at little or no cost for the northern European countries, in which baseline emissions growth is expected to be slow, but at much greater cost for the southern European countries, which expect rapid growth in baseline emissions.

Finally we note that the scope and basis of cost curves can vary greatly. The Tata Energy Research Institute has developed a detailed appraisal that for India focusses on investment requirements, rather than net costs/savings. Most curves have been confined to the energy sector, or parts thereof, but others (such as the Indian study) include reforestation, and some address other gases as well. Nordhaus (30) presents an approximate composite curve that seeks to include chlorofluorocarbons (CFCs) as well in a global greenhouse-gas abatement curve. The Nordhaus analysis also reinforces the fact that cost curves are a way of presenting data, not of generating results; it seeks to summarize a wide range of results from economic models, and has no "negative cost" section.

3.2 Limitations and Interpretation

Abatement cost curves reflect the weaknesses and strengths of the procedures used to produce them. The simplest technology curves usefully summarize technical data, but may have substantial limitations as guides to actual abatement costs. In part this is because, unless they are developed iteratively using quite sophisticated system models, they may neglect interdependencies among abatement options and thus "double count" some emissions savings—the CO_2 savings from reducing electricity demand may for example be much reduced if nonfossil sources are introduced later to displace coal power generation. They may also neglect interactions between various end-uses, for example that between heat and lighting in widely diverse building environments. Frequently also they do not reflect adequately the timescales involved in bringing the technologies into place and the underlying growth in demand that may occur in the interim.

Even after such issues are carefully incorporated, technology assessments and cost curves (particularly for end-use technologies) still demonstrate a large potential for emission savings apparently at "negative cost"—technologies that would both reduce emissions and yield net financial savings. Typically, these suggest a potential to reduce emissions by well over 20% at net cost savings. The uncertainties, however, are very large, and, to be meaningful, numbers have to be defined very carefully in terms of scope and timescale. Based on an extensive review of technologies and related cost-curve studies, Grubb (21, Chapter 2) concludes that "substituting identified and cost-effective technologies in OECD countries could in principle increase the efficiency of electricity use by up to 50%, and of other applications by 15–40%, over the next two decades. Fully optimizing energy systems would yield larger savings, but it is far from clear how much of this potential can be tapped."

Thus, technology studies and cost curves show that a large "energy-efficiency gap" exists between the apparent technical potential for cost-effective improvements, and what is currently taken up in energy markets. In well-functioning markets, cost-effective options should be exploited anyway, since someone should profit by doing so. Some of the cost-effective potential may be taken up over time. But if such technologies are not being exploited, this may indicate that other important factors are not captured in technology analysis. For example, there may be hidden costs, or people may be unaware of the options, or there may be other obstacles to uptake. The acceptability of different options may also vary, for least cost is by no means the only criterion that matters to people. This illustrates the fact that the apparent technical potential in fact comprises a number of different components. As illustrated in Figure 5, realizable gains consist of:

1. those that are economically attractive in their own right and that will be installed without policy changes;
2. those that would not be obtained unless institutional constraints and barriers are removed, and/or other micro-economic policies are implemented to increase the take-up of cost-effective options;
3. those that are justified on the basis of nongreenhouse external benefits (e.g. reduced other environmental impacts, increased energy security).

In addition, some apparently cost-effective savings cannot be realized. The real economic potential differs from apparent potential due to:

1. "take back" or "rebound" of savings (improved efficiency reduces the cost of the associated energy service and therefore stimulates increased demand for the energy service);
2. unavoidable hidden costs (there may be costs associated with the use of a technology or policies to stimulate its uptake that are not revealed in a simplified analysis);
3. consumer preference (the technologies may not be a perfect substitute in the provision of the energy service, which may either increase or decrease consumer readiness to take up more efficient technologies, depending on their characteristics). For example, it would be technically

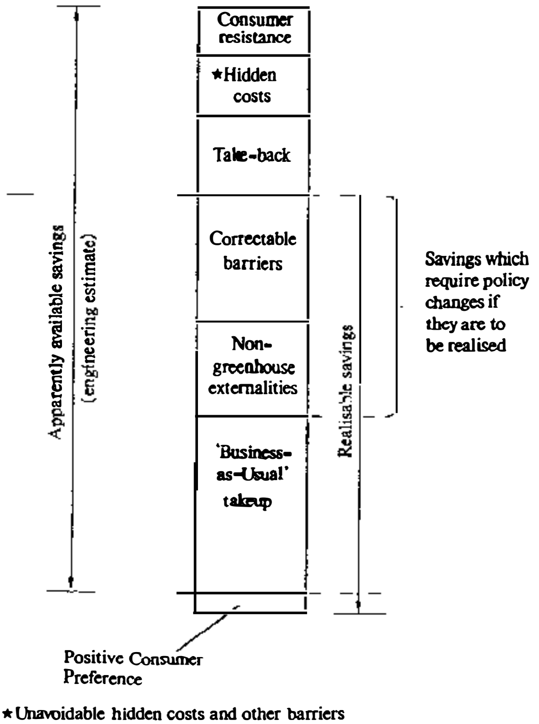


Figure 5 Energy-efficiency: Engineering potential and realizable gains—a classification. Source: Grubb (21).

possible and highly "cost-effective" to mandate a doubling of car efficiency in most countries; but it would probably make the vehicles available smaller and less powerful, which people may consider unacceptable (often this can also be considered as an aspect of hidden costs).

These different components need to be understood before drawing conclusions about the scope for "cost-free" reductions. We underline that such cost curves identify a technical potential, but there is no expectation that all of this can be realized. Part of the key is to consider specific policies for introducing better technologies, set against explicit baseline scenarios that incorporate some "business as usual" uptake. Johansson et al (31) present a cost curve described partly in terms of particular policy changes to introduce more efficient energy technologies in the United States, drawing in part on much more detailed implementation studies. Drawing on such studies, estimates of the practical potential based on such cost curves are discussed in Section 7.3 below.

To conclude, cost curves can be extremely useful and flexible ways of displaying data, and those that summarize technical potentials consistently indicate a large potential for technologies that can reduce CO_2 emissions with net cost reductions. But they can only reflect the strengths and weaknesses of the models used to generate the data, and the extent to which these models reflect interdependencies, hidden costs, and issues of implementation and timescales. What matters is not the cost curve itself, but the underlying methods and models used to produce results. In this context, modelling studies that seek to encompass whole systems and economies have attracted particular attention, and it is to these that we now turn.

4. A REVIEW OF SYSTEM-WIDE ABATEMENT COST ESTIMATES

A wide variety of abatement costing studies at the global and national levels have been carried out.[4] In this section, we summarize the results from cost studies first at the global level, and then from various national cost estimates across a range of modelling methods and countries, focussing first on the extensive range of US studies, then other OECD studies, and finally studies of non-OECD regions. The subsequent sections examine the reasons for differing cost results.

4.1 Global Studies

In this section we summarize results from six major models used to estimate the global costs of limiting CO_2 emissions, listed in Table 1. As summarized immediately below (modelling terms and classification are discussed in Section 5), four of these use fundamentally different global energy/economic models, one uses an economic growth modelling framework oriented towards technology development, and one is a global bottom-up study. Other global models have been developed, notably the models of Rutherford (CRTM) and Peck & Teisberg (CETA), the IEA (32), McKibben & Wilcoxen (33), and the ICF "global macro-energy model" used as part of the "atmospheric stabilization framework (ASF)" for US Environmental Protection Agency (EPA) studies (34). These and others (35) are not included here because

[4]In addition, many local studies, which focus on policy-based studies for particular cities or utilities, have been conducted. These generally emphasize implementing the "cost-free" potential identified in bottom-up studies, but are too varied and specific to cover here, and are often not published in the open literature.

Table 1 Global CO_2 abatement cost modelling studies

Author (reference)	Key	CO_2 reduction from baseline	CO_2 reduction from reference year[a]	GNP impact/cost (reduction) from baseline
Anderson & Bird (45)	AB (2050)	68%	−17%	2.8%
Burniaux et al (72)	B (2020)	37%	17%	1.8%
Burniaux et al (43)	B (2050)	64%, 64%, 66%	−18%, −18%, −11%	2.1%, 1.0%, 0.3%[b]
Edmonds & Barns (81)	EB (2025)	14%, 36%, 47%, 70%		0.1%, 0.5%, 0.7%, 2.2%[c]
Edmonds & Barns (82)	EB (2020, 2050, 2095)	45%, 70%, 88%	22%, 41%, 53%	1.9%, 3.7%, 5.7%
Manne & Richels (39)	MR (2100)	75%	−16%	4.0%
Manne (132)	M (2020, 2050, 2100)	45%, 70%, 88%	13%, 25%, 21%	2.9%, 2.7%, 4.7%
Mintzer (13)	Mi (2075)	88%	67%	3.0%
Oliveira Martins et al (133)	OM (2020, 2050)	45%, 70%	−2%, 2%	1.9%, 2.6%
Perroni & Rutherford (134)	PR (2010)	23%		1.0%
Rutherford (41)	R (2020, 2050, 2100)	45%, 70%, 88%	15%, 28%, 43%	1.5%, 2.4%, 3.6%
Whalley & Wigle (36)	WW (2030)	50%		4.4%, 4.4%, 4.2%[d]
Goldemberg et al (22)	G (2020)	50%	0%	0%[e]

[a] Negative values imply an increase in CO_2

[b] Toronto-type agreement in all three cases, with tradeable permits in the second and third cases and removal of energy subsidies in the third case.

[c] Costs as estimated from consumer + producer surplus (see text).

[d] The three numbers refer to three different tax forms: a national producer tax, a national consumer tax, and a global tax with per capita redistribution of revenues.

[e] The cost value is indicative of the estimate by this study's authors that their scenario would incur no additional costs; it is not a modelling result.

they are either based on models already covered or do not generate results in a relevant comparable form.[5]

The six major global models/studies reviewed here are:

1. *Whalley & Wigle* (36, 37) use a comparative static, economic general equilibrium model, incorporating trade but with only two fuel types (carbon and noncarbon) and no representation or backstop or other technologies. Their analysis focussed on trade and the implications of different ways of applying taxes and distributing emission constraints.
2. The *Global 2100* model of Manne & Richels (38–40) is a top-down general equilibrium model with a small selection of supply-side energy technologies, including carbon-free "backstop" technologies, which are available in unlimited quantities when the price becomes high enough. The model is fully optimizing within each of five regions, but there is limited trade between regions, so the result is not a global least-cost abatement. (The constraints used involved relatively high losses for the Soviet Union and China in particular.) Derivatives of this model include Rutherford's Carbon Rights Trade Model (CRTM) (41), which relaxes the no-trade constraint, and the Carbon Emissions Trajectory Assessment (CETA) (42), which aggregates the regions and incorporates a climate damage function.
3. The *Edmonds-Reilly-Barns* model (ERB) (3, 4) is an energy–greenhouse gas simulation model with detailed representation of energy supply technologies, including cost curves, with energy trade between each of nine regions. The model has been widely distributed and used by different authors. The model contains a highly simplified macro-economic linkage intended to reflect feedback effects, not for GNP evaluation; emissions reduction costs are much better inferred from the incremental costs incurred, which is the measure reported in this paper (see Section 5.3).
4. The OECD's ***GREEN*** model (43, 44) is a 12-region general equilibrium

[5]The CRTM and CETA are both derivatives of the Manne-Richels GLOBAL 2100 models, and behave in similar ways concerning abatement costs (except concerning trade for CRTM), and the ASF energy submodel is a derivative of the ERB model. The IEA model is relatively short run (to 2005), with only CO_2 and tax levels but not cost results published as part of the general OECD comparisons. The recent McKibben & Wilcoxen model is fundamentally different, but it is heavily focussed on the US and trade interactions and does not report global results. Some Australian studies (Section 4.3) use the WEDGE global model to examine trade impacts but report costs only for Australia. The Nordhaus DICE (dynamic integrated climate-economy) model is a global integrated growth model designed to estimate the impact of abatement and global warming on economic growth, and to search for global optimal benefit/cost models, but it requires an abatement cost function as input (rather than as a result), which Nordhaus derives from the results of other top-down studies.

model, which in its more recent versions is a multiperiod model with capital stock modelling that encompasses both trade and backstop technologies.

5. *Anderson & Bird* (45) employ a simple economic growth model to illustrate bounds on the economic impact of abatement strategies that are based on expansion of renewable energy. The key feature of their analysis is inclusion of a relationship between investment and cost reduction in alternative supply technologies.
6. *The Goldemberg et al* (46) study *Energy for a Sustainable World* is the only bottom-up global study. While not an abatement costing study as such, its detailed disaggregation of global energy use and available technologies concludes that global energy demand could increase by only 10% from current levels by the year 2020 through full exploitation of cost-effective technologies for improving energy-efficiency.

In Figure 6 we summarize the major published results from these modelling studies, plotting the degree of abatement against the cost measured directly (for energy sector models) or as GNP loss, relative to the projected GNP. Figure 6*a* shows the results in terms of reductions from the baseline projection generated by the model; simple calculation shows that the average rate of abtement in almost all these studies, despite their apparent diversity, is 1.3–2.0% per year below the baseline projection. Figure 6*b* illustrates the same results, but in terms of the level relative to the base year (usually 1990). Contrasting the two curves shows that emission changes from a base year show less of a pattern, due primarily to the wide variation in the baseline emission projections, discussed in Sections 6 and 7.2. Because of such variation, in this study we concentrate primarily on reductions relative to the reference projection without CO_2 constraints (the baseline). Thus, in the presentation of results from studies we seek to abstract from the scale of the economy by normalizing results to both the reference GNP and the reference fossil-fuel CO_2 emission trajectory. To the extent that system scale is simply a linear multiplier of results, this makes results comparable relative to the baseline. The essential linearity of costs with scale has been shown to characterize the ERB model (81). The scale (e.g. of baseline emissions growth), however, has powerful implications for the ease or difficulty of achieving a specific target emission reduction.

Additional information on these global studies is provided by Figure 7*a*, which shows the relationship between the relative CO_2 reduction and required "carbon tax" (marginal abatement cost as reported by the model in the target year), and by Figure 7*b*, which shows the relationship between the reported carbon tax and the average GNP loss in the target year. Interestingly, whereas for a fixed analysis the marginal cost must always be greater than the average cost, this plot shows no such relationship. For some models this may reflect anomalies in the way that marginal cost impacts are translated into GNP impacts (see Section 5.3); another source of such behavior is that in some models the CO_2 constraints are introduced so as to impose a much higher marginal cost over the first few decades than in the very long run (see Section 8.3). All these global studies impose a fixed path of emission constraint; only the simpler CETA (42) and DICE (35) models optimize the path of abatement to reach a given concentration level.

Because of such anomalies, there is no uniquely preferable single measure for cost comparisons. We have to draw on the models and results as generated to date, and for all subsequent analysis in this paper we choose the target date GNP loss (or total additional energy sector cost) relative to projected baseline GNP as the most appropriate single cost indicator.

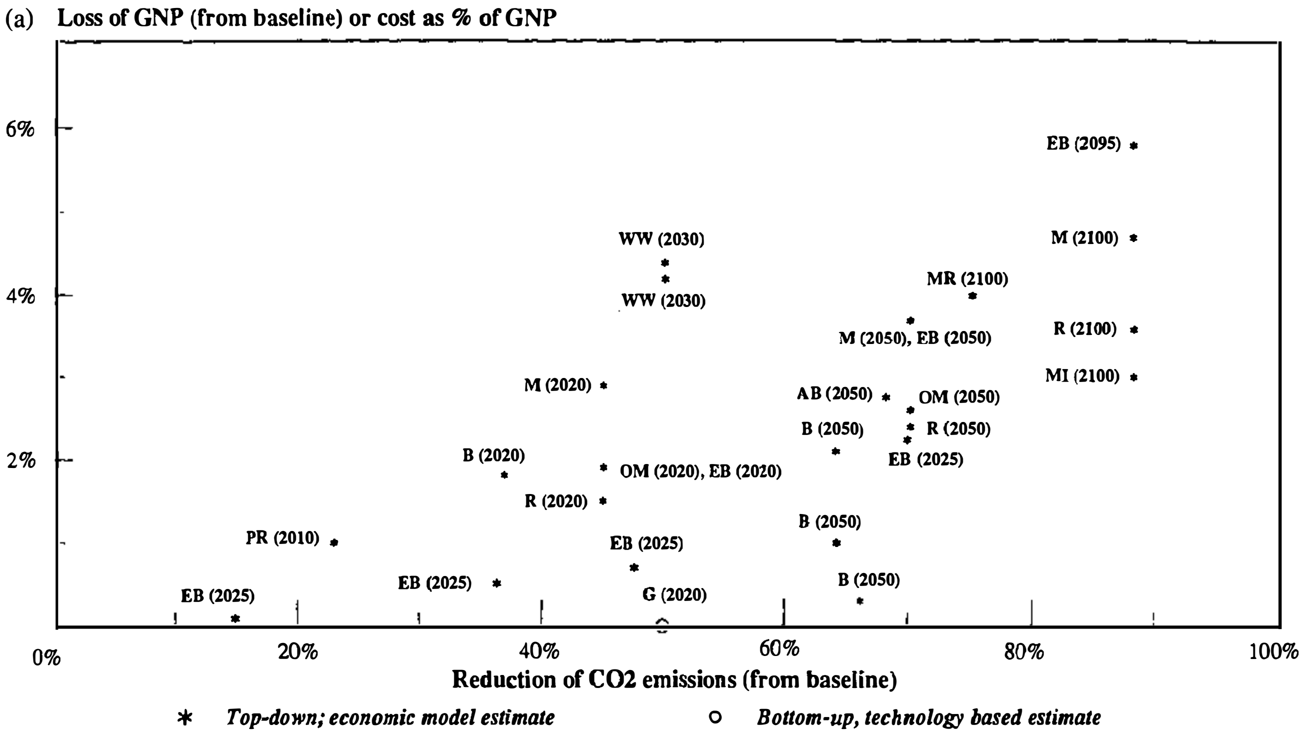
Even when normalized relative to the differing baseline projections, however, the results still show great variation. The Whalley-Wigle results define the high end of the cost spectrum. The relatively high costs probably reflect the limitations imposed by only having one generic carbon fuel, the lack of technology representation, and an extraordinarily high baseline projection, which scales up the global energy system 10-fold over the century, because there is no allowance for autonomous efficiency improvements (see Sections 6 and 7).[6] The Goldemberg et al bottom-up results define a lower bound, with emissions reductions perhaps up to 50% estimated at no cost.[7] However, some of the sensitivity runs of the global top-down models, when given more optimistic estimates of energy-efficiency improvements and supply technology development, can also produce very low costs (e.g. see discussions in Section 6).

Not including the Whalley-Wigle outlier for the reasons above, the resulting spread of results roughly indicate that the costs of a long-run 50% reduction in global CO_2 emissions could range from negligible to a loss of about 3% in global GNP. Reductions of 80–90% depress GNP by 2–6%; at the other end of the curve, the global economic models (as well as the engineering models) suggest that emission reductions of at least 10–15% can be obtained at very low cost.

These global models are highly aggregated and capture technical issues, macro-economic issues, regional differences, and trade effects with varying

[6]The Whalley-Wigle model also uses an explicit estimate of welfare loss (Hicksian equivalent), but so does the GREEN model, which generates much lower costs, and so this does not appear to be a central factor.

[7]These studies do not define a baseline scenario, or carbon emissions; the point is estimated on the basis of their projected total energy demand and fuel-mix trends compared against the central baseline projections from a range of other studies for that period.


(a) Loss of GNP (from baseline) or cost as % of GNP
6%
4%
2%
0%
20%
40%
60%
80%
100%
Reduction of CO2 emissions (from baseline)
EB (2095)
M (2100)
WW (2030)
WW (2030)
MR (2100)
M (2050), EB (2050)
R (2100)
MI (2100)
M (2020)
AB (2050)
OM (2050)
B (2050)
R (2050)
EB (2025)
B (2020)
OM (2020), EB (2020)
R (2020)
PR (2010)
B (2050)
EB (2025)
EB (2025)
B (2050)
EB (2025)
G (2020)
* Top-down; economic model estimate
o Bottom-up, technology based estimate

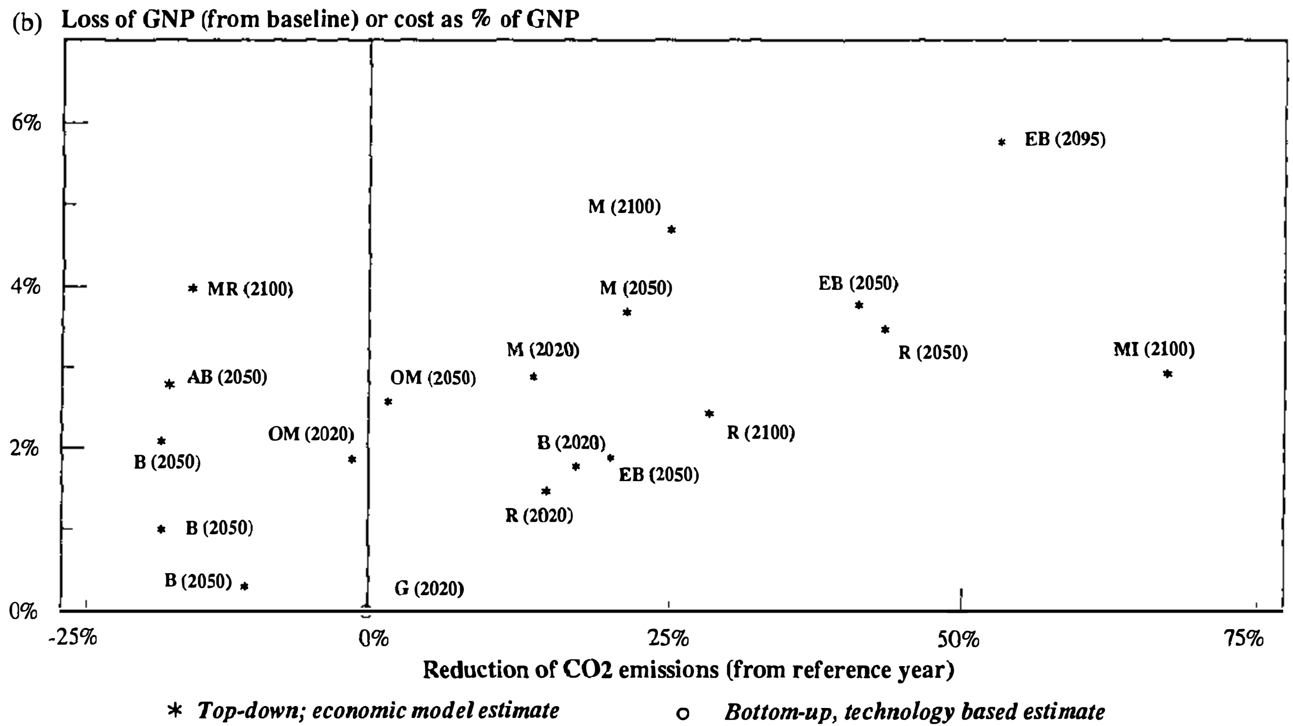
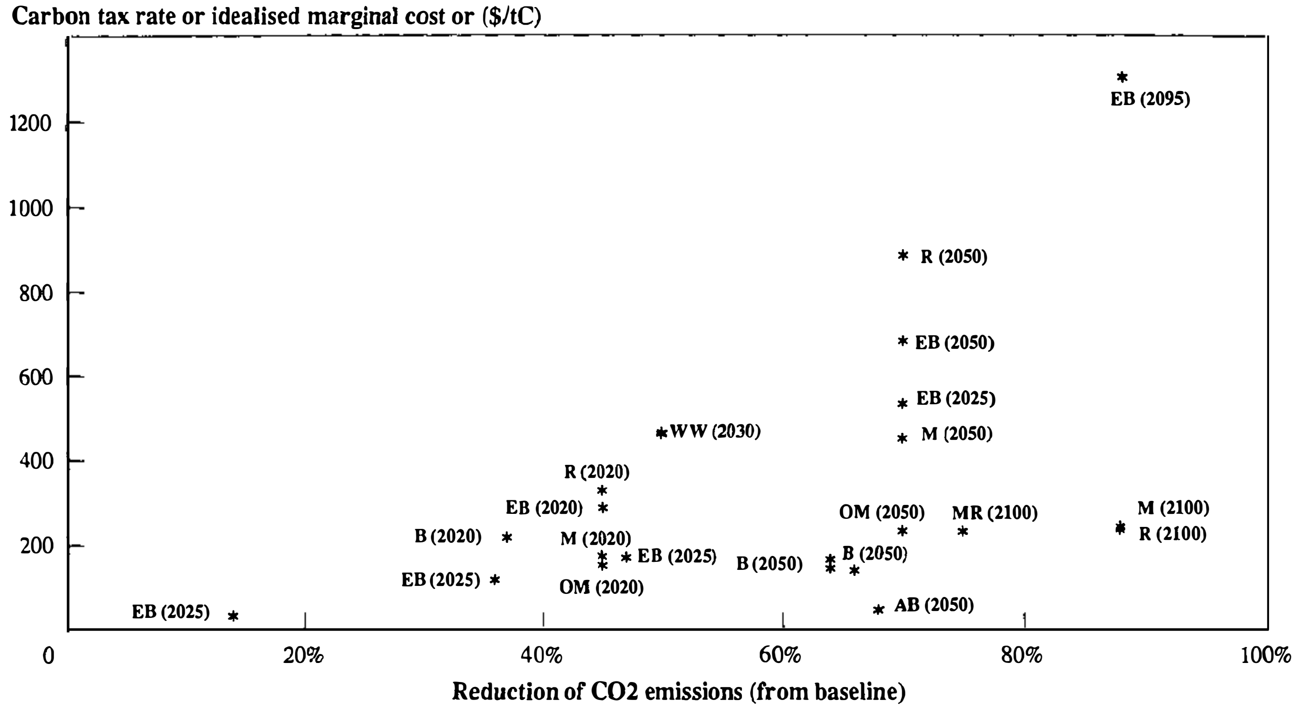


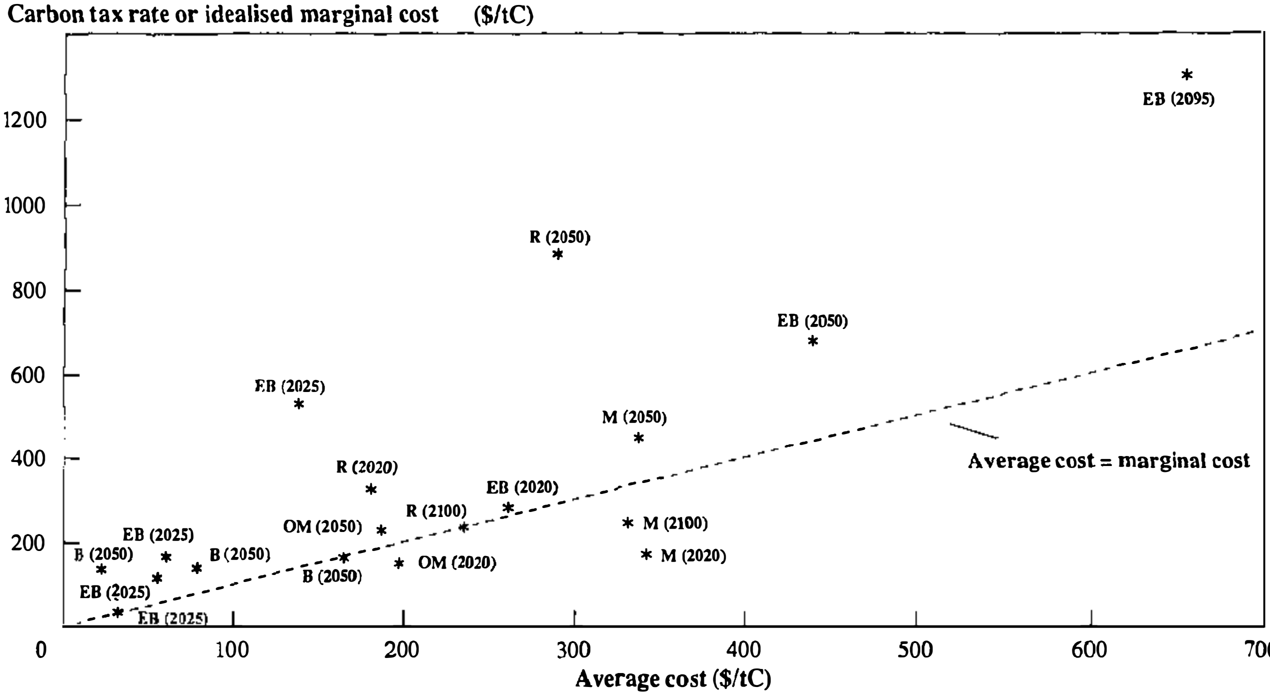
Figure 6 Global studies of CO_2 abatement costs, relative to: *a.* baseline projection, *b.* reference year. For Key (both parts) see Table 1. Note to part *b:* a negative reduction indicates an increase in emissions.

(a)



Some of the plotted carbon tax values are averages of different regional taxes. Where taxes vary over the study period, the end year tax is shown.
For Key see Table 1

(b)



Some of the plotted carbon tax values are averages of different regional taxes. Where taxes vary over the study period, the end year tax is shown.
For Key see Table 1

Figure 7 Global studies: relationship between *a.* relative CO_2 abatement and marginal cost *b.* average GNP loss and marginal cost. Some of the plotted carbon tax values are averages of different regional taxes. Where taxes vary over the study period, the end-year tax is shown. For Key see Table 1.

degrees of detail. They inevitably sacrifice local and technological detail in order to represent important regional differences and (in some) incorporate trade. To start to narrow down the range requires a fuller examination, which we present below, of the factors affecting model results.

4.2 Abatement Costing Studies for the United States

A wide range of national studies has been carried out; of these, the US ones have received the most attention. Table 2 and Figure 8 show the range of estimates of the impact on GNP of CO_2 emissions reductions relative to the projected baseline emissions.

The survey of US studies shows predominantly top-down economic studies. Many bottom-up/engineering studies have also been carried out, but most have been confined to cost-curve or subsectoral studies. In addition to the earlier examples cited in Section 3, important recent studies include those of the National Academy of Sciences (NAS) (47), and the Office of Technology Assessment of the US Congress (OTA) (48).[8] These, like most engineering-based studies, maintain that major efficiency improvements (and hence CO_2 reductions) can be obtained at little or no cost. These estimates have been included in Figure 8 as indicative bottom-up cost estimates.

As with the global studies, a wide range of cost estimates is observable. For example, for the same loss of GNP of about 2%, CO_2 emission reductions can range from 20% (US Congressional Budget Office—CBO—-78) to 80% (Manne & Richels—40) below baseline. One major reason for such differences is that the reductions are sought on different timescales; the CBO study seeks a 20% reduction by 2000, while the 80% reduction in the Manne & Richels study is achieved at the end of the next century.

Excepting the very rapid reductions imposed in the CBO studies for the year 2000, the early Goulder (74) studies form a high-cost outlier.[9] Bottom-up studies, and those that examine the recycling of tax revenues (discussed below) have produced some very low and negative abatement cost estimates. These studies are discussed in Sections 7 and 8 below.

[8]Results of a major comprehensive bottom-up study by nongovernmental groups (152) were obtained by the authors only at a late stage of this paper. This study examined scenarios out to 2030 for the US energy system, and produced much more optimistic results than either the NAS or the OTA study; the central "economic" abatement scenario was stated to give an average cost saving over the period 1990–2030 of 0.57% of GNP for an emission reduction of 67% below the reference projection in the year 2030.

[9]These are derived from a short-run macro-economic model (Section 5.3) with a lump-sum rebate of the tax revenues, which is the least favorable case (Section 8.1). Goulder notes that these results "should be interpreted with caution ... the model does not isolate the electric power industry or distinguish [nonfossil] from fossil based electricity ... in addition there are very considerable uncertainties about many of the important parameters of the model."

Table 2 US CO_2 abatement cost modelling studies

Author (reference)	Key[a]	CO_2 reduction from baseline	GNP impact/cost (reduction) from baseline
Barns et al (135)	BG (2020)	26%, 45%, 60%	0.6%, 2.0%, 3.2%
Barns et al (135)	BG (2050)	45%, 70%, 84%	1.9%, 4.9%, 7.5%
Barns et al (135)	BG (2095)	67%, 88%, 96%	4.3%, 8%, 10.9%
DRI (49)	B (2020)	37%	1.8%
CBO-PCAEO, DRI (78)	CB1, CB2 (2000)	8%, 16%	1.9%, 2%
CBO-DGEM (78)	CB3 (2000)	36%	0.6%
CBO-IEA-ORAU (78)	CBG (2100)	11%, 36%, 50%, 75%	1.1%, 2.2%, 0.9%, 3.0%[b]
Edmonds & Barns (136)	EB (2020), EB (2100)	35%, 59%	1.3%, 2.3%
Goulder (74)	G (2050)	13%, 18%, 27%	1.0%, 2.2%, 4.5%
Jackson (25)	J (2005)	34%, 40%, 46%	−0.2%, −0.1%, 0.1%
Jorgenson & Wilcoxen (92)	JW (2060)	20%, 36%	0.5%, 1.1%
Jorgenson & Wilcoxen (92)	JW (2100)	10%, 20%, 30%	0.2%, 0.5%, 1.1%
Jorgenson & Wilcoxen (137)	JW (2020)	8%, 14%, 32%	0.3%, 0.5%, 1.6%
Manne & Richels (38)	MR (2020)	45%	2.2%
Manne & Richels (38)	MR (2100)	50%, 77%, 88%	0.8%, 2.5%, 4.0%[c]
Manne (132)	MRG (2020)	26%, 45%, 60%	0.8%, 2.2%, 4.2%
Manne (132)	MRG (2050)	45%, 70%, 84%	1.4%, 2.7%, 3.3%
Manne (132)	MRG (2100)	67%, 88%, 96%	2.3%, 3.1%, 3.4%
Mills et al (24)	M (2010)	21%	−1.2%[d]
NAS (47)	N	24%, 40%	0%, 0.8%
Oliveira Martins et al (133)	OMG (2020)	26%, 45%, 60%	0.2%, 1.1%, 2.4%
Oliveira Martins et al (133)	OMG (2050)	45%, 75%, 84%	0.4%, 1.3%, 2.4%
OTA (48)	O (2015)	23%, 53%, 53%	−0.2%[e], −0.2%[e], 1.8%
Rutherford (41)	RG (2020)	26%, 45%, 60%	0.5%, 1.3%, 2.5%
Rutherford (41)	RG (2050)	84%, 45%, 70%	2.4%, 1.2%, 2.5%
Rutherford (41)	RG (2100)	67%, 88%, 96%	1.8%, 2.6%, 2.8%
Shackleton et al (76)	SJW (2010), SLINK (2010)	22%, 2%	−0.6%, 0.1%
Shackleton et al (76)	SDRI (2010), SG (2010)	5%, 28%	−0.4%, 0.2%
US Energy Choices (152)	USEC (2030)	67.5%	−0.6%

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

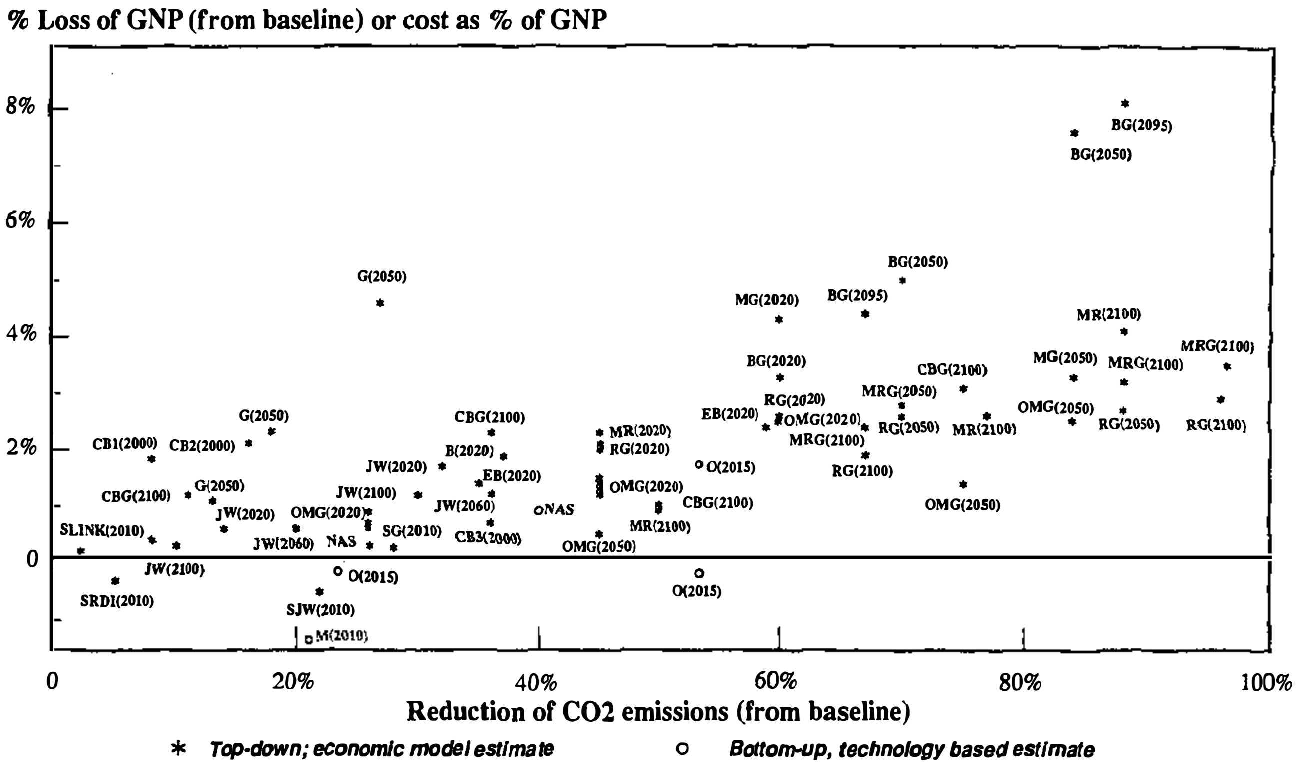


Figure 8 US studies: Cost of CO_2 abatement relative to baseline projection. Labels are not attached to all points given danger of crowding. For key see Table 2.

Excepting these, the spread of results is pretty consistent with the global results, with 50% emission reductions from baseline yielding losses up to a little more than 2% of GNP. The coincidence between US and global results may reflect partially the importance of US emissions and costs, but also the dominance of US-based modelling approaches in global studies.

4.3 Non-US OECD Studies

Table 3 lists a number of emissions reduction studies of non-US OECD countries. One striking feature is that nearly all these studies have a much shorter term focus than the global studies or most of the US studies; most in fact are focussed either on emissions stabilization by 2000 or on the "Toronto target" of 20% reduction by 2005.

The results are displayed in Figure 9. Immense variation is once again apparent, even in terms of reductions from the baseline projection. No clear pattern emerges, other than the fact that the bottom-up studies again give much lower costs (see also the detailed bottom-up comparative studies of EC member countries discussed in the previous section). We have not included these or many other bottom-up studies that repeat the message; nor have we included studies by Data Resources Inc. for the US Department of Commerce (49) for different reasons.[10]

In general, the cost range is broader than in the global studies, perhaps reflecting the impact of transitional costs arising from the relatively rapid reductions required in some of these studies, captured by the short-run models, an issue discussed further below. The detailed EC studies of the macro-economic impacts of carbon taxation, using short-run macro-economic models, produce a wide variety of results; these results depend heavily on how the tax revenues are used, as discussed in Section 8.1 below where we argue that the extremes of the short-run cost estimates (high and low) are not useful as a guide to real CO_2 abatement costs because they reflect rather the use of a tax to shift resources from one kind of economic activity to another. The Finnish study by Christensen (141), with very high losses for modest reductions by 2010, is a similar outlier on the high side, and two of the Japanese studies also yield exceptionally high costs (for the Yamaji study (118) at least this is because the carbon tax revenues are removed from the economy). The variations make it

[10]These studies used a DRI macro-economic model to examine the costs of 20% absolute reductions by 2020. The models used are essentially short run in character, with little representation of technology or various other issues that are likely to be important over time horizons of 30 years. Further details of neither the models employed nor the other assumptions used were easily available, though it appears that substitution elasticities were very low, which coupled with the lack of technology leads to implausibly high carbon taxes, the revenues from which are not used in an efficient way. Consequently, we are skeptical of the results and do not believe the study could be useful for comparative analysis.

Table 3 Non-US OECD CO_2 abatement cost modelling studies

Country	Author (reference)	Key[a]	CO_2 reduction from baseline	GNP impact/cost (reduction) from baseline
Australia	Dixon et al (138)	AD (2005)	47%	2.4%
Australia	Industry Commission (139)	AICG (2005)	40%	0.8%
Australia	Marks et al (88)	AM (2005)	44%	1.5%[b]
Belgium	Proost & van Regemorter (140)	BP (2010)	28%	1.8%
EC	DRI (49)	ECDRI (2005)	12%	0.8%
Finland	Christensen (141)	FC (2010)	23%, 21%	6.9%, 4.8%[c]
France	Hermes-Midas (80)	FHM (2005)	11%	0.7%
Germany	Hermes-Midas (80)	GHM (2005)	13%	1.3%
Italy	Hermes-Midas (80)	IHM (2005)	13%	1.9%
Japan	Ban (142)	JB (2000)	18%, 18%	0.4%, 1.7%[d]
Japan	Goto (143)	JG (2000, 2010, 2030)	23%, 41%, 66%	0.2%, 0.8%, 1%
Japan	Nagata et al (144)	JN (2005)	26%	4.9%
Japan	Yamaji et al (118)	JYC (2005)	36%	6%[e]
Netherlands	NEPP (145)	NEN (2010)	25%, 25%	4.2%, 0.6%[f]
Norway	Bye, Bye & Lorentson (146)	NB (2000)	16%	1.5%[g]
Norway	Glomsrod et al (129)	NG (2010)	26%	2.7%
Sweden	Bergman (148)	SWB (2000)	10%, 20%, 30%, 40%, 51%	0%, 1.4%, 2.6%, 3.9%, 5.6%
Sweden	Mills et al (24)	SWM (2010)	44%, 87%	−0.3%, −0.2%[h]
UK	Barker (122)	UKB (2005)	12%	−0.2%, +0.4%[i]
UK	Barker & Lewney (149)	UKBL (2005)	32%	0%
UK	Sondheimer (150)	UKS (2000)	4%	−0.5%
UK	Hermes-Midas (80)	UKHM (2005)	7%	1.9%

[a] The letters in the Key refer to the country and author; in cases where a global model is used a "G" is added before the date of the estimate.
[b] Study combines technology with macro-economic assessment of GDP impact.
[c] Unilateral action and global action.
[d] Tax case and regulation case.
[e] Values of both 5% and 6% have been given.
[f] National policy scenario and global policy scenario.
[g] GDP costs for OECD range from 1 to 2%.
[h] Estimated from average value of saved emissions ($143/tC and $41/tC respectively).
[i] GNP gain when OECD tax levied with VAT reduced to maintain revenue neutrality; GNP loss when tax used to reduce the PSBR.

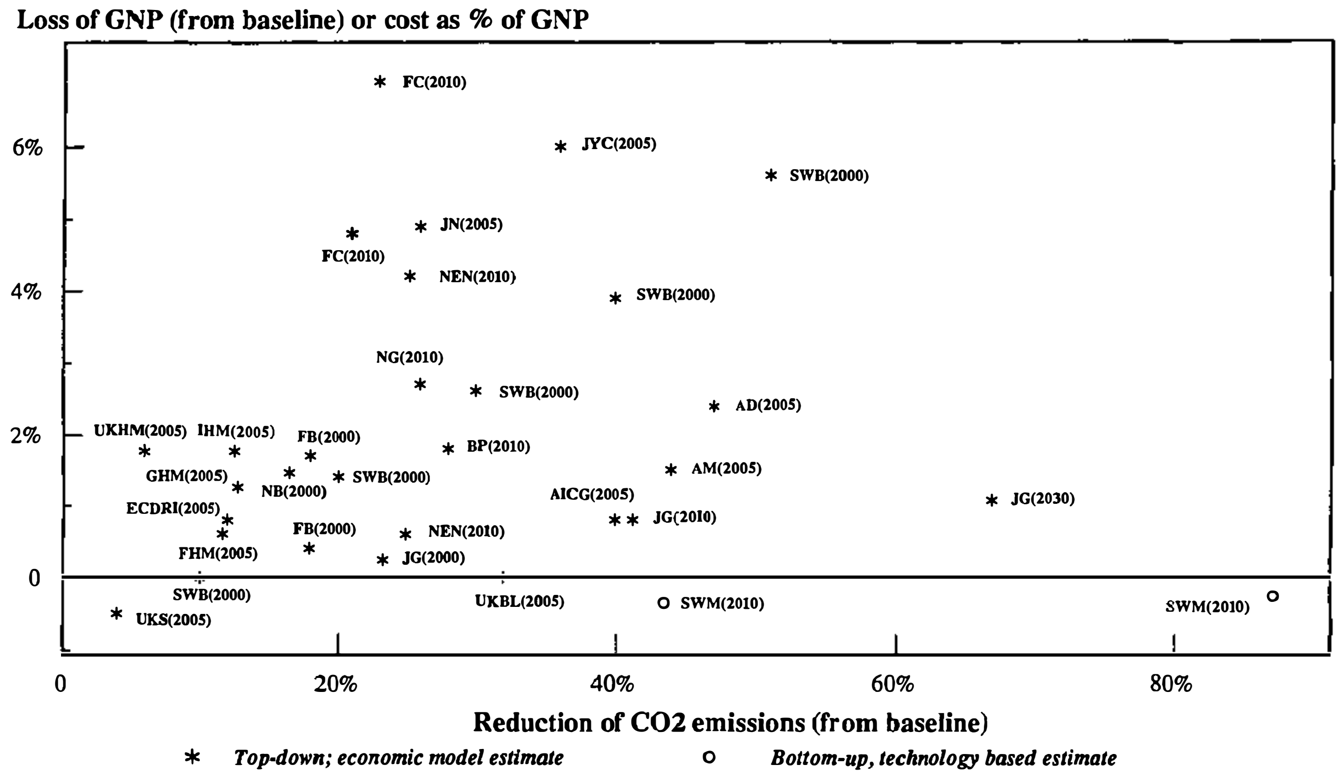


Figure 9 Non-US OECD studies: cost of CO_2 abatement relative to baseline projection. For key see Table 3.

hard to discern any pattern, but even with these outliers excluded, the relative costs for these short-run, national reductions are mostly somewhat larger than for equivalent long-run reductions in the US and global studies, with several exceeding 3% GNP losses.

4.4 *The Transitional Economies*

Studies of abatement costs for the former centrally planned economies of Eastern Europe, listed in Table 4, have also used both top-down and bottom-up approaches, but data are insufficient to summarize usefully as a scatter diagram. An energy technology cost curve estimated for Poland (50, 51) has been shown above (Figure 3). Figure 10 shows a more general curve of the cost of energy savings, based on a number of Soviet technology studies, set against the estimated cost of supply, for the former Soviet Union (52). All of these bottom-up studies indicate a large potential for reducing CO_2 emissions with net economic savings; in Figure 10, the marginal cost of savings only rises above that of new supply for savings well in excess of 10 EJ, which is more than 20% of Soviet primary energy demand in 1989.

This potential arises from the history of highly subsidized energy prices in these regions, and other cumulative inefficiencies in the structure of incentives. Note also from Figure 10 that the economic savings potential is around 10% greater if the Soviet Union can access Western technologies. Unterwurzacher & Wirl (53) estimated in 1991 that increasing prices to world market levels in Poland, Hungary, and Czechoslovakia would reduce emissions by 30%. Of course, the realizable potential may be a very different matter and depends in part on the progress of economic restructuring. In fact CO_2 emissions in the former East Germany have collapsed by at least 30% as uncompetitive heavy industry has more or less shut down in the process of unification. In Poland, provisional trend/technology results also indicate significant CO_2 reductions as a by-product of the economic restructuring process (54).

Manne & Richels include the Soviet Union as an independent region in their Global 2100 model, and calculate much higher GNP losses [5% in (39), reduced to 3% in (40)] there than for the rest of the world in the first half of the next century. This striking contrast with bottom-up studies reflects the difficulties top-down studies have with economies undergoing restructure. They rely on the existence of a market mechanism that in many instances is barely functioning, and such studies will likely miss many of the important features of these economies, such as current structural inefficiencies. It may take some time before a market-based modelling approach becomes appropriate. For the present, bottom-up engineering assessments appear much more relevant.

Table 4 CO_2 abatement cost modelling studies for transition economies and China

Country	Author (reference)	Key[a]	CO_2 reduction from baseline	GNP impact/cost (reduction) from baseline
China	Barns et al (135)	CBG (2020, 2050, 2095)	45%, 70%, 88%	2.8%, 4.3%, 6.2%
China	Burniaux et al (72)	CBUG (2050)	84%	2.3%
China	Manne (132)	CMG (2020, 2050, 2100)	45%, 70%, 88%	2.7%, 3.8%, 5%
China	Oliveira Martins et al (133)	COMG (2020, 2050)	45%, 70%	1.1%, 1.3%
China	Rutherford (41)	CRG (2020, 2050, 2100)	45%, 70%, 88%	1.3%, 2.5%, 2.6%
Poland	Leach & Nowak (54)	PLW (2005)	37%, 53%	−0.1%a, −0.1%[b]
USSR	Burniaux et al (43)	UBUG (2050	2.7%	0.2%
USSR	Burniaux et al (43)	UBUG (2020, 2050, 2100)	45%, 70%, 88%	0.9%, 2.3%, 3.7%
USSR	Manne (132)	UMG (2020, 2050, 2100)	45%, 70%, 88%	3.1%, 6.4%, 5.6%
USSR	Oliveira Martins et al (133)	UOMG (2020)	45%, 70%	1.7%, 3.7%
USSR	Rutherford (41)	URG (2020, 2050, 2100)	45%, 70%, 88%	1.5%, 5.8%, 4.1%

[a]The letters in the Key refer to the country and author; in cases where a global model is used a "G" is added before the date of the estimate.
[b]GDP gain of 0.1% is indicative of a possible net gain; it is not a modelling result.

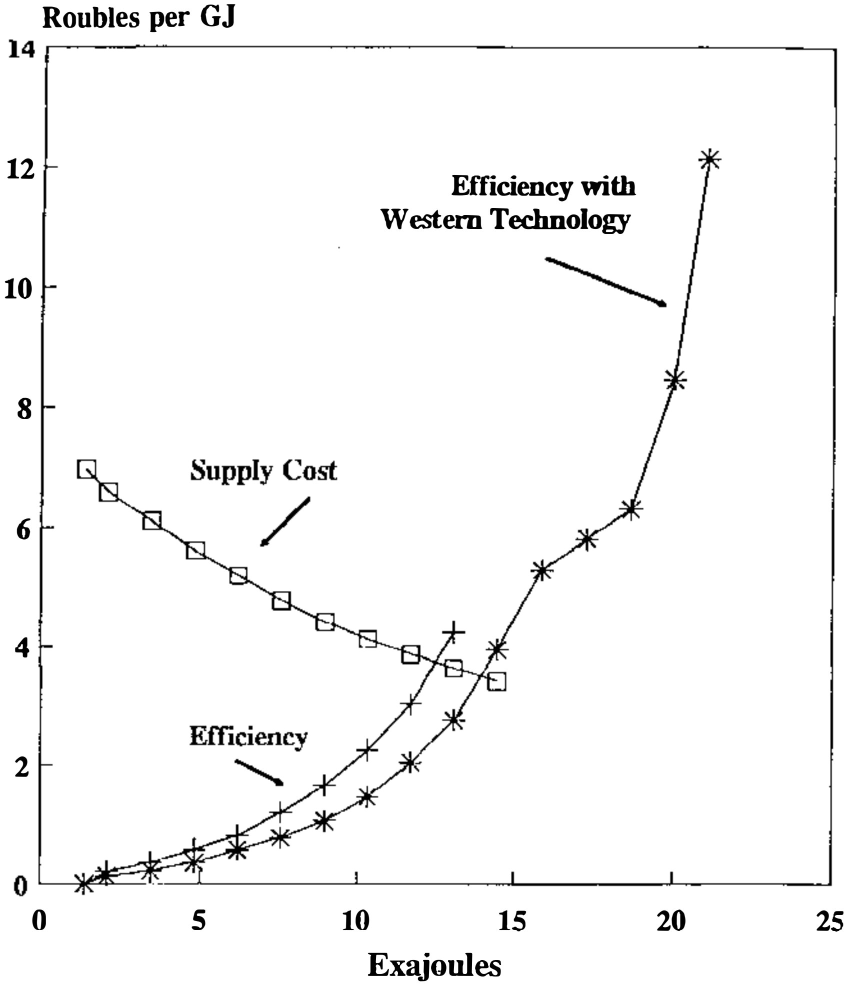


Figure 10 Soviet energy-efficiency and supply cost curves. Source: Chandler (52).

4.5 Developing Countries including China

Some of the above issues also apply to developing countries. Although concerns are frequently expressed about the limited data available concerning developing countries, considerable data exist concerning the situation in most major developing countries, especially with respect to commercial energy supply. Data on detailed end-uses, agriculture, and noncommercial energy sectors is sparser and less reliable, though usable estimates exist.

The past few years have also seen a number of studies of the potential for abating greenhouse gases in developing countries. Some of these are reported in Table 5. For example, the country reports to the IPCC Energy and Industries subgroup (55) did include a number of studies from developing countries, some drawing on more extensive internal work. In addition, Sathaye (56) reported initial results from a series of nine developing-country studies coordinated by the US Lawrence Berkeley Laboratory. However, these studies focussed on scenarios and did not attempt to estimate abatement costs. Some of the detailed studies for the Asian Energy Institute network reported in the UNEP study (16, Chapter 5) attempt bottom-up estimates of short-term abatement costs or investment requirements.

Some of the global models do separate developing-country and oil-exporting regions. The global studies have also highlighted the growing importance of China in contributing to greenhouse gas emissions during the next century. The early Manne & Richels results (39) suggested that Chinese GNP in the year 2050 could be depressed by up to 8% below the (greatly increased) reference level, if emissions are restricted to no more than double current levels, partly because of the apparent lack of alternatives to coal and modelling inability to import energy [though this was reduced to a 2% GNP loss, rising to 5% by 2100, in revised analysis (40)]. The GREEN model suggests much lower abatement costs for China (44).

In estimates derived from global studies that model trade (e.g. 36, 37), GNP impacts for some of the smaller developing countries especially can be dominated by trade and price effects arising from the action of other countries. These studies emphasize the large potential GNP loss for energy-exporting developing countries; the loss could arise from abatement efforts elsewhere that depress the market for traded fuels. Conversely, energy-importing countries (which include the poorest countries) would gain from such effects.

Concerning domestic abatement efforts, a number of cost curves have been estimated (see e.g. Figure 2 for Brazil), which indicate substantial technical potential for savings with net economic benefits. However, the only integrated system-wide cost estimates that the authors could find, excepting those from global models for China, are those of Blitzer et al (57, 58) for Egypt and an unpublished study of Zimbabwe by the UK consultants Touche Ross, reported in UNEP (16).

The Blitzer et al studies estimate a very large potential GNP impact from stabilizing CO_2 emissions in Egypt, with losses in some cases of more than 10% of GNP. This is based on a short-run macro-economic model of the Egyptian economy that is modeled with very limited capital mobility between sectors, and with oil and gas as the only future energy supply options. It recognizes none of the technical inefficiencies in the economy (i.e. assumes

Table 5 CO_2 abatement cost modelling studies for developing countries

Country	Author (reference)	Key[a]	CO2 reduction from baseline	GNP impact/cost (reduction) from baseline
Brazil	Burniaux et al (43)	BBG (2050)	63%	1.8%
China	Barns et al (135)	CBG (2095, 2050, 2020)	45%, 70%, 88%	2.8%, 4.3%, 8.8%
China	Manne (132)	CMG (2050, 2020, 2100)	45%, 70%, 88%	2.7%, 3.8%, 5.0%
China	Oliveira Martins et al (133)	COMG (2050, 2020)	45%, 70%	1.1%, 1.3%
China	Rutherford (41)	CRG (2020, 2050, 2100)	45%, 70%, 88%	1.3%, 2.5%, 2.6%
Egypt	Blitzer et al (57, 58)	EBI (2002)	15%, 35%, 40%	2.7%, 15%, 19%
India	Burniaux et al (43)	IBG (2050)	85%	1.9%

[a] The letters in the Key refer to the country and author; in cases where a global model is used a "G" is added before the date of the estimate.

zero scope for cost-free energy-efficiency improvements). Excepting the modest abatement available from switching from oil to gas, emissions savings can only be achieved by reducing energy consumption, which, given the constraints on capital mobility, can only be achieved by reducing economic activity or changing its structure. Consequently, the costs reported are clearly excessive. However, separate runs of the model that placed emission constraints on each sector of the economy individually did emphasize that GNP losses would be greater still if these additional restrictions were imposed.

The Touche Ross study of Zimbabwe reached precisely opposite conclusions. Using an engineering approach, widespread cost-effective options were identified that could both limit emissions growth and improve overall economic performance. However, these assessments neglect a variety of hidden costs and fundamental institutional obstacles; they also include some elements that are expected to be achieved anyway as part of current structural adjustments in the Zimbabwean economy. These and other limitations, which suggest that abatement costs in this case may be substantially underestimated, are summarized in the Zimbabwean case study of the UNEP report (16).

The limited range and appropriateness of studies for the transitional and developing economies make the use of scatter diagrams, as were used for presenting OECD results, not in our judgment very meaningful in this case. We do, however, note one striking observation; the gap between top-down and bottom-up approaches is larger even than observed for OECD countries. Top-down models mostly report restricting developing-country emissions, even relative to projected increases, to be more expensive than equivalent relative constraints in OECD countries [e.g. Rutherford (41)[11]]. It is not clear why this should be the case. Bottom-up studies, conversely, identify a potential for improving energy-efficiency in these regions at a net economic benefit that is even larger than that identified for OECD countries.

Despite this, it seems possible to draw two firm observations from the existing developing-country emissions abatement studies: many cost-effective technology options exist for improving energy-efficiency; but such potential will be swamped by the pressure for emissions growth in such rapidly expanding economies, so that actually stabilizing developing-country emissions at current levels is nevertheless likely to be very costly. More sophisticated and quantitative system-wide analysis of abatement impacts is, however, only just beginning, and as outlined in UNEP (16), the

[11]Results from this version of the CRTM (a trade extension of GLOBAL 2100) reported a long-term average GNP loss of 4% across the developing world for the OECD scenario in which all regions reduce CO_2 emissions by 2% per year below baseline (assumed optimal) projections. GNP losses for the US and the rest of the OECD were estimated as 2.5% and 1.5%, respectively.

complexities are such that it may take many years to mature towards consensus even on very rough cost estimates and understanding of the key issues.

5. MODEL SCOPE AND TYPE

The review of cost estimates in the previous two sections shows the enormous disparity in modelling results. It is very difficult to disentangle the various reasons for these differences, due to the nonlinearity of the relationships involved, the diversity of the tools used to develop emissions reductions cost estimates, the many and varied assumptions employed, and the enormity of the task required to obtain all of the models, establish a protocol for analysis, and systematically unravel the relative contributions. First steps in that direction have been taken by teams at the Energy Modelling Forum (59–62) and OECD (63, 64). In both cases, participating modellers were asked to adopt standard assumptions to the degree possible and to provide standardized model results. Both sets of comparisons have focussed on top-down models (the Energy Modelling Forum recently embarked on a similar exercise with "bottom-up" models). It is clear from these activities that great variation in results can be generated through the use of different models. This variation is greatly reduced through the use of standardized assumptions.

In this section we identify the different types of models used, and discuss some of the implications that might be expected to flow from the selection of a particular model type. The following section then discusses data differences. Then, in Sections 7 and 8 we analyze the factors that appear to have the most significant impact on abatement cost estimates.

We begin by noting that all models share certain unavoidable limitations:

1. First, a model is necessarily a simplified representation of reality, in terms of what the concerned researchers feel are important aspects that should be captured. A given model may not capture all the important economic relationships.
2. Second, despite these simplifications, all such models are still rather complex and must necessarily rely on a large quantity of data and numerous parameter estimates. Robust estimation of these is itself a major research undertaking, and serious doubts may arise about the validity of many of the actual numerical values employed. Studies of model sensitivities, and structured uncertainty studies in which the values of key parameters are varied over plausible ranges, are required to examine how much these uncertainties may affect model results. Such studies have often not been adequately performed.

3. Third, the timescales involved require assumptions to be made about changes in technology and life-styles. Conjectures about such changes are inevitably uncertain and cannot be formally validated.

These limitations may be exacerbated by the fact that most studies employ models that were not initially designed to shed light on the cost of emissions reductions [exceptions are the OECD's GREEN model (43, 64) the ERB (3, 4), and the forthcoming Second Generation Model (SGM) (65)].

Consequently, all modelling results need to be treated with some caution, depending in part on the timescale of application, the care with which the model has been developed, the extent to which it is appropriate to the application used, and the care with which inputs have been formulated. The ultimate argument for such modelling efforts is not that they give precise and certain answers, but rather that they are the only consistent way of estimating abatement costs at all and of identifying the important factors that affect them.

Energy-economy models can be classified in various ways. In this section we draw distinctions along six dimensions of classification.

5.1 "Top-Down" and "Bottom-Up" Models

We have noted the major distinction between "top-down" economic models and "bottom-up" engineering/technology-based models. We noted that high positive abatement costs are frequently associated with top-down/economic approaches and low and negative costs are frequently associated with bottom-up/engineering approaches.

As outlined in Section 2, the underlying theoretical distinction lies between the economic and engineering paradigms. This can be discussed in terms of a relatively simple illustration (Figure 11). In economics, technology is featured as the set of techniques by which inputs, such as capital, labor and energy, can be transformed into useful outputs. The figure shows a graph of energy versus other (e.g. capital) inputs. Each cross represents an individual technique or technology. The "best" techniques define the "production frontier," as illustrated. In principle, efficient markets should result in investment only in the technically efficient techniques on this frontier (after allowing for lags associated with old stock), because such investments can reduce all costs compared with other technologies.

Economic models all assume that markets work efficiently in the sense that all new investments (after allowing for hidden costs) define the "production frontier." This is assumed to be consistent with cost-minimizing (or utility-maximizing) behavior in response to the observed price signals: various models can encompass other inefficiencies, such as externalities and fiscal imperfections arising from taxes and subsidies, but still share this assumption.

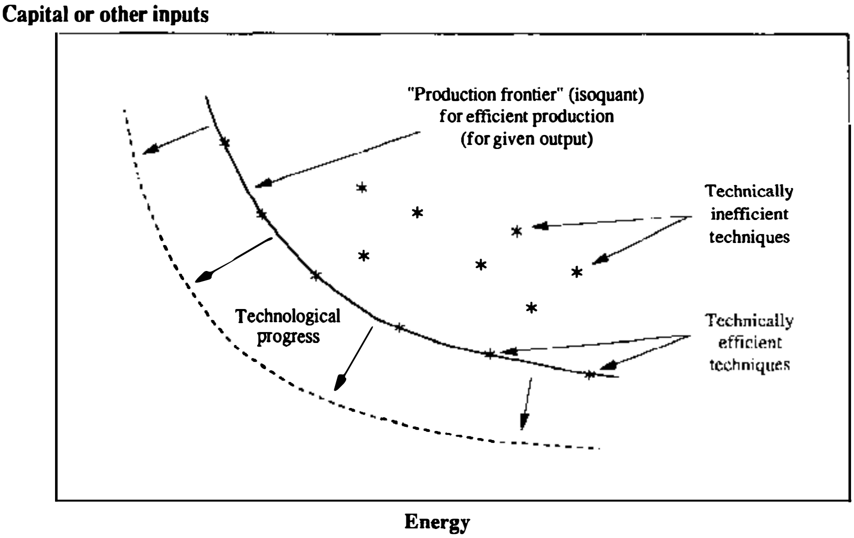


Figure 11 Technological efficiency and the "production frontier." Source UNEP (16).

Observed behavior (historical data) combined with the optimizing assumption defines an observed production frontier. The models assume that no investments are available that lie beyond this frontier (though future technical change may move it). To the extent that real-world inefficiencies exist, they are implicitly incorporated in the inferred frontier. Relative price changes move investments along this frontier (e.g. substitute labor for energy) as defined by the estimated elasticities; a purely economic model has no explicit technologies, which are simply implicit in the elasticities used.

Studies using engineering models have often focussed on identifying potential least-cost abatement opportunities by assessing directly the costs of all the technological options. Such assessment is independent of observed market behavior. This also defines a "production frontier." If markets are technically efficient, the "frontier" revealed by market behavior should correspond to that calculated by engineering studies. As illustrated previously, this is not the case. Engineering studies reveal widespread potential for investments beyond the limit of the "production frontier" suggested by market behavior and built into economic models. The explanation can be considered in terms of the contrasting limitations of the economic and engineering paradigms. Economic models are slave to the assumption of cost-minimizing behavior noted above. Limitations of purely engineering models include:

1. The cost concept is based on an idealized evaluation of technologies and options. The existence of hidden costs is typically ignored.

2. The cost of implementation measures (e.g. information campaigns, standard setting, and compliance processes) is not included.
3. Market imperfections and other economic barriers mean that the technical potential can never be fully realized.
4. Macro-economic relationships (multiplier effects, structural effects, price effects) and indicators (GNP, employment, etc) are not included in the models.

Top-down and bottom-up are very imprecise terms. Although models generally known as "top-down" all determine energy demand through aggregate, economically driven indices (GNP and/or productivity growth, and price elasticities), they can vary greatly in the modelling of energy supply. Some of the "top-down" models are purely economic, with supply changes being driven only by substitution elasticities. Others are primarily economic, but incorporate a "backstop technology"—a technology that can come in, in unlimited quantities, once a certain price threshold is reached. Yet in other "top-down" models (such as the ERB), supply is driven largely on an engineering basis of supply technology costs, chosen from a database of supply technology cost curves.

Nearly all "bottom-up" models contain extensive representation of supply technologies, but the key practical distinction as it has emerged in the CO_2 costing literature centers on the modelling of energy end-use and the introduction of end-use technologies. Bottom-up end-use studies indicate a large potential for reducing both emissions and costs relative to a traditional top-down extrapolation of energy demand. In other words, they show that the top-down projections are not optimal in terms of the technologies available; and the major savings come by contrasting this with a scenario that is an engineering optimum.

Why does this create such a large difference between bottom-up and top-down studies? The primary reason is to be found in Figure 5, which was discussed in Section 3. Neglecting the segment referring to externalities, which may or may not be reflected in either top-down or bottom-up studies, top-down projections of energy demand incorporate only efficiency improvements corresponding to the bottom segment of the column—the "business as usual" takeup. Bottom-up models, on the other hand, include all the available technologies, without distinction as to under which category in the column they fall. Consequently, we can conclude with some confidence that, neglecting externalities:

1. top-down modelling studies tend to underestimate the potential for low-cost efficiency improvements (and overestimate abatement costs) because they ignore a whole category of gains that could be tapped by nonprice policy changes; whereas

2. bottom-up end-use modelling studies overestimate the potential (and underestimate abatement costs) because they neglect various "hidden" costs and constraints that limit the uptake of apparently cost-effective technologies.

Which is more "realistic" depends on the relative size of different segments in Figure 5—something that cannot be determined without separate study of specific implementation policies and costs, discussed in Section 7.2. But we can say with some confidence that the real near-term potential for limiting CO_2 emissions at low or negative costs lies somewhere between the optimism of such bottom-up studies, and the relative pessimism of many top-down studies. Finally, we note that although these issues are most important relative to demand, they also can apply to energy supply, particularly concerning apparently "cost-effective" decentralized renewable energy options that are nevertheless not being exploited.

We emphasize again that the systematically differing results are largely a reflection of the non-optimality of the baseline implicit in such bottom-up studies—and the questions it raises about the assumptions built into top-down model baseline and abatement projections. This is perhaps the key difference between the modelling approaches. If the baseline in bottom-up studies used optimal technologies, the baseline emission projections would be much lower. This was illustrated clearly in a study by Morris et al (66), which included end-use technologies in the MARKAL engineering model and found that obtaining base-case emissions anything near as high as official or macro-economic forecasts proved almost impossible; the model chose more energy-efficient end-use technologies, and more renewable energy technologies, irrespective of CO_2 constraints. Further reductions were, however, relatively expensive, relying more on supply substitution, as the stock of more efficient end-use technologies was largely selected already in the optimal baseline.

Thus there is no inherent reason why "top-down" studies should yield positive costs or "bottom-up" models should yield negative costs. The sign of the cost hinges critically on the approach applied to computing costs, in particular, assumptions regarding optimality of the baseline. For example, Bradley et al (67) and Edmonds, Barns, Wise, and Ton (68) recognize a non-optimal baseline and illustrate negative abatement costs within a "top-down" energy-economy approach; whereas the Morris et al (66) study uses a wholly engineering model and obtains positive costs for any reductions beyond those captured in the (optimal, and much lower) baseline.

Some attempts have been made to integrate top-down and bottom-up models explicitly. Most notably, the Global 2100 model has been linked with the MARKAL engineering model (by replacing the energy technology submodel in Global 2100 that formed the energy component previously) in a bid to combine the best features of both into a single computational framework (69). However, this still does not resolve the dilemma about whether projections, for baseline or abatement scenarios, adopt the engineering optimum or econometric extrapolation of energy demand, and this linked model has been criticized on the grounds that one still dominates the other (70).

5.2 Time Horizons and Adjustment Processes: Short-term Transitional versus Long-term Equilibrium

Different models are designed for application over different timescales. There are no standard definitions, but in many relevant branches of economic analysis the short term is taken to be less than 5 years, the medium term is between 3 and 15 years, and the long term is more than 10 years. The timescale is a distinction of major importance, particularly for economic models, because different economic processes are important on different timescales, and thus the timescale for which models are designed fundamentally affects their structures and objectives. Models for relatively long-run analysis may to a reasonable approximation assume an economic equilibrium in which resources are fully allocated. Short-run models focus on "transitional" and disequilibrium effects such as transitional market responses, capital constraints, unemployment, and inflation. This distinction parallels the structural distinction drawn by Boero et al (71) between *resource allocation models* and *macro-economic models*.

MEDIUM TO LONG TERM: EQUILIBRIUM/RESOURCE ALLOCATION MODELS These models focus on the allocation of available resources, within the energy sector or the broader economy. This category includes both optimizing bottom-up models (which seek to optimize resource allocation within the bounds set by available technology), and all the main long-run and global energy/CO_2 models. The latter are generally termed equilibrium models.

At one extreme of the long-term modelling dimension are models that can only consider the energy/investment mix for a "snapshot" year and compare this to another, without any information on the transition between them; these are comparative static models, such as the Whalley & Wigle model (36, 37) and an early form of the GREEN model (72). Such models can enable detail in representing the system, but at the expense of modelling developments over time. In contrast, dynamic models cover medium- and long-term phenomena, extending across several time periods.

At the opposite of this extreme within the equilibrium models, some are designed to run in annual steps over a period of a few decades. These can include considerable detail on different sectors, whose use of different resources in response to price changes is estimated econometrically from data over previous years. The main examples are the Jorgensen/Wilcoxen (73) and Goulder (74) models for the United States.

Equilibrium models such as Global 2100 and GREEN [in its more recent versions (43, 64)] and the ERB model lie between these extremes. They are designed to operate in steps of 5–15 years, to look at the changing allocation of resources under different constraints over periods of many decades, and the way this may change under CO_2 constraints.

The treatment of capital stocks in these models can have important implications for costs. "Putty-putty" models represent capital stocks as perfectly interchangeable between sectors and over time. Nuclear power plants can be transformed into solar photovoltaic arrays instantaneously and without cost. "Putty-clay" models, on the other hand, allow no transfer of capital between applications. Once an investment has occurred, the technology cannot be altered (see Section 8.3). Resource allocation/equilibrium models cannot, however, model other aspects of transitional costs arising from disequilibria. In this respect, and in their assumption of optimal investments subject to constraints, they have been criticized for underestimating likely abatement costs (though the same caveats apply to the reference projection as well, which is similarly optimal within constraints and free from disequilibria).

SHORT TO MEDIUM RUN: MARKET SIMULATION/MACROECONOMIC MODELS Short-run models by contrast focus primarily or exclusively on the dynamics of transition, rather than the long-term equilibrium allocation of resources.

One class of short-run models are *sectoral market simulation models,* such as detailed models of electricity or oil markets and pricing, or of industrial sector energy demand. The diversity of such models reflects the range of specific markets that they have attempted to model. Few such models as yet appear to have been applied to assessing abatement costs; one notable exception is the application by Ingham, Maw, and Ulph (75) of separate market models for the industrial, domestic, and transport sectors in the United Kingdom. However, such models may come to assume much greater importance as governments move closer to considering detailed policy measures tailored to specific sectors. Frequently (as in 75) they focus on sector responses to carbon taxes rather than costs.

Of more general interest for costing is the recent application of models known usually simply as *macro-economic models*. This is the name usually (if imprecisely) given to the models developed over many years for studying the short-run dynamic behavior of national economies. Typically these models contain explicit representation of investment and consumption in different sectors, and markets do not necessarily clear; there can be unemployment, idle production capacity, or capital shortage. Such models generally contain a strong Keynesian component, though many other aspects of macro-economic theory have also been brought to bear in them. Recent applications to CO_2 abatement are discussed below.

Such models can generate a wide range of macro-economic indices such as GNP, inflation, employments, etc. For this reason they are of particular interest for assessing the short-term macro-economic impact of CO_2 abatement. However, such models may contain very limited representation of the energy sector, and some may not even model energy as a separate good within the economy. Few contain a representative set of energy-technology options. Such short-run macro-economic models are thus highly country- and model-specific, and vary greatly in the extent to which they can be applied to assessing CO_2 abatement. The models are best at representing transitional costs; results may become unstable and questionable when the models are run too far ahead, because the economic feedbacks that keep economies from straying too far from economic equilibrium are generally not well represented.

No study has focussed primarily on a comparison of short-run macro-economic with general equilibrium (GE) models, but such a comparison is implicit in the studies of Shackleton et al (76). This took two macro-economic models (DRI and LINK) and two general equilibrium models (DGEM and Goulder), all of which the model authors considered appropriate to run over a period of 2–3 decades. Each was subject to the same carbon tax ($40 per ton C). Figure 12 shows that the models behaved in very different ways. Concerning the impact on CO_2, the macro models suggest a reduction of 0–8% depending on the way in which carbon tax revenues are used (see Section 8.1; even a CO_2 increase is observed from a tax recycling that boosts economic growth); the equilibrium models suggest 20–30% reductions depending only on which model is used. Even more striking, the macro models show a wide variety of GNP responses, varying greatly over time, and including substantial increases from some tax recycling options; the GE models show a much smoother response, with more modest impacts.

All this corresponds to the theoretical differences. The short-run macro models reflect the resistance of the economy to change, but also the cumulative impact of greater investment unconstrained by equilibrium requirements. The GE models allow capital to move easily across the economy to respond to the price changes, giving a much stronger CO2 response. It seems reasonable to suggest that the longer-term results from the short-run macro-economic models are questionable (and highly sensitive to various assumed macro-economic investment and other responses), as are the short-

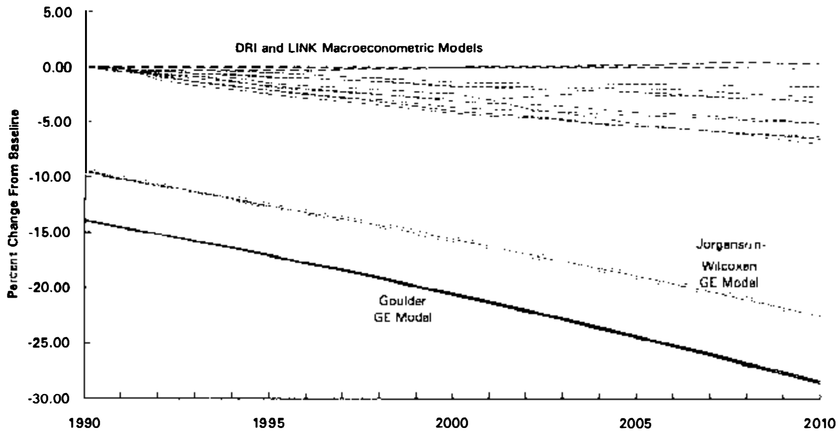


Figure 12 Dynamic CO_2 response to a carbon tax: Comparison of macro-economic and general equilibrium models. Note: This figure shows the response of CO_2 emissions to a \$40 per tonne carbon tax phased in from 1990 to 2010. Source: R. Shackleton, private communication.

term GE results; the most realistic outcome may be to assume a progression over time from the macro towards the GE results, but even this is speculative. Beyond this we cannot generalize, but we emphasize the importance of resolving such great variation based purely on model structure. McKibben & Wilcoxen (33) are the only researchers to have yet applied a model that can simultaneously address unemployment and GE class problems.

Finally we note that between the short- and long-run models, some progress has been made in developing medium-run models that combine elements from both short-run macro-economic and resource allocation/equilibrium models [see discussion in Boero et al (71)]. These may be seen as short-run models that are expanded to include adjustment to long-term equilibria. That is, medium-run models are mainly demand determined and allow for market disequilibria; however, a central part of the models aims to describe the adjustment process from short-term market disequilibria to long-term market equilibria. Finally, we note that there are some top-down modelling approaches that do not fit into these categories at all, such as the growth models employed by Nordhaus (35) and Anderson & Bird (45).

5.3 Sectoral Coverage: Energy versus General Economy

Another important distinction is that between models that address only a limited part of the economy (in this case, the energy sector) and those that encompass the whole economy, which usually have a much more simplified representation of any particular sector. Among equilibrium models, the distinction is known as that between *partial equilibrium* and *general equi-*

librium models; the parallel distinction for short-run models is that between energy market and macro-economic models; a more general terminology would be that of *[energy] sector* and *general economy* model.

Sectoral models focus heavily or exclusively on particular economic sectors (in this case, usually just the energy sector or parts thereof); insofar as the rest of the economy is represented, it is in a highly simplified way. They address the problem of describing behavior in a single area of the economy, for example energy, but ignore or treat summarily all other economic functions. An energy market model would have no description of the labor or capital markets.

Energy sector models come in many varieties. Bottom-up technology models are all sectoral; so are many equilibrium models, such as the ERB (3, 4). Investment planning models, such as the electricity expansion models widely used for assessing power sector investments, are more focussed sectoral models. Models of the international oil market—a very important but little analyzed issue in assessing abatement costs—are sectoral but global models.

Sectoral models yield an estimate of costs in a particular sector, but cannot take account of the macro-economic linkages of that sector with the rest of the economy. They cannot, for example, estimate how the labor or investment requirements in that sector may affect the resources available to other sectors.

By contrast, *general economy* models encompass all major economic sectors simultaneously. They recognize feedbacks and interrelationships between sectors. In principle, this enables them to estimate the full long-run GNP impacts of restrictions (such as CO_2 constraints). In practice, this is obtained at the expense of considerable simplification of the energy sector.

General economy models are the only kind that can reflect important features in the rest of the economy. This may include, for example, economic distortions outside the energy sector. In particular, existing taxes impose varying burdens on economies. If the revenues from a carbon tax are used to reduce such taxes, the gains may in principle offset the losses, completely altering assumptions about the net impact on the GNP of such taxes. This seems to have attracted attention only recently [Dower & Zimmerman (77)]; relatively early discussions of this are given by the CBO (78) and Grubb (79), and subsequent modelling studies are reviewed in Section 7.

The past few years have seen the development of linked models that seek to integrate the detail of energy sector models with the economic consistency of general economy models. In Europe, the macro-economic HERMES model has been linked with the MIDAS energy supply model and applied to analyzing abatement strategies in the four largest EC countries, including interactions between these economies (80), to generate the results illustrated in Figure 9. The Manne & Richels GLOBAL 2100 model (39) contains considerably more energy supply detail than other general equilibrium models by integrating an energy technology model (ETA) into a simple general equilibrium model (MACRO, which clears markets for all goods and services treated as a single aggregate). The SGM (65), which is under development, extends this approach. It is a general equilibrium model that was designed to address greenhouse-related issues, and thus desegregates economic activities on the basis of importance to the greenhouse issue.

The ERB model is an energy market rather than general economy model, but it contains a "GNP feedback" parameter, which was incorporated to ensure that the impact of large changes in energy sector costs on the scale of economic activity would be reflected in terms of its impact back on energy demand. The parameter is not intended to provide consistent estimates of the costs of emissions reductions, though many studies have used it as such.[12] As noted above, costs must be developed using consumer plus producer surplus techniques (81, 82). Other sectoral models, such as Fossil2 (83), require similar approaches to make consistent cost estimates.

5.4 Optimization and Simulation Techniques

Largely independent of the above differences, models can adopt different approaches to optimization. Some models optimize energy investments over time by minimizing explicitly the total discounted costs (or per capita consumption), using linear or nonlinear techniques. Several engineering models use linear programming, most notably the EFOM model (29) used extensively within the EC, and MARKAL (84), promoted internationally by the ETSAP program of the International Energy Agency. The top-down Global 2100 model uses nonlinear dynamic optimization, as does its derivative CETA (42). Such optimization approaches in effect assume perfect investment (within the confines of the model), with perfect foresight. It is debatable whether this is a drawback or advantage.[13]

[12]The feedback parameter is based on the relationship between energy prices and GNP during the 1970s oil shocks, as a result of which GNP losses reported by the model are unreliable and probably excessive. Edmonds & Barns discuss proper procedures for cost evaluation and warn against the temptation to use the reported GNP figure. The graphs in this study use the total cost measure suggested by Edmonds & Barns (81, 82), which are much lower than the GNP figures reported by the ERB model. We have here excluded results from Cline, which used the GNP measure from the ERB model, at his request, and other results that use the model's GNP output.

[13]Linear programming poses particular problems, notably the need to use linear (or piecewise linear) cost functions, and the related "big bang" problem: small variations in input parameters, such as prices, can lead to large variations in the extent to which technologies are implemented, and the most attractive technologies are implemented to their full extent before others are considered, in contrast to reality. This is usually dealt with through the introduction of constraints that limit the introduction of technologies, forcing the models towards a "simulation" model.

Modelling partial foresight is, however, very difficult, and the main alternative approach is to simulate investment decisions on the basis of "static expectations," i.e. static projection of conditions at the time of investment. This "myopic" assumption is used in ERB, GREEN, and the CRTM trading derivative of Global 2100—according to Dean & Hoeller (64), no software yet exists for solving such large dynamic general equilibrium models under the assumption of perfect foresight. The SGM model is being developed to incorporate a variety of options for determining investments on the basis of future expectations (including a formulation of partial foresight).

Thus the mechanism for selecting investments is fundamentally different between investment simulation and optimization models, and this might be expected to have a major impact on results. In fact, this does not appear to be the case. A recent comparison by the Energy Modelling Forum (unpublished) of results from Global 2100 (dynamic optimization) with those from the ERB model (investment simulation) shows that standardizing for key assumptions leads to remarkably similar energy and emission results. Assuming a competitive economy, variations in key input assumptions (such as those discussed below) thus appear far more important than the approach used for selecting investments in the model.

Short-run macro-economic models are concerned primarily with the simulation of aggregated investment responses in terms of labor, capital, etc but do not seek to optimize investments; they do not represent specific technologies at all. Some other models are purely for simulation of system operation, without automated investment modelling, and they report on the implications of an investment strategy that is specified externally [e.g. the Danish BRUS model (85)]. This can enable much greater detail in representing the system, and avoids the limitations of linear optimization especially, though there are inevitably drawbacks from having to specify investments manually and check their consistency [UNEP (16), Chapter 3)].

5.5 Level of Aggregation

Models differ greatly in their degree of disaggregation. To some extent this is the obverse of the model scope. Models that, for example, focus on household electricity demand can represent this and the options for improving household electricity efficiency, in great detail. Global, economy-wide models have to be highly aggregated.

At one end of the spectrum are models such as LEAP (86) and the BRUS model (85) used in the Danish Energy 2000 study (87). Their demand sectors are generally disaggregated with respect to specific industrial subsectors and processes, residential and service categories, transport modes, etc, with the aim of achieving homogeneous entities whose long-term behavior can be defined through consistent scenario projections. Similarly, energy conversion and supply technologies are represented at the plant type and device levels. This allows detailed modelling of the alternatives for technical innovation, fuel switching, etc.

With regard to emissions of pollutants and CO_2, this type of disaggregation into specific technologies makes it possible to take account of the different characteristics of energy technologies. A very detailed analysis of abatement options can thus be carried out. This will include energy savings at the end-use level, changes in the conversion system, and fuel substitution. At the other end of the spectrum are models such as GREEN and Global 2100, which treat energy and the world in a highly aggregated manner.

In general, the level of aggregation is closely related to the other aspects; for example, a multiperiod, global, general-economy model by necessity will have a highly aggregated representation of energy demand and supply, with little if any technological detail. Great detail in representing energy supply, conversion, and end-use markets and technologies is only possible in models that are specific to the energy sector, and focus on simulation rather than full system optimization. The benefits need to be weighed against these limitations.

5.6 Geographic Coverage, Trade, and "Leakage"

Another important division of scope is geographical. Global models describe the world economy divided into "regions" such as North America, Europe, the Organization of Petroleum-Exporting Countries (OPEC), Southern Asia, etc, and many can represent interactions via trade and monetary transactions between different parts of the world economy. Global models have been developed and applied primarily to examine aggregate questions such as the likely rate and pattern of emissions growth, the relative gains and losses from differing distributions of international CO_2-reduction, and international interactions of abatement efforts, including trade issues. A limited number of global models have been applied, as summarized in Section 4.1.

National models focus on specific aspects of single countries and can give more detailed descriptions of the economic interactions within the country. World market conditions are normally taken as exogenous. It is possible, however, to link national models; trade and monetary transactions between countries may be endogenized in order to analyze the effects that national policies in one country may have on the economy of other countries.

Allowing trade in goods and emission targets lowers overall abatement costs. Cline (17, Chapter 4) criticizes the Global 2100 model for its lack of trade in either production or energy resources, which leads to each region effectively optimizing its economy using only local resources, and thus increasing the global cost of reducing CO_2 emissions. Trade in emissions rights can lead to significantly lower costs in achieving overall emissions reductions (see Section 8.3). However, while overall costs may be reduced through trade, individual nations may either gain or lose, depending on the allocation of emissions rights [Edmonds et al (68)].

Global abatement efforts will affect internationally traded fuel prices, and thus have particular impacts on countries that depend heavily on energy exports or imports. Any study that does not take the global perspective into account may underestimate the economic impact of measures to reduce CO_2 on energy-exporting countries and overestimate that on energy-importing countries. Marks et al (88) address this issue by looking at the effect of a fall in the world price of coal; Perroni & Rutherford (89), the OECD studies (notably Ref. 90), and Whalley & Wigle (36, 37) also address the issue of trade. Global models are also required to examine the issue of "leakage," by which abatement in one region may be offset by international price and trade reactions (discussed in Section 8).

The cost estimates of studies that take these trade issues into account do not therefore simply reflect the impact of the domestic policies on the economy. A distinction needs to be made between the costs that stem from the domestic policy options and the economic impact of trade effects and capital transfers.

5.7 Modelling Classifications: A Resume

An understanding of different models is required because different models have different strengths and weaknesses. Models for studying CO_2 abatement costs have been developed in different ways, often by adapting existing models. They are able to handle some issues (or sectors) better than others: different models are thus suited to different purposes. Models cannot—or at least should not—be interpreted as giving complete and accurate answers, but rather used for the insights they offer when the results are combined with an understanding of the model structure and limitations.

There is no universal or accepted way of classifying models. In this section we have noted at least six dimensions. Of these the division between "top-down" economic and "bottom-up" engineering is of great practical importance, despite its occasional ambiguity. Within top-down models, the distinction between long-run equilibrium and shorter-run macro-economic models is central, as is that between partial (sectoral) and general economy models. Neither of these latter distinctions is relevant to bottom-up models, for which important distinctions are those between partial models (generating a cost curve of savings related to a top-down or unspecified baseline), and full system representation, and within the latter, the choice between opti-

Table 6 Model classification and examples applied to CO_2 abatement costing

	Bottom-up	Top-down						
	Equilibrium (resource allocation)				Growth	Energy market/macro-economic		
Sectoral division: Models/authors	Partial		Linked	General		Partial	Linked	General
National	OTA NAS Mills (& many others)	MARKAL	ETA-MACRO MARKAL-MACRO	DGEM (Jorgensen & Wilcoxen) Goulder Bergman Glomsrod Proost & Van Regemorter		e.g. electricity market models Ingham & Ulph	GDMEEM (N. Goto)	LINK MDM (Barker) ORANI (Marks)
Regional	EFOM	MIDAS					MIDAS-HERMES	QUEST HERMES G-CUBED (McKibben & Wilcoxen) DRI—Europe
Global	Goldemberg	ERB	Global 2100 CRTM CETA SGM	GREEN Whalley & Wigle WEDGE	(Optimizing) DICE (Nordhaus) (Non-optimizing) Anderson & Bird	e.g. International oil market models		

mization and simulation. Table 6 classifies the major models discussed in this paper according to this scheme, which has a pragmatic focus on the factors of greatest importance to abatement costing. Other classification approaches by Boero et al (71), and Beaver (60, 61) have similar elements but differ in detail.

6. NUMERICAL ASSUMPTIONS AND SENSITIVITIES

Assumptions drive model results. Critical parameters can be usefully (though not exclusively) divided into those that govern the overall scale of the system and reference missions, and those that directly affect the relative cost of emissions reductions. GNP and population growth rates, income elasticities and the rate of "autonomous end-use energy-intensity improvement" ("AEEI") primarily affect the baseline scale; background fossil-fuel prices strongly affect both the baseline emissions and abatement costs; the cost of low-carbon technologies and price elasticities largely drive abatement costs though they also affect baseline emissions.

6.1 Population and GNP Growth Rates

The demand for energy is driven by population and per capita energy demand, and all economic models at least assume that the latter is driven by per capita GNP. It is consequently much more difficult to restrict the growth in emissions for a developing country with a high population and economic growth rate, such as India, than for a more slowly growing developed economy, for example, Germany, which has a static or declining population.

The uncertainties in future global population are reflected in abatement studies; estimates for the year 2025 for example include 9.5 billion for the NAS (47) and 8.2 billion for Edmonds & Barns (81). However, the latter study found that there was little impact from a reduction in population growth for approximately 15 years, that is until labor force and therefore GNP was affected. Projections suggest that the increase in global GNP will be much greater and more uncertain than population growth, and so differences in GNP projections account for a greater part of variation in baseline emissions.

Different baseline GNP and energy demand assumptions across studies complicate comparisons of the GNP loss associated with a target CO_2 reduction. In models that derive GNP from labor productivity, this is correspondingly critical. For example, in the United States in 2020, GNP baseline estimates range from \$7.5 to \$11.5 trillion [CSIS (91) and Edmonds & Barns (82), respectively]; the low costs of CO_2 stabilization in the

Jorgenson & Wilcoxen (92) study have been attributed partially to their lower GNP projection.

The difference that baseline GNP makes to energy demand is more complex, as growth in any economy will inevitably vary across sectors over time; greater GNP growth in reality would not necessarily imply that the growth within all sectors of the economy is increased proportionately.

6.2 Energy/GNP Relationships and the "AEEI"

While GNP is a major determinant of energy demand, many factors can affect the relationship between them. A few models incorporate explicitly a non-unitary energy-income elasticity, which implies a changing energy/GNP ratio as GNP grows. Most models, however, express such a change, if any, in terms of an exogenous parameter that defines the rate at which the energy/GNP ratio would change in the absence of price changes. This rate of exogenous (or "autonomous") end-use energy-intensity improvement (AEEI) then becomes a major determinant of baseline energy demand for long-term projection; the higher the rate of energy-intensity improvement, the lower will be the baseline CO_2 emissions, and the lower the costs of reducing relative to a given base year. The parameter has been widely described as a measure of technical progress, but as we emphasize below (Section 7.2), it compounds many different elements.

A range of AEEIs has been adopted. The main studies with the GREEN (44) and ERB (3, 4, 68, 81, 82) models assume an AEEI of 1% per year for all of the regions of the world. Manne & Richels (39) assumed a more pessimistic set of values averaging 0.4% for the world, while Mintzer (13) adopts a much more optimistic 1.5%. The difference in values between the Manne & Richels and the ERB studies account for a very large difference in long-term projected baselines (respectively, 40 and 23 Mt C per year by 2100). The sensitivity study by Edmonds & Barns (81) confirms the importance of this parameter. In their later sensitivity analysis, Manne & Richels (40, 94) used AEEIs ranging from 0% to 1.5%. With an AEEI at 1.5%, the energy requirements at the end of the next century would be one-fifth of the demand had an AEEI of 0% been used.

6.3 Future Energy Prices, Resource Modelling, and Supply Elasticities

High background fossil-fuel prices lower energy demand and CO_2 emissions, and reduce the relative costs of moving to lower carbon fuels. Limited resources (e.g. of oil) have the same effect, implicitly or explicitly raising the prices as resources are depleted. Resources are, however, uncertain, and the course of fuel prices is even more uncertain.

Various approaches may be taken towards estimating the future cost and availability of different fuels. National studies may define national production costs but define exogenous global prices with great variation; for example, Chandler & Nicholls (95) assume that prices of natural gas and oil will rise by 2.5% per year and those for electricity and coal by 1% per year, while the OTA (48) projects prices for these fuels to rise at around 4% per year and nearly 2% per year, respectively.

Global models reflect resource/supply cost issues explicitly, through direct estimation of the resource base and supply elasticities. High supply elasticities mean lower fuel price rises as supply increases. GREEN assumes zero supply elasticity for oil outside OPEC (i.e. volume set by fixed production constraints), but price is determined by OPEC supply elasticities varying from 1 to 3; supply elasticities are higher for gas and coal and much lower for nonfossil sources until backstop technologies become relevant.[14] The OECD analysts involved (43, 64) note estimates of supply elasticities to be very uncertain, and other models assume 1.0 where relevant.

6.4 Price/Substitution Elasticity of Demand for Energy

The impact of price changes on energy demand is determined by the price elasticity of energy demand, or in general economy models, the substitution elasticity between energy and other factors of production. The lower the relevant elasticity, the less energy demand is curtailed by higher energy prices, and the greater the tax that is required to reduce energy demand and consequently CO_2 emissions. The long-run elasticities assumed in the EC bottom-up study [COHERENCE (29)] vary among countries and range from −0.4 for France and the United Kingdom to −1.0 for Belgium; the short-run elasticities range from −0.1 to −0.25 for the same countries. These differences account for part of the national differences; evidence for elasticities especially in EC countries is discussed in Mors (96) and Pearson & Smith (97).

In the global models, assumed long-run elasticities range from (−)0.3–0.4 for the Manne & Richels US and Global 2100 studies, to (−)0.6–1.0 for the OECD's GREEN model;[15] short-run elasticities are about one-tenth this value. The OECD values were chosen after an extensive literature

[14]GREEN uses supply elasticities for gas of 3.0 in the OECD and 4.0 elsewhere; for coal, 0.4 in the OECD and Soviet Union and 5.0 elsewhere; and a very low 0.2 for zero-carbon sources, reflecting assumed constraints on hydro and nuclear. Other nonfossil sources are described directly as backstop technologies available at fixed cost.

[15]Specifically, Global 2100 assumes −0.4 for OECD regions and −0.3 for the rest of the world; GREEN assumes an energy-capital elasticity of −0.6, and a labor to joint capital/energy elasticity of −1.0.

search (43, 64). For the United States, Jorgenson & Wilcoxen (73) estimate −0.15; Barrett (98) and Capros et al (99) discuss elasticities in the European context.

The notion of elasticities assumes a symmetric response to price changes; if prices rise and then fall back to previous levels, the energy-intensity will (after allowing for lags) return to former levels. As noted below (Section 7.2), this basic assumption, and the values assumed for modelling, are disputed and have been particularly called into question by recent trends and studies.

6.5 Technology Developments and Costs

Assumptions concerning the cost and rate of implementation of more efficient or lower carbon technologies affect both baseline emissions and relative abatement costs. The initial Manne & Richels results for the United States (38) were strongly criticized by Williams (100) as being based on unreasonably pessimistic assumptions for efficiency improvements and the costs of alternative supply technologies. In response, Manne & Richels (94) examine three different background scenarios, which they termed technology optimistic, technology intermediate, and technology pessimistic. The last of these corresponds to their initial famous estimate that CO_2 abatement could cost the US $3.6 trillion over the next century, and yields some of the higher cost points on Figures 6 and 8 above. Assumptions for the first, "technology optimistic," reduced these total costs by a factor of 20 for the (fixed) abatement target set, because of the combined impact on baseline emissions (primarily from the higher AEEI) and the halved costs for "backstop" low-carbon supply technologies. As a result, Manne & Richels noted that "the direct economic losses are quite sensitive to assumptions about both demand and supply ... for the losses [from carbon constraints] to approach zero, however, the most optimistic combination of supply and demand assumptions must be adopted".

This confirms that results are very sensitive to the assumptions concerning technology costs, again a result noted in the sensitivity study by Edmonds & Barns (81). Almost all studies fix the costs of supply technologies as exogenous data; Anderson & Bird (45) is the only study in which technology costs decline with increasing investment.

6.6 Energy Sector Impact on GNP

The impact of changes in energy demand and energy sector costs on GNP is complex. General economy models capture the relationship consistently, but the resulting elasticity can still vary considerably. For example, the Global 2100 modelling approach (and by implication, the CRTM and CETA models also) contains a "nested CES" (constant elasticity of substitution) production function[16] to relate energy input to economic output. Cline (17, Chapter 4) criticizes the parameters chosen, claiming that they yield an excessive impact of energy sector changes on GNP—a claim disputed by Manne & Richels.[17]

For sectoral or partial equilibrium models, the impact of energy sector costs or carbon taxes on GNP may be estimated (if at all) by a direct elasticity ("GNP feedback") parameter, as available in the ERB model. Such studies have been criticized for overestimating the feedback and consequently overestimating the cost of reducing CO_2; as noted in Section 5.3 above, Edmonds & Barns (81) recognize this limitation and suggest the use of consumer plus producer surplus changes as the best method of computing cost for the ERB model.

6.7 Interfuel Substitution Elasticities

Substantial CO_2 reduction can be achieved by switching towards less carbon-intensive fuels. In models with a purely engineering approach to supply this is captured by supply technology costs; for models with econometric supply modelling, it is governed by the interfuel substitution elasticity. GREEN assumes a long-run interfuel elasticity in production of 2.0 and a short-run value (reflecting existing supply infrastructure) of 0.5. Halving these values lowered global baseline emissions by 13% in 2050; the impact on abatement costs may be expected to be much larger unless the bulk of substitution is governed by backstop technologies.

7. KEY DETERMINANTS: TECHNOLOGICAL VS ECONOMIC PERSPECTIVES

7.1 Introduction

We have explored the range of reported results on the costs of limiting CO_2, and the technical modelling and data issues that affect such estimates.

[16]A CES function has the form $Q = (\sum_{i=1}^{N} a_i X_i^{\rho})^{1/\rho}$, where Q is output, X_i for i = 1 ... N are inputs used to produce Q, a_i for i = 1 ... N are constants, and ρ is the parameter that controls the elasticity of substitution.

[17]Cline states "The implied elasticity of output with respect to energy is one-sixth ... more than twice the factor share of energy in the US economy .. the output elasticity of a factor (energy) is usually expected to equal its share in output ... this would imply a GNP loss of about 2 percent rather than the model's estimated 3 percent (central variation)." Manne & Richels respond that this is a natural consequence of the form of production function and energy factor substitution elasticity chosen, and that both of these reflect widely accepted assumptions (personal communication).

We now turn to a deeper analysis of the issues that determine abatement costs and the more credible results. This section examines the gulf that may be characterized (not always accurately) as that between "technology-engineering" and "economic" perspectives, in terms of assumptions concerning energy demand and policy, structural, and technological assumptions. The subsequent section examines how the abatement strategy and scope of analysis affect the reported results.

It would be facile to suppose that the differences between "economic" and "engineering" views are confined to a few modelling parameters. They reflect very different perspectives, almost paradigms, about driving forces in the energy economy. A report from a UNEP workshop that sought to bridge the divide (101) observed that:

> To economists, energy is a factor of production: it is an input into economic growth, and one which can substitute for labor or capital, depending on relative prices. While energy-efficiency may improve due to technical development, so does that of other factor inputs; and efficiency improvements lower the relative price of energy, increasing the extent to which it may be applied. Also, fossil fuels dominate because of demonstrable convenience and low cost. Thus whilst recognizing the potential importance of technical improvements, and even market imperfections which prevent optimal energy use, to most economists there is every reason to expect energy consumption to grow with expanding GNP, and no particular reason to expect technical developments to reduce CO_2 emissions relative to the business-as-usual case without incurring substantial costs. It is a compelling case, with much long-term historical weight behind it.
>
> To scientists and engineers, on the other hand, energy is not an abstract input but a physical means to particular ends. The applications which consume much energy are those of heating, heavy construction, metals, etc—basic infrastructure and comfort—and travel. In developed economies, most infrastructure needs have been met, travel may be approaching limits of congestion and time budgets, and much new economic activity is in areas which consume trivial amounts of energy, such as information technology, general entertainments, etc. *Thus to most scientists and engineers economic growth is becoming less and less relevant to energy needs [in developed economies]. In addition, very large technical improvements in efficiency, which need not incur much extra costs, are readily demonstrable; technology is powerful and adaptable to changing conditions* (such as requirement for nonfossil sources); and it is hard to believe that human society is incapable of finding ways of putting such options into effect (this applies primarily to developed economies, but may also be of great relevance to developing ones if they can move directly to advanced technologies). This too appears to be a strong case, with at least partial support from recent trends, but it leads to a very different outlook from the "economist's" outlook sketched above.

This shows that the different perspectives lead to widely different assumptions concerning several factors: the relationship between energy demand and future economic growth in the absence of any abatement measures; the scope for exploiting more efficient technologies; and the scope for developing new technologies as needs (such as CO_2 reduction) require. The rest of the section looks at each of these aspects.

7.2 Baseline Energy Demand and the AEEI

Section 6 notes that energy demand in the absence of abatement measures depends on GNP (population times per capita GNP) growth rates, energy prices, and the response of demand to these, and the parameter usually translated as the rate of "autonomous end-use energy-intensity improvement" (AEEI). The impact of GNP and energy price changes is recognized by all analysts, as are the uncertainties. The major contrast in views arises from the differing assumptions about the AEEI. The enormous impact of this parameter has been noted in Section 6.2. Dean & Hoeller (64) state that "unfortunately there is relatively little backing in the economic literature for specific values of the AEEI ... the inability to tie [it] down to a much narrower range ... is a severe handicap, an uncertainty which needs to be recognized".

Among the major global and US studies, Whalley & Wigle (36, 37) and Manne & Richels (38, 39) adopt the lowest values for AEEI (0 and around 0.5 respectively). Williams (100) strongly criticized such values as too low; Manne & Richels (40) defend their value of AEEI on the grounds that it appears consistent with observed trends in the United States. However, it is difficult to separate the various factors in their analysis (e.g. price, income distribution, and time sampling effects), and Wilson & Swisher (70) strongly dispute their interpretation, concluding that "one can produce an experiment that justifies whatever AEEI one likes within very broad ranges".

We cannot suggest a definite value for this parameter, but it is important to understand it. The parameter has been badly misnamed: it is a measure of all nonprice-induced changes in gross energy-intensity—which may be neither autonomous, nor concern energy-efficiency alone. It is not simply a measure of technical progress, for it conflates at least three different factors. One indeed is *technical developments* that increase energy productivity. But another is *structural change,* i.e. shifts in the mix of economic activities (which may require widely different amounts of energy per unit value added). The third is *policy-driven uptake of more efficient technologies,* due to regulatory (as opposed to price) changes, greater than would occur without those changes.

Technical change is indeed hard to predict. Studies by Meyers & Schipper (102, 103) suggest that in manufacturing alone, technical change has increased energy productivity in OECD countries by about 2% per year for at least the past two decades; this includes price effects, but in fact there is no clear change in the trend that correlates with the energy price shocks (perhaps because of the lags in manufacturing equipment). Technical change appears more closely related to the price shocks in other sectors.

Structural change encompasses the phenomena of saturation in energy-intensive activities (such as home heating and primary heavy industries), and shifts towards less energy-intensive activities. A range of studies have noted that structural change, both between sectors and within manufacturing industry, has played an important part in restraining energy demand in the OECD in the past 20 years (103). Williams et al (104) provide considerable evidence for expecting the observed trend in manufacturing to continue. On the basis of this and other relevant literature, and various saturation effects, Grubb (79, Chapter 6) argues that an autonomous structural trend towards lower energy-intensities (i.e. rising AEEI) is to be expected as countries develop and as economic growth moves towards increasingly refined products and services.

We tentatively suggest that the lower values of AEEI in long-term studies (significantly below 1.0, especially for OECD countries) are dubious because of saturation and structural change effects. If correct, this points to baseline emissions towards the lower end of the range of long-run model predictions, making any fixed target much easier to reach and also reducing the scale and hence relative costs of reductions. This is, however, tentative; there are substantial uncertainties and a clear need for greater understanding of technical and structural trends, and integration of such studies in abatement cost modelling.

The AEEI is not the only controversial issue surrounding the relationship between GNP and energy demand. As noted in Section 6.4, considerable uncertainty surrounds estimates of the price elasticity of energy demand. Most studies have sought to estimate elasticities from the response of demand to the energy price rises of the 1970s and early 1980s. More recent trends, if anything, increase the uncertainties. Although energy demand has started to rise again in OECD countries following the price falls since the mid-1980s, the response has not been nearly as great as predicted by the simple reversible statistics of elasticity. Engineers have long maintained that the efficiency gains would not be lost, because they are embodied in better knowledge and techniques that will not be abandoned even if energy prices fall. The recent trends at least partially support this view, and econometric studies (105) have now started to question the basis of constant elasticities that assume symmetric responses to price increases and falls. Weisacker (106) also emphasizes the importance of recent analysis of price responses, and shows how it could have substantial implications for long-term abatement costs and strategies.

7.3 Regulatory Instruments and the Energy-Efficiency Gap

Most top-down models assume the optimal operation of markets in response to observed price signals (Section 5.1), in which case economic theory suggests taxes to be the optimal means of abatement. The observation of the large "efficiency gap" demonstrated by engineering studies (Section 3) calls this into question. Many economic discussions reject the relevance of this data; Nordhaus (30) for example states in his review that believing in such "free lunches" requires "an act of faith that is not warranted by economic evidence".

As discussed in Section 3.2, the "efficiency gap" comprises many different components. If it can be wholly explained in terms of lags in take-up, unavoidable hidden costs, etc, then it is a phenomenon of little direct relevance to the actual costs of limiting CO_2 emissions. However, many barriers to the uptake of more efficient technologies have been identified; Reddy (107) gives an extensive and clear analysis of the different kinds of barriers, and Grubb (79, Chapter 4) notes at least eight different categories. The reality of unexploited opportunities is beyond doubt.

It is accepted that some things can be done to improve the uptake of efficient techniques, for example, with government campaigns to improve information and the awareness of consumers of energy-efficiency and conservation. Most top-down studies in effect assume such measures to be enacted irrespective of CO_2 abatement, and ignore or dispute the scope for other more direct cost-effective actions. However, experience and modelling studies of regulatory policies demonstrate that such measures can and have been effective. Examples include studies of the US National Appliance Standard and Car Efficiency (CAFE) standards [Rolin & Beyea (108)]; of US building standards [Norberg-Bohm (109), Bradley et al (67)]; and a variety of measures internationally reviewed in Johansson et al (31).

Regulatory changes to encourage utility demand-side management programs have been widely advanced as a way of capturing the "free lunch" by getting utilities to invest in end-use efficiency. The "hidden costs" in such policies are debated. Joskow & Marron (110) conducted a survey of experience in US programs and concluded that "reported costs exceed those of the technology potential analysis because program costs are higher and energy savings are lower than these studies assume ... although many of the programmes still appear cost effective".

The important fact remains that modelling studies of specific regulatory options frequently yield lower, rather than higher, estimates of abatement costs than those derived from carbon taxation designed to achieve similar abatement. Such studies of regulatory measures thus contrast with the common economic assumption that regulatory options are more expensive than using economic incentives. This is because such policies address areas of significant market "failure".

In terms of economic model parameters, this may also be understood in terms of the AEEI, for policy-driven changes is its third component. The critical question is not then just its value, but the extent to which it in fact is a variable that may be affected by policy.

So how large is the potential "free lunch" of zero-cost energy-efficiency improvements captured by regulatory change? The end-use technology studies discussed in Section 3 frequently suggest a long-run technical potential to reduce energy demand without extra costs by 20–50%. Schipper et al (103) discuss the implementation and potential of energy-efficiency programs across the OECD in detail. They too conclude that there is large potential, but emphasize that the achievable potential will always be substantially smaller than the apparent technical potential, and that exploiting it will depend on more aggressive and sophisticated policies. Taking account of the various implementation issues points at best to the lower end of the 20–50% range being available—though we note that further technological development would also be expected.

This, combined with the estimates of Schipper (103) and a range of other more sector-specific studies (such as the regulatory studies noted above) suggest that over a couple of decades, targeted energy-efficiency programs might reduce energy demand by up to 20% of the level projected in the absence of any such policies, at costs lower than that of the displaced supply. Cost-effective savings of 20% is also the figure adopted by Cline from his review of engineering studies (17, Chapter 5). Furthermore, even many top-down studies indicate that reductions of 10–20% may be available at very low cost. While acknowledging the many uncertainties, we consider 20% reductions to be a reasonable estimate of the credible size of the "free lunch."

It is still debatable quite how this may be interpreted in relation to top-down studies. The US National Academy of Sciences study (47) compares bottom-up and top-down results, and highlights the large differences between the results up to moderate emission reductions, but also states there is a broad overlap at higher emissions; the "negative cost" of bottom-up studies corresponds to "low cost" in top-down studies, after which both approaches converge on rising marginal costs for further abatement.

A different view is given by other comparisons of top-down and bottom-up results. A critique and comparison of data from economic modelling as summarized by Nordhaus (30), and their relationship to bottom-up results, is presented by Wilson & Swisher (70), who indicate that bottom-up studies suggest cheaper abatement right across the range, up to abatement of 70% or more. Their data suggest that the whole cost curve from the top-down studies reviewed by Nordhaus has to be shifted by 20–40% to reflect the technical opportunities identified by bottom-up studies, which would greatly alter the pattern shown in the graphs of Section 4.[18]

In reality, the data from studies are too scattered to reach a definitive conclusion; the actual situation is likely to lie between these extremes, implying a need for some reduction in abatement costs from top-down models across the range to allow for the potential of regulatory-driven improvements in energy-efficiency. A further factor is that, with expanded markets for more energy-efficient technologies, these technologies might develop faster, thus permanently raising the AEEI. The impact of such a change has already been noted.

7.4 Technology Assumptions and Modelling

Ultimately, the costs of limiting CO_2 emissions will depend heavily on the technologies available, not only technologies for more efficient use of energy, but also for the production, conversion, and utilization of lower-carbon energy sources. The importance of technology, as well as assumptions concerning its developments and costs, has been widely acknowledged: it forms the central element of Williams's (100) critique of the Manne & Richels (38) conclusions, and sensitivity studies by Manne & Richels (40) and Edmonds & Barns (81) have demonstrated that estimates of abatement costs depend crucially on technology assumptions.

Yet the care with which such assumptions have been developed varies widely, and the models employed to date have limited representation of technology issues. Models that do incorporate some explicit representation of technology include the Global 2100 model and its derivatives (CRTM and CETA), more recent variants of the OECD GREEN model, and the ERB model, which has a fuller representation of technology in compensation for its weaker macro-economic linkages. Sensitivity studies with all these models illustrate the crucial importance of technological assumptions.

To establish reasonable assumptions, it is pertinent to start with current data, and visible trends and options. With respect to supply-side options, data such as that collated and summarized in many publications [e.g. Refs. 18–22; for review of sources see UNEP (16)] illustrates the immense range of possibilities. They span technologies that are proven and largely mature

[18]In effect this means that if the baseline in top-down studies is equated with a "business as usual," rather than a "least cost" path, all the points derived from top-down models in the scatter diagrams of Section 4 should be shifted perhaps 20 percentage points to the right so that emissions reductions of 20% are costless. This excepts the shorter-run studies run over 10–15 years, when a "free lunch" potential of perhaps 1% per year (i.e. an increase in the AEEI by 1 percentage point) below baseline might be more appropriate.

(such as combined-cycle gas turbines—CCGTs), proven but still developing (such as wind energy and higher-efficiency clean coal conversion), confidently predicted [such as much cheaper photovoltaics (PV) systems and integrated biomass gasification], to a wide variety of lesser or more speculative options. Most recently, an immense study of the prospects for modernized renewable energy technologies (111) argued that these could meet about half global energy demand by the middle of the next century at little if any additional cost; the studies of wind energy in this volume estimated that the costs of modern wind turbines were already almost competitive against coal power stations for large-scale exploitation in countries such as the United States with extensive wind energy resources. None of the CO_2 abatement models contain explicit representation of wind energy technology, and for large countries such as the United States and the former Soviet Union, this alone might substantially lower abatement cost estimates.

No models can capture the full range of options available; by inevitably excluding some, there can be an in-built tendency to overestimate abatement costs (unless this is offset by using over-optimistic assumptions concerning those that are included). Some abatement studies use data already being rendered obsolete as options already identified for cost reductions are exploited. Williams (100) provides one of the most detailed critiques of the technological assumptions used in the Manne & Richels base case assumptions and their derivatives, and argues that many of the assumed costs are higher than can already be predicted with confidence.

This leads naturally to the issue of technology development and cost reductions. This is uncertain terrain, but not a complete black box. Technologies do not arise, improve, and penetrate markets at random, especially for large and complex technologies such as those involved in energy provision. Technology development follows market demand, with the associated public and private R&D investment and learning processes as technologies develop towards market maturity. Yet despite this well-attested and understood fact, almost all the abatement costing studies to date model technology development as "exogenous"—the costs of abatement technologies are defined as input data and do not vary explicitly with the level of investment, incentives, and market penetration in the model. That alone must be considered as a severe limitation.

Anderson & Bird (45) provide one of the few abatement cost analyses to date that explicitly includes production scale economies. They apply this to renewable technologies within a simple investment/growth model of global economic expansion. Their analysis produces lower cost estimates than most of the more complex studies that model the economy and energy sector in more detail, but wholly neglect the issue of technology development.

A very different approach to the issue of endogenous technological development is that by Hogan & Jorgenson (93). This econometric study related changes in productivity trends (which are equated with technical progress), in different sectors of the US economy, to price changes in the different inputs. Although energy productivity did improve when energy prices rose, this was more than offset by reduced productivity growth in other factor inputs at the same time. They found that overall, "technology change has been negatively correlated with energy prices . . . if energy prices increase, the rate of productivity growth will decrease." However, such results may be very sensitive to the model specification, and as argued in Grubb (79, Chapter 3), the transition from "has been" to "will" in this excerpt conceals the importance of innumerable extraneous factors in the years analyzed, most notably the macro-economic impact of the sudden and externally imposed oil price shocks. It is highly debatable whether the data reveal anything useful about the economy-wide and long-term technological impact of smoother price changes arising from domestic policies such as carbon taxes, and other abatement policies.

The potential for substantial cost reductions associated with larger-scale deployment of low CO_2 technologies, combined with the observations above about possible irreversibilities in the impact of price changes, points to the possibility that there may be various choices of technological trajectories differing little in cost. One is to continue along a carbon-intensive path. Another is to invest enough to alter the course of new investments over the next decade or two towards more efficient, and low-carbon, technologies. As investment patterns and institutions and infrastructures adapt to these new technologies, their costs will fall, perhaps until they become the naturally preferred options. The world would be on a different technological trajectory. Although the transition may be costly, especially if it is forced rapidly, given the nature of technology development and economies of scale it cannot be assumed that this would be a much more costly long-term path (147).

This is an example of the issue of "bifurcation," identified especially by Hourcade (112) as a concept that "encompasses many network industries where market forces tend, beyond a bifurcation point, to reinforce the first choice ... in a self-fulfilling process." Hourcade highlights that this is not only a matter of scale economies; once investment is made in transport infrastructure or town planning, for example, it attracts a major network of other investments that reinforce the original choice and make later changes much more costly than if development occurred along a different trajectory. Hourcade develops a technology-oriented economic model and projects various scenarios that differ by up to 50% in long-run CO_2 emissions for the same estimated costs.

The prospects for technology development, production scale economies, and exploitation of bifurcations to lower emissions suggest that the cost estimates in many economic studies are implausibly high. Indeed, some use data that appear to indicate costs higher than those of some currently identified technologies, and make little or no allowance for future technical improvements especially in nonfossil sources.

We do, however, note that there are considerable constraints on the rate at which such technologies could be developed and deployed; as modelled most clearly by Anderson & Bird (45), the deployment of major new supply technologies will take many decades.

On these grounds we consider the higher long-term (beyond c.2025) costs illustrated on the graphs in Section 4 to be relatively implausible.

8. KEY DETERMINANTS: ABATEMENT STRATEGIES AND SCOPE OF ANALYSIS

Even when issues relating to technology costs and deployment are put on a comparable basis, there are many other important sources of difference among economic modelling studies arising from the form of abatement strategy and the scope of analysis. In this section we examine the most important of these.

8.1 Subsidies, Tax Forms, and the Use of Tax Revenues

Various forms of taxes (and subsidies) can be used to limit emissions. Different types of taxes lead to different reductions in CO_2 and to different impacts on the economy [Scheraga & Leary (113)]. Most of the economic models considered assume abatement to be achieved by a carbon tax, imposed on the carbon content of primary fuels. However, taxes could be applied to subsets of fuels, downstream on derived fuel products, or otherwise not in proportion to carbon content of fuels, e.g. on gasoline only or on the energy content of fuels. This generally results in greater economic costs (lower tax efficiency). Thus, a gasoline tax is less efficient than a carbon tax at reducing carbon emissions (95); and taxes on electricity production are much less efficient than a tax on input fuels; the latter do not encourage fuel switching, only reducing CO_2 by depressing demand for electricity (114).

The distributional effects between countries vary greatly according to whether the tax is imposed by producers or by the consuming countries [Whalley & Wigle (37)]. Carbon/energy taxes also have substantial distributional effects within countries, as they frequently have greater impact on the poor and always have greater impacts on energy-producing sectors. Distributional impacts can often be offset by accompanying measures that redistribute some of the revenue back to those adversely affected.

Of greater relevance to the assessment of total abatement costs is that energy production in most countries is subject to a complex set of taxes and subsidies, and abatement costs inevitably depend on the existing tax structure. Where heavy taxes are already imposed (as with oil products in many OECD countries), the macro-economic impact of additional taxation is likely to be greater than in the absence of existing taxation; conversely, where energy is subsidized, removal of subsidies (or equivalent taxation) will often yield macro-economic benefits. Many models ignore initial subsidies and taxes.

The OECD (115, 116) and the World Bank (117) identify a range of energy subsidies, widespread outside the OECD but also widely applied to coal in OECD countries. These subsidies amount to an estimated $235 billion, equating to a carbon subsidy of $92 per ton outside the OECD and indicating a significant potential for limiting emissions at net economic benefits by removing subsidies. These figures are dominated by the former Soviet Union ($160 billion), which is anyway undergoing radical price reform, but the potential impact in countries such as India and China is clearly important. However, in such countries the distributional impact of removing subsidies is especially severe because of the poverty and lack of any social security protection; social impacts and political constraints are central in practical considerations. We also note that structures of subsidies and taxes are not arbitrary; oil taxes in OECD countries, for example, reflect perceived external costs associated with dependence on foreign oil.

Where net taxes are applied, the impact on GNP depends on how the revenues generated are used. Yamaji (118) assumed that the carbon tax revenue left the Japanese economy, likening an imposition of a carbon tax to the oil price shocks of the 1970s. The resulting estimates of the impact on GNP (a 5% loss) are much larger than if most of the revenue were kept within the economy. The US Congressional Budget Office (78) compared the effect of a revenue-raising tax (which removes money from the economy to reduce the federal budget deficit) with a fiscally neutral carbon tax, and found the impact on GNP to be much lower in the latter case.

The short-term CBO studies (78) have since been complemented with more broad-ranging and longer-term studies of tax-recycling issues, notably Bradley et al (67), Brinner et al (120), Scheraga & Leary (113), the European Commission (121), and Shackleton et al (76), which show evidence that while initially depressed, GNP could be raised in the long term by some recycling strategies. These papers explore the implications of a variety of tax recycling options. Table 7 illustrates key results, qualitatively because of the uncertainties in these (mostly short-run macro-economic) models, and the extent to which the impacts vary over time, as discussed in Section 5.2. Figure 13 shows the results of two alternative tax recycling options (lump-sum rebate and investment tax credit) for four different models as compared by Shackleton et al (76).

If the tax revenues are taken out of the economy (e.g. unaccounted for or spent abroad), all impacts on the national economy are negative. For other uses of the tax revenues, different macro-economic indices frequently

Table 7 Tax recycling: Summary of qualitative results (impacts)[a]

Uses of tax revenues	Shackleton et al (76), US[b]				Barker (122), UK[c]		Hermes (72)[c]	Quest (71)[c]
	JW	Goulder	DRI	LINK	EC tax	OECD tax		
Budget deficit reduction								
GNP		−−	(−)	−−	−−		−−	−−
Employment					−		−	−
Inflation					−−		−−	−−
VAT offset								
GNP					+	+		−
Unemployment					+	++		+
Inflation					(−)	(+)		−
Income tax reduction								
GNP	−	−−	−	−	(+)	+	−	−−
Unemployment					(+)	+?	0	−
Inflation					−−	−−	−−	−−
Investment tax reduction (US studies)					Employers' social security contributions			
GNP	0	−	++	++			−	−
Unemployment							+	0
Inflation							−−	−−

[a]Key: +, Positive impact (0.1–1% improvement on baseline); (+), less than 0.1% impact; ++, greater than 1% impact, −, negative impact (0.1–1% improvement on baseline); (−), less than 0.1% impact; −−, greater than 1% impact.
[b]Tax of $40/tC, results reported for 2010.
[c]Tax of $10/boe (about $80/tC), introduced by 2000, results reported for 2005.

move in different directions. For the carbon tax levels considered (up to about $80 per ton C), nearly all these studies find some ways in which the net effect is to boost GNP, as compared to a projection in which existing tax structures are unchanged.

These results reflect at least two different factors. First, a carbon tax raises money largely from consumption; this may be transferred to qualitatively different economic activities. If the revenues are used to stimulate investment directly, this reduces consumption but soon increases GNP. If the revenues are used to reduce budget deficits, consumption and GNP are initially depressed but they may slowly recover as the lower interest rates etc improve the investment climate; Brinner et al (120) suggest that the GNP impact in the United States becomes positive within 15 years, although EC studies suggest a slower recovery. Conversely, if the revenues are used to boost consumption, investment is diminished and shortly thereafter GNP growth. It is doubtful the extent to which the gains or losses should really be credited to CO_2 reduction, since they partly reflect a channeling of resources from one kind of economic activity to another. We do not therefore consider the extreme points in Figure 9 especially, which reflect such transfers, to be of great relevance. More neutral schemes of tax recycling,

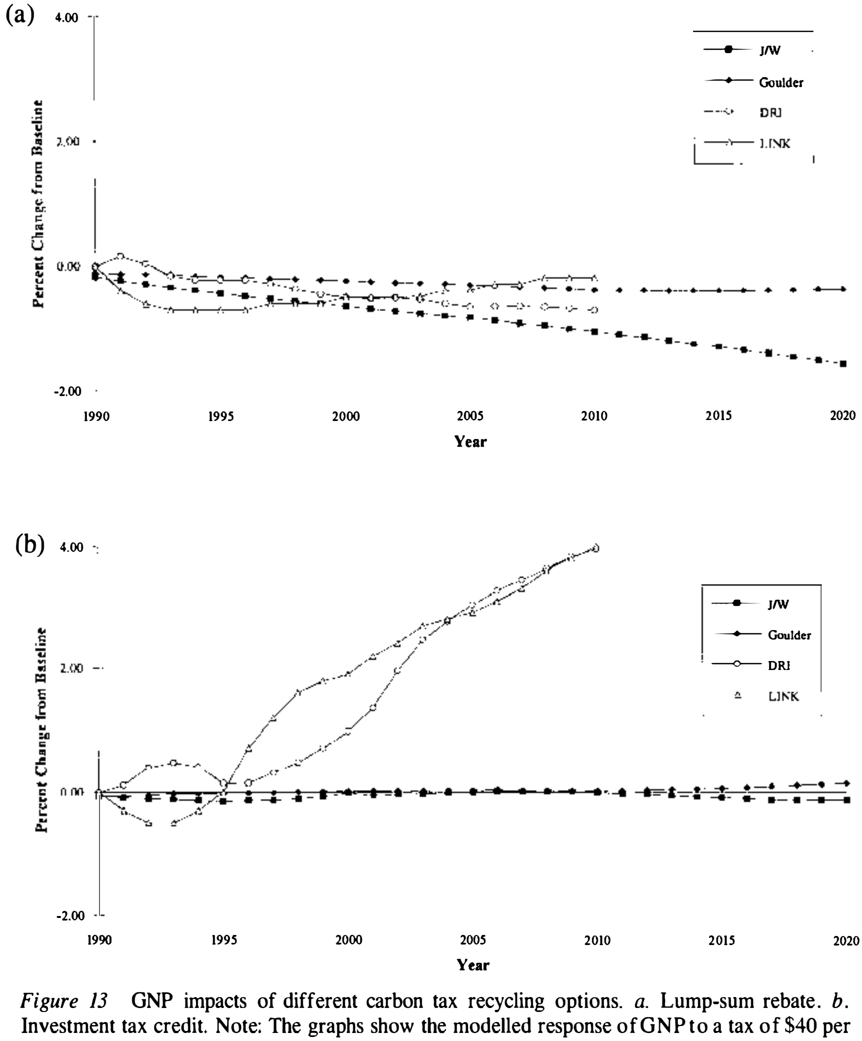


Figure 13 GNP impacts of different carbon tax recycling options. *a.* Lump-sum rebate. *b.* Investment tax credit. Note: The graphs show the modelled response of GNP to a tax of $40 per tonne C introduced in 1990 in the United States. Source: Shackleton et al (76).

for example associated with value-added tax (VAT) offsets or reduced social security contributions, are more directly relevant. As indicated in the table, models differ with respect to the sign of associated GNP (and employment) impacts, but mostly show the impacts to be relatively small.

This reflects the second element, which is that carbon taxes at the levels considered may be genuinely less distortionary than the most distortionary existing taxes. There is still some debate as to how valid it is to count such changes as a credit for carbon taxation. As with the efficiency "free lunch" debate, should not governments make the current tax structures optimal irrespective of abatement efforts, with gains that should not be credited to carbon taxation? There are no easy answers to this. Certainly it is to be hoped that tax structures become more optimal over time. But there are also real constraints on taxation policy, and objectives other than just efficiency; Hourcade (112) notes growing political and trade constraints on traditional taxes and concludes that "it is timely to consider the taxation of 'bads' (such as pollution) as an answer to the general problem of raising revenues." In any case, if carbon taxes represent an efficient way of limiting emissions, it would be perverse to say that the revenues should not be used in the most desirable way—or alternatively, to say that economists should not model reality because the starting point is not optimal.

For longer-term assessment, current quirks of taxation systems may be less significant, but it is still important to recognize that governments need to raise revenues; carbon taxes will reduce the revenue required from other taxes and models need to reflect this reality. In general, the distortionary impact of a tax increases nonlinearly with its level, so it is efficient to spread the tax base as broadly as possible. Consequently, even in the absence of a CO_2 problem, the optimal level of energy/carbon taxation would not be zero.

Consequently we can conclude that modelling studies that neglect such distortions in the rest of the tax system—and the consequent potential gains from carbon tax recycling—tend to overestimate the GNP impact of carbon taxation. This includes all the long-run (post 2010) points in the graphs in Section 4, and many of the shorter-term studies as well, where the practical GNP gains may be more significant.

8.2 Scope of Abatement, Trade, and Leakage

Climate change is a global problem, and the more countries that take part in abatement, the lower the costs of limiting global emissions will be. Studies emphasize that action by industrialized countries may have a significant short-term impact, but that the costs of restraining global emissions rise rapidly if developing countries are not soon included. Furthermore, even if all the major countries participate, the costs are greater if each is bound to fixed emission targets, because some regions may then incur much higher costs than others as noted by e.g. Edmonds et al (68).

Table 8 shows one estimate of the impact of allowing countries freedom to choose where to invest to limit emissions (i.e. trade in emission commitments). Despite a no-trade case that involves similar rate of emissions reduction below baseline (2% per year), there are still significant differences in marginal abatement costs (reflected in the tax rate) between regions, and thus savings (of 10–45%) to be made from trading. Less uniform (relative

Table 8 Cost savings from emissions trading under two models[a]

Target date	Trade?	ERB Tax (\$/tC)[b]	ERB GDP loss (%)[c]	GREEN Tax (\$/tC)[b]	GREEN GDP loss (%)
2020	No trade	283	1.9	149	1.9
	Trade	238	1.6	106	1.0
2050	No trade	680	3.7	230	2.6
	Trade	498	3.3	182	1.9

[a] Source: Dean & Hoeller (64)
[b] Global tax or mean of taxes required to achieve CO_2 reduction at 2% per year below baseline trend in each region.
[c] GDP loss reported by model, not net surplus cost in energy sector (see Section 5.3).

to baseline) initial commitments would increase the benefits of trading accordingly; an extreme case was a special run of the Whalley-Wigle model (36, 37) that showed that the costs of obtaining the same degree of abatement, but with equal per capita emissions globally, would be roughly twice the costs of achieving the same reductions if emissions trading is allowed. Clearly models that do not allow such trade will report costs greater than necessary.

A related issue is that of "leakage." Emission constraints in some countries may lower traded fuel prices and change terms of trade in a way that increases in CO_2 emissions in non-abating regions. Early studies with the Rutherford model (CRTM, 41) suggested this could be a large effect, but more recent studies have decreased such estimates. The OECD GREEN (90) and ERB (68) models identify leakage rates from OECD action at only a few per cent, while noting that it is sensitive to the assumed coal supply elasticities, and that not all aspects of leakage are captured by the model.

As countries move towards considering energy and carbon taxes, there is bound to be more focus on trade-related aspects and the way they may affect national abatement costs and impacts. Research in this area is still in early stages, but a preliminary analysis and discussion is given by Horton et al (123), and a substantial review of the issues and models (including many covered in this paper) is given by Pezzy (124).

8.3 Rate and Pattern of Emissions Abatement

Most studies—including those reviewed—have focussed on measuring costs for a given degree of emissions abatement. It is clear that the costs must also depend on the rate of abatement. This is partly because relatively "slow" abatement can be achieved by introducing lower carbon technologies as older vintages are naturally retired. Figure 14 illustrates this, by comparing

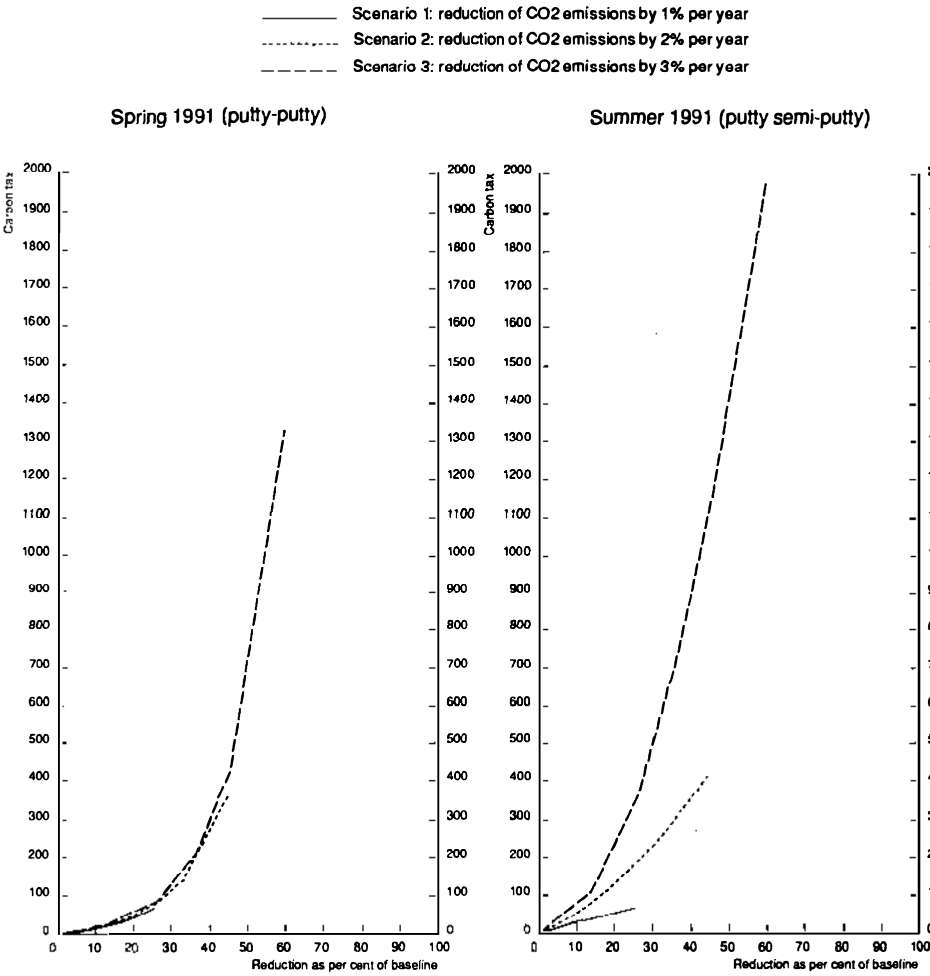


Figure 14 Carbon taxes for different rates of abatement: impact of modelling capital stock (GREEN model). Note: The graphs show the carbon tax ($/tC) required to reduce global CO_2 emissions as shown by the year 2050 before and after introducing modelling of capital stock. Source: Hoeller, Dean, and Hayafuji (151).

results of the GREEN model before and after it was extended to include "semi-putty" vintage modelling, which reflects the additional costs of being forced to retire capital stock prematurely. The modelling improvement has little effect on the costs of CO_2 abatement at a rate of 1% per year below the baseline trend, but for abatement at a rate of 3% per year below the baseline trend, the costs are very much higher when the stock effect is included.

In reality, many other factors also make more rapid abatement more costly. A variety of macro-economic disequilibria come into play—capital or labor cannot move rapidly from one sector to another, in response to relative price and other changes. Since resource allocation/equilibrium models do not capture these effects, they tend (other things being equal) to underestimate the costs of rapid abatement; unlike most other factors noted, this suggests that most of the points in Figures 6–8—most of which are derived from resource-allocation models—underestimate costs in this respect, especially for more rapid (shorter-term and more extreme) abatement.

The observation above that short-run macro-economic models indicate a much smaller response of emissions to a given level of carbon tax is another indication that such models show the economy to be more resistant to change than do equilibrium models such as GREEN. The real dependence of costs on the rate of abatement may thus be even greater than suggested by the GREEN results in Figure 14. A plot of the data from modelling studies presented in Section 4 against the rate of abatement (not reproduced here) does not, however, reveal a particularly strong relationship. We suggest that this is because the results are mostly from equilibrium models, which themselves have a wide variety of capital stock modelling (if any). Few studies with short-run macro-economic models have been carried out, and these focus on different ways of recycling carbon tax revenues; the issue of how costs vary with the rate of abatement does not seem to have been examined methodically with macro models.

A third issue relating directly to the rate of abatement is that of technology development and diffusion. This is inherently a process that takes time, particularly in energy supply. Marchetti and others at IIASA (125) proposed a general principle that it takes around 50 years for a new supply technology to become dominant. More detailed technology studies reveal a more complex picture, with the rates of diffusion dependent on the nature of the technology and existing infrastructure; Grubb & Walker (126) argue that electricity supply could change much more rapidly than the "50 years" rule implies, but that fundamental changes to noncarbon transport fuels could be still slower.

Clearly, long timescales are involved, and these estimates do not include timescales for basic research and development. Consequently, rapid reductions will have to use less developed technologies than will slower reductions. This observation has been interpreted as a way of saying that delayed reductions are cheaper, but the implication rather is that costs will be minimized by setting the process of transition in motion as early as possible, because that will give the maximum time in which to develop, deploy, and refine lower carbon technologies. For a given total emissions over the next century, for example, simply delaying initial abatement efforts would both delay the start of such a transition, and increase the rate and degree of abatement that would ultimately have to be pursued.

In this context, we note the relevance of the whole pattern of abatement imposed in abatement costing studies. The ultimate objective is to reduce accumulation of CO_2 in the atmosphere. Studies that impose a set time-path of emissions make no attempt to explore possible less costly emission paths to the same end. The original Manne-Richels studies, for example, show carbon taxes rising to more than \$650 per ton C, settling back down to a level of \$250 per ton C set by the "backstop technology." Peck & Tiesberg (42) point out that this is clearly not "efficient"; greater long-run abatement can be achieved with less long-run GNP impact by a time path that involves steadily rising carbon taxes. A more efficient time path of abatement would thus lower the GNP impact of studies shown in Figures 6–9. By how much is difficult to say, indeed, there are so many issues inadequately addressed in this context (e.g. concerning technology development and diffusion) that firm conclusions would be premature, but it is an important area for further exploration.

8.4 Externalities and Multicriteria Assessment

CO_2 is but one of many external impacts associated with energy. Other pollutants are produced, and other issues, ranging from energy security to road congestion, are important but not included in traditional economic studies. Attempts to quantify other externalities [e.g. Hohmeyer (127); Ottinger et al (128)] suggest these can be significant. A study by Glomsrod et al for Norway (129) appears to be the only one that includes the reduction of these other impacts as quantified "side-benefits" in a study of CO_2 abatement. This and a review by Pearce (130) suggest that including these "secondary benefits" can alter cost assessments radically.

One aspect of such conclusions—in common with those relating to the "efficiency gap," subsidies, and carbon tax recycling—is the potential for net economic gains from abatement efforts that reduce current market imperfections. Where the gains from reducing other externalities are so large, it would make sense to address them directly (in many countries this is already happening); once this is done, the further incidental benefits of CO_2 control would be much reduced. Nevertheless, it is also important that modelling studies reflect the actual situation, including current external costs associated with energy supply, which CO_2 abatement would also help to address. Again the consequence is that the costs displayed in Figures 6–9, which ignore such external benefits of CO_2 control, should be lowered according to the value accorded to the avoided externalities.

It should also be recognized that externalities may operate to increase the cost of emissions reductions. For example, large hydropower schemes may offer very cheap power for a region and produce no CO_2. But they have many other impacts. Whether or not hydro schemes are actually desirable is a complex political judgment about different sorts of costs and benefits, including land-use and ecological impact. All this points to the fact that many criteria other than economic cost need to be factored in to any comprehensive analysis of CO_2 abatement. Like much else in the analysis of abatement costs and strategies, it is not a choice that can be dictated by economic analysis alone.

9. CONCLUSIONS

Our survey and analysis of the literature on fossil-fuel CO_2 abatement costing shows a very wide spread of reported results, and the analysis reveals many different features that explain these differences.

9.1 General Conclusions

I. Estimates of the costs of limiting fossil-fuel CO_2 emissions span a very wide range. The principal factors that affect estimates are as follows.

A. The choice of modelling approach and focus, notably:
—top-down or bottom-up;
—associated regulatory modelling;
—short-run macro-economic or long-run equilibrium;
—the linkage between energy sector in impacts and GNP;
—modelling of technology development in response to incentives.

B. The numerical assumptions concerning:
—energy-GNP trends as governed by income elasticities and autonomous energy-intensity improvements;
—fossil-fuel reserves and associated future prices and supply elasticities;
—the degree (elasticity) and reversibility of energy demand responses to price changes;
—technology development and costs (including production scale economies), or equivalent substitution elasticities.

C. The nature of the abatement strategy and the scope of analysis:
—the reflection of existing tax and subsidy distortions and associated use of carbon tax revenues;
—the scope of abatement and allowance for emissions trade among participants;
—the rate and pattern of emissions abatement;
—the extent to which external costs and benefits associated with energy supply are reflected.

II. "Bottom-up" engineering models tend to underestimate costs by neglecting issues of implementation and other hidden costs. "Top-down" economic models tend to overestimate costs by neglecting the potential for enhancing structural change and energy-efficiency gains through regulatory policy. We suggest that real "cost-free" reductions of up to 20% below the baseline projection over a couple of decades is a reasonable estimate of this potential, but realizing such reductions will require extensive implementation of policy instruments to improve market efficiencies.

III. Within the range of abatement issues and options, there are at least four kinds of options that reduce CO_2 emissions but may incur macro-economic gains: regulatory policies to reduce the "efficiency gap" as noted above; removal of subsidies for carbon fuels; use of carbon tax revenues to reduce existing tax distortions; and the reduction of high non-CO_2 externalities. In each case the possibilities raise similar questions about the extent to which the benefits of associated policy reform should be credited to CO_2 abatement. In each case we conclude that some credit is justified, but that not all the potential should be credited as benefits of CO_2 abatement.

IV. There is a need for much more extensive economic research on the issues identified above. Our review also illustrates the importance of conducting sensitivity studies with respect to the assumptions embodied in cost modelling studies, and of presenting these assumptions with clarity. More careful consideration of the use of GNP as an indicator of welfare, and study of complementary and alternative indicators, is also required.

9.2 Quantitative Conclusions

For comparative cost purposes, it is useful to express abatement relative to a baseline projection of expected emissions in the absence of specific abatement efforts. More attention needs to be devoted to definition of the baseline case. However, in general, we conclude the following.

V. *Short-run abatement costs*. The results for regional and shorter-term studies of abatement costs vary very widely; the reported costs of emission reductions of 15–40% below baseline (not base year) over the next 15–20 years, for example, range from GNP gains of more than 1% to a several percent loss in GNP.

However, the higher losses in this range reflect the fiscal effect of removing carbon tax revenues from the economy, and also ignore the potential for energy-efficiency programs; while the larger GNP gains either reflect the use of carbon taxes to transfer resources from consumption to investment or reflect pure technology potentials. These extremes are of questionable relevance as measures of abatement costs, which in reality may be expected to lie well within these outlier values.

VI. *Long-run abatement costs*. The range in long-run cost estimates is not quite so broad. With few exceptions, long-run modelling results portray that reducing CO_2 emissions at a rate averaging up to 2% per year below baseline, leading to a halving of relative emissions by the middle of the next century, may reduce the associated long-run global GNP by up to 3%, with the lower bound of costs being almost negligible.

VII. For most (but not all) of the issues listed in (I) above, using more realistic or plausible assumptions reduces abatement cost estimates as compared with the most widely reported top-down economic modelling studies. The evidence presented from sensitivity studies and other modelling studies suggests that reasonable allowance for technology development, removal of subsidies and recycling of carbon tax revenues, and the reflection of avoided externalities alone might halve the more pessimistic estimates of abatement costs. Consequently, we suggest that a realistic range for the GNP loss from halving long-run CO_2 emissions (relative to the emissions in most "baseline" projections) is 0–1.5%.

The upper bound of this range is large in absolute terms (for example it represents $600 billion out of a projected global GNP of $40,000 billion), but is small compared with other uncertainties and influences on GNP; it is equivalent to reducing average GNP growth rates over 50 years from 3% per year to 2.97% per year. Efficient distribution of abatement efforts between regions and over time could further lower these costs.

VIII. Costs will depend heavily on the rate at which abatement is imposed. The conclusions cited above refer to moderate rates of abatement. Study of this issue is seriously inadequate, but the costs may start to rise sharply for abatement at rates exceeding 1–2% per year below the baseline trend.

IX. To put these in context, we note that projections by the World Energy Council (131) and many others suggest that global CO_2 emissions, in the absence of CO_2 abatement policies or other policy changes that significantly restrain CO_2 emissions, may grow at a rate averaging around 1.6% per year (±0.4% per year) for many decades.[19] Given all the uncertainties and possibilities for lower abatement costs identified in this paper, our survey

[19]For example, the World Energy Conference reference scenario projects an almost linear increase in CO_2 emissions to 42% above 1990 levels by the year 2020. The models in the OECD model comparison study (64) span a range up to a 60% increase by this date.

and analysis therefore suggests that keeping long-term global CO_2 emissions to about current levels—which is much more severe than current proposals to stabilize emissions in industrialized countries—may if carried out in an efficient manner be expected to reduce global GNP towards the middle of the next century by no more than 1–1.5%, and average GNP growth rates over the period by less than 0.02–0.03% per year.

Consequently, we suggest that the real difficulties of abatement lie in the design and implementation of nationally and globally efficient policies, and the geographical, sectoral, and social distribution of abatement impacts. Many analytic issues remain to be resolved, but for constraining CO_2 emissions, the key problems appear to be not massive, macro-economic losses, but rather the politics of implementation, winners, and losers.

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