MIT Joint Program on the Science and Policy of Global Change

CO_2 Emissions Limits: Economic Adjustments and the Distribution of Burdens

H.D. Jacoby, R.S. Eckaus, A.D. Ellerman, R.G. Prinn,
D.M. Reiner, and Z. Yang

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The MIT Joint Program on the Science and Policy of Global Change is an organization for research, independent policy analysis, and public education in global environmental change. It seeks to provide leadership in understanding scientific, economic, and ecological aspects of this difficult issue, and combining them into policy assessments that serve the needs of ongoing national and international discussions. To this end, the Program brings together an interdisciplinary group from two established research centers at MIT: the Center for Global Change Science (CGCS) and the Center for Energy and Environmental Policy Research (CEEPR). These two centers bridge many key areas of the needed intellectual work, and additional essential areas are covered by other MIT departments, by collaboration with the Ecosystems Center of the Marine Biology Laboratory (MBL) at Woods Hole, and by short- and long-term visitors to the Program. The Program involves sponsorship and active participation by industry, government, and non-profit organizations.

To inform processes of policy development and implementation, climate change research needs to focus on improving the prediction of those variables that are most relevant to economic, social, and environmental effects. In turn, the greenhouse gas and atmospheric aerosol assumptions underlying climate analysis need to be related to the economic, technological, and political forces that drive emissions, and to the results of international agreements and mitigation. Further, assessments of possible societal and ecosystem impacts, and analysis of mitigation strategies, need to be based on realistic evaluation of the uncertainties of climate science.

This report is one of a series intended to communicate research results and improve public understanding of climate issues, thereby contributing to informed debate about the climate issue, the uncertainties, and the economic and social implications of policy alternatives.

Henry D. Jacoby and Ronald G. Prinn,
Program Co-Directors

For more information, contact the Program office:

MIT Joint Program on the Science and Policy of Global Change
Postal Address: 77 Massachusetts Avenue
MIT E40-271
Cambridge, MA 02139-4307 (USA)
Location: One Amherst Street, Cambridge
Building E40, Room 271
Massachusetts Institute of Technology
Access: Telphone: (617) 253-7492
Fax: (617) 253-9845
E-mail: globalchange@mit.edu
Web site: http://web.mit.edu/globalchange/www

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Henry D. Jacoby, Richard S. Eckaus, A. Denny Ellerman,
Ronald G. Prinn, David M. Reiner, and Zili Yang

1. THE ASSESSMENT TASK

National acceptance of Quantified Emissions Limitation and Reduction Objectives (QELROs), as suggested under the Berlin Mandate of the Framework Convention on Climate Change (United Nations, 1995), implies the imposition of constraints on emissions of CO_2 and perhaps other greenhouse gases. Such actions taken by a subset of countries can have a number of economic impacts, not only on those adopting the restrictions but on other regions of the world as well. Controls that lead to reductions in economic activity in one country will reduce the demand for exports of other countries, influencing their levels of economic activity. The relative prices of different sources of energy will shift, with consequent effects on the relative prices of non-energy goods. These changes in relative prices will occur both within countries (leading to in-country substitution) and between countries (leading to trade adjustments), thus further influencing economic performance. The final effects on greenhouse gas emissions will be the result of all of these interacting changes.

As a result of this complex web of adjustments, economic burdens will imposed on countries that have not accepted obligations under the Framework Convention on Climate Change. Emissions reductions achieved by one set of countries may actually be partially counteracted by increases elsewhere (which is the so-called carbon “leakage” effect). If, in an effort to reduce costs, countries facing emissions restrictions adopt some form of trading in emissions rights, these effects may be moderated. The magnitude of the amelioration depends on many factors, importantly including the particular selection of nations that participate in the trading.

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Here a sample QELRO proposal is used to explore how the various adjustment mechanisms may combine to determine the magnitude and distribution of economic burdens, and the level of leakage. To place the analysis in the context of the larger climate-change issue, we follow the effects of this proposal through the climate system, to assess its effect on estimates of one indicator of climate change. We cannot, however, overcome the limitations of inadequate knowledge of many of the technical and behavioral relations, and their parameters, that are relevant to this issue. Moreover, the results are sensitive to the model specifications used. So the analytical exercise reported below should be interpreted as illustrating the types and degrees of interaction that might result from emissions restrictions such as those in discussion in the Framework Convention.

Under the case chosen for study here, the nations of the OECD[1] agree to stabilize their CO_2 emissions at 1990 levels by the year 2000, to bring these emissions down to 80% of 1990 levels by 2010, and to stabilize their emissions at that level to the end of the analysis period, which is 2100. Several schemes of this type have been proposed to the Ad-Hoc Group on the Berlin Mandate, which is the arm of the Climate Convention where emissions limits are being negotiated. Our version is close to a proposal by the Alliance of Small Island States (AOSIS) and Germany[2], and for convenience we refer to our sample scheme as an “AOSIS-type protocol.” Emissions of other anthropogenic greenhouse gases (methane, nitrous oxide, chlorofluorcarbons) or of aerosol-producing sulfur dioxide would be influenced by this commitment, but they are not a direct object of the control policy in this example.

It is further assumed that this protocol is adopted in the late 1990s, and is sustained as the only climate policy over the next century. Its impacts are then calculated by comparison with a no-policy case, where no actions are taken to control greenhouse emissions over this period. This “policy scenario” construction allows isolation of the effects of our sample control proposal, but care must be taken in interpreting the results. As seen by their proponents, AOSIS-type protocols are not climate policies in themselves, but the first steps on a path that should lead to subsequent commitments by the wealthier countries, and eventually to emissions restraint by all Climate Convention signatories. Also, decisions for the next century are not at any point made once and for all the future. We will learn with time, and will revisit choices made now. For clarity in the study of the impacts of QELROs currently under consideration, however, these potential future adjustments are set aside.

2. THE MIT ANALYSIS SYSTEM

The study is carried out using the Integrated Global System Model for the analysis of climate change developed by the MIT Joint Program on the Science and Policy of Global Change (Prinn, *et al.*, 1996).[3] The MIT Model is comprised of several components, including (1) a model of

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[1] Our OECD definition does not include all its current members. The OECD includes the United States, Japan, the 12 members of the European Community, Canada, Australia, New Zealand, EFTA (excluding Switzerland and Iceland), and Turkey. Mexico, a recent addition, is not an Annex I country under the Climate Convention and is not included in the OECD as defined in this analysis.

[2] Their proposal provides for a reduction of CO_2 emissions to 20% below 1990 levels by the year 2005, with the restrictions applying not just to the OECD but to other countries listed in Annex I to the Climate Convention, *i.e.*, those of the Former Soviet Union and Central and Eastern Europe (United Nations, 1994).

[3] The Model has been developed with the support of a government-industry partnership including the U.S. Department of Energy (901214-HAR; DE-FG02-94ER61937; DE-FG02-93ER61713), U.S. National Science Foundation (9523616-ATM), U.S. National Oceanic and Atmospheric Administration (NA56GP0376), and U.S. Environmental Protection Agency (CR-820662-02), and a group of corporate sponsors from the United States, Europe and Japan.

economic growth and associated anthropogenic emissions of climate-relevant gases, (2) a coupled model of atmospheric chemistry and climate, (3) a model of the effects of climate change on terrestrial ecosystems, and (4) a model of the effects of CO_2 and climate changes on the natural cycles of key greenhouse gases. In these experiments we report only one aspect of the climate consequences predicted in the model, which is the change in global temperature.

2.1 The EPPA Model

The analysis reported here makes primary use of one component of this global analysis model, the MIT Emissions Prediction and Policy Analysis (EPPA) Model (Yang, *et al.*, 1996). EPPA is a recursive-dynamic computable general equilibrium (CGE) model which is derived from the General Equilibrium Environmental (GREEN) Model developed by the OECD (Burniaux, *et al.*, 1992a). In the design of the EPPA model, many changes have been made in the GREEN formulation, but the specification of production, consumption and trade conditions remains much the same, as does a major portion of the underlying data base.

As summarized in Figure 1, the EPPA model describes the global economy as an interconnected set of national and regional entities, each with supplies of input factors (*e.g.*, labor, capital, land and other resources), consumer demand functions, and production technologies. By providing inputs to the production process, consumers earn the income to purchase final goods, and the circular flow of income and expenditure in such a model is captured in a simplified version of a national accounting system. It is an "equilibrium" model because it finds a set of product and factor prices that balance supplies and demands in each period. It is "general" in that it clears *all* markets and not just one or two. It is called "computable" because numerical solutions are found with the use of modern digital computers. The EPPA model is "recursive," meaning that it is solved by stepping forward in time, but without the ability to anticipate possible future changes in relative prices, or the imposition of new constraints. It is "dynamic" in the sense that the capital stocks available in any period are an inheritance from decisions in previous periods.

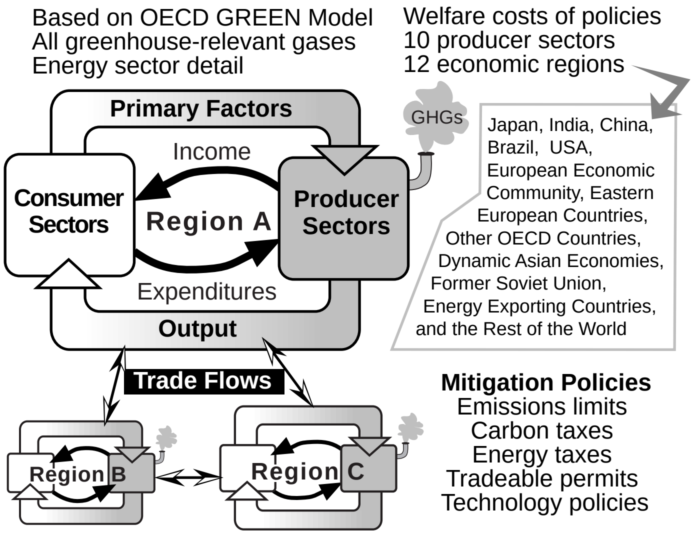

Figure 1. Features of the EPPA Model

The model covers the period 1985 to 2100 in five-year steps. The world is divided into 12 regions, as shown in Table 1, which are linked by multilateral trade. The economic structure of each region consists of eight fully elaborated production sectors (three non-energy and five energy) and four consumption sectors, all shown in the table, plus one government sector and one investment sector (not shown). The detail of the production sectors is designed to highlight sub-components of the energy sector because of their importance in the emissions of greenhouse-relevant gases.

Table 1. Key dimensions of the EPPA model.

Production sectors	**Consumer sectors**
Non-Energy	1. Food and beverages
1. Agriculture	2. Fuel and power
2. Energy-intensive industries	3. Transport and communication
3. Other industries and services	4. Other goods and services
Energy	
4. Crude oil	
5. Natural gas	**Primary Factors**
6. Refined oil	1. Labor
7. Coal	2. Capital (by vintage)
8. Electricity, gas and water	3. Fixed factors for each fuel, and for land in agriculture
Future Supply Technology	
9. Carbon liquids backstop[1]	
10. Carbon-free electric backstop[2]	

Regions (and abbreviations)		**Gases (and chemical formulae)**	
1. United States	USA	1. Carbon Dioxide	CO_2
2. Japan	JPN	2. Methane	CH_4
3. European Community	EEC	3. Nitrous Oxide	N_2O
4. Other OECD[3]	OOE	4. Chlorofluorocarbons	CFCs
5. Central and Eastern Europe[4]	EET	5. Nitrogen Oxides	NO_x
6. The Former Soviet Union	FSU	6. Carbon Monoxide	CO
7. Energy-exporting LDCs[5]	EEX	7. Sulfur Oxides	SO_x
8. China	CHN		
9. India	IND		
10. Dynamic Asian Economies[6]	DAE		
11. Brazil	BRA		
12. Rest of the World	ROW		

[1] Liquid fuel derived from tars, oil sands, and oil shale
[2] Carbon-free electricity derived from advanced nuclear, solar, or wind
[3] Australia, Canada, New Zealand, EFTA (excluding Switzerland and Iceland), and Turkey
[4] Bulgaria, Czechoslovakia, Hungary, Poland, Romania, and Yugoslavia
[5] OPEC countries and other oil-exporting, gas-exporting, and coal-exporting countries (see Burniaux, *et al.*, 1992b)
[6] Hong Kong, Philippines, Singapore, South Korea, Taiwan, and Thailand

The current version of the model also incorporates two potential future energy supply or “backstop” production sectors, represented as Leontief functions of their inputs of labor and capital. One of the sectors represents an industry whose production is based on heavy oils, tar sands and oil shale, and which produces a perfect substitute for refined oil. Because of extensive processing requirements, substantial CO_2 is emitted by the production of this technology (and is credited to its regions of origin) as well as at the place where the refined oil is consumed. The other backstop sector is a non-carbon electricity source, which represents the possible expansion of technologies like advanced nuclear and solar power.

The non-carbon electric backstop is available in all regions. However, the carbon-liquids backstop is assumed to be produced in only three regions which are known to have substantial amounts of the necessary resources: The Energy Exporting Countries (*e.g.*, Venezuelan tars and heavy oils), the Other OECD (*e.g.*, Canadian and Australian tar sands) and the United States (*e.g.*, Western oil shales). The location of this carbon-liquids potential will prove important in interpreting the results below.

Each of the eight producer sectors is modeled by a nested set of production functions which allows a flexible representation of the degree of substitution between inputs to the production processes. The output of each sector results from the combination of energy and intermediate goods (provided by other production sectors), and three primary factors: capital, labor, and a fixed factor. The fixed factor represents land in agriculture, reserves in the production of oil, gas and coal, and the supply of nuclear and hydroelectric power to the electric sector. It also is assumed, in the model solutions described here, that there are multiple vintages of capital, each with characteristics fixed at the time of investment.

All goods are traded among regions. With the exception of two of these, imported goods are imperfect substitutes for the equivalent domestic ones, and goods imported from alternative foreign regions are imperfect substitutes for one another. The two exceptions are crude oil and natural gas: imported and domestic supplies of each are treated as perfect substitutes. Calculated within the model are all relative prices, including the wage rate and the return to capital. The returns to capital, along with the level of aggregate income, determine the level of savings (and thus of investment and capital formation). The model is calibrated with 1985 data, with a data set consisting of social accounting matrices for each of the 12 regions, and a bilateral trade matrix. The data set now in use was compiled by the OECD (Burniaux, *et al.*, 1992b).

Energy use in production and consumption produces varying amounts of CO_2, CH_4, N_2O, SO_2, CO and NO_x, depending on the fossil source and the policies assumed to be in place. (Emissions of CO_2 from deforestation are exogenous to the EPPA model.) Similarly, trace gas emissions result from non-energy-consuming activities included in the model (*e.g.*, a component of anthropogenic CH_4 is driven by the level of activity in the agriculture sector). Emissions by region are then converted to emissions by latitude, which are the necessary inputs to the model of atmospheric chemistry and climate described below.

The major driving factors in the model are population change, the rate of productivity growth (stated in terms of labor productivity and denoted LPG), and a rate of Autonomous Energy Efficiency Improvement (AEEI), which reflects the effect of non-price-driven technical change on the energy intensity of economic activity. Another important influence on economic growth, the rate of capital formation, is endogenous to the model. Finally, a key determinant of the carbon intensity of economic growth, which also has an important influence on the distribution of burdens of a policy of carbon restriction, is the assumed costs of the backstop technologies (production sectors 9 and 10 in Table 1) relative to conventional sources.

Policies implemented in the EPPA model may take the form of either price instruments (taxes or subsidies) or quantitative measures (quotas). The quantitative instruments are CO_2 emission quotas imposed on individual regions or blocks of regions (*e.g.*, the OECD), and quotas can be tradable among regions. Carbon quotas depress the demand for output from the more carbon-intensive energy sectors, and shift the equilibria in the economy away from the no-policy baseline. The adjustments are complex and may include substitution among fuels; substitution in production among inputs of energy, capital, labor, and fixed factor; changes in the mix of goods consumed; and shifts in international trade, both in energy and non-energy goods.

As a result of these economic adjustments to carbon constraint in a particular country, there is, in general, a reduction in GDP and consumption levels. The opposite effect can occur, however, when the tax or quota has the effect of offsetting the distortion from an existing subsidy. The effect on other countries also may be either positive or negative, depending on trade effects. To summarize these economic consequences of emissions restraints, we use a measure of economic welfare which is related to aggregate consumption within a region, discounted over time in most cases.

2.2 The Climate Component of the MIT Integrated Framework

To illustrate the climate consequences of our AOSIS-type protocol, we apply a coupled model of atmospheric chemistry and climate dynamics, which also is part of the larger MIT Integrated Global System Model (Prinn, *et al.*, 1966). A two dimensional (2D) land- and ocean-resolving statistical-dynamical model is used to address climate dynamics (Sokolov and Stone, 1994). It is a modified version of a model developed at the NASA Goddard Institute for Space Studies or GISS. The model's numerical procedures and the parameterizations of physical processes (radiation, convection, *etc.*) closely parallel those of the GISS general circulation model (GCM). The grid used in the model consists of 24 points in latitude, corresponding to a resolution of 7.826˚. The model has nine layers in the vertical: two in the planetary boundary layer, five in the troposphere, and two in the stratosphere. The important feature of the model, from the point of view of coupling chemistry and climate dynamics, is the radiation code of the GISS GCM that it incorporates. This code includes all significant greenhouse gases (H_2O, CO_2, CH_4, N_2O, CFCs, *etc.*), and twelve types of aerosols. Many revisions have been made to the model at MIT, including the incorporation of a real land-ocean distribution, and a capacity to handle alternative formulations of cloud dynamics. In climate simulations, the 2D atmospheric model is coupled to an ocean model with parameterized horizontal and vertical transports.

For predictions of atmospheric composition, a 2D atmospheric chemistry model is used which is run interactively with the climate model and has the same horizontal and vertical grid points. It incorporates 25 chemical species, including CO_2, CH_4, N_2O, O_3, CO, H_2O, NO_x, HO_x, SO_2, sulfate aerosols, and chlorofluorocarbons. The coupled atmospheric chemistry and climate model computes the longitudinal means of trace gas and aerosol concentrations over land and ocean.[4]

3. THE SENSITIVITY OF RESULTS TO ECONOMIC ASSUMPTIONS

Estimates of future greenhouse gas emissions, and of the effects of emission restrictions, are highly sensitive to underlying assumptions about economic conditions over the next century. This fact has been emphasized by a number of studies using emissions models less detailed than EPPA, beginning with early work by Nordhaus and Yohe (1983) and continuing to a number of more recent studies such as those by Dowlatabadi and Morgan (1993) or Hope, *et al.* (1993). Efforts also have been devoted to exploring the uncertainty in multi-region, multi-sector models, examples

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[4] Other capabilities of the MIT system—such as estimation of the impacts of increased CO_2 and climate change on terrestrial ecosystems and the ocean uptake of carbon, and the effects of climate change on the natural cycles of other greenhouse gases—are not applied in the calculations shown here.

being those applying the Edmonds-Reilly model (*e.g.*, Edmonds, *et al.*, 1986; Margolis, 1995; Tschang and Dowlatabadi, 1995), or Global 2100 (Manne and Richels, 1994).

To emphasize the importance of this uncertainty for the assessment of proposed QELRO schemes, we have explored the sensitivity of our own model estimates to key inputs. As noted earlier, four input assumptions have the greatest influence on future emissions trajectories: population growth, the rate of labor productivity growth, the rate of non-price induced improvement in energy efficiency, and the relative costs of the backstop technologies. All these factors are subject to substantial uncertainty. To test the consequences of this fact, key parameters describing three of the four factors were subjected to an uncertainty analysis, applying a probabilistic collocation method under development at MIT (Webster, Tatang and McRae, 1996; Webster, 1996). The judgment of EPPA model developers was applied to the estimation of probability distributions for all of the parameters above except the rates of population growth, and the resulting dispersion of key model outputs was calculated (Webster, 1996).

Figure 2 shows the probability density functions for the prediction of global carbon emissions. With predictions beginning in 1985, the variance of the estimate in 2020 is relatively small. For the more distant years, however, the variance increases, as shown by distributions for the years 2050 and 2100. Indeed, in terms of relative likelihood there is very little basis to distinguish between an emissions forecast anywhere in the range of 13 GtC to 23 GtC per year in 2100. Thus, when considering the results presented below, it should be remembered that a prediction anywhere in the central part of the distribution in Figure 2 is of near equal likelihood, and therefore the choice of the Reference Case (whose end-point is indicated “R” in Figure 2) is arbitrary within this range.

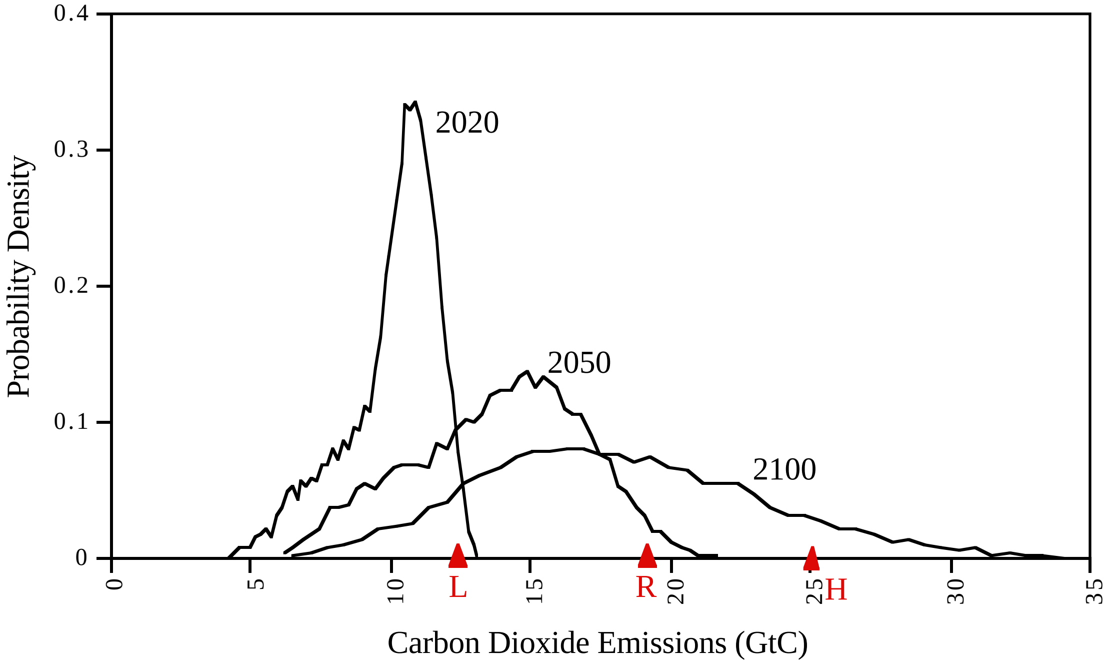

Figure 2. Distribution of CO_2 emissions in 2020, 2050 and 2100 calculated by the EPPA model. The points R, L, and H indicate emissions for the reference, and higher and lower scenarios in 2100.

The implications of this uncertainty for the choice of a reference or base case are illustrated in Table 2, which presents climate and cost predictions for the Reference Case we use below, and for Higher and Lower predictions chosen from the distribution in Figure 2 (where they are indicated as H and L). In the calculation of climate effects, a "reference" version of the coupled chemistry-climate model is used in all cases. Although this component of the analysis also is subject to many uncertainties (Jacoby and Prinn, 1994), these are not explored in this paper. Results of a study using the MIT model of the sensitivity of climate-change predictions to uncertainty in key aspects of the science is provided in Prinn, *et al.* (1996).

As can be seen in Table 2, over this range of (nearly indistinguishable) economic predictions, global CO_2 concentrations by the end of the next century range between 539 ppm and 770 ppm. The associated temperature changes range from 1.55˚ C to 3.36˚ C. These uncertainty ranges should be kept in mind in assessing an AOSIS-type protocol, which we now proceed to study using the Reference Case prediction shown in Figure 2 and Table 2 as a standard for comparison.

Table 2. Sensitivity of the climate and effects of the AOSIS protocol to uncertainty in the factors driving emissions, in the Reference Case and Higher and Lower alternatives.

	Emissions Case		
Policy case	Lower	Reference	Higher
No Policy			
CO_2 Emissions in 2100 (GtC)	12.4	19.0	25.1
CO_2 Conc. in 2100 (ppm)	539	668	770
ΔT, 1990 to 2100 (˚C)	1.92	2.53	3.36
AOSIS-Like Protocol			
CO_2 Emissions in 2100 (GtC)	10.5	14.1	17.8
CO_2 Conc. in 2100 (ppm)	507	575	635
ΔT, 1990 to 2100 (˚C)	1.55	2.11	2.82

4. THE BURDENS OF EMISSION RESTRICTION

4.1 The Distribution Among Regions

When a carbon constraint is accepted by some regions, the overall system of production, consumption and trade adapts, and the effects are felt both in those countries that are taking direct action to reduce emissions and in countries that are taking no direct action. The consequences for each region of our sample protocol, measured in terms of the consumption-based welfare index, are shown in Figure 3. The EPPA model distinguishes four OECD regions: the United States (USA), the European Community (EEC), Japan (JPN) and the rest of the OECD (OOE). Under the first set of AOSIS-like conditions imposed here, each of these OECD regions meets the emissions target independently (the implications of intra-OECD trading are considered later). The depressing effect on the regional economies of the CO_2 constraints, which force adjustments to a lower production frontier and a different composition of output, are clearly shown.[5]

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[5] The consumption-based welfare index used here (or a companion GDP measure) does not take account of any economic gains from potential climate effects avoided by the CO_2 controls. Also, no account is taken of environmental benefits from the reduction of other pollutants associated with energy production.

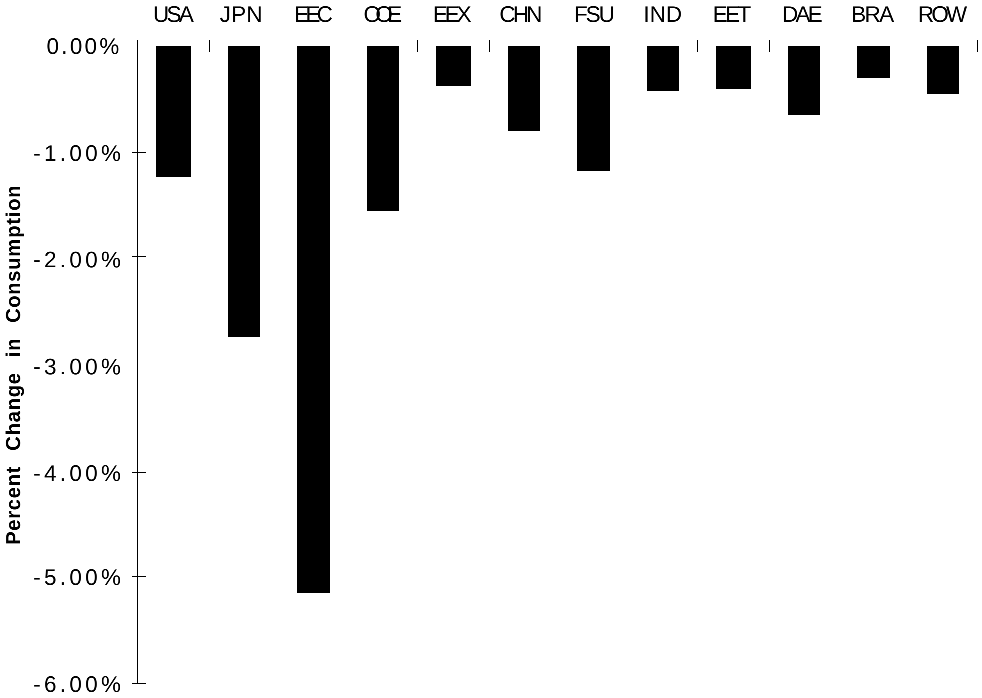

Figure 3. Regional economic impacts of a version of an AOSIS-type protocol (expressed as the cumulative percentage reduction in consumption between 2000 and 2100, discounted at 5%) computed from runs of the EPPA model. See Table 1 for regional abbreviations.

The differences in welfare losses among the sub-regions of the OECD are striking.[6] The costs to the United States and the Other OECD are relatively small. This occurs because, in the Reference run, both regions make use of the carbon-liquids backstop technology, which is relatively carbon-intensive. If AOSIS-like restrictions are in effect it is relatively easy in this model to avoid emissions growth by foregoing the development of this non-conventional carbon fuels industry. The EEC fares worse than its companion regions because it is not using the backstop carbon fuel under Reference conditions with no policy (since it does not have the necessary natural resource base). As a result, reductions in their carbon emissions are achieved only with more drastic changes in resource allocation and consumption patterns. The relatively light burden of the AOSIS protocol on Japan is explained by another phenomenon related to the backstop technologies. The current cost of electric power in Japan is relatively high by world standards, so that the non-carbon electric backstop enters earlier than in other OECD regions under the no-policy reference case. The emissions restrictions simply accelerate the diffusion of a non-carbon backstop that is not far from being economic at the start of the analysis. In addition, the EPPA model's representation of the structure of the Japanese economy permits an easier substitution of electricity for other energy forms than is possible for other regions. These calculations indicate the important role of backstop

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[6] Our results vary from those from an earlier effort by Martin, *et al.* (1992) using EPPA's parent GREEN model, largely because of differences in the formulation of backstop technologies. The strong effect of the backstops on the distribution of burden is illustrated below. A more recent study of burden distribution by Edmonds, *et al.* (1995) is not comparable, because the model used does not consider trade in non-energy commodities, which is a main avenue of accomodation to emissions restriction.

assumptions in these types of assessments. To illustrate this point in more detail, their effects will be tested further in Section 4.2.

Under the conditions of the Reference Case, every region suffers some degree of welfare loss as a result of the reduced demand in the industrialized world, and the consequent adjustments in international trade. Thus, although their losses are smaller than those in the OECD, other world regions also bear a portion of the burden of the assumed emissions restraints. The changes projected for the Energy Exporting Countries (EEX), where the burden is relatively light in relation to other non-OECD regions, are particularly noteworthy. Many adjustments contribute to this effect, but the main one concerns the net exports of crude oil and refined oil by EEX countries. Under the model of resource depletion incorporated in the EPPA model, crude oil production in the EEX does not change much when comparing the Reference Case to the AOSIS protocol. Furthermore, the EEX also has the resources to produce exportable refined oil from the carbon-liquids backstop technology. With our sample protocol, which does not restrain emissions in the EEX region, net exports of these liquids (with their carbon emissions at the point of supply) are larger than under the no-policy case. That is because EEX production substitutes for the cutback in carbon liquids production in the two OECD regions that can produce the carbon-fluids technology (USA and OOE).[7] This picture changes substantially under the hypothesis of a world with no backstops, as we show next.

4.2 The Significance of Assumptions About Backstop Technologies

Assumptions about the availability and relative cost of the two backstop technologies have a significant effect on the distribution of burdens of the AOSIS protocol (and on the estimated leakage, as shown below). To demonstrate this point, we have formulated a dramatically different case. We hypothesize a world where all the conditions in the Reference Case remain the same, except the backstop technologies do not exist. The stark comparison is particularly useful in illuminating the mechanisms that distribute the economic burden among regions, and determine the levels of leakage. By coincidence, the Reference Case with no backstops implies total carbon emissions that are close to the Reference with backstops (with no emissions limits in either case). In effect, for the relative costs assumed, the low-carbon and high-carbon alternatives roughly balance one another, so that total emissions over the period are only 4% higher in the “no backstops” world. The pattern of regional emissions is very different between the two, however.

The economic burden in this case is shown in Figure 4, which again presents the percent welfare loss over the period 2000 to 2100, for each of the model regions. Note that gains and losses shown in Figure 4 are *not* comparable with those in Figure 3 for the case with backstops. These are two different worlds: in particular, the GDP and consumption levels in the “no-policy” version are not the same with and without backstops, and so the levels of burden and gain associated with the two cases do not have a common basis. What is important is the change in the *distribution* of burdens among regions.

The region that is most affected is the Energy Exporting Countries (EEX). The imposition of the AOSIS-type restriction tends to lower the price of oil and coal relative to other goods. Without the production of backstop fuels to offset this effect, the economic losses in the EEX region are large relative to other regions. Japan also is relatively strongly affected, compared to the case with backstops, mainly because of the absence of the non-carbon backstop. The other non-OECD

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[7] Resources of tars, oil sands and oil shale are unevenly distributed among the countries that make up the EEX, and analysis disaggregating this region likely would reveal a diverse pattern of economic impacts.

regions (excluding EEX) present a mixed picture of losers and gainers depending on the details of their sensitivity to energy prices and their patterns of trade.

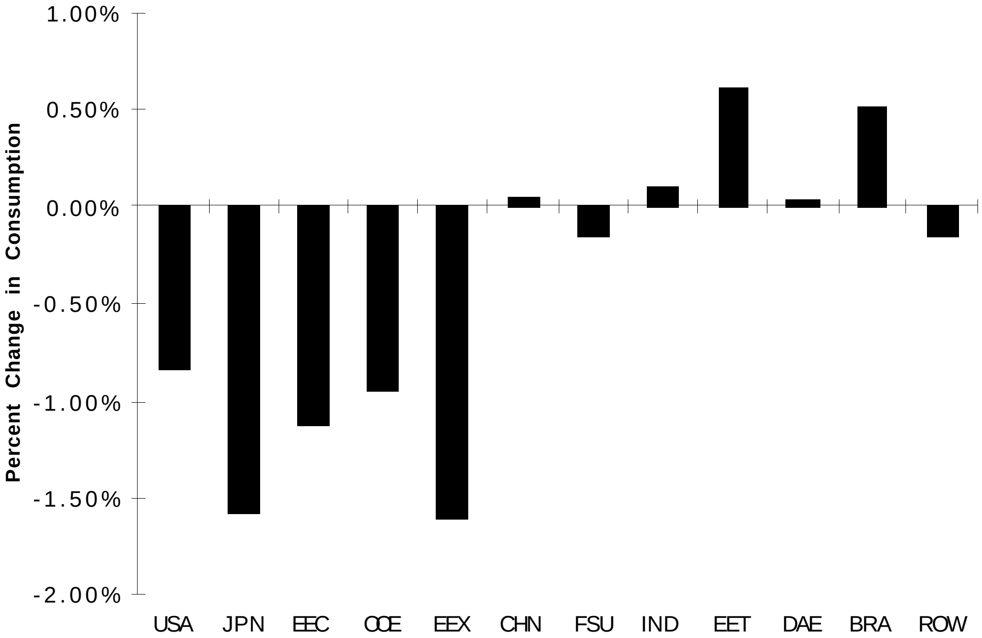

Figure 4. Regional economic impacts of a version of an AOSIS-type Protocol, for the Reference Case with no backstop technologies (definitions as in Figure 3). Only the relative distribution (not the absolute levels) is comparable with Figure 3.

5. CARBON LEAKAGE

If one set of world regions constrains activities that produce CO_2, then adjustments caused by changes in relative prices and shifts in trade patterns may cause increases in carbon emissions elsewhere, which partially offset the gains achieved. This phenomenon is often referred to as the carbon "leakage" associated with a policy that is applied to a subset of world regions. A number of other studies have considered this phenomenon using multi-region models, including Pezzy (1992), Oliveira-Martins (1992), Manne (1993), Manne and Martins (1994) and Edmonds (1995). The range of estimates is very wide (IPCC, 1995), in part because the models are different and in part because they assume different degrees of policy stringency.

Taking our AOSIS-type restrictions as an example, carbon leakage can be defined as the increase in CO_2 emissions in non-OECD regions that is the result of emissions restraints in OECD regions (compared to the Reference Case without restraints), stated as a percentage of the reduction in emissions in the OECD. Under this definition, the leakage from the AOSIS-type protocol under the Reference Case (with backstop technologies) is 6.8% for the period 2000 to 2100. Among the other leakage studies above, our results are closest to those from EPPA's parent GREEN model, and interestingly these are the only two of the cited models that consider trade in non-energy goods.

The magnitude of carbon leakage is, of course, a function of the details of the economic assumptions, as illustrated below, but the primary mechanisms producing it can be illustrated using

Figure 5. The figure shows the percentage change in carbon emissions, by region, resulting from the AOSIS-type protocol, and separates this net change into two components: one related to GDP change alone and another that can be attributed to the many substitution possibilities, between goods and across countries. As a rough approximation of the GDP effect, an estimate is made of the change in CO_2 emissions if the GDP changes underlying the results in Figure 3 are imposed while the energy composition of GDP is held constant (*i.e.*, no substitution effects). This component is shown in Figure 5 by the white bars, and it can be seen that there would be some reduction in carbon emissions over the period 2000-2100 in each region. The rest of the net change in carbon emissions with the AOSIS protocol is then attributed to the many substitution effects. The net change in CO_2 emissions over the century in each region is the sum of the black and white bars.

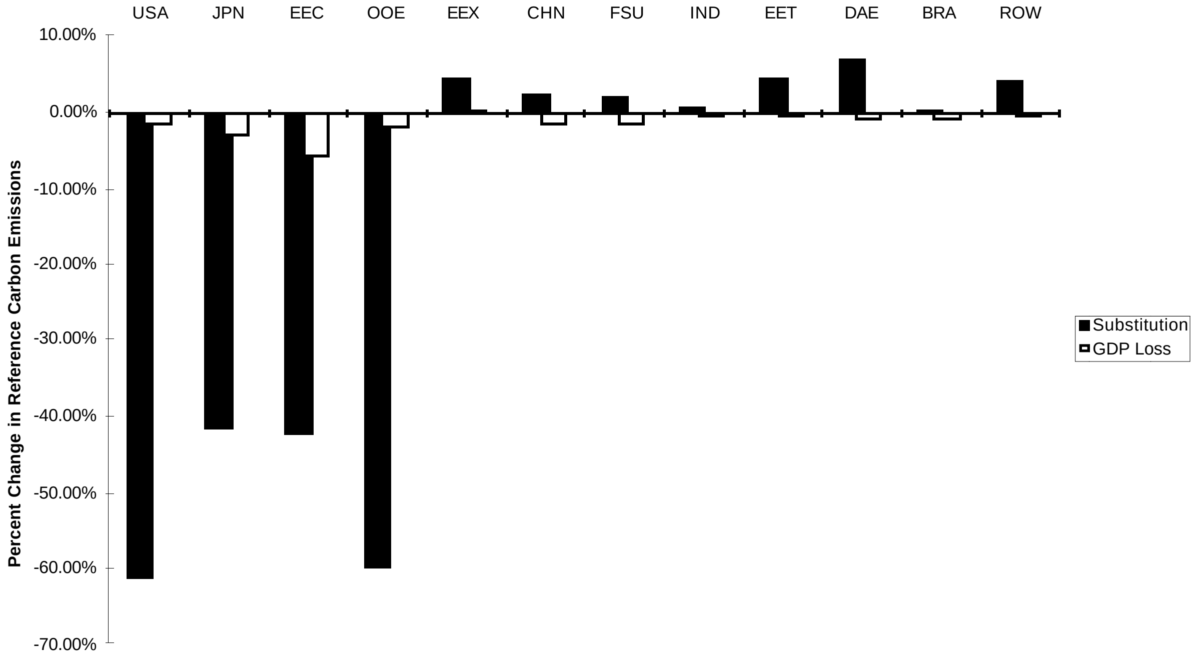

Figure 5. Percentage change in carbon emissions between 2000 and 2100 due to substitution effects and GDP loss resulting from an AOSIS-type protocol as computed from the differences between two runs of the EPPA model, for the Reference Case with backstops. See Table 1 for regional abbreviations.

Several aspects of these results are worth noting. The overwhelming influence in OECD adjustments to the emissions constraint is the substitution effect, including substitutions among fuels, among means of production of particular output goods, among sectors of consumption, and among goods imported and exported. Similarly, the slowed growth in non-OECD economies (see Figure 3) yields but a small reduction in their CO_2 emissions. It is the much larger substitution effects that lead to leakage. Two main substitution phenomena contribute to this result. First, the production of liquid fuels from tars, tar sands and shale oil resources (the carbon-fluids backstop) in the Energy Exporting Countries makes them a large source of leakage. AOSIS-type commitments would restrain the expansion of this emerging industry in the two OECD regions that have the needed resources (USA and OOE), but there is no restraint on the EEX, and its carbon-fluids industry would grow faster, with a resultant increase in carbon emissions. Second, OECD regions become less competitive, relative to selected non-OECD regions, in the production of the products of the Energy-Intensive Industries sector. This adjustment is most significant in the Dynamic Asian Economies (DAE), which increase their production of energy-intensive goods (which they export to the OECD countries in the main) and import additional energy (*e.g.*, coal from OECD sources) to fuel the process.

For the Reference Case with backstop technologies available, the pattern of leakage over time is shown on the left-hand side of Figure 6. (The bars on the graph show the net change in carbon emissions, over the periods shown, comparing a world under the AOSIS protocol with one that has no policy of carbon restraint.) In the period 2000 to 2050, the leakage rate is 5.3%, with the EEX production of the carbon-intensive backstop being a primary cause. In the second half of the century, the carbon-liquids backstop continues to grow in the EEX, and substitution through goods markets intensifies, so the leakage rate rises to 7.7% under assumed OECD emissions control, compared to a no-policy world.

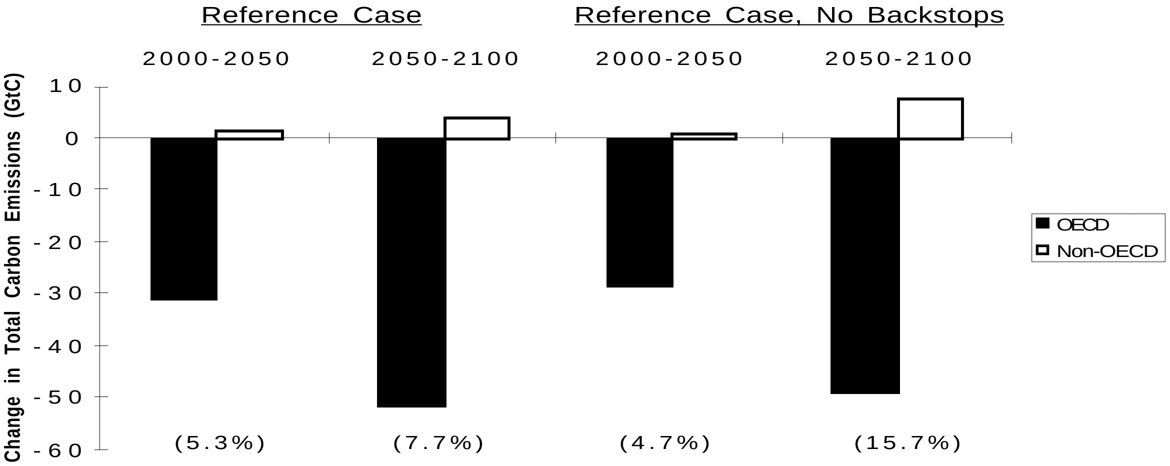

Figure 6. Carbon leakage under the AOSIS protocol, for 2000 to 2050 and 2050 to 2100, under different assumptions about the availability of backstop technologies, computed from differences between runs of the EPPA model. Leakage rates are shown in parentheses.

This adjustment through goods trade is most clearly seen in a case where the influence of the carbon-fluids backstop is not present. Without backstops, the leakage rate is roughly the same as with them, for the period 2000 to 2050, as shown in Figure 6. As growth proceeds into the 2050 to 2100 period, however, the emissions restrictions bind more tightly, and the leakage increases. Figure 7 illustrates a main cause of this increase for a single period, 2050. The results shown are trade values in constant 1985 $US (in effect, a quantity index). The net exports of some sectors (Agriculture, Refined Oil, Crude Oil and Natural Gas) differ little between the “no-policy” case and that with OECD restriction. As can be seen in the figure, however, under our assumed emissions restrictions (in contrast to the no-policy case) the non-OECD regions are exporters rather than importers of energy-intensive goods, and their imports of products of the Other Industry sector are reduced. To fuel this shift, coal imports from the OECD are higher.

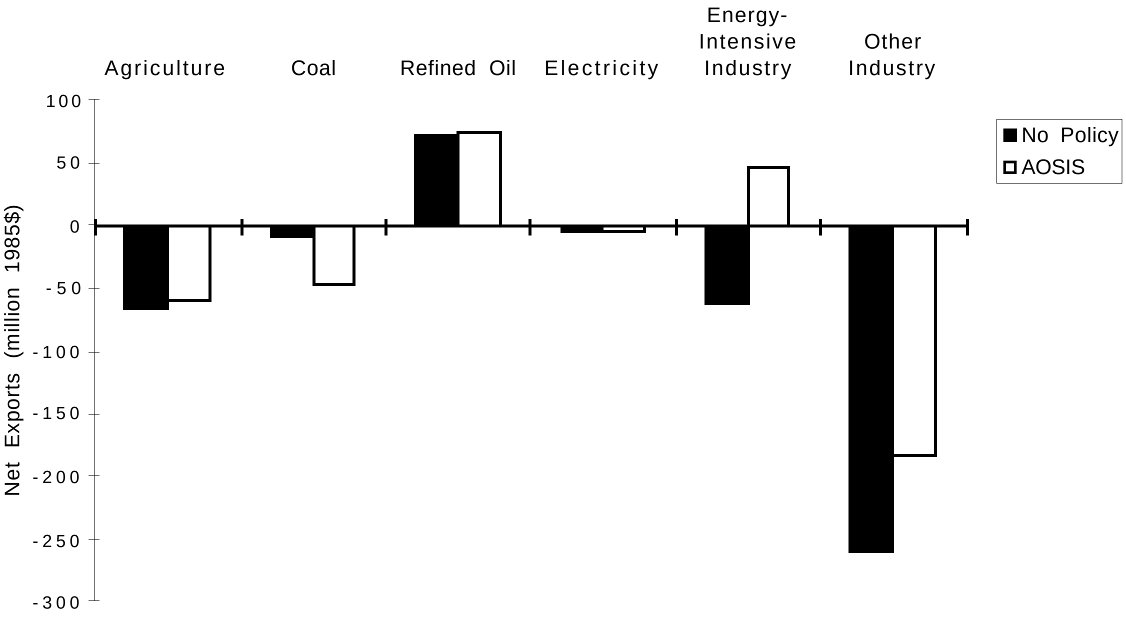

Figure 7. Trade of the non-OECD regions in 2050, with and without the AOSIS protocol, calculated from runs of the EPPA model without backstop technologies. Numbers greater than zero are net exports, those less than zero are net imports.

6. THE ROLE OF EMISSIONS TRADING

Meeting a commitment to reduce emissions by domestic actions alone is relatively expensive, and countries will seek efficiency by exploiting the cheapest opportunities for reducing carbon emissions, wherever they may be available. One approach is to engage in individual bilateral agreements that allow countries facing a constraint to undertake or fund CO_2 reduction measures in other countries. On a project-by-project basis such programs fall under the rubric of Joint Implementation (JI) or Activities Implemented Jointly (AIJ).

A comprehensive approach to the goals of JI and/or AIJ would be to set up a market for carbon emissions by allocating emissions quotas and allowing countries to engage in trading for those rights. There is no precedent for a market in emissions rights on such a scale, and the feasibility of involving a large number of nations in such a system remains to be explored. The transactions costs are unknown as well. Nonetheless, even analysis of idealized versions of such schemes can give important insight regarding the general magnitude of the economic benefits that a trading regime can offer.

Previous studies of permit trading systems, such as efforts by Martin, *et al.* (1992), Manne and Richels (1995) and Edmonds (1995), have tended to assume that participation in the permit trading regime was universal. In practice, however, these arrangements may take several forms. The trading may be limited to countries facing the same regime of emissions constraints; it could include these plus some other subset of countries, or it could involve all parties to the Framework Convention. We have explored the implications of these forms of agreement for the cost of meeting an AOSIS-type constraint, and for the distribution of burdens and leakage. Figure 8 shows the result for the cost to the OECD, over several decades of meeting the AOSIS-type protocol. The comparisons are made using the Reference Case with backstops, and the same consumption-based index is used to measure welfare loss. Four regimes are shown: (1) no trading, (2) trading among the four OECD regions only, (3) extension of OECD trading to all Annex I countries by including countries of the Former Soviet Union and Central and Eastern Europe (denoted as FSU and EET in Table 1 and earlier figures), and (4) full global trading.

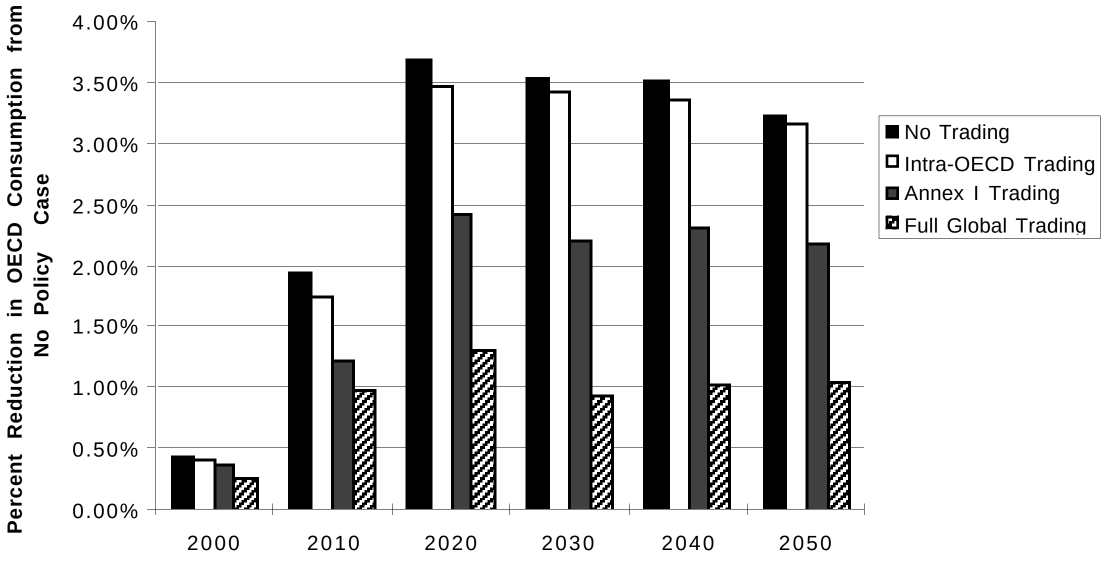

Figure 8. Costs to the OECD of meeting the AOSIS protocol under no trading and three definitions of a regime of emissions trading, for selected decades, calculated from runs of the EPPA model.

Trading limited to OECD regions does not yield very great reductions in cost: the economies of the sub-regions are simply too similar to one another in structure and in opportunities for carbon reduction.[8] Full global trading, on the other hand, yields very large reductions in cost to the OECD regions of meeting our assumed AOSIS-type commitment. That opportunity benefits the non-OECD regions as well, for they receive payments for emissions reductions they would not otherwise make. It also is interesting to note that not all non-OECD regions need participate in order for real gains to be achieved from a trading regime. With trading only among the Annex I group, a large fraction of the benefits to the OECD of full global trading are gained, as shown in the figure.[9]

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[8] Analysis treating the OECD at the country level (disaggregating the EEC and Other OECD), where the economic circumstances would be more diverse, likely would show greater gains from trade than the four-region version applied here.

[9] The definition of carbon leakage used above no longer holds if trading is allowed. The calculation with trading gives non-OECD countries an annual quota equal to their emissions (including leakage) if there were no trading. This quota is fully utilized, so global emissions are the same with trading and without it.

7. CONCLUDING OBSERVATIONS

Any attempt to assess the impacts of a policy of emissions limitation, if followed for a century, must give due attention to the very large uncertainties in the needed predictions. Nonetheless, an exercise like this does contribute some useful qualitative insights.

- Even if emissions limits are applied independently to a subset of world regions, the burden of meeting these emissions reduction targets will fall not only on the parties to the agreement but on others as well, because of changes that are mediated through international trade. Not all non-participating regions need lose, but many will.
- Carbon “leakage” will accompany a policy restriction that applies only to a subset of world regions. Countries outside the region of constraint will become more competitive in the production of highly carbon emitting energy sources, and in the production and export of energy-intensive goods.
- If large-scale expansion is a realistic prospect for the existing (but yet small) industries producing the backstop technologies as defined here, the implications are great, not only for total carbon emissions but for the distribution of burdens, and for leakage.
- The differences in economic conditions and opportunities for carbon reduction between the OECD and non-OECD nations are great, so the benefit from trading is very large, with much room for bargaining over compensation. Further, it would not be necessary for all regions to participate in the trading for a substantial fraction of the potential gains to be realized.

Beyond the issues of economic burdens and carbon leakage that are the focus of this paper, these results have another set of implications for current proposals for restrictions on emissions. By itself, the effort required by our AOSIS-type protocol yields only a small impact on the threat of global warming. Indeed, predicted temperature changes depend more on what is assumed about economic growth, productivity improvement in energy use, and the relative costs of future technologies than it does on policy measures such as the one studied here. Yet the uncertainty about these causal factors is great, so that over a wide range, suggested by Figure 2, we do not know what the human contribution to atmospheric gas concentrations will be. In these circumstances, the evaluation of QELROs proposed for near-term agreement need to consider whether policy measures can be easily adapted over time, as we learn more about these key influences. Further, given the limits on what can be achieved with restraints applied to only a subset of countries, these studies must seek to identify policy designs that offer the prospect of attracting participation by all world regions.

8. REFERENCES

Burniaux, J., G. Nicoletti and J. Oliveira-Martins (1992a). "GREEN: A Global Model for Quantifying the Cost of Policies to Curb CO_2 Emissions," *OECD Economic Studies*, **19**, Paris.

Burniaux, J., J.P. Martin, G. Nicoletti and J. Oliveira-Martins (1992b). "GREEN - A Multi-Sector, Multi-Region General Equilibrium Model for Quantifying the Costs of Curbing CO_2 Emissions: A Technical Manual," OECD Economics Department Working Paper No. 116, Paris.

Dowlatabadi, H. and M.G. Morgan (1993). "A Model Framework for Integrated Studies of the Climate Problem," *Energy Policy,* **21**, 209-221.

Edmonds, J. and D.W. Barns (1992). "Factors Affecting the Long-Term Cost of Global Fossil Fuel CO_2 Emissions Reductions," *International Journal of Global Energy Issues,* **4**(3), 140-166.

Edmonds, J.A., J.A. Reilly, J.M. Gardner and A. Brenkert (1986). "Uncertainty in Future Energy Use and Fossil Fuel CO_2 Emissions 1975 to 2025," Report No. DOE/NBB-0081, Office of Energy Research, U.S. Department of Energy, Washington, DC.

Edmonds, J., M. Wise and D.W. Barns (1995). "Carbon Coalitions: The Cost and Effectiveness of Energy Agreements to Alter Trajectories of Atmospheric Carbon Dioxide Emissions," *Energy Policy*, **23**(4/5), 309-335.

Hope, C.H., J. Anderson and P. Wenman (1993). "Policy Analysis of the Greenhouse Effect: An Application of the PAGE Model," *Energy Policy,* **21**, 327-338.

IPCC (1996). *Climate Change 1995 - Economic and Social Dimensions of Climate Change.* Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK.

Jacoby, H.D. and R. Prinn (1994). "Uncertainty in Climate Change Policy Analysis," Joint Program on the Science and Policy of Global Change, Report No. 1, MIT, Cambridge, MA.

Manne, A.S. and J. Oliveira-Martins (1994). "Comparison of Model Structure and Policy Scenarios: GREEN and 12RT," OECD Economics Department Working Paper No. 146, Paris.

Manne, A.S. and R.G. Richels (1994). "The Costs of Stabilizing Global CO_2 Emissions: A Probabilistic Analysis Based on Expert Judgments," *The Energy Journal,* **15/1**, 31-56.

Manne, A.S. and R.G. Richels (1995). "The Greenhouse Debate: Economic Efficiency, Burden Sharing and Hedging Strategies," *The Energy Journal*, **16**(4), 1-37.

Margolis, R.M. (1995). "Probabilistic Policy Experiments: The Use of Energy-Economic-Environmental Models in the Climate Change Policy Process," *International Journal of Environment and Pollution,* **5/1**, 1-20.

Martin, J.P., J. Burniaux, G. Nicoletti and J. Oliveira-Martins (1992). "The Costs of International Agreements to Reduce CO_2 Emissions: Evidence from Green," *OECD Economic Studies,* **19**, Paris.

Nordhaus, W.D. and G.W. Yohe (1983). "Future Carbon Dioxide Emissions from Fossil Fuels," *Climate Change: Report of the Carbon Dioxide Assessment Committee,* National Academy of Sciences, Washington, DC.

Oliveira-Martins, J., J-M. Burniaux and J.P. Martin (1992). "Trade and the Effectiveness of Unilateral CO_2-Abatement Policies: Evidence from GREEN," *OECD Economic Studies,* **19**, Paris, 123-140.

Pezzy, J. (1992). "Analysis of Unilateral CO_2 Control in the European Community and OECD," *The Energy Journal,* **13**, 159-171.

Prinn, R., *et al.* (1996). "Integrated Global System Model for Climate Policy Analysis: I. Model Framework and Sensitivity Studies," Joint Program on the Science and Policy of Global Change, Report No. 7, MIT, Cambridge, MA.

Sokolov, A.P. and P.H. Stone (1995). "Description and Validation of the MIT Version of the GISS 2D Model," Joint Program on the Science and Policy of Global Change, Report No. 2, MIT, Cambridge, MA.

Tschang, F.T. and H. Dowlatabadi (1995). "A Bayesian Technique for Refining the Uncertainty in Global Energy Model Forecasts," *International Journal of Forecasting,* **11**, 43-61.

United Nations, Framework Convention on Climate Change (1994). "Draft Protocol to the United Nations Framework Convention on Climate Change on Greenhouse Gas Emission Reduction."

United Nations, Framework Convention on Climate Change, Conference of the Parties (1995). "Conclusion of Outstanding Issues and Adoption of Decisions," Berlin, 7 April.

Webster, M.D., M.A. Tatang and G.J. McRae (1996). "Application of the Probabilistic Collocation Method for an Uncertainty Analysis of a Simple Ocean Model," Joint Program on the Science and Policy of Global Change, Report No. 4, MIT, Cambridge, MA.

Webster, M.D. (1996). "Analysis of Uncertainty in Large Models with Application to Climate Policy," MS Thesis, Massachusetts Institute of Technology, May.

Yang, Z., *et al.* (1996). "The MIT Emissions Prediction and Policy Assessment (EPPA) Model," Joint Program on the Science and Policy of Global Change, Report No. 6, MIT, Cambridge, MA.