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UNFINISHED BUSINESS
The Economics of The Kyoto Protocol

JA Edmonds
CN MacCracken
RD Sands
SH Kim

July 1998

Prepared for
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ABSTRACT

The Kyoto Protocol to the Framework Convention on Climate Change (FCCC) was negotiated by over 130 nations meeting in the city whose name it bears. It was completed on the morning of December 11, 1997, after three days of continuous negotiations. The product of these deliberations is a complex and incomplete document knitting together the diversity of interests and perspectives represented by the more than 130 delegations. Because the document is complex its implications are not immediately obvious. If it enters into force, the Kyoto Protocol will have far reaching implications for all nations—both nations with obligations under the Protocol and those without obligations. National energy systems, and the world's energy system, could be forever changed.

In this paper we develop an assessment of the energy and economic implications of achieving the goals of the Kyoto Protocol. We find that many of the details of the Protocol that remain to be worked out introduce critical uncertainties affecting the cost of compliance. There are also physical and economic uncertainties that further complicate the analysis. Physical uncertainties include future non-CO_2 greenhouse gas emissions and the cost of their mitigation. Political uncertainties include the resolution of negotiations to establish rules for determining and allocating land-use emissions rights, mechanisms for Annex I trading, and participation by non-Annex I members in the Clean Development Mechanism. In addition, there are uncertainties in economic behavior, for example the behavior of Eastern Europe and the Former Soviet Union in supplying emissions credits under Annex I trading. These uncertainties in turn could affect private sector investments in anticipation the Protocol's entrance into force. The longer the rules remain unclear, the less able decision makers will be to incorporate these rules into their investment decisions.

We find that the cost of implementing the Protocol in the United States can vary by more than an order of magnitude. The marginal cost could be as low as $25 per tonne of carbon if a global system of emissions mitigation could be quickly and effectively implemented. But it could also exceed $250 per tonne of carbon if the United States must meet its emissions limitations entirely through domestic actions, and if the electric power sector if forced to shoulder most of the burden of compliance.

UNFINISHED BUSINESS
The Economics of the Kyoto Protocol

Jae Edmonds
Christopher N. MacCracken
Ronald D. Sands
Marshall A. Wise
Son H. Kim

Pacific Northwest National Laboratory

The Kyoto Protocol was negotiated by over 130 nations meeting in the city whose name it bears. It was completed on the morning of December 11, 1997, after three days of continuous negotiations. The product of these deliberations is a complex and incomplete document knitting together the diversity of interests and perspectives represented by the more than 130 delegations. Because the document is complex its implications are not immediately obvious. If it enters into force, the Kyoto Protocol could have far reaching implications for both Annex I[1] and non-Annex I member states. National energy systems, and the world's energy system, could be forever changed.

In this paper we develop an assessment of the energy and economic implications of achieving the goals of the Kyoto Protocol. We find that many of the details of the Protocol that remain to be worked out introduce critical uncertainties affecting the cost of compliance. There are also physical and economic uncertainties which further complicate the analysis. Physical uncertainties include future non-CO_2 greenhouse gas emissions and the cost of their mitigation. Political uncertainties include the resolution of negotiations to establish rules for determining and allocating land-use emissions rights, mechanisms for Annex I trading, and participation by non-Annex I members in the Clean Development Mechanism. In addition, there are uncertainties in economic behavior, for example the behavior of Eastern Europe and the Former Soviet Union in supplying emissions credits under Annex I trading.

We begin by describing the major features of the Kyoto Protocol, the variety of policy issues remaining to be resolved, and our general approach to modeling those issues. We then review some of the necessary assumptions for this exercise, as well as the structure and calibration of the Second Generation Model (SGM). The SGM was used to simulate the impact of mitigation policies on the economies participating in the Kyoto Protocol. Finally, we discuss the results of our analysis in several areas, including the impacts of independent compliance, emission permit trading, the Clean Development

[1] The Kyoto Protocol actually prescribes emissions limitations for countries listed in Annex B to the Protocol. These countries are: Australia, Austria, Belgium, Bulgaria, Canada, Croatia, Czech Republic, Denmark, Estonia, European Community, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Latvia, Liechtenstein, Lithuania, Luxembourg, Monaco, Netherlands, New Zealand, Norway, Poland, Portugal, Romania, Russian Federation, Slovakia, Slovenia, Spain, Sweden, Switzerland, Ukraine, United Kingdom of Great Britain and Northern Ireland, and the United States of America. This list varies somewhat from the countries contained in Annex I to the FCCC. Several countries such as Slovakia, Slovenia, Liechtenstein, and Monaco have been added, while Belarus and Turkey are listed in Annex I of the FCCC but not Annex B of the Kyoto Protocol. In this analysis we refer only to Annex I, with Annex B obligations allocated appropriately as specified in Appendix A of this report.

Mechanism, the inclusion of the six greenhouse gases, and land-use emissions. We will focus on the impacts on regional energy systems and measures of compliance cost.

KEY FEATURES OF THE KYOTO PROTOCOL

Targets and Timetables: The most prominent feature of the Kyoto Protocol is the quantified emissions limitations and reduction commitments. Thirty-nine parties accepted quantified emissions limitations or reduction commitments. These are given in Appendix A to this paper, which lists emissions limitations and reduction commitments by SGM region.

We can summarize obligations as follows.

- Western European nations accepted an eight percent reduction relative to 1990 emissions, with the exception of Iceland and Norway which were allowed 110 and 101 percent of 1990 emissions respectively.
- Eastern European nations generally had the same obligation as Western European nations with some exceptions—Croatia was 95 percent, and Hungary and Poland were 94 percent of base year emissions.
- The Russian Federation and Ukraine were allowed 1990 emissions levels, while Latvia, Estonia and Lithuania agreed to eight-percent reductions.
- Japan and Canada agreed to a six-percent reduction from base.
- The United States of America agreed to reduce emissions seven percent below 1990 levels. And,
- Australia was allowed to increase emissions eight percent above 1990 levels and New Zealand was allowed to emit up to 1990 levels.

The Six Gas Approach: Emissions were defined in terms of a basket of six gases: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexaflouride (SF_6). Gases are compared to each other using global warming potential (GWP) coefficients as developed by the IPCC. The use of GWPs allows for the aggregation of the six greenhouse gases specified in the Protocol into a singe value based on each gas' carbon equivalent. We will discuss the use of carbon equivalent emissions in this analysis later in the paper.

Land-Use Change Emissions Accounting: One of the most important and controversial features of the Kyoto Protocol was the treatment of emissions of greenhouse gases from of land-use change. A very complicated set of rules was developed which addressed both political and scientific concerns. These rules are highly asymmetrical. They describe how nations compute their base year emissions, against which all future mitigation is measured. We will provide further discussion of the rules under consideration and their impact on mitigation costs in a later section.

Emissions Trading: The principle of emissions trading was established in the Kyoto Protocol. However, several important issues were left unresolved. Emissions trading could occur between Annex I parties. Specific arrangements under which trade would occur, however, were left to be worked out in the future. The Protocol also established the principle that, "trading shall be supplemental to domestic actions for the purpose of meeting quantified emission limitation and reduction." There may therefore be potential limits on the use of emissions trading to satisfy a commitment.

The Clean Development Mechanism: The Protocol also established a Clean Development Mechanism (CDM). The CDM was established "to assist Parties not included in Annex I in achieving sustainable development and in contributing to the ultimate objective of the Convention. and to assist Parties included in Annex I in achieving compliance with their quantified emission limitation and reduction commitments under Article 3." It allows emissions mitigation credits to be developed by non-Annex I parties beginning in the year 2000, as long as these activities are supplemental to activities that would have been undertaken in the normal course of events. It also identified a certification authority to insure that emissions mitigation activities were in fact real and supplemental. As with emissions trading, the rules were left to be developed. Further, the degree to which this mechanism can capture emissions mitigation potential outside Annex I remains unclear.

Compliance: Unlike the Montreal Protocol, which established sanctions for non-compliance, the Kyoto Protocol establishes no such penalties.

Entry into Force: The Protocol is open to ratification beginning March 16, 1999. To enter into force, the protocol must be ratified by at least 55 Parties to the Convention, and ratifying parties must represent at least 55 percent of the total Annex I carbon dioxide emissions for 1990. This means that if parties representing 45 percent of Annex I emissions remain outside the Protocol, it cannot enter into force. It is particularly important whether or not the United States presents an instrument of ratification, acceptance, approval or accession. It alone represents nearly one-third of 1990 Annex I emissions. As of June 2, 1998, 37 countries had signed the Protocol. The United States had yet to sign the Protocol.

APPROACH

We examine the economic consequences of implementing the Kyoto agreement using the SGM. The SGM is a computable general equilibrium economic model that projects economic activity, energy consumption, and carbon emissions for twelve world regions. It is designed specifically to address issues associated with global change with special emphasis given toward performing the following types of analysis:

1. Provide estimates of future time paths of environmentally important emissions associated with economic activity.

2. Provide estimates of the economic cost of actions to reduce greenhouse gas emissions.

Sectors

The SGM has nine producing sectors and twelve inputs to production. The inputs are land, labor, capital, and the nine produced goods. Economic detail is maintained in the energy supply and transformation sectors that are important for greenhouse gas emissions projections, but aggregated elsewhere into one large "everything else" sector.

Five different fuels are used for producing electricity, resulting in at least five subsectors for the electric generating sector. A separate economic production function, of the constant elasticity of substitution (CES) functional form, is used for each sector or subsector. Capital investment decisions depend on an assumed lifetime of capital for each sector or subsector. Capital lifetimes range from 15 years in the oil, gas, and coal production sectors to 70 years for hydroelectric power. The relative size of each production sector and subsector for the United States is shown in Table 1.

Table 1. Producing Sectors in the SGM

	Producing Sector	Gross Output in 1985 (millions of 1985 $)	
1	Agriculture	468,618	
2	Everything Else	5,086,486	
3	Oil Production	64,171	
4	Gas Production	45,804	
5	Coal Production	20,006	
6	Uranium Processing	2,195	
7	Electricity Generation	165,800	
	a. oil		10,959
	b. gas		34,152
	c. coal		85,930
	d. nuclear		21,370
	e. hydro		13,389
8	Petroleum Refining	145,015	
9	Gas Transmission and Distribution	105,330	

Market Clearing

In the SGM, markets are said to *clear*. In other words, the SGM solves for the set of prices for all markets (or sectors) in the modeled economy so that demands and supplies of each market are in equilibrium. The set of prices in which the equilibrium holds is called the *market-clearing* price set. In an equilibrium model like the SGM, markets are linked to other markets through the market-clearing process. For example, a change in the demand for coal will have an effect on not just the price of coal, but also the prices of oil, gas, and, at least indirectly, the prices of all markets in the economy.

Carbon permit prices and taxes are also solved by the SGM as part of the market equilibrium. Specifically, the SGM finds the carbon price such that the amount of carbon emitted is just equal to the carbon constraint of the region or group of regions under a carbon emissions limitation constraint. The 12 SGM regions are listed in Table 2.

Table 2. Regions in the SGM

Annex I	Non-Annex I
United States	China
Canada	India
Western Europe	Mexico
Japan	South Korea
Australia	Rest of World[2]
Former Soviet Union	
Eastern Europe	

[2] The Rest of World includes Latin America, Africa, and other Asian countries.

Carbon Taxes and Revenue Recycling

The SGM uses a carbon tax within each region to provide an economic incentive for the economy to substitute away from carbon. Revenues obtained from the carbon tax can be very large, and how the revenues are recycled, or redistributed to the economy, makes a difference in the final economic cost. For this exercise, we assume that all carbon tax revenues are recycled back to consumers through a lump-sum government transfer.

For the cases where emissions rights are traded between countries, each SGM region is allocated an initial number of carbon emissions permits based on its commitments as defined in the Kyoto Protocol. Carbon permits can then be traded between countries at a price that clears the international market in these permits.

Modes of Operation

All of the SGM regions were initially developed as single-region models with a base year of 1985. Each regional model operates in five-year time steps. The model has been run with forecast horizons ranging up to the year 2100. Most of the single-region models were developed in collaboration with experts from that country. It is possible to run all of the regions individually or simultaneously in a global model with international trade. The three modes of operation for the SGM are:

1. Single Region
2. Global with Partial Market Clearing
3. Global with Full Market Clearing

Single-region operation. For each SGM region, all produced goods are classified as being tradable, non-tradable, or traded at a fixed quantity. When SGM regions are operated independently, a fixed world price is assumed for certain tradable goods; regions may import or export as much of that good as desired at that fixed world price, subject to an overall balance of payments constraint. For all non-tradable goods, the quantity of trade is fixed in advance. The following assignments are used when a regional model is operated independently:

1.	Numeraire Sector:	Everything else (price always equals 1)
2.	Fixed World Price:	Crude oil
3.	Fixed Trade Quantities:	Agriculture, coal, nuclear fuel, refined petroleum, electricity
4.	Nontradables:	Distributed gas, land, labor

For each region, the large 'everything else' sector is the numeraire, with its price fixed at 1 for all time periods. The prices of the other sectors in the economy are reported relative to this fixed value. The 'everything else' good is a tradable good for all regions. An exogenous balance-of-payments constraint is specified in advance for each region. Most regions are assumed to move linearly from a historical trade balance in 1985 to balanced trade by 2005.

Given a trial set of prices, the SGM computes supply and demand for all producing sectors and primary factors of production. Markets for the non-tradable goods and goods traded at fixed quantities are brought into equilibrium by searching for a set of prices that equate supply and demand. Prices are adjusted until supply and demand are within 0.01 percent of each other.

Global model with partial market clearing. The global version of the SGM is used when there is at least one market that must clear globally. For the scenarios described in this paper, the market is the tradable carbon emission permits market. The model searches for a global carbon tax, which can be interpreted as a world carbon permit price, which clears the market for permits.

Each region is initially allocated a number of carbon permits and may trade those permits at the world permit price. Some regions will be sellers of permits and some will be buyers. After trading permits, all regions must hold permits equal to the domestic level of carbon emissions.

All regions are still subject to a period-by-period balance of payments constraint. The model does not allow borrowing to pay for carbon emissions permits. Imports of permits must be paid for with exports of some other good.

Global model with full market clearing. There are no longer any markets with a fixed world price. A set of world prices is found that clears all world markets. Also, world markets can be created for goods that were traded in fixed quantities in the single-region model.

All of the scenarios described in this paper were run in the second mode, global with partial market clearing. This mode was chosen for two reasons. The first is that we chose to adopt a fixed time path of world oil prices for SGM model runs that were completed for the United States Government during the spring of 1997. This meant that the world oil market would not be allowed to clear in the model. The second reason is that model results are often easier to interpret when some variables in the model remain predetermined over time.

Data Requirements

Three types of data are used to construct and calibrate each region of the SGM:

1. Economic and Demographic Data
2. Energy Balances
3. Technology Descriptions

Economic data include input-output tables and supplemental information from the national income accounts. Population projections were obtained from the World Bank. Energy balance tables were obtained either from the International Energy Agency or from government agencies within a region.

Input-output tables describe, in value terms, the flow of goods between industries and consumers in an economy. However, a model concerned with quantities of carbon emissions must also be concerned with quantities of energy. An input-output table alone is not sufficient to determine the quantities of oil, gas, coal, electricity, and refined petroleum that are produced and consumed. Supplemental information on energy quantities is required to map currency units from an input-output table to energy units needed to calculate levels of carbon emissions. We combine economic input-output tables with energy balance tables to create a hybrid input-output table with units of joules for energy products and real dollars for all other products. Miller and Blair (1985) provide a general description of, and the motivation for using, hybrid input-output tables.

Individual energy technologies are characterized by the annualized cost of providing an energy service. Data needed to determine the annualized cost include capital cost, equipment lifetime, annual fuel requirements, the interest rate, and other annual maintenance and operating costs.

REFERENCE CASE AND CALIBRATION

The cost of reducing greenhouse gas emissions is dependent on the reference case. The higher the growth rates of emissions in the reference case the greater the cost of meeting the Kyoto commitments. Therefore, much effort is expended to create an acceptable reference case before running any of the mitigation scenarios.

Results for this study are reported for the years 1990 through 2020. The United States reference case was closely calibrated to the Annual Energy Outlook 1998 (AEO98). Projections of carbon emissions, population, gross domestic product (GDP), energy consumption, and electricity generation for the Annex I regions are described below.

For the other global regions, economic and energy consumption growth rates were roughly calibrated to regional projections from the World Energy Outlook 1996 (WEO96). For the Eastern Europe and Former Soviet Union regions, projected energy consumption levels were adjusted downward from the WEO96 projection to reflect recent events. Population projections for all regions with the exception of the United States were set exogenously based on the World Population Projections 1994-1995, published by the World Bank. The United States population projection was set according to AEO98 projections. The international crude oil price trajectory was also taken from the AEO98. Prices for all other fuels and goods in the model were determined endogenously.

The general calibration procedure was to first match GDP growth by adjusting parameters that control total factor productivity in the 'everything else' sector. Then energy consumption by fuel was calibrated by adjusting input-specific technical change parameters. Carbon emissions are an output of the model derived directly from primary energy consumption by applying fuel-specific emission factors.

Gross Domestic Product

Table 3 shows average annual growth rates for the seven Annex I regions for GDP, CO_2 emissions, carbon equivalent emissions, and primary energy consumption. The negative growth rates shown for the Former Soviet Union and Eastern Europe reflect the economic downturn between 1990 and 1995 that resulted in the decline in emissions discussed above. GDP growth rates for the Annex I regions were matched to projections in the sources noted above by adjusting the total factor productivity parameters for the large 'everything else' sectors.

Table 3. Projected Average Annual Growth in GDP, CO_2 Emissions, Carbon Equivalent Emissions and Primary Energy Consumption from 1990 to 2010 in the SGM Reference Case

Region	GDP	CO_2 Emissions	Carbon Equivalent Emissions	Primary Energy Consumption
Canada	2.6%	1.8%	1.8%	1.4%
Former Soviet Union	0.4%	-1.1%	-1.1%	-0.9%
Japan	1.9%	1.5%	1.7%	1.5%
United States	2.2%	1.5%	1.4%	1.5%
Western Europe	2.4%	1.3%	0.8%	1.3%
Australia	2.8%	1.8%	1.6%	1.7%
Eastern Europe	1.1%	-0.3%	-0.3%	-0.03%

Carbon Equivalent Emissions

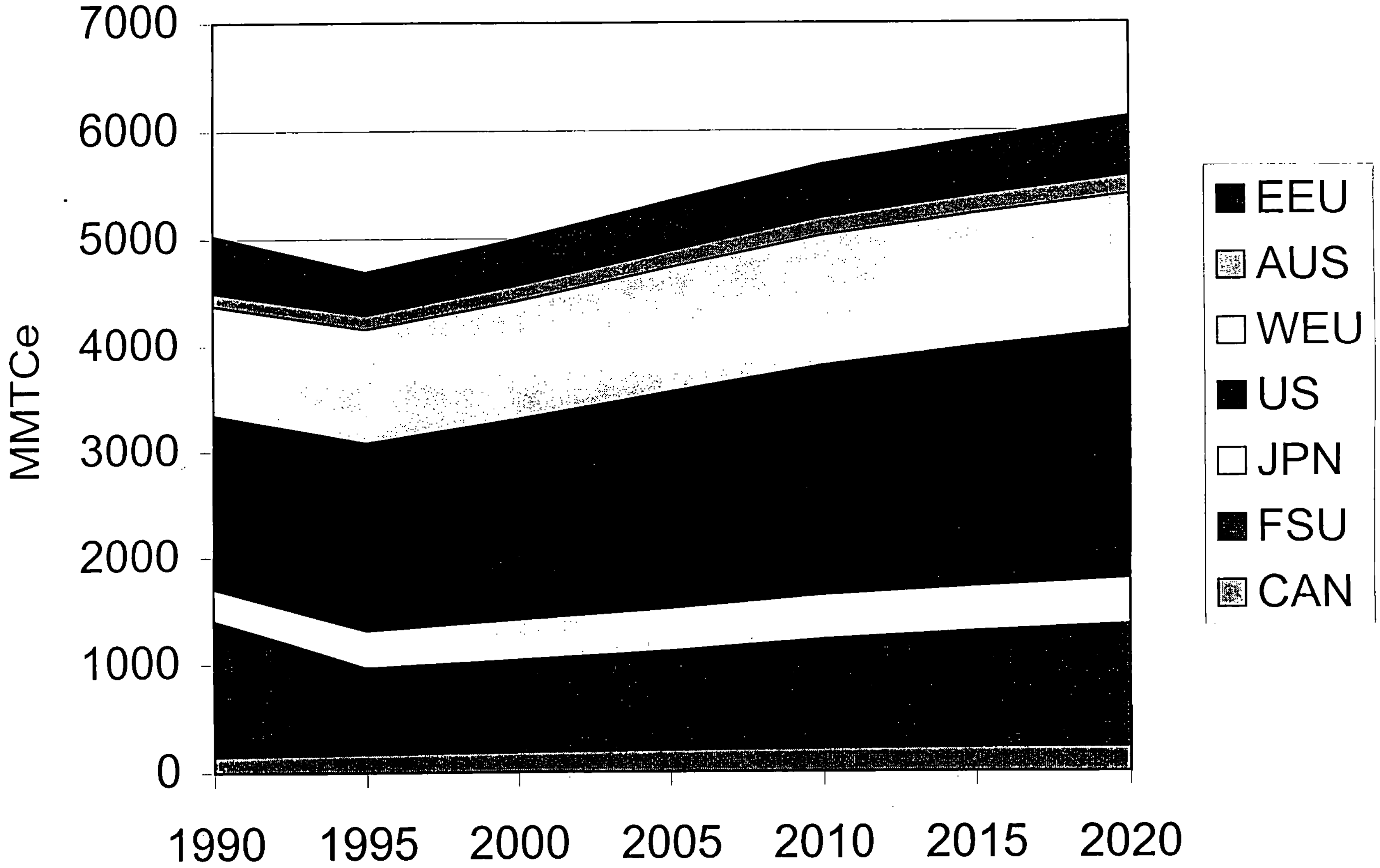
For the purpose of this analysis, we generated non-CO_2 greenhouse gas emissions trajectories for each Annex I region based on values provided by the Working Group on Public Health and Fossil Fuel Combustion (1997). We used these trajectories, measured in million metric tons (tonnes) of carbon equivalent, in conjunction with our carbon dioxide emissions trajectories, to adequately represent the basket of six gases called for in the Protocol. As a result, the baseline trajectories and required commitments in this analysis are expressed in terms of carbon equivalent rather than carbon or carbon dioxide.

Figure 1 shows emissions paths for the reference case in million tonnes of carbon equivalent (MMTCe) by region. The reference case assumes that no additional emissions mitigation policies are undertaken to control emissions of greenhouse gases to the atmosphere. In 1990, total carbon equivalent emissions in the Annex I regions were 5,035 MMTCe. Model results show that total Annex I emissions actually drop from 1990 to 1995 as the decline in Eastern Europe and the Former Soviet Union overwhelm emissions growth in the other Annex I regions. After 1995, Annex I emissions rise as those two regions begin their recovery and as fossil fuel consumption increases in all regions. By 2010, Annex I emissions reach 5,686 million tonnes, or a 13 percent increase in total emissions at an average emissions growth rate of 0.61 percent per year.

[Figure 1. Baseline Carbon Equivalent Emissions for Annex I]

Energy Consumption

Annex I primary energy consumption grows at an average annual rate of 0.86 percent between 1990 and 2010. Over 88 percent of that growth is in the form of fossil fuels, and nearly 53 percent is supplied by natural gas alone. Figure 2 shows the percentage of total primary energy consumption supplied by fossil fuels by region in 2010. The total percentage and the composition of that fossil fuel consumption have a significant impact on the costs of mitigating carbon equivalent emissions.



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[Figure 2. Percentage of Total Primary Energy Consumption Supplied by Fossil Fuels in 2010]

Petroleum remains the major source of energy through 2010, but its share of total consumption declines over time, giving way to natural gas and, to a lesser extent, renewable energy sources. Coal is the third largest source of energy and its consumption remains steady at slightly more than 20 percent of total consumption. Nuclear energy's contribution to energy consumption also remains steady with declines in the United States roughly matched by increases in Western Europe.

Electricity Generation

Figure 3 shows electricity generation by fuel in 2010 for the Annex I regions. The composition varies greatly from region to region. The United States, Australia, and Eastern Europe, for example, rely heavily on coal while Canada generates almost 60 percent of its electricity from hydroelectric sources. Western Europe has the most balanced composition with no one fuel supplying more than one-third of the total generation.

[Figure 3. Total Electricity Generation by Fuel in 2010]

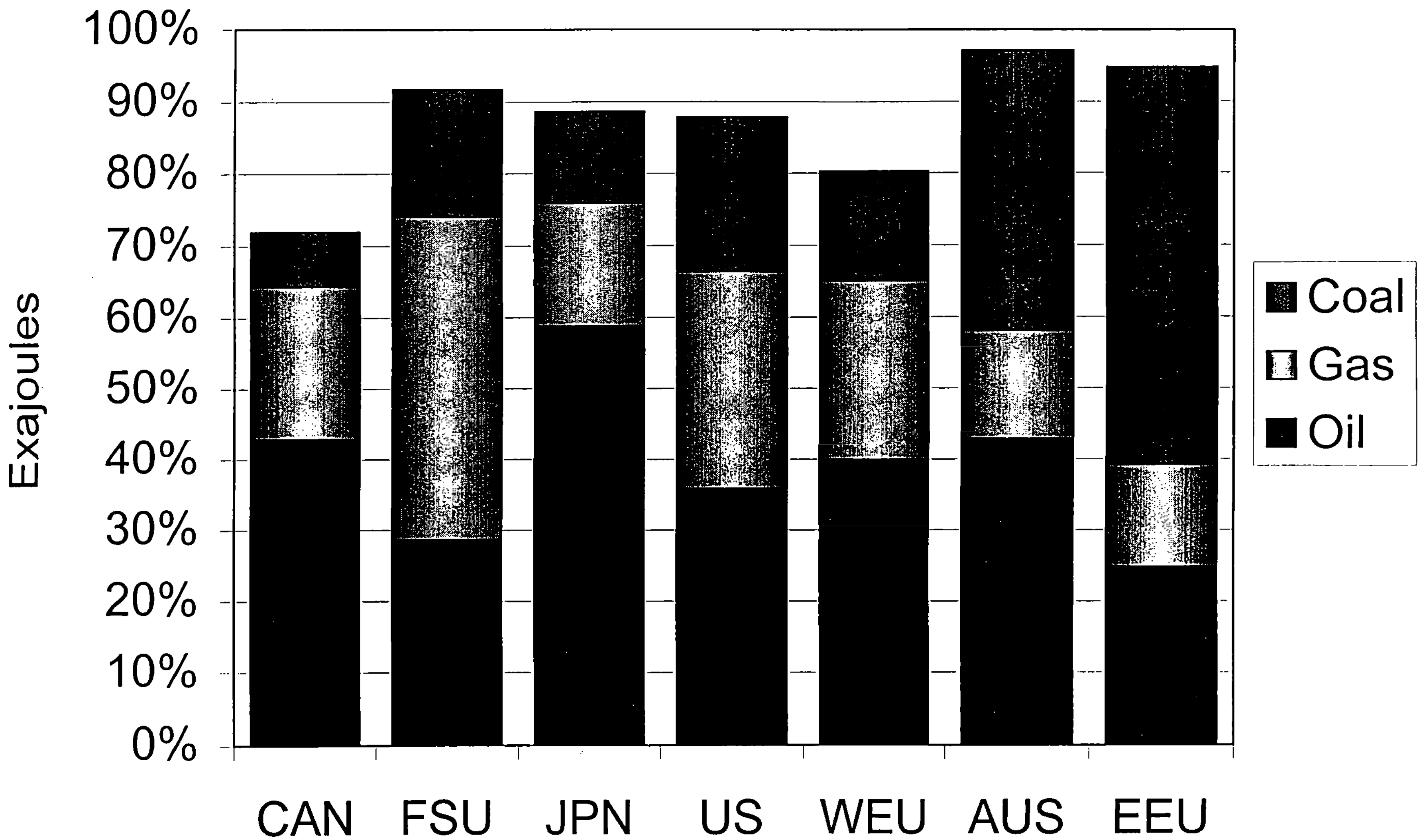
MEASURING AND REPORTING MITIGATION COSTS

At least two measures of cost are available from the SGM and from other models as well. The first measure, which we call the *direct cost*, can be thought of as either a deadweight loss or the integral under the marginal cost curve for carbon. Using either approach, direct cost is approximately equal to one-half of the carbon tax (or permit price) times the reduction in carbon emissions. For the permit trading cases, direct costs are then adjusted by the value of transfer payments required to purchase or sell permits. This measure of net cost is simple to construct and is comparable across models. We will discuss the measurement of costs further in the discussion section at the end of the paper.

COMPLIANCE

In the following sections, we systematically address the question of compliance cost for the Kyoto Protocol. In each mitigation scenario, allowable emissions are reduced linearly from the reference level in 2000 to the emissions target in 2010. We treat the year 2010 as a typical year within the 2008 to 2012 budget period and assume that average cost experienced in the budget years before and after are on average the same as for the year 2010. We address five different issues:

1. The impacts of independent compliance,
2. The impacts of joint compliance with Annex I trading, and
3. The impacts of joint compliance with Annex I trading with an operational Clean Development Mechanism.
4. The effect of non-CO_2 greenhouse gases on compliance costs, and
5. The effect of carbon sinks on compliance costs.



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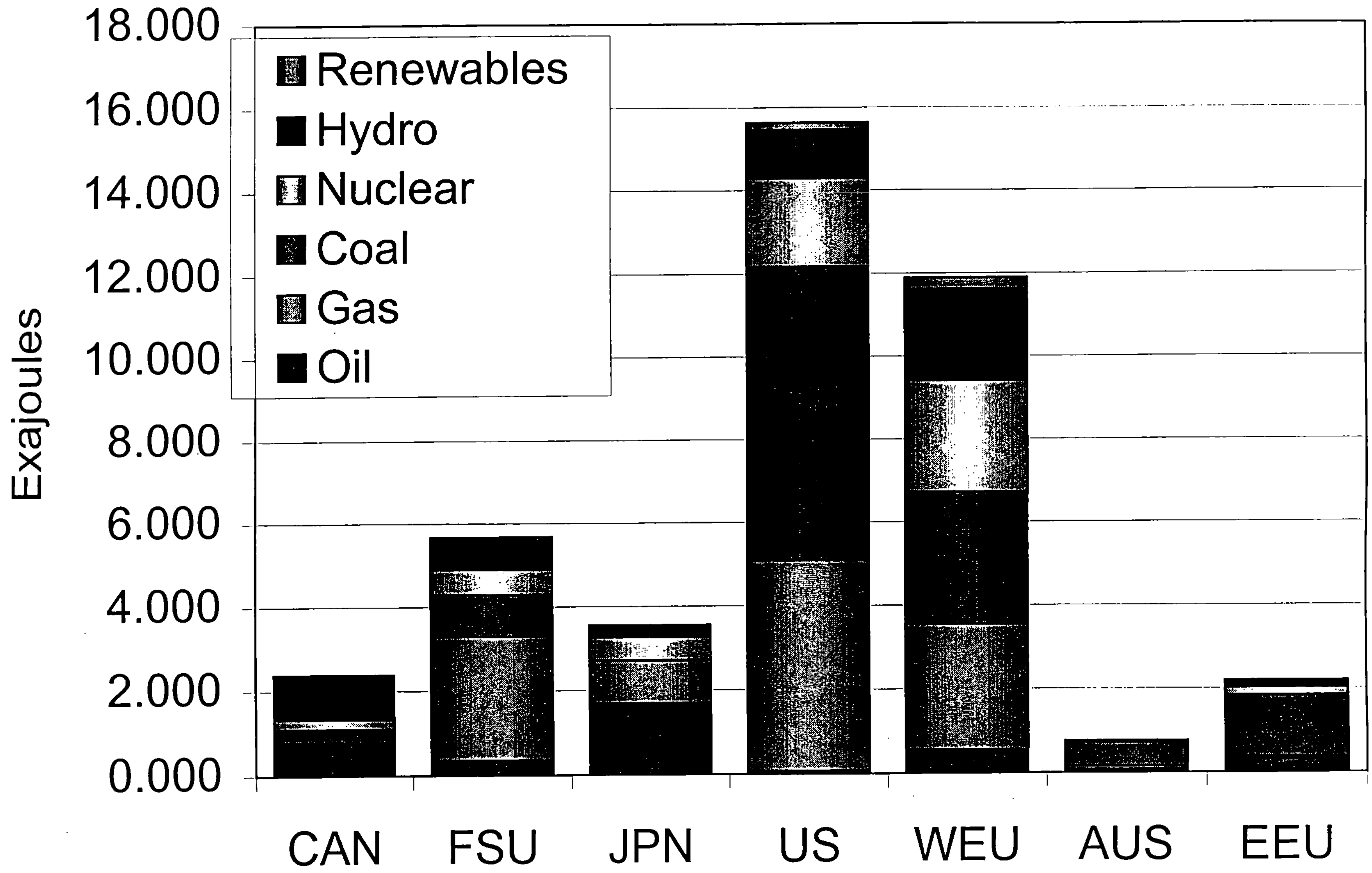
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INDEPENDENT COMPLIANCE

In the independent mitigation case, each Annex I region must individually meet its quantified emissions limitations without any trading of permits across regions. A time series of carbon taxes is determined for each region to reduce emissions to be equal to its allocated emissions rights. In our examination of independent compliance we assume that non-CO_2 greenhouse gases grow at exogenously specified rates in the reference case. Because we are ignorant about the mitigation cost functions for these other gases, we assume that their aggregate mitigation cost functions are similar to fossil fuel carbon. Thus, we compute non-CO_2 greenhouse gas mitigation cost as a proportion of fossil fuel carbon mitigation cost. In other words, the same percentage of total non-CO_2 emissions is abated for a given tax as the percentage of carbon dioxide emissions abated for that same tax. In a later portion of this paper we will investigate the implications of relaxing this assumption. Similarly, we apply ad hoc assumptions regarding land-use emissions mitigation. Although most of the Annex I regions had net sequestration in 1990, we assume for this analysis that regions receive no credits for this sequestration in the compliance period.[3] As with the mitigation cost assumptions, this assumption about credits for emissions sequestration will be relaxed in analysis discussed later in the paper.

Several issues arise in the analysis of independent compliance. Successful compliance will change the regional and world energy systems. The individual energy circumstances characteristic of each region will shape the nature and cost of compliance. For example, the electric power sector plays an important role in shaping the cost of compliance. In the United States the substitution of natural gas for coal plays an important role in Western Europe the role of nuclear power is raised.

Some technology options have significant lead times to their deployment. For example, it takes time to build the gas pipeline infrastructure needed to re-power coal fired electricity generating facilities, to build and deploy gas turbines, and to build and license new nuclear power plants. Sub-optimal investment decisions may result from uncertainty regarding whether or not and under what conditions the Protocol will ever enter into force as well as national implementation policies.

Costs

We first compute the carbon taxes or equivalent carbon permit prices required to bring each region into compliance independently on the assumption that independent compliance is fully anticipated by all public and private sector investment decisions taken after the year 2000. These results are shown in Table 4. Values are included for 2020 to show what the potential compliance costs would be if the requirements of the Kyoto Protocol were to be extended beyond one budget period.

[3] The exception to this is Australia. Because Australia was a net land-use emitter in 1990, its land-use emissions are included in its Kyoto target. Australia is also projected to be a net emitter in the compliance period in this analysis and these emissions are added to the carbon equivalent emissions to generate its baseline emissions in 2010.

Table 4. Emissions Mitigation Relative to Reference and Emissions Taxes Required to Meet Kyoto Quantified Emissions Limitations and Reduction Commitments (MMTCe/year and 1992 US$ per Tonne of Carbon Equivalent)

	Emissions Mitigation Relative to Reference to Meet Kyoto Quantified Emissions Limitations And Reduction Commitments (MMTCe/yr.)		Carbon Permit Price or Tax Needed to Achieve Independent Compliance (1992 US $/tonne Ce)	
Region	2010	2020	2010	2020
Canada	73	87	357	396
Former Soviet Union	--	--	--	--
Japan	137	152	462	434
United States	630	812	134	173
Western Europe	272	313	170[a] 191[b]	182[a] 235[b]
Australia	34	44	117	142
Eastern Europe	2	54	2	41

[a] Allows new nuclear power capacity to be built. [b] No new nuclear power capacity allowed.

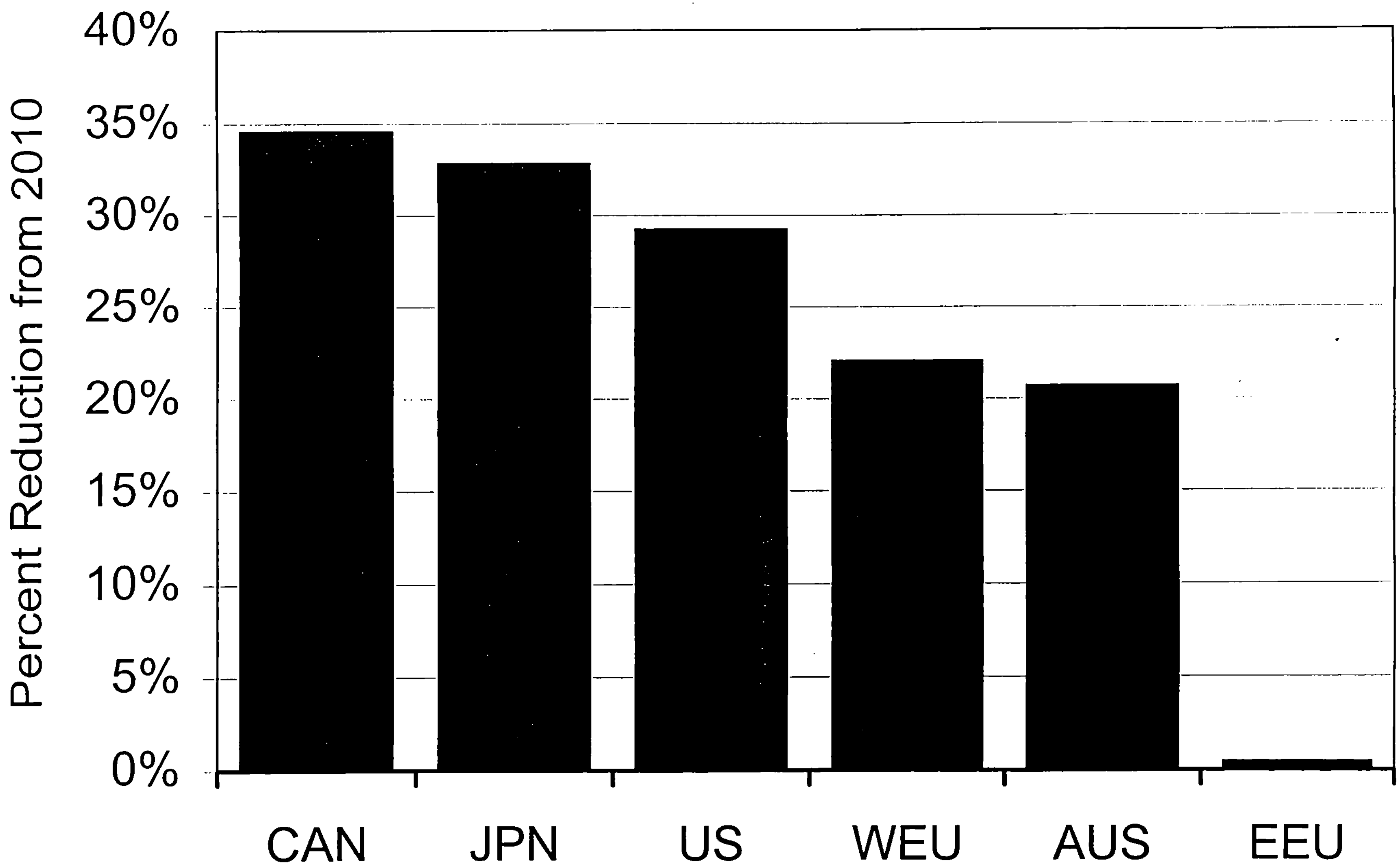
Permit fees of this magnitude change domestic and international energy systems. The changes in national energy systems vary greatly from region to region. Different growth rates in the Annex I regions result in varying amounts of mitigation required to comply with the Kyoto Annex I emissions limitations. Figure 4 shows the percent reduction in emissions from 2010 required by each region to meet its emissions goal. As mentioned earlier in the discussion of the construction of the regional reference cases, emissions growth rates, by affecting the emissions projection in 2010, significantly affect the cost of mitigation. Within the OECD regions, permit prices under independent mitigation are lowest in Australia, where it requires $117 per tonne of carbon equivalent to comply with the Protocol in 2010, and highest in Japan, where the price rises to $462 per tonne.

[Figure 4. Percentage Reduction in Emissions Required to Meet Kyoto Constraint]

Energy Sector Adjustments in the United States

In the absence of emissions trading, the Kyoto quantified emissions limitations and reduction commitments anchor a nation's energy system to 1990. There are a limited number of ways to relax this constraint. Nations can either

- Capture and sequester carbon—in the time frame of the first commitment period this is limited to afforestation and reforestation;
- Undertake Fuel Switching—either expanding the production of non-carbon emitting energy sources such as hydro, nuclear, and solar power or biomass, or shifting from fuels with high carbon to energy rations, such as coal, to fossil fuels with low carbon to energy rations, such as natural gas;


40%
35%
30%
25%
20%
15%
10%
5%
0%
Percent Reduction from 2010
CAN
JPN
US
WEU
AUS
EEU

- Conserve Energy—increasing the amount of services provided by a fixed energy input, or a reduction in the provision of energy services.

One of the notable responses in the United States is the substitution of natural gas for coal in the production of electric power. Fuel switching from coal to natural gas and renewable fuels in the United States electricity generation sector accounts for roughly 40 percent of the reduction in total emissions. Energy conservation makes up the remaining 60 percent of the reduction.

The domestic carbon tax of $134 in 2010 in the independent compliance case results in a reduction of total energy consumption by 20 percent relative to the reference case. Consumption of coal drops by two-thirds while consumption of petroleum drops by 20 percent. Consumption of natural gas, however, increases by 2 percent due to fuel switching. Figure 5 shows the change in energy consumption by fuel in the year 2010 under the independent compliance regime relative to the 2010 baseline value.[4] Although we do not account for carbon capture and sequestration in this analysis, the figure does show evidence of fuel switching and conservation. In the United States, the carbon tax leads to a slight increase in gas and a significant amount of conservation. Meeting the commitment in Western Europe leads to significantly less conservation but a much greater degree of fuel switching from fossil fuels to nuclear power. Note that even though emissions are drawn below 1990 levels, the scale of the total energy system remains above 1990 levels for all regions but Japan. The fuel switching mentioned above allows the emissions targets to be met without reducing total consumption by the same percentage as the required reduction in emissions.

[Figure 5. Change in 2010 Energy Consumption from Baseline by region and fuel]

Total electricity generation in the United States drops by 22 percent as a result of the carbon tax. The tax results in the share of electricity generated from coal dropping from 52 percent in the reference case to 20 percent in the independent compliance case. The reduction in electricity generation from coal is partially compensated for by fuel switching to natural gas. The share of electricity generation from natural gas doubles from 20 percent in the reference case to 40 percent in the independent compliance case. Even so, conservation accounts for 70 percent of the drop in total generation from reference levels. Figure 6 shows how the utility sector in the United States switches from coal-burning to gas-burning electricity generation technologies with the advent of a carbon tax.

[Figure 6: The relationship between carbon tax and coal utilization in the SGM]

The imposition of taxes or permit fees has a depressing effect on the price of coal. But interestingly, it has relatively little effect on the price of natural gas. The increased demand for gas to replace coal in power generation is roughly offset by a decrease in the demand for natural gas for end-use applications, leaving the market price relatively stable.

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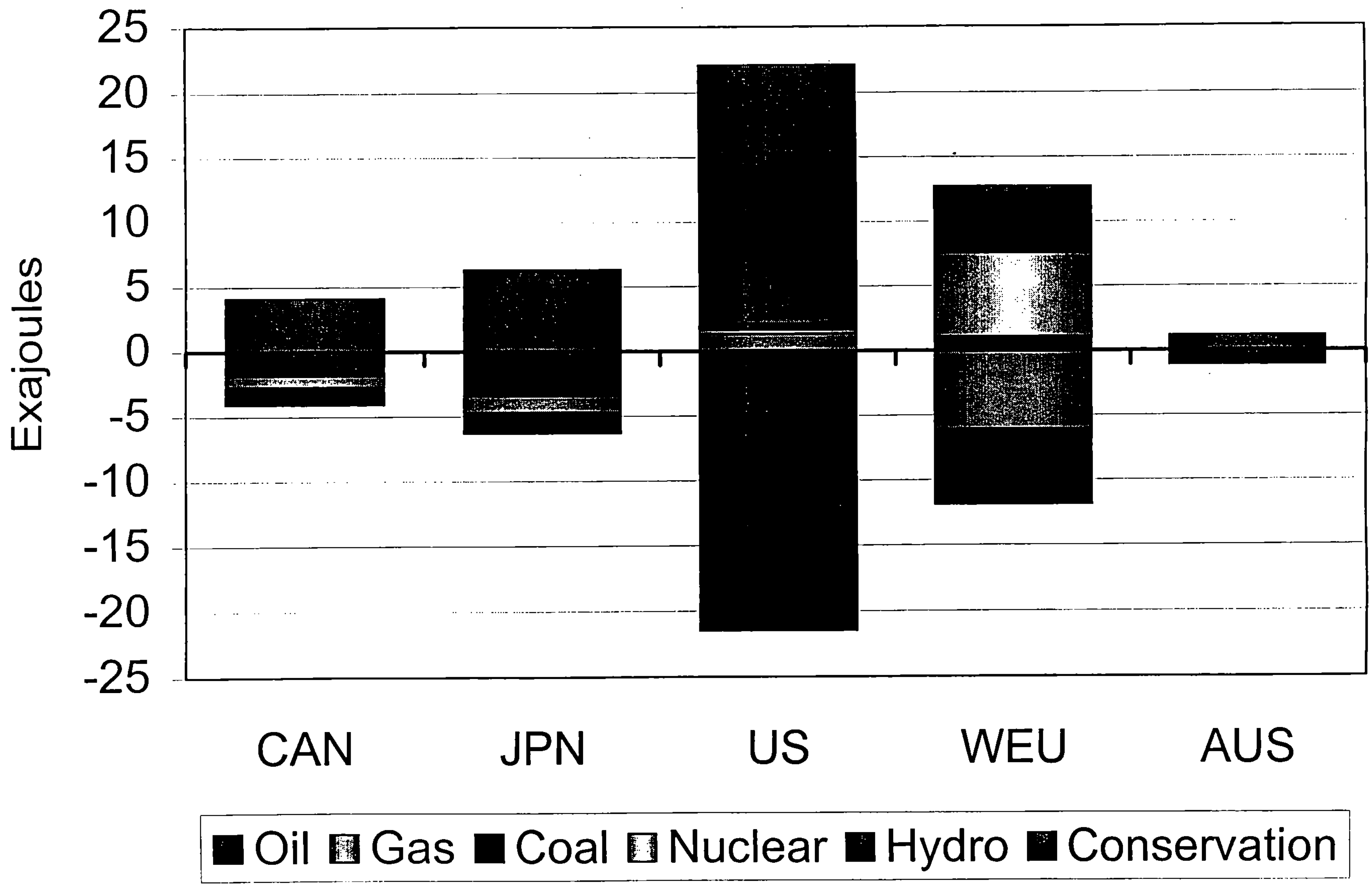
[4] Eastern Europe is not shown in the chart because the impact of the tax on its energy system is so small so as not to be noticeable on the chart. The Former Soviet Union is not included because it is not required by the Protocol to undertake domestic mitigation.


25
20
15
10
5
0
-5
-10
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Exajoules
CAN
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US
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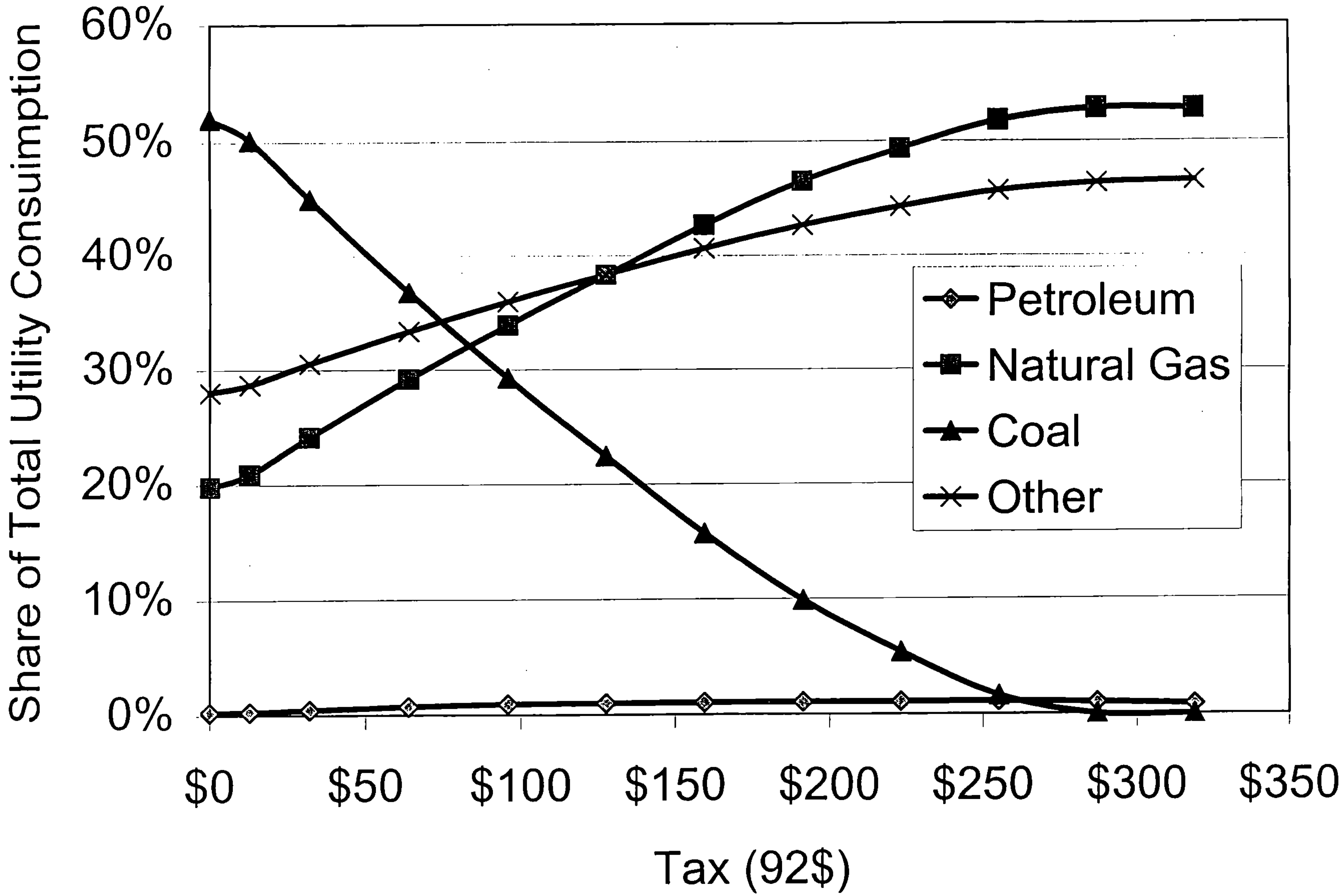
Coal
Nuclear
Hydro
Conservation



Share of Total Utility Consuimption
60%
50%
40%
30%
20%
10%
0%
$0
$50
$100
$150
$200
$250
$300
$350
Tax (92$)
Petroleum
Natural Gas
Coal
Other

Certain caveats apply to the discussion above concerning the substitution of natural gas-fired electricity generation capacity for existing coal-fired capacity. The analysis requires that the tax be levied indefinitely. If the tax policy is believed to be only temporary, the optimal degree of substitution is diminished and the tax level required for Protocol compliance raised. The tax level required for mitigation also depends on the cost of developing the infrastructure necessary to supply natural gas to potential new users. Extending pipelines to particular areas, for example, might increase the cost of gas enough so as to discourage switching from coal-fired plants in those areas.

Energy Sector Adjustments in Australia

The energy system in Australia reflects a relative abundance of coal and scarcity of domestic natural gas supply. It has the lowest cost of independent compliance among OECD regions primarily because it has the highest allowable percentage emissions growth relative to 1990, eight percent. Independent compliance with the Kyoto Protocol is accomplished primarily by reducing coal usage and secondarily with reductions in oil consumption.

Energy Sector Adjustments in Western Europe

The energy system in Western Europe is very different from that of the United States. Whereas relatively low energy tax rates and high dependence on coal for electric power generation characterize the United States, Western Europe is characterized by relatively high energy-tax rates and only modest use of coal for power generation. As Figure 5 shows, the model responds to a constraint on carbon emissions by shifting to non-carbon power generating technologies—in particular, nuclear power. This is a case that may be either politically or technically impossible to realize. Outside of France few nations would allow a significant expansion of nuclear power. Furthermore, given the lead time required to build and deploy a new nuclear facility, even in France, this option will be available for only a brief period. If it takes ten years to bring a new facility on line, that process must commence in 1998 to have an influence on the first compliance year, 2008.

When no new nuclear power generation capacity is allowed, the cost of compliance rises from $170 per tonne of carbon equivalent in 2010 to $191. Without a nuclear option more of the Western European mitigation must come from conservation.

The model shows relatively little energy conservation in Western Europe relative to the other Annex I regions. This reflects the fact that existing energy prices are already high, and whereas a $100 per tonne carbon equivalent tax raises the price of end-use fuels by between 20 and 25 percent in the United States, this is not the case in Western Europe. As a consequence of the relatively smaller price signal in Western Europe than in the United States, there is a relatively smaller conservation response.

Energy Sector Adjustments in Canada and Japan

The energy systems in Canada and Japan are quite different in many regards. The Canadian energy system obtains a high fraction of electric power from hydroelectric facilities, while oil and gas dominate the Japanese system. Canada is a nation with low population density, with a transportation system reflecting a greater need to transport people greater distances. In contrast Japan has relatively high population density and a transportation sector geared appropriately. However, these two systems are similar in that both systems have relatively little coal use and have high percentage emissions mitigation requirements—more than 30%—relative to the reference case emissions in the year 2010. The lack of domestic coal to replace relatively cheaply with an alternative fuel leaves both nations with the two highest marginal independent-compliance costs in our analysis.

Imperfect Energy Transitions

In the preceding analysis we have assumed that investment decisions begin to be altered starting in the year 2000. This assumption implies a smooth compliance transition, which need not be the case. We have run excursions to explore the implication of a less than perfect transition under independent compliance in the United States in the year 2010. In one exercise, we systematically reduced the mitigation potential available outside the electric utility sector. As the ability of the non-utility sectors to reduce emissions is diminished, the burden borne by the electric power sector increases—implying higher marginal abatement costs. The relationship between the burden borne by the utility sector and marginal abatement cost is shown in Figure 7.

[Figure 7: The Relationship Between Utility Emissions Mitigation and Marginal Cost in the United States in the Year 2010.]

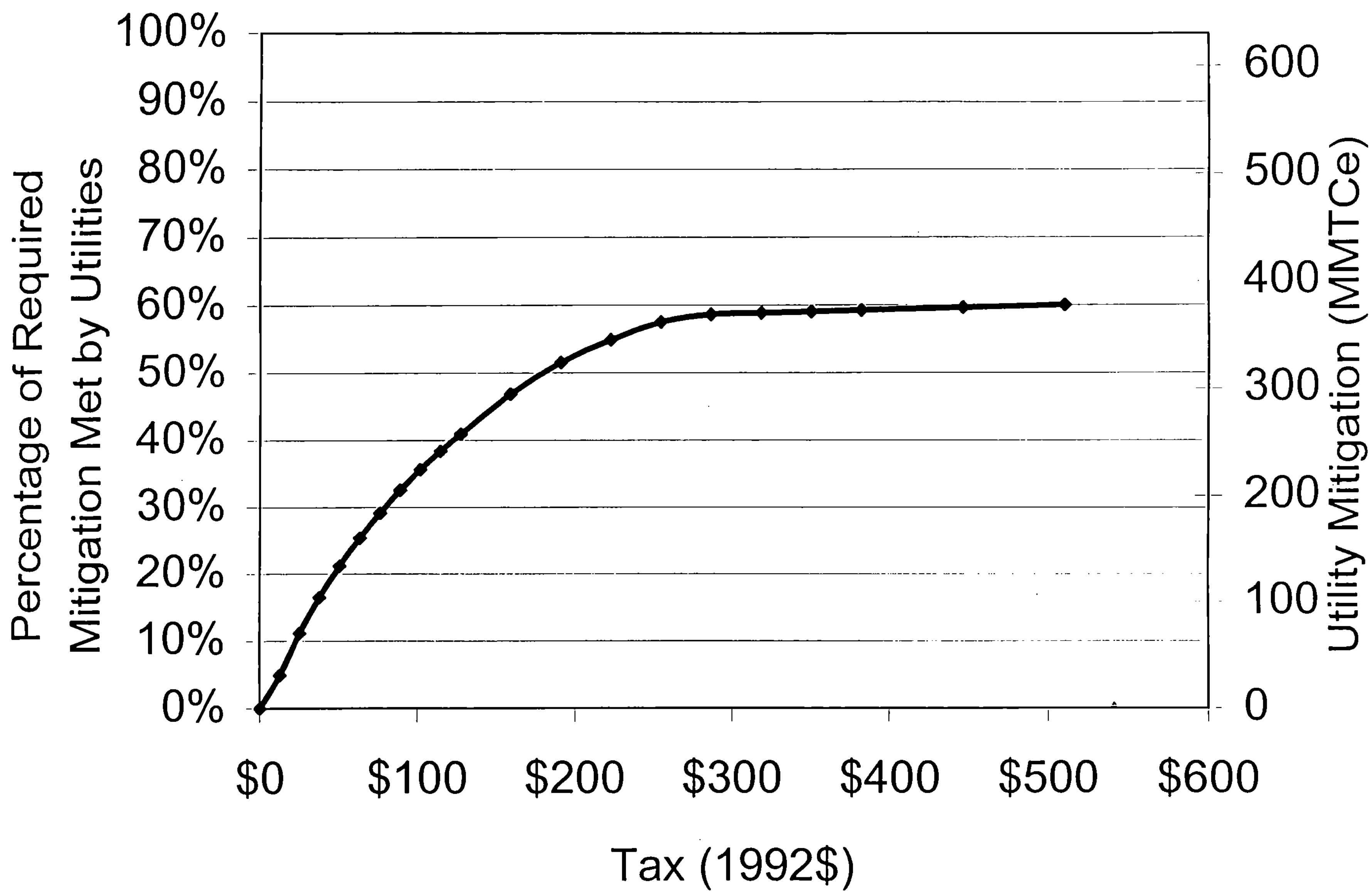
At a marginal cost of approximately $100 per tonne carbon equivalent utilities provide approximately 35 percent of the mitigation in the year 2010, by backing out coal and replacing it with gas. At $175 per tonne carbon equivalent, utilities provide approximately half of the mitigation in the year 2010. But the marginal cost must reach $450 per tonne carbon equivalent before the mitigation reaches 60 percent of the 2010 requirement. If the non-utility sectors have difficulty in reducing emissions, either because technical options are unavailable, or because emissions mitigation requirements were not anticipated in investment planning during the decade prior to the first compliance year, 2008, then the marginal cost could exceed $250 per tonne of carbon equivalent emission.

Relaxing the assumption that utilities begin anticipating implementation of the Kyoto Protocol in investment decisions from the year 2000 onward has a similar effect on the marginal cost of mitigation. In the case of perfect foresight, utilities replace existing coal-fired capacity with gas turbines. This implies building new gas transmission and distribution lines as well as the turbines. When no anticipatory actions are undertaken, utilities are left with the option of either, paying for the carbon emissions and continuing to operate the plant, or shutting down. Utilities that are forced to shut down loose the value of the capital stock and cease to generate power but reduce emissions by the full amount of plant's capacity.

ANNEX I TRADING

In an Annex I trading regime, regions may only emit more carbon than their allocated emissions rights allow if another Annex I region is willing to sell a corresponding number of its permits, thereby forcing the seller region to reduce its domestic emissions beyond the required target. This is modeled as if a common carbon tax were applied to all Annex I regions to meet the overall Annex I emissions target. Since the overall Annex I target is met with equality, excess emissions in permit buying regions are exactly matched by emissions credits in permit selling regions. The permit price is inferred to be the common Annex I tax rate and is used to compute the value of sales and purchases.

Allowing trade among Annex I parties raises a number of additional, important issues. These include:



Percentage of Required Mitigation Met by Utilities
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
600
500
400
300
200
100
0
Utility Mitigation (MMTCe)
$0
$100
$200
$300
$400
$500
$600
Tax (1992$)

1. Reference emissions in Annex I nations: Of particular interest is the degree and nature of recovery of Eastern Europe and the Former Soviet Union. These countries are the largest block of potential suppliers of emissions credits to the market. The number of credits available will have an important influence on the international price of credits, and the incentive to mitigate domestically;
2. Trade behavior: Since the number of sellers could be small, there is potential for monopolistic behavior. Thus a smaller number of permits could be placed on the market than are potentially available. The monopolistic selling position of a few nations could imply a floor on the price of mitigation credits;
3. Trade Rules: Rules may be written which restrict trade;
4. Incomplete markets: Market formation may be incomplete. Trade may occur among a subset of regions. For example, the European Union could form one trading regime and the other Annex I nations could form another. This is sometimes referred to as the "double bubble."

Eastern Europe and Former Soviet Union Permit Allocations

While carbon equivalent emissions in most regions are anticipated to continually increase beyond commitment levels over time, this is not the case for the Eastern Europe and Former Soviet Union regions. Emissions in these regions have declined since 1990. Their reference case emissions trajectories reflect this decline from 1990 to 1995 and then increase slowly from 1995 onward. As noted earlier, Eastern European parties to the Kyoto Protocol have different quantified emissions limitations than the Russian Federation and the Ukraine, Table 5. Economic growth and the nature of restructuring will play an important role in determining the potential supply of emissions permits originating from these two regions. Because the Russian Federation and Ukraine can emit 1990 emissions levels, they have potentially greater emissions rights in excess of their quantified emissions limitation than Eastern European nations as a group.

Table 5. Quantified Emissions Limitations for Eastern Europe and the Former Soviet Union

SGM REGION	CONVENTION PARTY	QUANTIFIED EMISSIONS LIMITATIONS
Eastern Europe	Bulgaria	92
Eastern Europe	Croatia	95
Eastern Europe	Czech Republic	92
Eastern Europe	Finland	92
Eastern Europe	Hungary	94
Eastern Europe	Poland	94
Eastern Europe	Romania	92
Eastern Europe	Slovakia	92
Eastern Europe	Slovenia	92
Former Soviet Union	Estonia	92
Former Soviet Union	Latvia	92
Former Soviet Union	Lithuania	92
Former Soviet Union	Russian Federation	100
Former Soviet Union	Ukraine	100

To the extent that compliance period reference case emissions are lower than in 1990 in the Former Soviet Union, emissions permits will be greater than reference level emissions. This excess is sometimes referred to as "paper credits" or "hot air" and is equal to the difference between the lower post-1990 emissions and the policy-level (i.e., 1990) emissions. For example, the Former Soviet Union's reference emissions level in 2010 is 1,019 MMTCe, significantly lower than its 1990 emissions of 1,265 MMTCe. Under the Kyoto Protocol it would therefore receive 246 MMTCe worth of permits more in 2010 than its projected emissions, giving it 246 MMTCe worth of permits to sell without incurring any emissions reductions of its own.

"Hot Air"

It has been argued that this excess should not be tradable because it leads to lower environmental benefits than if these emissions could not be traded. The argument is that if each region meets its commitments independently, then total Annex I emissions will be lower than the quantitative emissions limitation. If trade is allowed, then Annex I emissions will be exactly equal to the quantified emissions limitation. The difference is the amount of extra emissions that go into the atmosphere due to trade in the first budget period. The problem with this argument is that it is static. It presumes that there is only one budget period. But if there is only one budget period and there is no subsequent mitigation commitment, then it is hard to see why any party would ever undertake a Kyoto commitment.

But, if there were multiple budget periods, and no trade, the excess permits would be banked by the Former Soviet Union and Eastern European parties for use in subsequent periods when national emissions exceeded the quantified emissions limitation. These parties' emissions would therefore simply be moved into the future. Over time, cumulative Annex I emissions would therefore be the same whether or not trade in "hot air" or "paper credits" is allowed. And to the extent that there is any difference to the environment, the long-term, year 2050, concentration is somewhat lower if the emissions are released earlier in the century than later. The carbon cycle has a bit longer in that case to remove carbon from the atmosphere.

The Cost of Compliance with Annex I Trading

Trading regimes are inherently more complicated than non-trading regimes, particularly when the rules for trade have not been established. But even if the rules were known, the circumstance could exist in which the number of buyers and/or sellers is small, raising the issue of market power. We examine four cases:

1. Competitive permit supply
2. Monopolistic permit supply
3. Trade limitation
4. The "Double Bubble"

Competitive Permit Supply

Under a competitive permit supply model, suppliers of permits are numerous and no single permit vender can affect the price received by withholding permits from the market. This would be the case if all permits were distributed within nations to numerous private parties. The competitive prices of Annex I permits in comparison to independent compliance costs are shown in Table 6.

Table 6. Emissions Taxes/Permit Prices Required to Meet Policy Goal (1992 US$ per Tonne of Carbon Equivalent)

	Independent Compliance		Annex I Trading	
	2010	2020	2010	2020
Canada	357	396	61	85
Former Soviet Union	--	--		
Japan	462	434		
United States	134	173		
Western Europe	170	182		
Australia	117	142		
Eastern Europe	2	41		

Permit prices are lower with Annex I trading than with independent compliance, Table 6. In the independent emissions mitigation case, greenhouse gas emitters in the United States may undertake emissions mitigation options available only within the United States. In the Annex I joint case, however, regions are included that have mitigation options with significantly lower costs, thereby lowering the marginal cost to the emissions permit market of meeting the desired emissions targets. This flexibility in meeting emissions targets has a significant impact on costs as well as permit prices, especially in the case in which "hot air" is available on the market at no cost to the supplier.

A fixed emissions level and an increasing reference case emissions level imply both a rising percentage emissions reduction and a rising price of meeting the fixed emissions target over time. Increasing population in the United States, and the economic growth that accompanies it, put upward pressure on emissions that in turn forces larger shifts away from coal toward natural gas and renewable energy sources.

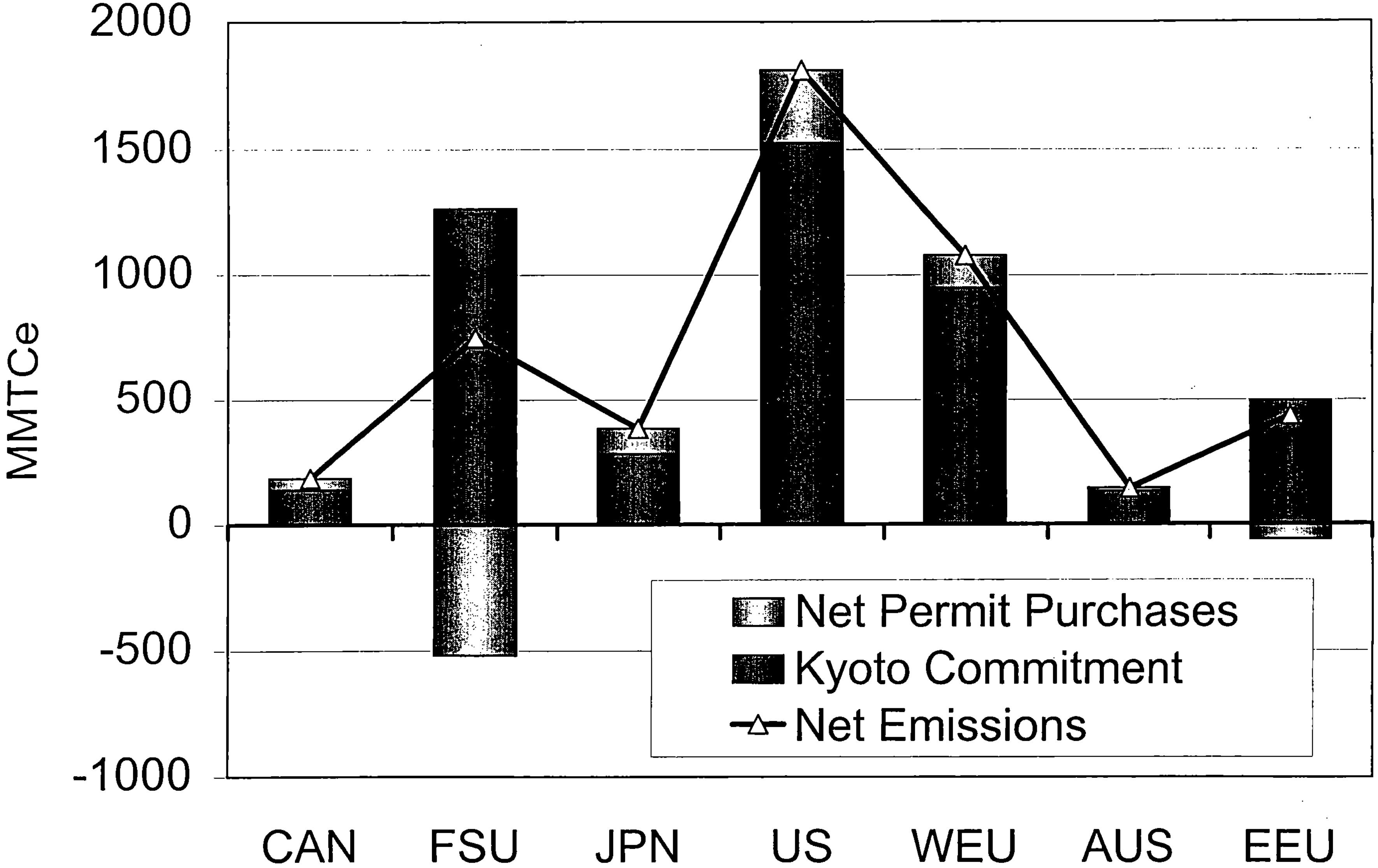
As the permit prices decrease across trading regimes, the United States purchases increasing quantities of permits from abroad, thereby enabling it to emit more than its allocated permits alone would allow. Figure 8 shows total emissions in 2010 for each region disaggregated into emissions allowable under the Kyoto commitment, or the level allowed under independent compliance, and additional emissions granted by the purchase of permits. Under the independent emissions mitigation regime, the United States is limited to emitting only what it is allocated under the Kyoto Protocol. With Annex I trading, however, the United States purchases 288 MMTCe worth of permits in 2010 from the Former Soviet Union and Eastern Europe.

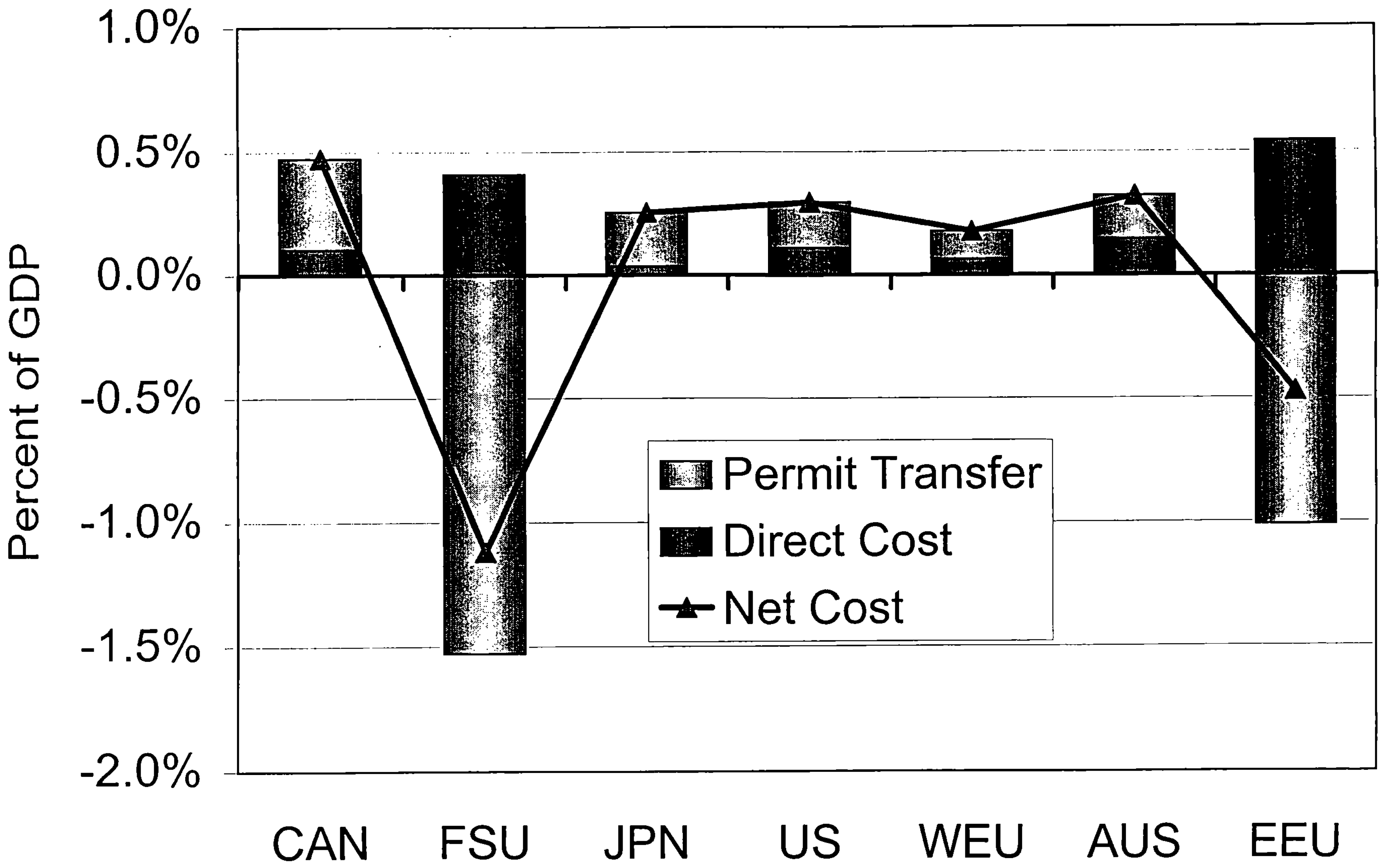
[Figure 8. Annex I Emissions by region – Kyoto Protocol]

Cost calculations for the emissions trading cases are different than in the independent case. Costs for the trading case must take into account the value of permits traded. For a buyer of permits, such as the United States, net cost therefore includes the direct cost of domestic mitigation plus expenditures on carbon permits. A breakdown of these two cost components is shown for the Annex I trading case with competitive permit supply in Figure 9. The direct costs of domestic mitigation range from 15 to 45 percent of the net cost. The remaining cost, the difference between the 'direct cost' and 'net cost' lines in Figure 9, is the value of emissions permits that would be purchased from other Annex I countries.

[Figure 9. Breakdown of costs by region – Kyoto Protocol]

Increased growth in the regional energy systems is allowed by the early application of the purchased permits. Figure 10 shows the percent change in primary energy consumption in 2010 relative to 1990 baseline consumption for permit buyers for three cases: the baseline, independent compliance, and Annex I permit trading.. Annex I permit trading restores a portion of the growth in the regional energy systems lost under independent compliance. The impacts of permit trading are especially evident in Japan. Whereas total energy consumption must actually decrease in 2010 relative to 1990 in order to satisfy the independent commitment, an Annex I permit trading regime allows Japanese energy consumption to expand to approximately two-thirds of reference case emissions growth. The Former Soviet Union and Eastern Europe regions, the permit sellers under Annex I trading, face no or very limited reductions in energy growth under independent compliance but undertake larger reductions in a permit trading regime to generate more marketable permits. The heavy dependence on coal in Eastern Europe and the multiplicity of conservation opportunities in the Former Soviet Union provide inexpensive mitigation credits. These reductions are predicated on a competitive model of economic behavior. The conditions necessary for such a model may be unrealized. We further note that we assume no problems with


2000
1500
1000
500
0
-500
-1000
MMTCe
CAN
FSU
JPN
US
WEU
AUS
EEU
Net Permit Purchases
Kyoto Commitment
Net Emissions


1.0%
0.5%
0.0%
-0.5%
-1.0%
-1.5%
-2.0%
Percent of GDP
Permit Transfer
Direct Cost
Net Cost
CAN
FSU
JPN
US
WEU
AUS
EEU

measurement or verification of emissions mitigation. Such real-world problems could limit market performance.

[Figure 10. % Change in Energy Consumption from 1990 Baseline – Ind. Compliance v. Annex I trading]

Monopolistic Permit Supply

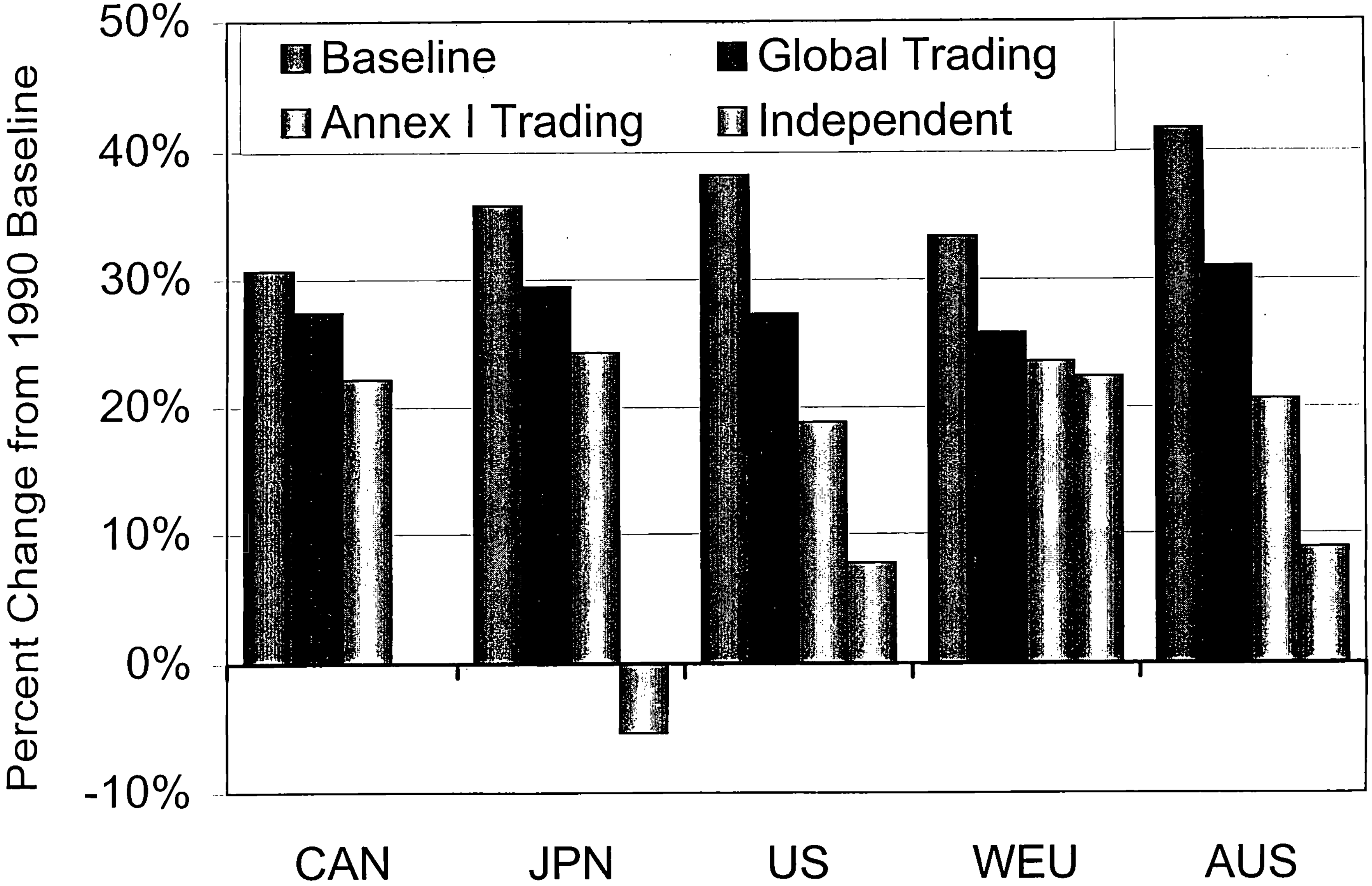
If the Russian Federation and Ukraine were the dominant sellers of emissions mitigation credits, these governments could control the supply of permits centrally. From a national perspective, it is never optimal ever to sell permits beyond the point at which total revenues begin to fall. Since from the perspective of a monopolist adding permits to the market always lowers the price, the trick is to never add permits beyond the point at which the price declines faster than permits are being added to the market. If profits can be maximized without exhausting the supply of "hot air" then supply cost is zero and no more sophisticated model is required for a single period analysis. Of course, adding multiple-periods or non-zero costs of permit creation to the problem create situations in which still fewer permits might be introduced for sale in the first budget period.

If a seller anticipates that the price of a permit will rise faster than the rate of interest, then it pays to hold the permit for sale in a later period. If, on the other hand, the seller anticipates that the permit price will rise less rapidly than the rate of interest, it pays to cash the permit and invest the proceeds. Note that the price of permits rose at a rate less than three percent per year in the competitive case.

For the purpose of this analysis, we combine the Former Soviet Union and Eastern Europe regions and treat them as a single monopolist. The monopolist maximizes its profits, or the difference between its revenues from permit trading and its costs of domestic mitigation, in each time period without respect to the potential value of the permits in later periods. The potential supply of permits available to the permit buying regions includes any excess in emissions right above reference emissions, "hot air", which might exist in the Former Soviet Union and any permits created by domestic mitigation undertaken within the seller regions. The monopolist controls the supply of permits and sells the permits at the resulting market price.

In the year 2010 a revenue-maximizing monopolist would withhold permits to the point at which the price rose to $92 per tonne of carbon equivalent. This market price is fifty percent higher than the competitive market price. The sellers restrict the supply of permits to 62 percent of the permits available in the competitive case. As a result, the combined sellers generate 11 percent more profits under a monopolistic supply regime than under the competitive supply regime. Note, however, that even the monopolistic permit price under the Annex I permit trading regime is significantly less than the carbon taxes faced by the regions under independent compliance.

As one might expect given the level of the permit price, monopolistic permit pricing restricts the regional energy systems by more than competitive Annex I trading but by less than the independent compliance regime. Energy consumption in Japan, for example, increases by 20 percent from 1990 to 2010 under monopolistic pricing, near to the 24 percent achieved under competitive pricing and well above the drastic reductions undertaken in an independent compliance regime. Growth in the United States is reduced from 19 percent in the competitive case to 13 percent in the monopolistic case.



Percent Change from 1990 Baseline
50%
40%
30%
20%
10%
0%
-10%
Baseline
Global Trading
Annex I Trading
Independent
CAN
JPN
US
WEU
AUS

Limited Trading

The fraction of a party's quantified emissions limitation and reduction commitment that may be satisfied with allowances originating outside of that party's boundaries may be limited. Such limits may be non-binding. That is, they may be set at levels at which regions' behavior would not be constrained. If they are set at binding levels, then the marginal cost of mitigation for a party is simply that cost of the final mitigation action necessary to satisfy the domestic requirement. In a competitive permit supply market the marginal cost of international permits would be set by the interplay of supply and demand among parties for whom the constraint is non-binding.

At the June meeting of the Framework Convention on Climate Change's subsidiary bodies in Bonn, Germany, two proposals were presented regarding Annex I permit trading and limits on that trading. The United States and seven other industrialized nations, including the Russian Federation and Japan, proposed that Annex I trading of all six greenhouse gases considered under the Kyoto Protocol be permitted without any limits on the number of permits bought and sold by a particular region. This proposal describes the trading system that we have used thus far in this analysis. Less than a week later, however, the European Union, Switzerland, and seven Eastern European nations proposed an as yet unspecified ceiling on the number of permits a nation could purchase from the international market. Their proposal also required that Annex I permit sales be limited so that net permit transfers from a country could not exceed the amount of emissions mitigated domestically. This condition would effectively limit the portion of its "hot air" that the Former Soviet Union could sell to the amount of domestic reductions that it undertakes. Such a rule would ensure that the total Annex I reductions under a permit trading regime would be at least as great as the total reductions required under independent mitigation. Such proposals are difficult to implement. The degree of realized mitigation is impossible to calculate. There is only one history that will ever be recorded, and therefore no unambiguous reference case will ever exist against which to compare the realized historical emission.

This is not a problem from the perspective of a model, however. We consider here a ceiling on permit purchases from the international market set at 10 percent of each region's allowable emissions under independent mitigation as defined in the Kyoto Protocol. For example, because the United States has an emissions cap of 1,524 MMTCe in 2010, it would be limited to purchasing a maximum of 152 MMTCe in permits from the international market to meet its obligation. As suggested in the European proposal discussed above, we also limit sales of "hot air" permits from the Former Soviet Union to the number of tonnes of carbon equivalent mitigated domestically. For the Former Soviet Union to sell all 246 MMTCe of permits, therefore, it would need to undertake at least 246 MMTCe of domestic mitigation.

A ceiling on permit purchases implies that each region will face a distinct marginal cost for its domestic mitigation activities and another cost for the permits it purchases from the international permit market. The domestic price, as in the independent mitigation case discussed above, will be a function of each particular region's marginal cost curve and the ceiling placed on permit trading. The marginal cost for each region is reported in Table 7.

Table 7. Permit Prices in 2010 Under Limited Permit Trading Case (1992 US$ per Tonne of Carbon Equivalent)

	Permit Price (1992 US$)	
	Domestic Marginal Cost in Buying Regions	Domestic Maringal Cost in Supplying Regions
Canada	200	
Former Soviet Union		26
Japan	308	
United States	92	
Western Europe	82	
Australia	60	
Eastern Europe		26

The entire market for permits under this regime can be satisfied with sellers providing permits to the market at price of $26 per tonne of carbon equivalent in Eastern Europe and the Former Soviet Union.

There is no unique market clearing price under this particular set of rules. The domestic price of mitigation within potentially buying regions and the cost of mitigation supply in potentially selling regions bound the range of prices.

The "Double Bubble"

As mentioned earlier, permit trading may occur among only a subset of the Annex I regions. In the "Double Bubble" case, the Western Europe region is removed from the Annex I trading bloc, leaving it to meet its obligations independently. For Western Europe, the necessary carbon taxes and energy impacts are the same as under its independent compliance case. But for the remaining regions in the permit market, the departure of Western Europe results in a 2010 permit price that is lower than in full Annex I competitive trading--$48 per tonne as compared to $61 under full Annex I trading.

THE CLEAN DEVELOPMENT MENCHANISM

The Clean Development Mechanism (CDM) was created as a vehicle which would allow non-Annex I nations to continue pursue economic growth while at the same time have access to additional resources for the purpose of reducing greenhouse gas emissions. In the words of the Protocol:

> *The purpose of the clean development mechanism shall be to assist Parties not included in Annex I in achieving sustainable development and in contributing to the ultimate objective of the Convention, and to assist Parties included in Annex I in achieving compliance with their quantified emission limitation and reduction commitments under Article 3.*

The CDM provides a mechanism in which certified emission reductions can be created on a project by project basis. Annex I parties can use these certified emission reductions to contribute to compliance with part of their quantified emission limitation.

The CDM is to be subject to the authority of the Conference of the Parties and will be supervised by an executive board.

Participation in the CDM is voluntary. Certified emission reduction credits can be created by projects as long as these projects:

1. Lead to real, measurable, and long-term benefits related to the mitigation of climate change, and
2. Undertake reductions in emissions that are in addition to any that would occur in the absence of the certified project activity.

Interestingly, the CDM can begin creating certified emission reduction credits beginning in the year 2000, and these credits can be applied to the first budget period.

At the writing of this paper the rules for creating certified emission reduction credits have not been written. Therefore, we can not directly simulate the impact of the CDM on permit prices and costs of mitigation. However, full global trading of emissions rights provides a lower bound on permit prices and mitigation costs. The CDM should provide a cost of mitigation that lies between the cost of Annex I trading and full global trading.

Full Global Permit Trading

In the global trading case, emissions rights are allocated to Annex I regions at the same levels as in the Annex I trading case. Under global trading, however, the Annex I regions are allowed to purchase permits from each other and from non-Annex I regions so long as the global emissions constraint is met. The global constraint in each period is composed of the Annex I constraint and the sum of the non-Annex I regions' reference level emissions in that period. The SGM is used to determine a global carbon tax just large enough to meet the global emissions target.

Non-Annex I regions are not required to constrain their emissions below reference levels in the global trading scenario. No mitigation targets or emissions trajectories are imposed on those regions. Under this hypothesized global trading regime, non-Annex I regions participate in the market for emissions permits only when it is to their economic benefit to do so. These regions are allocated permits equal to their projected reference emissions, so they are only required to reduce their emissions by an amount equal to the number of permits they wish to sell.

Expanding the potential supply of emissions mitigation results in significantly lower permit prices than those achieved even under the Annex I permit trading scenarios. Table 8 shows the 2010 permit price under global trading as compared to the independent compliance and Annex I trading regimes.

Table 8. Emissions Taxes/Permit Prices Required to Meet Policy Goal in 2010 (1992 US$ per Tonne of Carbon Equivalent)

	Independent Compliance	Annex I Trading		Global Trading
		Monopolistic	Competitive	
Canada	357	92	61	25
Former Soviet Union	0			
Japan	462			
United States	134			
Western Europe	170			
Australia	117			
Eastern Europe	2			

Table 9 shows the composition of the permit market in the global trading case. As mentioned above, permits sold by the non-Annex I regions are generated by equivalent emissions reductions in those regions. The 432 MMTCe of permits sold by the Former Soviet Union, however, includes 246 MMTCe of "hot air".

Table 9. Composition of the Emissions Permit Market in the Global Trading Case (Million Tonnes of Carbon Equivalent)

	Permits Traded (MMTCe)	
	Purchased	Sold
Canada	62	
Former Soviet Union		432
Japan	122	
United States	479	
Western Europe	207	
Australia	25	
Eastern Europe		24
China		331
India		35
Korea		3
Mexico		18
Rest of the World		52
Total	895	895

The additional permits supplied by China account for most of the difference in permit prices between the Annex I permit trading and global trading cases. To sell such a large number of permits, China reduces its energy consumption by nearly 20 percent in 2010 relative to the baseline consumption, with over 85 percent of that reduction coming from reduced coal consumption. Non-Annex I energy consumption and carbon equivalent emissions continue to grow even as they participate in mitigation activities. Mitigation in non-Annex I regions is achieved by changing the composition of new investments. These mitigation activities are undertaken at a cost significantly less than in other regions, however, thereby allowing the Annex I regions to emit more than in the Annex I trading or independent mitigation cases for less cost.

Costs as a percentage of GDP are obviously the lowest for the Annex I regions under the global trading case, although Eastern Europe and the Former Soviet Union lose some of their gains from trade to the non-Annex I permit sellers. Figure 11 shows the total costs as a percent of GDP to all regions broken into the direct cost and net permit trading revenues components for the global trading case.

[Figure 11. % of GDP cost for all regions under global trading by component]

The minor changes in the Annex I regions' energy systems reflect the lower permit price. Energy consumption in the United States in 2010 increases by 27 percent over 1990 levels, as compared to an increase of only 19 percent under Annex I competitive permit trading, as shown in Figure 10. The remaining Annex I permit buyers experience similar impacts, with energy growth from 1990 under global trading falling about half way between growth in Annex I trading and growth in the baseline case.

SUMMARY OF PARTICIPATION AND BEHAVIOR ANALYSIS

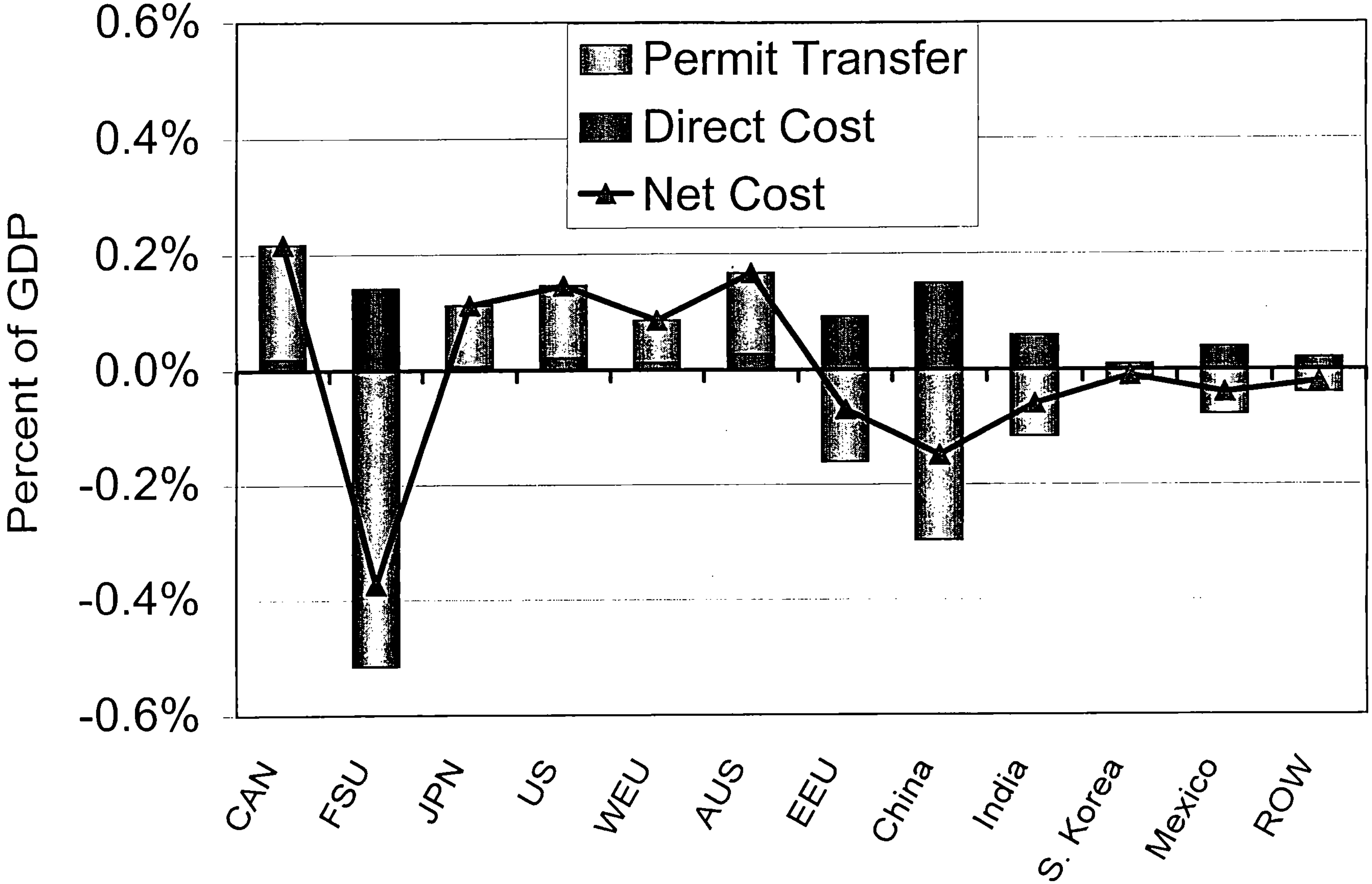
Where emissions mitigation can be undertaken and under what circumstances has a significant impact on the potential costs or benefits of participation in the Kyoto Protocol. Figure 12 shows the range of permit prices that the United States could face depending on which of the above permit trading frameworks is accepted as part of the final Protocol. Note that the other Annex I regions face the same range of permit prices as those shown in the figure except that the independent compliance values differ from region to region. Note also that in the case of Annex I Trading with EU Limits, that the permit value is indeterminate. We therefore present a range. While the lower end of the range is determined by the conditions in the permit supplying regions, the upper end of the range is always region specific.

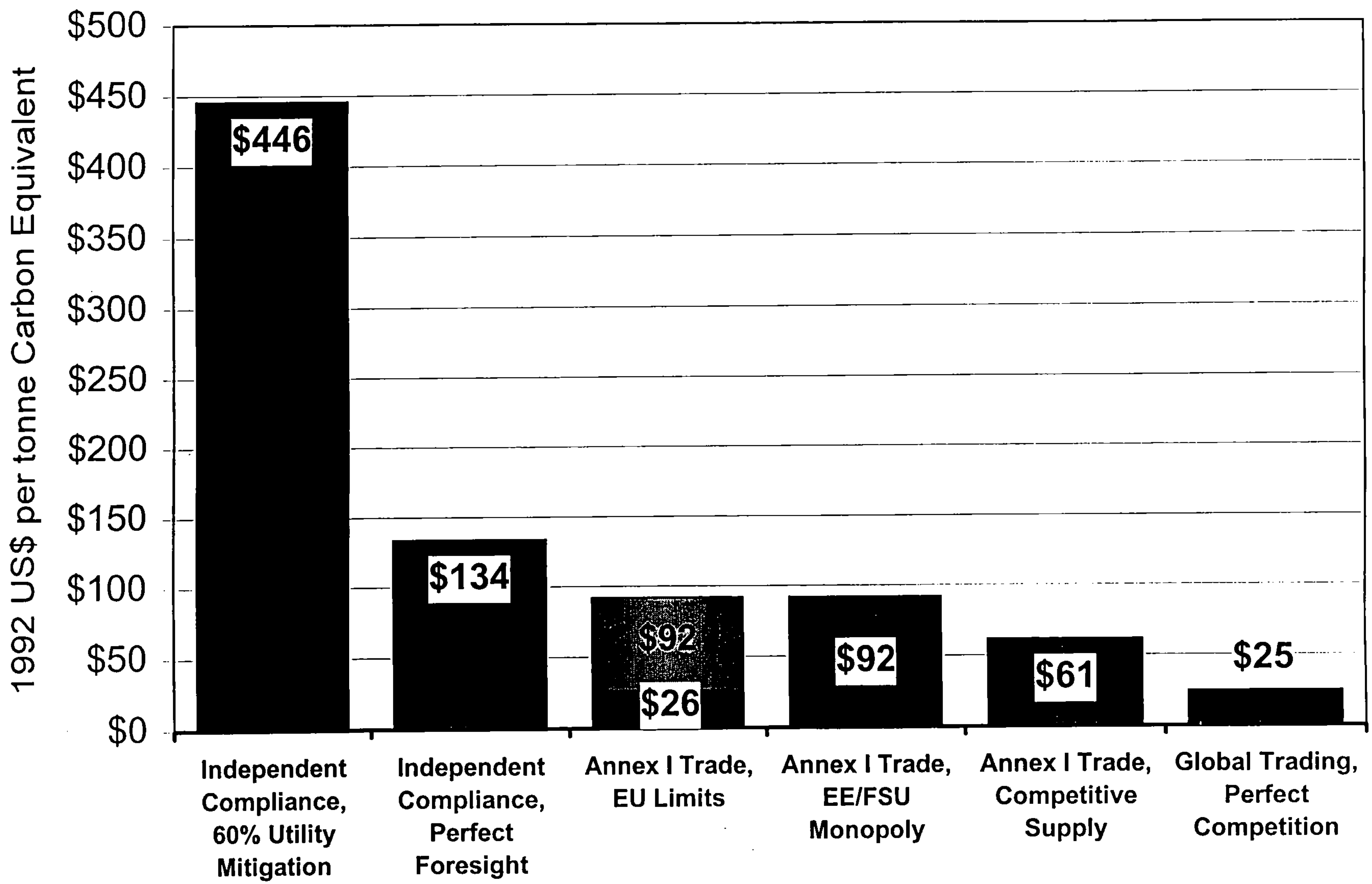
[Figure 12. Range of permit prices for US]

NON-CO_2 GREENHOUSE GASES

The complexity of the Kyoto Protocol is not limited to issues concerning conditions under which trade can occur. The protocol is also framed in terms of a suite of six gases and contains provisions for the inclusion of credits for terrestrial carbon sinks. This section will discuss the role of non-CO_2 greenhouse gases in determining costs and the following section will address the importance of land-use change emissions.

The contribution of non-CO_2 greenhouse gases to total carbon equivalent emissions in 1990 ranges from 10 percent in Japan to over 24 percent in Australia and Eastern Europe among the Annex I regions. Figure 13 shows the composition of total carbon equivalent emissions in 1990 and 2010 for the Annex I regions. The figure also shows the emissions target by region as specified in the Kyoto Protocol (see Appendix A). The Former Soviet Union faces a target that is above its 2010 baseline emissions level, resulting in the "hot air" discussed in previous sections. Australia is allocated an 8 percent increase in emissions from 1990 to 2010, so its target as shown in Figure 13 is greater than the sum of its 1990 greenhouse gas emissions.


Permit Transfer
Direct Cost
Net Cost
Percent of GDP
0.6%
0.4%
0.2%
0.0%
-0.2%
-0.4%
-0.6%
CAN
FSU
JPN
US
WEU
AUS
EEU
China
India
S. Korea
Mexico
ROW


1992 US$ per tonne Carbon Equivalent
$500
$450
$400
$350
$300
$250
$200
$150
$100
$50
$0
$446
$134
$92
$26
$92
$61
$25
Independent Compliance, 60% Utility Mitigation
Independent Compliance, Perfect Foresight
Annex I Trade, EU Limits
Annex I Trade, EE/FSU Monopoly
Annex I Trade, Competitive Supply
Global Trading, Perfect Competition

[Figure 13. Breakdown of Kyoto Target by CO2 and non-CO2 emissions]

The results until now have assumed that the mitigation costs of the non-CO_2 greenhouse gases are proportionate to the cost of mitigating emissions of fossil fuel carbon. In an attempt to bound the compliance costs with respect to these other gases, we modeled two additional mitigation cost cases. In the first case, the "$0 Cost" case, we assumed that all of the non-CO_2 greenhouse gases could be mitigated in 2010 at zero marginal cost, thereby reducing the commitment level by the 2010 emissions of these gases. In the second case, the "Infinite Cost" case, we assumed exactly the opposite – that the non-CO_2 gases were impossible to mitigate at any cost. The "Infinite Cost" case therefore assumes that the Kyoto commitment must be met using reductions in carbon dioxideonly.

Figure 14 shows the impacts on the marginal cost of mitigation for the Annex I regions of the three non-CO_2 greenhouse gas mitigation cost cases, including the original "Proportional Cost" case and the two additional cases discussed above. Note that all of these scenarios share the same "no sinks credits" assumption used in the previous cases. Permits prices for competitive Annex I trading go to zero under the "$0 Cost" case because of the reduced mitigation requirements in each country and the additional "hot air" available to the Former Soviet Union from its non-CO_2 gas credits. The Annex I competitive permit price under the "Infinite Cost" case increases from $61 under the "Proportional Cost" case to $78, causing total costs to increase as well.

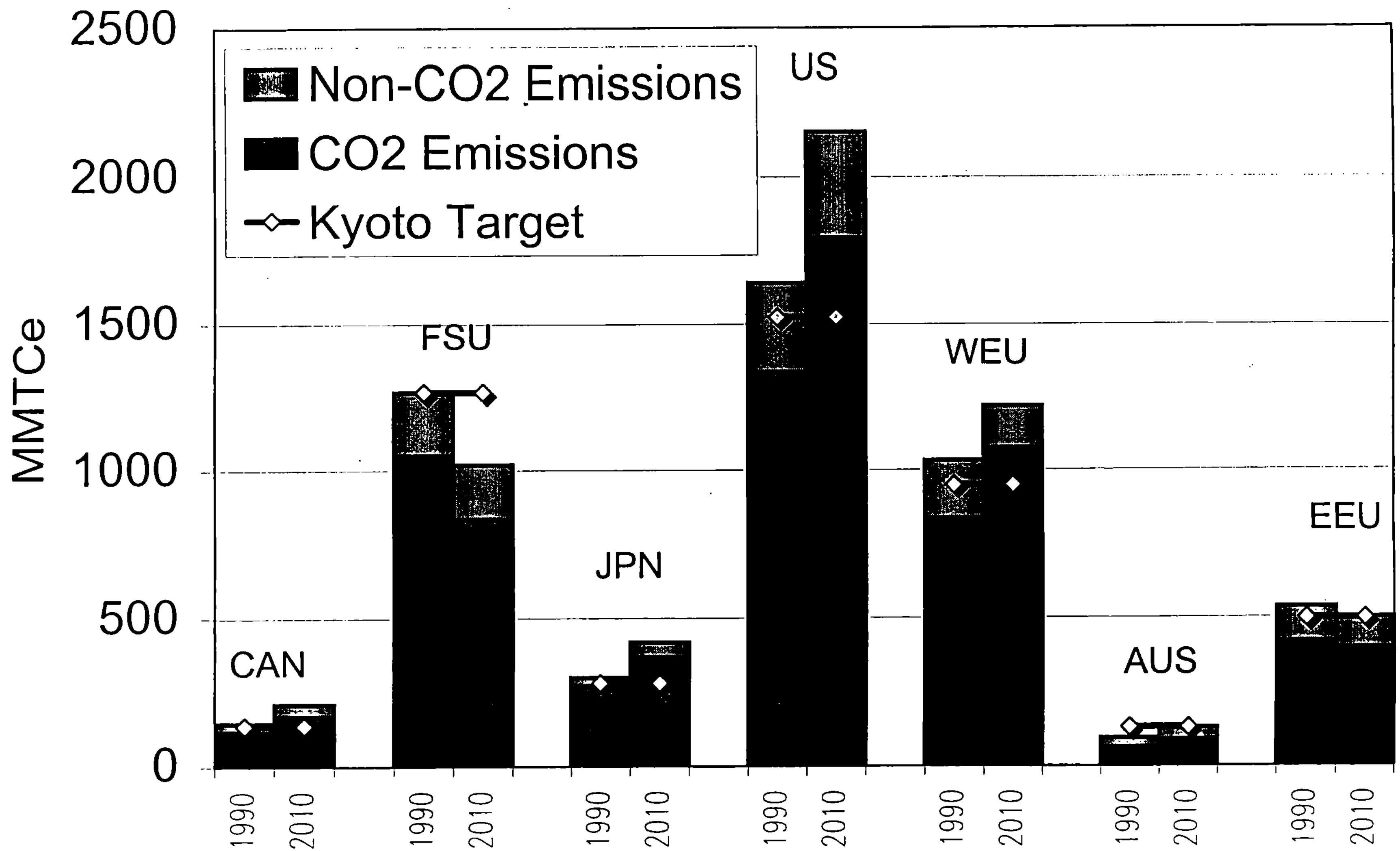
[Figure 14. Costs of compliance under 3 non-CO2 gas mitigation cost options – Independent Compliance]

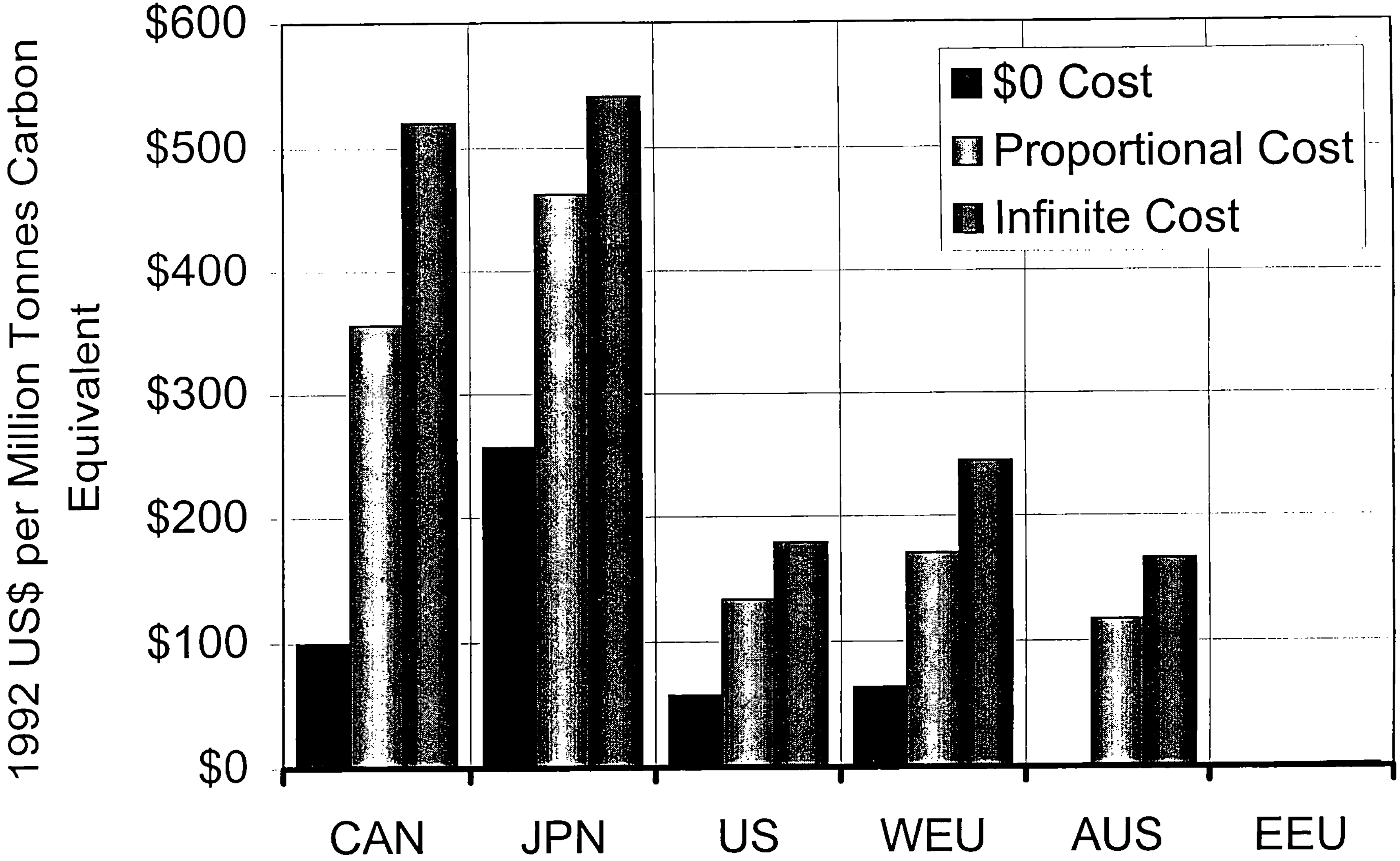
LAND-USE EMISSIONS

In the preceding analysis we have ignored the potential of terrestrial carbon sinks on net carbon emissions under the Protocol. But the Protocol makes provision for land-use change emissions and sinks and while land-use emissions are small relative to fossil fuel carbon emissions, their treatment can have a major impact on the initial cost of achieving any emissions mitigation objective. Land-use emissions are presently treated as a flow in determining the base year, that is 1990, emission rate. Most Annex I nations are in the process of reforesting, and therefore have net accumulation of carbon. This is treated as a negative emission when net anthropogenic emissions are accounted.

While this approach is appropriate for a global accounting of carbon flux, it may not be desirable as a methodology for setting 1990 base year emissions. The implication of this treatment is that if a nation were reforesting in 1990 and was committed to maintaining 1990 emissions rates under the Protocol, it could not reduce the rate of reforestation rate without lowering fossil fuel carbon emissions to below 1990 levels. Thus reforesting is not enough. The rate must be maintained. For nations that were deforesting, this method would create a base year emission target that is the sum of deforestation plus fossil fuel emissions which would in turn implicitly grant those nations a perpetual right to deforest. If the deforestation rate is ever reduced, for example as a consequence of destroying all forested areas, then fossil fuel emissions could be higher than 1990 levels by the 1990 rate of deforestation.

The delegates at Kyoto agreed that if a country had net carbon buildup on land—negative land-use change emissions—in the base year, the base year emission to be used for determining emissions limits


2500
2000
1500
1000
500
0
MMTCe
Non-CO2 Emissions
CO2 Emissions
Kyoto Target
CAN
FSU
JPN
US
WEU
AUS
EEU
1990
2010


$0 Cost
Proportional Cost
Infinite Cost
$600
$500
$400
$300
$200
$100
$0
1992 US$ per Million Tonnes Carbon Equivalent
CAN
JPN
US
WEU
AUS
EEU

would count only the country's industrial emissions. This method was termed the "gross" approach to accounting, a term which is anything but self-explanatory. The idea is that the country would note its stock of terrestrial carbon, not the change in stock. In other words, land-use emissions are ignored in computing the base emissions rate.

On the other hand, if a country were deforesting, or otherwise reducing its stock of terrestrial carbon, then it could count both industrial and land-use change emissions in building its base year emission inventory. This accounting method became known as the "net" approach.

In the budget period, 2008 to 2012, all countries count both industrial and net land-use emissions. For those countries with positive land-use change emissions in the base year, the accounting method was then the "net-net" approach in that net emissions flows are used in both the base year and the budget year. If a country is sequestering however, it counts as negative emissions only those accumulations of carbon that are the result of actions taken since 1990 in the areas of afforestation and reforestation. This method has come to be known as the "gross-net" approach in that net emissions are ignored in the base year but counted in the budget period.

Many issues remain to be worked out. The protocol stipulates that

> *The net changes in greenhouse gas emissions from sources and removals by sinks resulting from direct human-induced land-use change and forestry activities, limited to afforestation, reforestation, and deforestation since 1990, measured as verifiable changes in stocks in each commitment period shall be used to meet the commitments in this Article of each Party included in Annex I.*

This presents an interesting problem in what to count. Do soils beneath the forests count? Can normal anthropogenic forest management be counted? Given the nature of forest growth, the rate of carbon uptake in 2008 would be small for a program that began in 1998 due to the time pattern of carbon absorption by forests. Therefore, to the extent that carbon uptake by sinks is credited in the first budget period, it will largely be determined by an interaction between the rules and actions which were taken earlier. Unless interpreted very broadly, the language of the Protocol limits the potential impact of new initiatives.

For this analysis, we assume that the "gross-net" approach applies for all Annex I regions except Australia, for which we used the "net-net" approach. Because of the uncertainty surrounding the actual quantity of credits to be given for net land-use change emissions in the first budget period, we defined three levels of credits for each Annex I region, as shown in Table 10: no sinks credits, "half" sinks credits, and "full" sinks credits.[5] This quantity is specified exogenously in the budget period and is not priced in our analysis. For the analysis presented thus far, we have used the "no sinks" assumptions.

[5] Australia values from Working Group on Public Health and Fossil Fuel Combustion, 1997. Other values from personal communication with Joe Aldy, Council of Economic Advisers.

Table 10. Land-Use Change Emissions Assumptions for the First Budget Period (Million Tonnes of Carbon Equivalent)

	Land-Use Change Emissions Credits (MMTCe)		
	No Sinks	Half Sinks	Full Sinks
Canada	0	40	80
Former Soviet Union	0	103	205
Japan	0	13	25
United States	0	52	104
Western Europe	0	30	60
Australia	-36	-36	-36
Eastern Europe	0	4	8

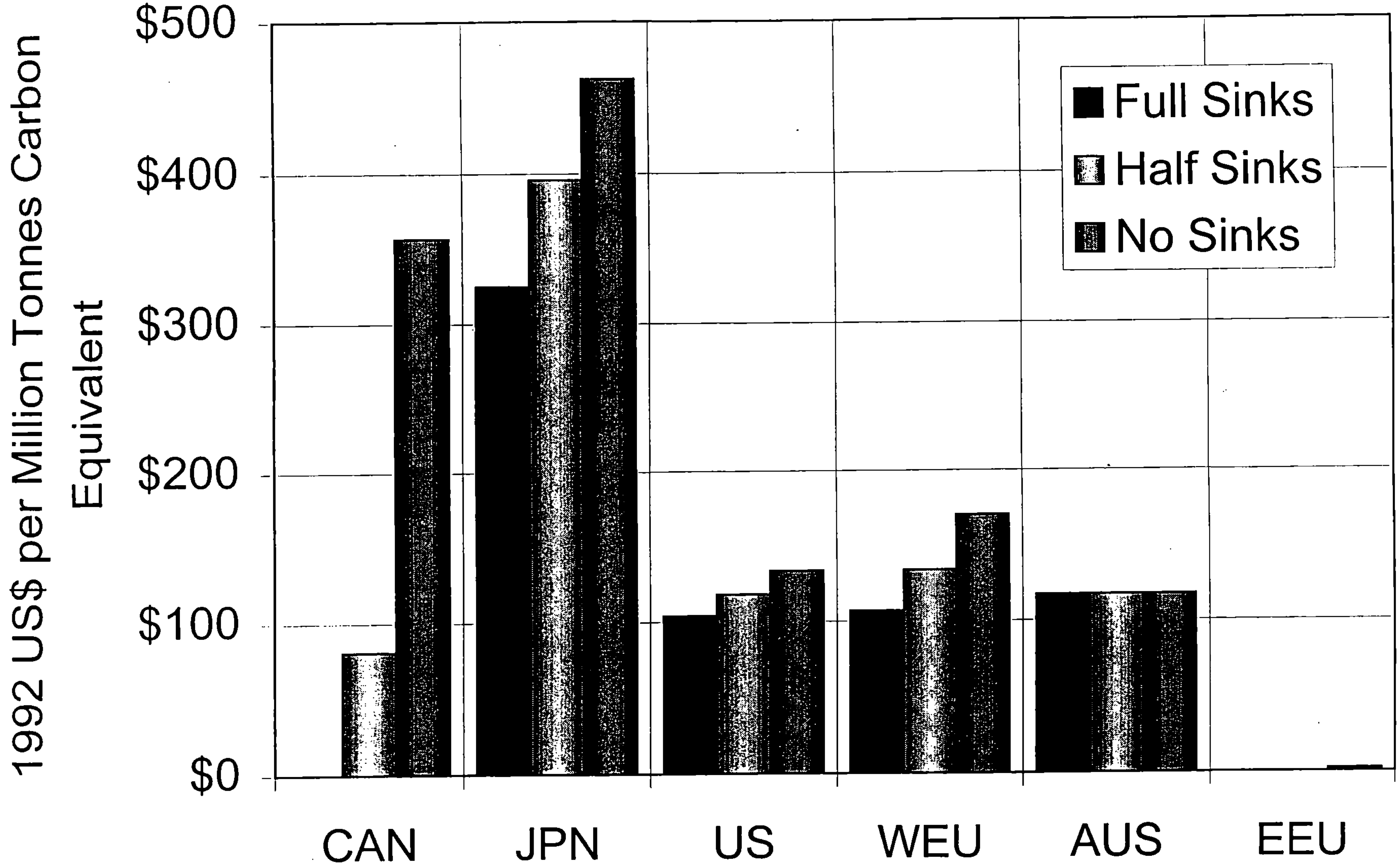
Varying the land-use change credit assumptions has significant impacts on the costs of independent compliance for some regions and on the cost of Annex I joint compliance. The application of "full sinks" credits in the Canadian case, for example, more than covers Canadian mitigation requirements in 2010 thereby bringing its cost of independent compliance to zero. The "half" and "full sinks" cases offer the Former Soviet Union and Eastern Europe even more "hot air" than in previous cases, increasing their potential benefit from permit trading. The increased "hot air" also reduces the 2010 permit price of competitive Annex I joint compliance from $61 per tonne in the "no sinks" case to $41 and $24 per tonne in the half and full sinks cases, respectively. The resulting costs to the Annex I regions for the three land-use change emissions credits assumptions are shown in Figure 15.

[Figure 15. Costs of compliance under three sink options – Independent compliance]

The economic implications of alternative treatments of land-use change emissions are large and made their treatment one of the most hotly debated issues in the Kyoto negotiations. It is interesting to note, however, that this is a short-term consideration. In the long term, land-use emissions mitigation potential is limited. Eventually all forestry programs approach steady-state carbon-to-land ratios. If a given plot of land is to continue to provide carbon uptake services, the existing biomass must be removed. Since the biomass resources can be used as a zero-cost energy form to replace fossil fuels, forestry programs ultimately mature into biomass energy programs.

DISCUSSION

In this section, we consider some of the lessons learned from the conduct of this analysis and present further discussion of issues relevant to this type of analysis. First, the method used to measure costs can significantly impact the potential burden placed on an economy by a particular policy. Second, economic costs depend a great deal on our assumptions about future carbon emissions. Third, several measures of cost are available from the SGM. Fourth, the distribution of costs among countries in a system of global permit trading is sensitive to assumptions on exchange rates as well as the initial allocation of permits. Fifth, any system of global trade in carbon permits implies potentially large transfers of wealth from one region to another. Finally, we discuss how some of our assumptions affect the results on costs.


1992 US$ per Million Tonnes Carbon Equivalent
$500
$400
$300
$200
$100
$0
Full Sinks
Half Sinks
No Sinks
CAN
JPN
US
WEU
AUS
EEU

Measurement and Reporting of Costs

As mentioned earlier in the paper, we reported direct costs in this analysis. Of ultimate interest, however, is the impact on some broader measure of economic activity (such as GDP) or on economic welfare (such as real consumption). There are many reasons why the change in GDP (or real consumption) is different than direct cost net of transfer payments. These other components of cost include the effects of pre-existing taxes, changes in terms of trade, and how tax revenues are recycled. In addition, measurement of GDP (or real consumption) depends on the choice of index and base year used to construct that index. This reflects real-world problems in constructing a quantity index for GDP when relative prices are changing.

Determining the size of the other cost components has proven difficult, and is a current topic of study for modeling groups participating in the Energy Modeling Forum. Some modeling groups, including the SGM group, have chosen to report only direct costs net of sales of emissions rights. Other groups have reported overall changes in economic welfare, but without an indication of the relative sizes of the other cost components.

If we ignore, for a moment, the wealth transfers from trading emissions rights, then it is useful to compare direct cost with the welfare loss from emissions mitigation. All of the other cost components make it possible for the direct cost of carbon mitigation to be different than the loss in economic welfare. If the welfare loss equals direct cost in each country, then all countries would gain from trading in emissions rights. If welfare losses are much greater than direct costs, there are cases where sellers of permits are made worse off by trading emissions rights in a competitive market. Other modelers have reported welfare losses much greater than direct costs, sometimes two to four times direct costs. If costs are truly this high, then the gains from trade in carbon emissions credits may be negative. That is trade, may make some **nations** (in this case nations selling carbon emissions rights) worse off rather than better off, even though the individual trading parties (in this case companies or persons) were all made better off. The implications of a substantial divergence between public and private interests in the absence of apparent market imperfections, is important and goes to the heart of the motivation for free and open trade.

Role of Reference Emissions in Shaping Marginal Mitigation Costs

All of the results in this study depend on assumptions used to create a reference emissions scenario from the present to 2020. The amount of regional emissions mitigation required to satisfy the Kyoto emissions limitation depends directly on reference case emissions. In the Annex I trading cases, carbon permit prices are particularly sensitive to reference scenarios for potential sellers of permits, especially Eastern Europe and the Former Soviet Union.

Among the Annex I countries, projecting future carbon emissions is especially uncertain for Eastern Europe and the Former Soviet Union. Of particular importance is when emissions in these regions will once again reach 1990 levels. If this point is reached before 2010, then we model EE and FSU just as any other Annex I country. If this point is reached after 2010, then emissions restrictions are not binding in EE and FSU until that point in time.

Foreign Exchange Rates

Permit prices for the global permit trading cases are very sensitive to assumptions about exchange rates. And while the United States follows a largely free market approach to exchange rates, most developing nations do not. Therefore it may be perfectly reasonable to assume that over the long-term the United States exchange rate with other free market trading partners would tend toward the purchasing power parity rate, this assumption is questionable with other partners. This is particularly true for developing countries where market exchange rates, in local currency per U.S. dollar, can be three to five times the corresponding exchange rate based on purchasing power parity. A global permit price of $100 per tonne translates, at market exchange rates, into a much higher relative price in the developing countries than in the United States.

Exchange rates based on purchasing power parity are usually used to compare income levels between countries, but market exchange rates must be used for goods actually traded between countries. This creates a potential problem for developing countries considering participation in a global permit trading program; carbon permits would be traded at market exchange rates, while GDP losses are better measured using purchasing power parity. For developing countries, losses in GDP could be greater than the value of carbon permits sold.

International Transfer Payments

We have modeled an international system of carbon permit trading that implies potentially large wealth transfers from buyers to sellers of permits. These transfers also change the pattern of other goods traded internationally. For a buyer of permits, this annual transfer of wealth is equal to the annual quantity of permits purchased times the world market price of the permits. The size of these transfers depends directly on the initial allocation of permits between countries. The initial allocation determines not only the amount of permits traded by each country, but also whether a country is a buyer or seller of permits.

For this study, the initial allocation of permits among Annex I countries is simply the emissions targets defined by the four mitigation scenarios. Non-Annex I regions were allocated permits equal to reference case emissions. These four mitigation scenarios represent only a few of the many possible ways of setting global emissions limits and allocating emissions rights among countries to meet those limits. Each allocation implies a different pattern of wealth transfers among countries.

Each region in the SGM is assigned a period-by-period balance of payments constraint. Buyers of carbon permits must, therefore, export more of other traded goods than otherwise to pay for the purchased permits. Conversely, sellers of permits use the permit revenues to increase imports of other goods.

Sensitivity of Costs to Model Assumptions

Economic costs reported by the SGM for the United States are sensitive to many of the model inputs. These include the choice of exchange rate, the inclusion of paper permits, and the method of revenue recycling.

If purchasing power parity exchange rates were used instead of market exchange rates for the developing countries, then any given world permit price would translate into a lower carbon tax in that country's local currency. For global trading cases, this would increase the global permit price needed to meet a global emissions limit, and the SGM would report higher costs for the United States.

For Eastern Europe and the Former Soviet Union, carbon permits were allocated based on their reference case, and not on 1990 emissions. If we had allocated permits based on 1990 levels, these extra 'paper credits' would create a less-stringent Annex I target. The model would then report a lower permit price for the trading cases, and a lower cost to the United States.

In this study, we assumed that all revenues from a carbon tax would be recycled as a lump sum to consumers. Another option is to use the carbon tax revenues to offset other taxes. This has the potential to reduce overall costs, since carbon tax revenues would displace other distortionary taxes.

SOME FINAL OBSERVATIONS

Economic costs are reduced with a permit-trading program that equalizes the marginal cost of carbon between countries. The least expensive emissions reductions are taken first, regardless of where they occur. The permit prices shown in Figure 12 provide a good example of the importance of maximizing the degree of participation in the Protocol. Compliance costs are low only if participation is broad, including both Annex I and non-Annex I, and essentially competitive. Failure of major energy using regions to participate in the Protocol or the failure of markets to effectively access low-cost emissions mitigation potential, raises compliance costs.

Limits on permit trading or monopolistic behavior on the part of the permit sellers, Eastern Europe and the Former Soviet Union, affect the permit prices and resulting costs to the regions of participating in an international market. The number of participants in the market and the addition of regions with a large number of permits, such as China, will also impact the market price. The ability of these permit selling regions, whomever they may be, to price discriminate across regions will largely determine where in each region's range of permit prices the final price for permits will fall.

The incorporation of the non-CO_2 gases into the Protocol, the cost of mitigating those gases, and the credits granted for land-use change emissions will directly affect the type and amount of mitigation required by each nation.

The compliance costs to the regions will depend heavily on their current energy systems and the degree to which carbon capture and sequestration, energy conservation, and fuel switching are possible within those systems.

The range of possible costs for complying with the terms of the Kyoto Protocol varies by more than an order of magnitude, depending on how the Protocol is interpreted and implemented. Under the most favorable circumstances, costs could be zero for several regions as a direct consequence of the treatment of land-use emissions. The nature and degree of international participation has a similarly large influence on the cost of compliance. For the United States emissions mitigation costs could be as low as $25 per tonne of carbon equivalent emissions if all nations were engaged in an effectively competitive carbon market. On the other hand marginal compliance costs could be more than an order of magnitude higher if compliance is limited to domestic measures and mitigation opportunities are limited.

APPENDIX A

ANNEX B TO THE KYOTO PROTOCOL
Listed by SGM Region

1	**Australia**	**108**	**AUS**
2	**New Zealand**	**100**	
3	Bulgaria	92	**EEU**
4	**Croatia**	**95**	**EEU**
5	Czech Republic	92	**EEU**
6	Finland	92	**EEU**
7	**Hungary**	**94**	**EEU**
8	**Poland**	**94**	**EEU**
9	Romania	92	**EEU**
10	Slovakia	92	**EEU**
11	Slovenia	92	**EEU**
12	Estonia	92	**FSU**
13	Latvia	92	**FSU**
14	Lithuania	92	**FSU**
15	**Russian Federation**	**100**	**FSU**
16	**Ukraine**	**100**	**FSU**
17	**Japan**	**94**	**JPN**
18	**Canada**	**94**	**CAN**
19	**The United States of America**	**93**	**US**
20	Austria	92	**WEU**
21	Belgium	92	**WEU**
22	Denmark	92	**WEU**
23	European Community	92	**WEU**
24	France	92	**WEU**
25	Germany	92	**WEU**
26	Greece	92	**WEU**
27	**Iceland**	**110**	**WEU**
28	Ireland	92	**WEU**
29	Italy	92	**WEU**
30	Liechtenstein	92	**WEU**
31	Luxembourg	92	**WEU**
32	Monaco	92	**WEU**
33	Netherlands	92	**WEU**
34	**Norway**	**101**	**WEU**
35	Portugal	92	**WEU**
36	Spain	92	**WEU**
37	Sweden	92	**WEU**
38	Switzerland	92	**WEU**
39	United Kingdom of Great Britain and Northern Ireland	92	**WEU**

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Working Paper

Return to 1990: The Cost of Mitigating United States Carbon Emissions in the Post-2000 Period

JA Edmonds
SH Kim
CN MacCracken
RD Sands
MA Wise

October 1997

Prepared for
U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

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Return to 1990
The Cost of Mitigating United States Carbon Emissions in the Post-2000 Period

James A. Edmonds
Son H. Kim
Christopher N. MacCracken
Ronald D. Sands
Marshall A. Wise

Pacific Northwest National Laboratory

More than 160 nations have signed the Framework Convention on Climate Change (FCCC). That agreement required Annex I nations, the developed nations of the world plus economies of the Former Soviet Union and Eastern Europe,[1] to undertake measures to return emissions to 1990 levels or below in the year 2000. The parties to the FCCC met in Berlin in the Spring of 1995 and determined that additional measures were required to implement the ultimate objective of the FCCC, "*to stabilize the concentration of greenhouse gases in the atmosphere at a level which would prevent dangerous anthropogenic interference with the climate system.*"

Subsequent to the Berlin discussions, nations of the world have begun to consider measures that would set quantifiable emissions limitation requirements in the post-2000 period for Annex I nations.[2] A variety of measures have been considered. The purpose of this paper is to explore the economic consequences of efficient policy instruments—carbon taxes or tradable emissions permits—which might be employed to achieve a variety of targets in the post-2000 time frame.

We begin by describing our general approach and the variety of policy runs to be considered. We then review some of the necessary assumptions for this exercise, as well as the structure and calibration of the Second Generation Model (SGM). Finally, we discuss the results of our analysis, including time paths of emissions and measures of cost.

---

[1] Australia, Austria, Belarus, Belgium, Bulgaria, Canada, Czechoslovakia, Denmark, European Economic Community, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Latvia, Lithuania, Luxembourg, Netherlands, New Zealand, Norway, Poland, Portugal, Romania, Russian Federation, Spain, Sweden, Switzerland, Turkey, Ukraine, United Kingdom of Great Britain and Northern Ireland, and the United States.

[2] In the United States, efforts were undertaken by the Interagency Analytical Team, and results were summarized in United States Government (1997). The Second Generation Modeling team was one of three modeling teams which participated in the evaluation of potential emission mitigation measures under discussion.

EMISSIONS MITIGATION SCENARIOS

Four scenarios were constructed that reduce carbon emissions in Annex I countries by 2010. The SGM was used to simulate the impact of these scenarios on the United States economy. In each scenario, emissions are reduced linearly from 2000 to the emissions target in 2010. Since the SGM operates with five-year time steps, emissions in the year 2000 are at reference case levels, and emissions targets in 2005 are half-way between year 2000 emissions and the target emissions level required in year 2010. Figure 1 shows United States emissions paths for the four scenarios as well as reference emissions.

M1990	Emissions from Annex I regions must be no greater than 1990 emissions levels beginning in the year 2010.
M1990+10%	Emissions from Annex I regions must be no greater than 10% above 1990 emissions levels, beginning in the year 2010.
M1990-10%	Emissions from Annex I regions must be no greater than 10% below 1990 emissions levels, beginning in the year 2010.
M1995	Emissions from Annex I regions must be no greater than 1995 emissions levels beginning in the year 2010.

[Figure 1. Carbon Emissions Scenarios for the United States]

These mitigation policies were run under three emissions trading regimes: independent emissions mitigation, Annex I joint mitigation, and Annex I mitigation with global permit trading. In the independent emissions mitigation case, each Annex I region must individually reach the stated emissions target without any trading of permits across regions. The Annex I joint mitigation case allows Annex I regions to trade permits amongst themselves so long as the total constraint is met in each time period. The global permit trading case allows permit trading across all regions, including those not in Annex I. The Annex I joint mitigation and global permit trading regimes result in a single Annex I or global permit price common to all regions in the market for carbon permits.

In none of the above scenarios and trading combinations are non-Annex I regions forced to constrain their emissions. No mitigation targets or emissions trajectories are imposed on those regions. Under the global permit trading regime, non-Annex I regions participate in the market for carbon permits only when it is to their economic benefit to do so. These regions are allocated permits equal to their projected baseline emissions, so they are only required to reduce their emissions by an amount equal to the number of permits they wish to sell.

Eastern Europe and Former Soviet Union Permit Allocations

Eastern Europe and the Former Soviet Union (EEFSU) present a special case because carbon emissions are currently below the benchmark year of 1990. Two approaches to permit allocations for EEFSU regions have been discussed in recent months. The first allocates permits based on the stated policy scenario (e.g., M1990 allocates permits based on 1990 emissions level) so that permits are allocated to EEFSU in the same way as they are to other Annex I regions. Because of the decline in emissions in those regions from 1990 to 1995, however, this approach ... 'paper credits' equal to the difference between the lower post-1990 emissions ... (i.e., 1990) emissions being granted to EEFSU. For example, the ... in 2010 is 836 TgC, significantly lower than its 1990 emissions of 1050 TgC. If granted ... equal to its 1990 emissions, the FSU would have 214 TgC ... projected emissions, giving the region 214 TgC worth of permits ... emissions reductions of its own.

The second approach to allocating permits to EEFSU is to grant permits equal to ... emissions in each period until the projected path is constrained by the policy. ... in the M1990-10% case, the FSU would be granted permits equal to its projected baseline ... because emissions in the policy years never recover to 1990 levels.

For the purpose of this exercise, we chose to use the latter approach in ... Eastern Europe and the Former Soviet Union. This baseline allocation ... stated Annex I emissions targets are achieved in both the independent mitigation ... trading scenarios.

APPROACH

The SGM is a computable general equilibrium economic model that projects ... energy consumption, and carbon emissions for twelve world regions, including the ... The twelve SGM regions listed in Table 1 provide the necessary ... system of global carbon permit trading. We also simulate a carbon ... the Annex I countries only, which are represented by seven of the twelve ... strategy has been to continually expand the number of regions by breaking ... of World region. The Rest of World includes Latin America, Africa, and other ...

Table 1. Regions in the SGM

Annex I	[illegible]
United States	[illegible]
Canada	[illegible]
Western Europe	[illegible]
Japan	South [illegible]
Australia	Rest of World
Former Soviet Union	
Eastern Europe	

While carbon emissions in most regions are anticipated to increase ... the Eastern Europe and Former Soviet Union Regions. Emissions in these regions have ... since 1990.

Each of the four emissions mitigation scenarios defines a set of emissions ... for the Annex I regions. Carbon taxes are used to constrain emissions for the cases of independent ... mitigation, Annex I joint mitigation, and Annex I mitigation with global ... rights.

In the independent case, each Annex I region meets its own emissions targets independently. A time series of carbon taxes is determined for each region to reduce emissions to be equal to its emissions rights.

With Annex I joint mitigation, a common carbon tax is applied to all Annex I regions to meet the overall Annex I emissions target. However, regions that emit more carbon than their emissions rights must pay the other Annex I regions an amount equal to the difference in emissions valued at the common carbon tax.

In the global trading case, emissions are reduced from the global reference case by the same amount as the difference between Annex I reference emissions and Annex I emissions rights. The SGM is used to determine a global carbon tax just large enough to meet the global emissions target. This global carbon tax turns out to be lower than the carbon taxes required for independent mitigation by Annex I countries. Therefore, Annex I countries emit more carbon than in the independent case, but still less than in the reference case. Annex I countries must purchase rights to emit carbon from the non-Annex I countries. The non-Annex I regions must reduce their own emissions levels to sell those permits to the Annex I regions.

In this paper, we summarize the following results for the United States for each scenario: time series of carbon emissions; carbon taxes required for emissions mitigation; and measures of the cost of mitigation.

MODEL OVERVIEW

The SGM is designed specifically to address issues associated with global change. The model is designed to perform the following types of analysis:

1. Provide estimates of future time paths of environmentally important emissions associated with economic activity.

2. Provide estimates of the economic cost of actions to reduce greenhouse gas emissions.

Sectors

The SGM has nine producing sectors and twelve inputs to production. The inputs are labor, land, capital, and the nine produced goods. Economic detail is maintained in the energy supply and transformation sectors, but collapsed elsewhere into one large "everything else" sector. Price stability is maintained by keeping the price for goods produced by the "everything else" sector equal to 1.0 during all time periods.

Five different fuels are used for producing electricity, resulting in five subsectors for the electric generating sector. A separate economic production function, of the constant elasticity of substitution (CES) functional form, is used for each sector or subsector. Capital investment decisions depend on an assumed lifetime of capital for each sector or subsector. Capital lifetimes range from 15 years in the oil, gas, and coal production sectors to 70 years for hydroelectric power. The relative size of each production sector and subsector is shown in Table 2.

Table 2. Producing Sectors in the SGM

	Producing Sector	Gross Output in 1985 (millions of 1985 $)	
1	Agriculture	468,618	
2	Everything Else	5,086,486	
3	Oil Production	64,171	
4	Gas Production	45,804	
5	Coal Production	20,006	
6	Uranium Processing	2,195	
7	Electricity Generation	165,800	
	a. oil		10,959
	b. gas		34,152
	c. coal		85,930
	d. nuclear		21,370
	e. hydro		13,389
8	Petroleum Refining	145,015	
9	Gas Transmission and Distribution	105,330	

Market Clearing

In the SGM, markets are said to *clear*. In other words, the SGM solves for the set of prices for all markets (or sectors) in the modeled economy so that demands and supplies of each market are in equilibrium. The set of prices in which the equilibrium holds is called the *market-clearing* price set. In an equilibrium model like the SGM, markets are linked to other markets through the market-clearing process. For example, a change in the demand for coal will have an effect on not just the price of coal, but also the prices of oil, gas, and, at least indirectly, the prices of all markets in the economy.

Carbon permit prices and taxes are also solved by the SGM as part of the market equilibrium. Specifically, the SGM finds the carbon price such that, given that market-clearing equilibrium prices hold in the rest of the markets, the amount of carbon emitted is just equal to the carbon constraint of the region or group of regions under a carbon emissions limitation constraint.

Carbon Taxes and Revenue Recycling

The SGM uses a carbon tax within each region to provide an economic incentive for the economy to substitute away from carbon. Revenues obtained from the carbon tax can be very large and it makes a difference, in terms of final economic cost, how the revenues are recycled. For this exercise, we assume that all carbon tax revenues are recycled back to consumers through a lump-sum government transfer.

For the cases where emissions rights are traded between countries, each SGM region is allocated an initial amount of carbon emissions permits. Carbon permits can then be traded between countries at a price that clears the global market in these permits.

Modes of Operation

All of the SGM regions were initially developed as single-region models with a base year of 1985. Each regional model operates in five-year time steps through either 2030, 2050, or 2100. Often, the models were developed in collaboration with experts from that country. It is possible to run all of the regions simultaneously in a global model with international trade. The three modes of operation for the SGM are:

1. Single Region
2. Global with Partial Market Clearing
3. Global with Full Market Clearing

Single-region operation. For each SGM region, all produced goods are classified as being tradable, nontradable, or traded at a fixed quantity. When SGM regions are operated independently, a fixed world price is assumed for each tradable good; regions may import or export as much of that good as desired at that fixed world price, subject to an overall balance of payments constraint. For all nontradable goods, the quantity of trade is fixed in advance. The following assignments are used when the United States model is operated independently:

Numeraire Sector:	everything else (price always equals 1)
Fixed World Price:	crude oil
Fixed Trade Quantities:	agriculture, coal, nuclear fuel, refined petroleum, electricity
Nontradables:	distributed gas, land, labor

Since only relative prices matter, we are allowed to fix the price of either one produced good or one primary factor of production. For each region, the large 'everything else' sector is the numeraire, with its price fixed at 1 for all time periods. This 'everything else' good is a tradable good for all regions. An exogenous balance of payments constraint is specified in advance for each region. Most regions are assumed to move linearly from a historical trade balance in 1985 to balanced trade by 2005.

Given a trial set of prices, the SGM computes supply and demand for all producing sectors and primary factors of production. Markets for the nontradables and goods traded at fixed quantities are brought into equilibrium by searching for a set of prices that equate supply and demand. Prices are adjusted until supply and demand are within 0.01% of each other.

Global model with partial market clearing. The global version of the SGM is used when there is at least one market that must clear globally. For the scenarios described in this paper, that market is tradable carbon emission permits. The model searches for a global carbon tax, which can be interpreted as a world carbon permit price, that clears the market for permits.

Each region is initially allocated a number of carbon permits and may trade those permits at the world permit price. Some regions will be sellers of permits and some will be buyers. After trading permits, all regions must hold permits equal to the domestic level of carbon emissions.

All regions are still subject to a period by period balance of payments constraint. The model does not allow borrowing to pay for carbon emissions permits. Imports of permits must be paid for with exports of some other good.

Global model with full market clearing. There are no longer any markets with a fixed world price. A set of world prices is found that clears all world markets. Also, world markets can be created for goods that were traded in fixed quantities in the single-region model.

All of the scenarios described in this paper were run in the second mode, global with partial market clearing. This mode was chosen for two reasons. The first is that we were asked to assume a fixed time path of world oil prices for SGM model runs that were completed for the United States Government during the spring of 1997. This meant that the world oil market would not be allowed to clear in the model. The second reason is that model results are often easier to interpret when some variables in the model remain fixed over time. Although we are missing any feedback from reduced world oil consumption to lower world oil prices, the magnitude of this feedback is highly uncertain and difficult to model.

Data Requirements

Three types of data are used to construct and calibrate each region of the SGM.

1. Economic and Demographic Data
2. Energy Balances
3. Technology Descriptions

Economic data include input-output tables and supplemental information from the national income accounts. Population projections were obtained from the World Bank. Energy balance tables were obtained either from the International Energy Agency or from government agencies within a region.

Input-output tables describe, in value terms, the flow of goods between industries and consumers in an economy. However, a model concerned with quantities of carbon emissions must also be concerned with quantities of energy. An input-output table, by itself, is not sufficient to determine the quantities of oil, gas, coal, electricity, and refined petroleum that are produced and consumed. Supplemental information on energy quantities is required to map currency units from an input-output table to energy units needed to calculate levels of carbon emissions. We combine economic input-output tables with energy balance tables to create a hybrid input-output table with units of joules for energy products and real dollars for all other products. Miller and Blair (1985) provide a general description of, and the motivation for using, hybrid input-output tables.

Individual energy technologies are characterized by the annualized cost of providing an energy service. Data needed to determine the annualized cost include capital cost, equipment lifetime, annual fuel requirements, the interest rate, and other annual maintenance and operating costs.

REFERENCE CASE AND CALIBRATION

The cost of reducing greenhouse gas emissions is very dependent on the reference case. The greater the level of reference case emissions, the higher the cost of returning to 1990 emissions. Therefore, much effort is expended on creating an acceptable reference case before running any of the mitigation scenarios.

The SGM operates in five-year time steps from 1985 through 2050; results for this study are reported for 1990 through 2020. The United States reference case was closely calibrated to the Annual Energy Outlook 1997 (AEO97). Since AEO97 projects only up to the year 2015, projections beyond 2015 are SGM model results and are not calibrated to any other established projections. Projections of carbon emissions, population, GDP, primary energy consumption, and electricity generation for the United States are described below.

For the other global regions, economic and primary energy consumption growth rates were roughly calibrated to regional projections from the World Energy Outlook 1996 (WEO96). For the Former Soviet Union region, projected primary energy consumption levels were adjusted down from the WEO96 projection. Population projections for these regions were based on the World Population Projections 1994-1995, published by the World Bank. In addition to the exogenously set population levels, the international crude oil price trajectory from the AEO97 was used as an exogenously set price. Prices for all other fuels and goods in the model were determined endogenously.

The general calibration procedure is to first match GDP growth by adjusting parameters that control total factor productivity in the 'everything else' sector. Then energy consumption by primary fuel is calibrated by adjusting input-specific technical change parameters. Carbon emissions are derived directly from primary energy consumption by applying fuel-specific emission factors.

Carbon Emissions

In 1990, total carbon dioxide emissions from the combustion of fossil fuels in the United States were 1,350 million metric tons of carbon. Model results show that total carbon dioxide emissions continue to rise as fossil fuel consumption increases and emissions reach 1,871 million metric ton by 2020. This amounts to a 39 percent increase in total emission and an emissions growth rate of 1 percent per year. Reference case carbon emissions were shown earlier in Figure 1.

Gross Domestic Product

The two most important determinants of GDP are population growth and rates of change in productivity. Total population levels for the United States were taken directly from AEO97. United States population grows from 250 million in 1990 to 323 million in 2020. This represents an annual population growth rate of 0.85 percent per year.

GDP for the United States was matched to AEO97 projections by changing the total factor productivity parameter for the 'everything else' sector. Beginning with the 1990 GDP of 6.1 trillion dollars, the economy grows at 2 percent annually to reach 10.6 trillion dollars by 2020.

Primary Energy Consumption

Total primary energy consumption from 1990 to 2015 was calibrated to be within 2 percent of projections from AEO97. Primary energy consumption by fuel is shown for the United States in Figure 2. Energy consumption rises from 86 EJ in 1990 to 116 EJ in 2015. This increase represents an annual growth rate of 1 percent. The energy consumption growth rate decreases with time and in 2020, the total consumption is 119 EJ and the annual growth rate is 0.5 percent.

Crude oil is the major source of primary energy in the early years; however, natural gas competes with crude oil as the leading source of fossil fuel by 2020. Coal is the third largest source of primary energy and its consumption grows steadily at slightly less than 1 percent per year. Nuclear energy's contribution to primary energy consumption declines, while energy from renewable sources increases with time.

[Figure 2. Primary Energy Consumption -- United States Reference Case]

Primary energy consumption does not grow as fast as GDP, which implies that the energy-GDP is ration is falling over time. Figure 3 shows the energy-GDP ratio generated by the SGM for the United States.

[Figure 3. Energy-GDP Ratio -- United States Reference Case]]

Electricity Generation

Projections of electricity generation are similar to that of the AEO97. SGM total electricity generation results are higher than the AEO97 projections by approximately 10 percent. Electricity generation from natural gas is the reason for the higher result. Total electricity generated in 1990 is nearly 11 EJ, which grows at 1.5 percent per year and expands to 17 EJ by 2020. The major source of electricity is from the combustion of coal; however, electricity generation from natural gas plays a significantly larger role with time. In 1990, electricity generation from coal contributed to 53 percent share of the total generation, while that from natural gas combustion contributed to 17 percent of the total. By 2020, the shares of electricity generation from coal and natural gas are closer. Electricity generation from coal and natural gas comprise 44 and 34 percent share of the total respectively. Highly efficient and low cost natural gas combined cycle power plants incorporated into the SGM contribute to the growth of natural gas as the fuel for electricity generation. Nuclear power's contribution to the overall demand for electricity decline with time as existing power plants are retired and no new additional plants are constructed. Renewable energy sources for electricity generation include hydroelectricity, solar photovoltaics and others. Generation of electricity from renewable sources increases slightly from 1990 to 2020; however, renewable energy's share of total electricity remains below 10 percent of the total.

COST OF EMISSIONS MITIGATION

Although this exercise did employ the 12-region version of the SGM, discussion of results in this paper will focus on the United States. The SGM provides output on regional GDP and its components and a detailed description of the composition of energy supply. In this analysis, we will focus on the broad economic impacts on the economy. Specifically, we will discuss the permit prices required to meet the various mitigation requirements and the costs to the United States economy of undertaking such policies. We will also discuss the impacts of the domestic carbon taxes on primary energy consumption.

Permit Prices

Table 3 shows the permit prices by trading regime required for the United States to meet its emissions targets under the four mitigation scenarios. Permit prices in the United States must reach $108 per metric ton of carbon to reduce United States emissions to 1990 levels in 2010. This price increases significantly with the tighter constraint imposed under the M1990-10% case. Permit prices in the M1995 and M1990+10% scenarios are very similar as only 5 TgC separate the constraints in the two cases.

Table 3. United States Carbon Taxes Required to Meet Policy Goal Eastern Europe & FSU Allocated Reference Case Permits (1992 US$ per Metric Ton of Carbon)

	Independent Mitigation		Annex I Joint Mitigation		Annex I Mitigation with Global Trade	
	2010	2020	2010	2020	2010	2020
M1990	108	170	72	87	26	27
M1990+10%	60	110	42	58	16	18
M1990–10%	173	260	109	122	38	36
M1995	61	112	70	106	26	32

Permit prices fall as more regions are included in the market for carbon permits. In the independent emissions mitigation case, carbon emitters in the United States may undertake emissions mitigation options available only within the United States. In the Annex I joint and global permit cases, however, regions are included that have mitigation options with significantly lower costs, thereby lowering the marginal cost to the carbon permit market of meeting the desired emissions targets. As we will discuss, this 'where' flexibility in meeting emissions targets has a significant impact on costs as well as permit prices.

Permit prices tend to increase over time as it becomes more expensive to reduce emissions to the desired goal. Increasing population in the United States, and the economic growth that accompanies it, put upward pressure on emissions that, in turn, forces larger shifts away from inexpensive coal toward more expensive natural gas and renewable energy sources. The availability of relatively inexpensive abatement options in the developing world allows the permit price to remain relatively constant over time in those cases.

As the permit prices decrease across trading regimes, the United States purchases more and more permits from abroad, thereby enabling it to emit more than its allocated permits alone would allow. Figure 4 shows United States emissions for the M1990 case across the three trading regimes. Under the independent emissions mitigation regime, the United States is limited to emitting only what it is allocated under the scenario, its 1990 emissions level. With Annex I trading, however, the United States purchases 209 TgC worth of permits in 2010 and 244 TgC in 2020. The purchases increase to 316 TgC and 436 TgC in 2010 and 2020, respectively, under the global trading regime. This 'where' flexibility reduces the amount by which a permit-buying region must reduce its emissions and, therefore, reduces the cost to the region.

[Figure 4. United States Carbon Emissions – M1990 Cases]

Primary Energy Consumption

Emissions mitigation is achieved through reduction in total primary energy consumption and fuel substitution in the electricity sector. The domestic carbon tax of $108 in 2010 in the M1990 case results in a reduction of total primary energy consumption by 16 percent relative to the reference case. Primary energy consumption of coal drops by 57 percent while consumption of crude oil drops by 12 percent. Consumption of natural gas increases by 1 percent due to fuel switching. For reductions in primary energy consumption by fuel, refer to Figure 5.

[Figure 5. United States Primary Energy Consumption in 2010]

Fuel substitution in the electricity sector results in the share of electricity generated from coal dropping from 45 in the reference case to 20 percent in the M1990 case. The reduction in electricity generation from coal is compensated for by increased generation from natural gas. The share of electricity generation from natural gas increases from 29 percent in the reference case to 51 percent M1990 case.

Cost Calculations

A very convenient way to characterize the response of any SGM region to a carbon tax is by constructing a marginal cost of carbon curve. Figure 6 is a scatter plot of various carbon taxes applied to the United States economy, and the corresponding reduction in carbon emissions. Data points plotted in Figure 6 are from the four independent mitigation scenarios for the United States. Note that a positive tax is required to achieve any reductions in carbon emissions.

[Figure 6. Marginal Cost of Carbon]

The marginal cost curve is used to calculate one measure of cost that we will call the *direct cost*. For any level of carbon emissions mitigation, the direct cost is defined as the area under the marginal cost curve up to that amount of mitigation. The first units of emissions reductions are very inexpensive, successive units become more and more expensive. Figure 7 shows the shows the size of these direct costs for the United States for the four independent mitigation scenarios. Direct costs are shown at five-year intervals through 2020 as a percentage of GDP. These costs are plotted as negative numbers in Figure 7. As expected, the M1990-10% scenario shows the greatest costs.

[Figure 7. Cost of Emissions Mitigation – No Trading]

Figure 8 focuses on the M1990 case and shows how costs to the United Sates are reduced with trade in emissions permits between countries. The 'independent' cost line shown in Figure 8 is the same as the M1990 cost line in Figure 7. In 2010, costs are reduced somewhat with Annex I trading and reduced by about one-half with global trading. In later years, the flexibility in where emissions reductions are undertaken impacts mitigation costs even more significantly.

[Figure 8. Illustration of 'Where' Flexibility – Costs for M1990 Cases]

Cost calculations for the emissions trading cases are different than in the independent case. Costs for the trading case take into account the value of permits traded. For a seller of permits, such as the United States, net cost includes the direct cost plus expenditures on carbon permits. A breakdown of these two cost components is shown for the M1990 Annex I trading case in Figure 9. Direct cost is roughly half of the net cost. The remaining cost, the difference between the 'direct cost' and 'net cost' lines in Figure 9, is the value of emissions permits that would be purchased from other Annex I countries.

[Figure 9. Cost Breakdown – M1990 Annex I Trading Case]

DISCUSSION

Several important issues have arisen during the development and operation of the SGM. In this section, we summarize some of the insights gained from our modeling activities. First, economic costs depend a great deal on our assumptions about future carbon emissions. Second, several measures of cost are available from the SGM. Third, the distribution of costs among countries in a system of global permit trading is sensitive to assumptions on exchange rates as well as the initial allocation of permits. Fourth, any system of global trade in carbon permits implies potentially large transfers of wealth from developed to developing nations. Finally, we discuss how some of our assumptions affect the results on costs.

Role of Reference Emissions in Shaping Marginal Mitigation Costs

All of the results in this study depend on assumptions used to create a reference emissions scenario from the present to 2020. The amount of mitigation required to return to 1990 levels depends directly on reference case emissions for each region. In the Annex I trading cases, carbon permit prices are particularly sensitive to reference scenarios for potential sellers of permits, especially Eastern Europe and the Former Soviet Union.

Among the Annex I countries, projecting future carbon emissions is especially uncertain for Eastern Europe and the Former Soviet Union. Of particular importance is when emissions in these regions will once again reach 1990 levels. If this point is reached before 2010, then we model EE and FSU just as any other Annex I country. If this point is reached after 2010, then emissions restrictions are not binding in EE and FSU until that point in time.

Measuring and Reporting Costs

At least two measures of cost are available from the SGM and from other models as well. The first measure, which we call the *direct cost*, can be thought of as either a deadweight loss or the integral under the marginal cost curve for carbon. Using either approach, direct cost is approximately equal to one-half of the carbon tax (or permit price) times the reduction in carbon emissions. For the permit trading cases, direct costs are then adjusted by the value of transfer payments required to purchase or sell permits. This measure of net cost is simple to construct and is comparable across models.

Of ultimate interest, however, is the net impact on some broader measure of economic activity (such as GDP) or on economic welfare (such as real consumption). There are many reasons why the change in GDP (or real consumption) is different than direct cost net of transfer payments. These other components of cost include the effects of pre-existing distortionary taxes, changes in terms of trade, and how tax revenues are recycled. In addition, measurement of GDP (or real consumption) depends on the choice of index and base year used to construct that index. This reflects real world problems in constructing a quantity index for GDP when relative prices are changing.

Foreign Exchange Rates

Permit prices for the global permit trading cases are very sensitive to assumptions on exchange rates. This is particularly true for developing countries where market exchange rates, in local currency per U.S. dollar, are three to five times the corresponding exchange rate based on purchasing power parity. A global permit price of $100 per metric ton translates, at market exchange rates, into a much higher relative price in the developing countries than in the United States.

Exchange rates based on purchasing power parity are usually used to compare income levels between countries, but market exchange rates must be used for goods actually traded between countries. This creates a potential problem for developing countries considering participation in a global permit trading program; carbon permits would be traded at market exchange rates, while GDP losses are better measured using purchasing power parity. For developing countries, losses in GDP could be greater than the value of carbon permits sold.

International Transfer Payments

Transfer payments required by some of the permit trading scenarios can become quite large. From the point of view of a buyer of permits, the amount spent on permits should be more than offset by the avoided cost of further emissions reductions.

Transfer payments of this size will affect the pattern of other goods traded internationally. Our model does not allow regions to borrow between time periods; trade must balance during each time period. Buyers of permits must export more of other goods to pay for the permits and adhere to a balance of payments constraint.

Sensitivity of Costs to Model Assumptions

Economic costs reported by the SGM for the United States are sensitive to many of the model inputs. These include the choice of exchange rate, the inclusion of paper permits, and the method of revenue recycling.

If purchasing power parity exchange rates were used instead of market exchange rates for the developing countries, then any given world permit price would translate into a lower carbon tax in that country's local currency. For global trading cases, this would increase the global permit price needed to meet a global emissions limit, and the SGM would report higher costs for the United States.

For regions with emissions below 1990 levels, carbon permits were allocated based on their reference case, and not on 1990 emissions. If we had allocated permits based on 1990 levels, these extra 'paper permits' would create a less-stringent Annex I target. The model would then report a lower permit price for the trading cases, and a lower cost to the United States.

In this study, we assumed that all revenues from a carbon tax would be recycled as a lump sum to consumers. Another option is to use the carbon tax revenues to offset other taxes. This has the potential to reduce overall costs, since carbon tax revenues would displace other distortionary taxes.

KEY OBSERVATIONS

Economic costs are reduced with a permit-trading program that equalizes the marginal cost of carbon between countries. The least expensive emissions reductions are taken first, regardless of where they occur. Costs shown in Figure 8 provide a good example of the importance of this 'where' flexibility.

For the four mitigation scenarios in this study, economic costs to the United States remain below 1% of GDP through at least the year 2020. This was the case even in the scenarios where the United States met its mitigation targets without international trading of carbon permits.

Each region in the SGM can be characterized by a marginal cost of carbon curve, as was shown in Figure 6. This shows the approximate carbon tax required for any given level of carbon emissions reduction. For the amount of emissions reductions needed in 2010 to return to 1990 levels, a carbon tax of $108 per metric ton of carbon is required.

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Figure 1. Carbon Dioxide Emissions Scenarios for the United States

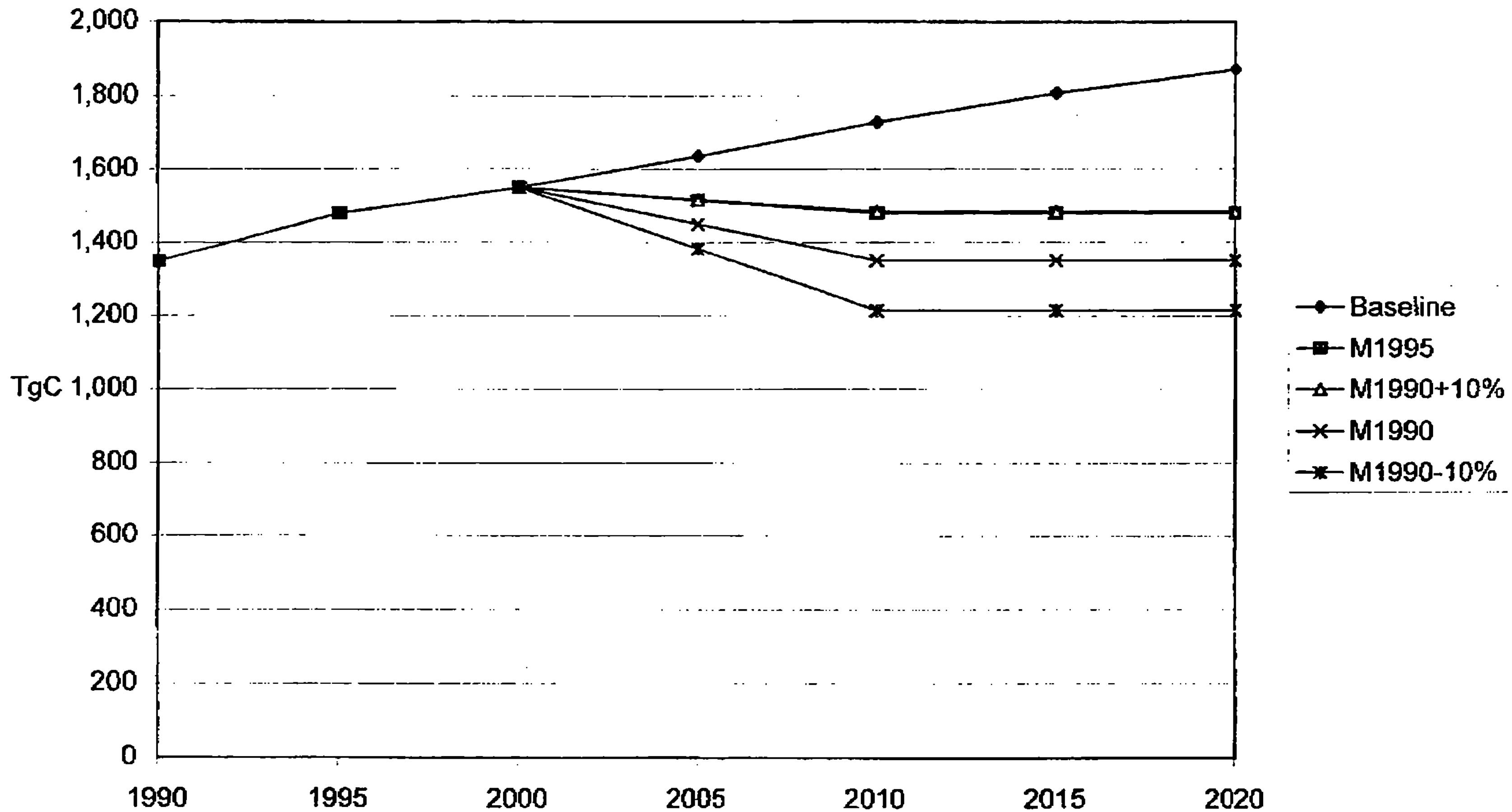

Figure 2. Primary Energy Consumption
United States Reference Case

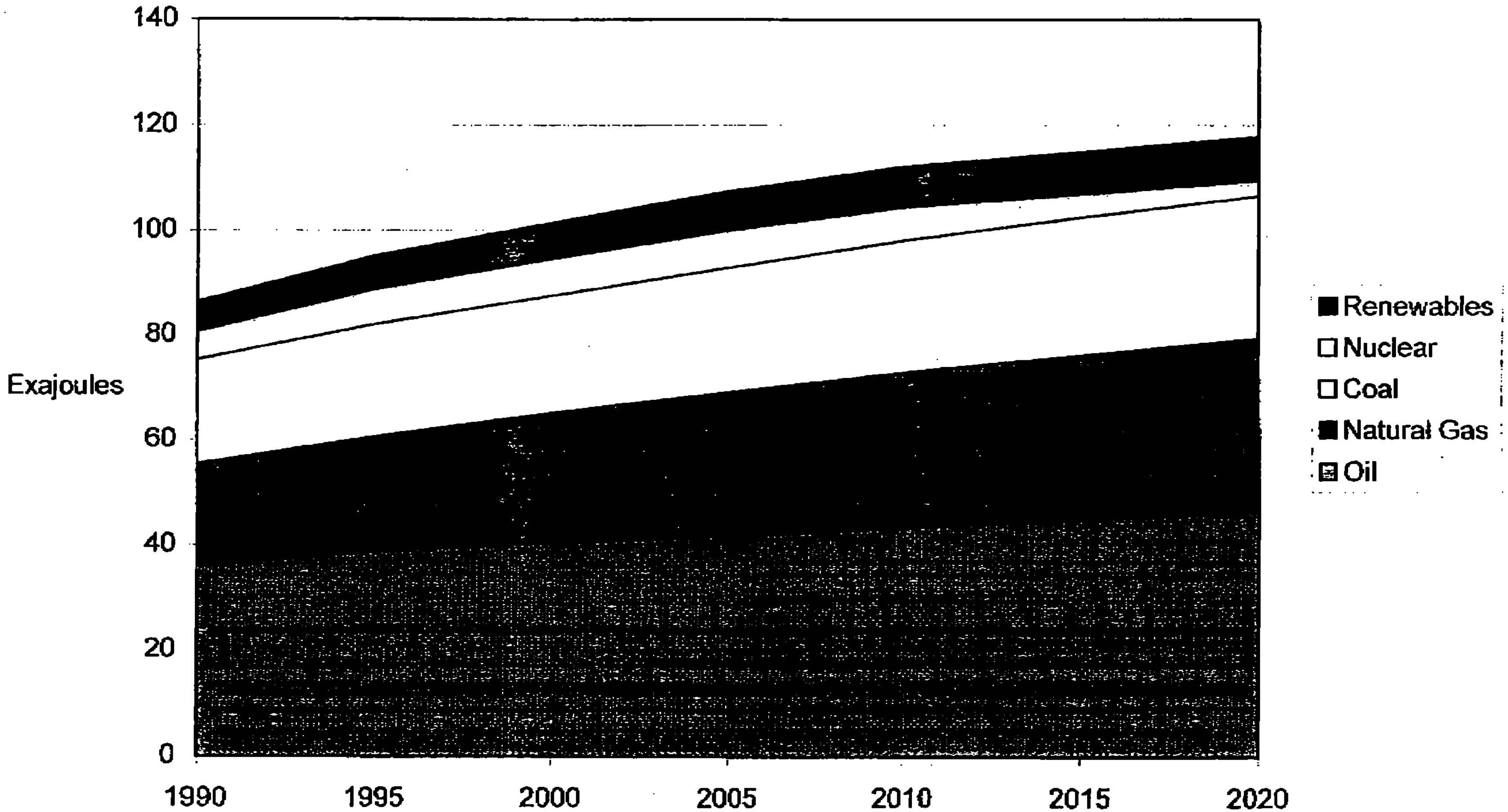

Figure 3. Energy-GDP Ratio
United States Reference Case

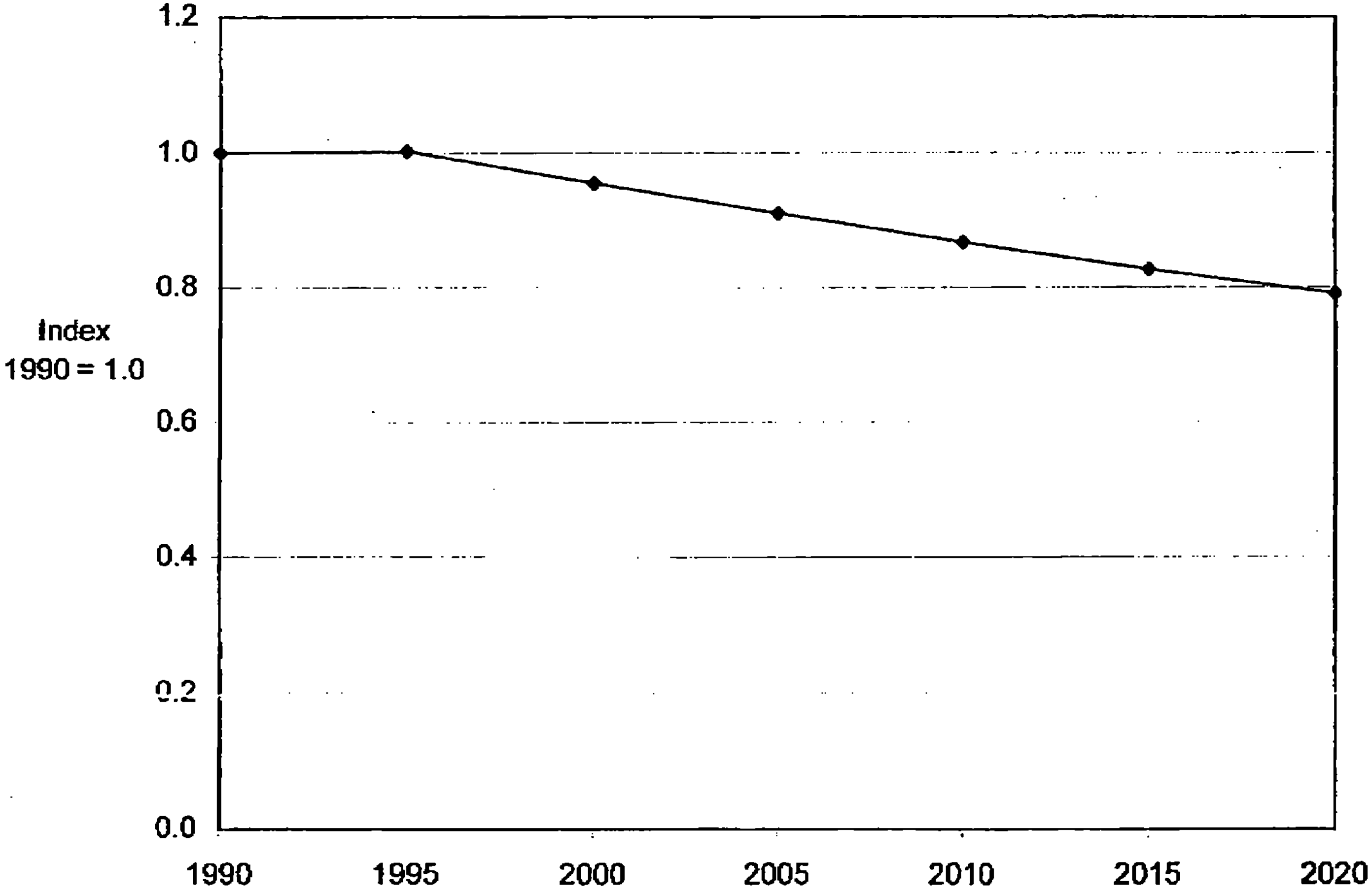

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Figure 4. United States Carbon Emissions
M1990 Cases

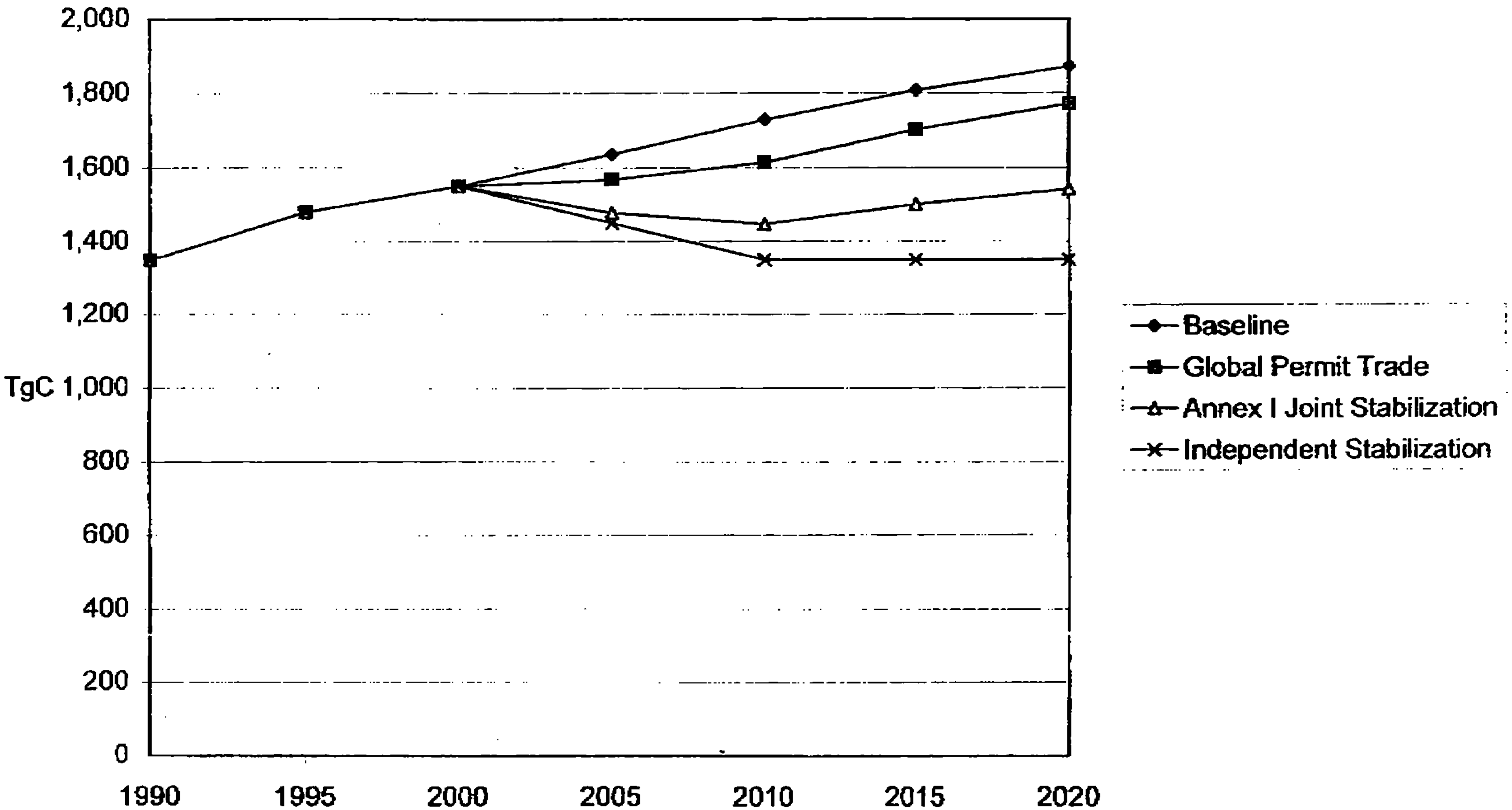


Figure 5. US Primary Energy Consumption in 2010

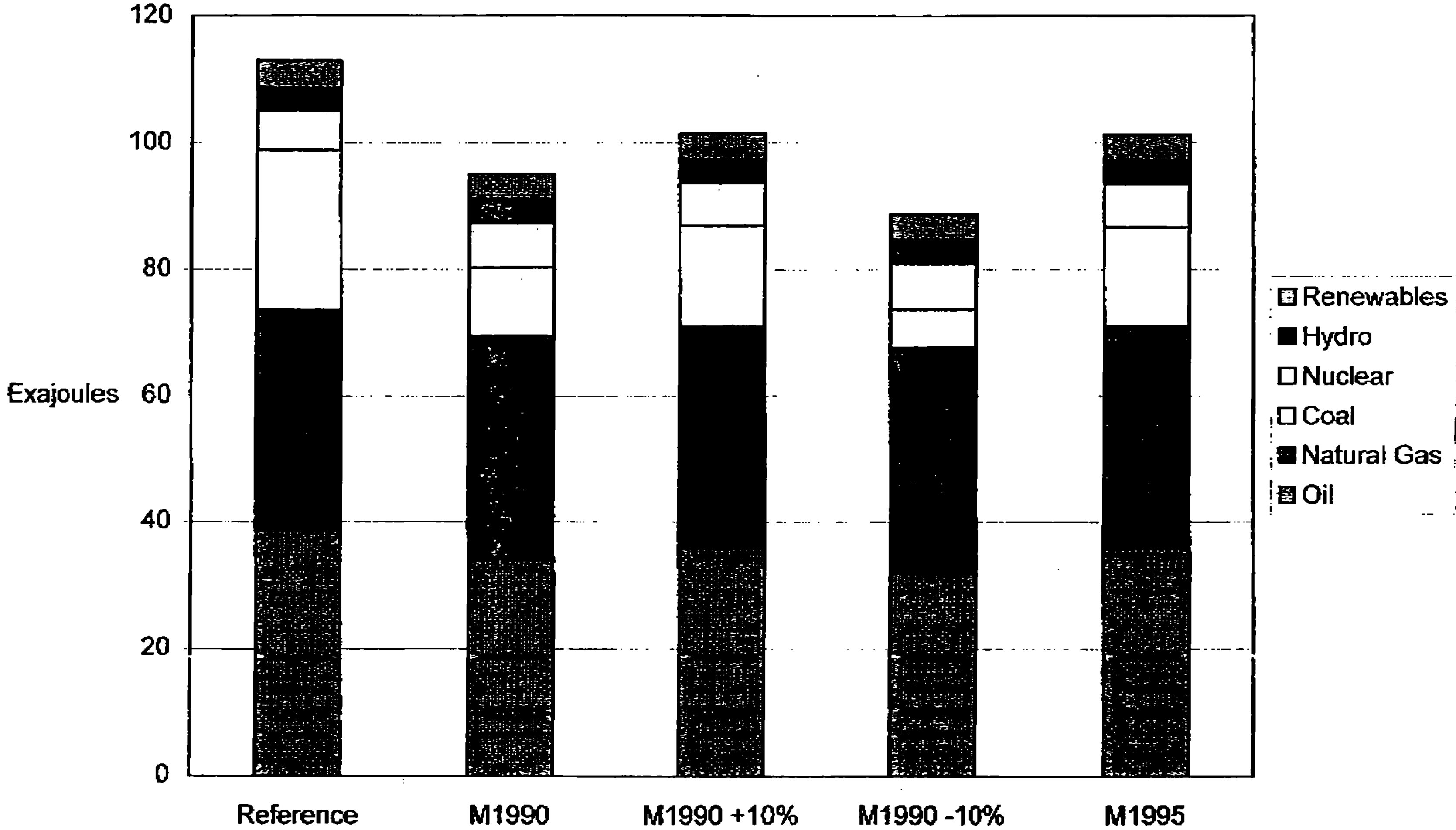


Figure 6. Marginal Cost of Carbon

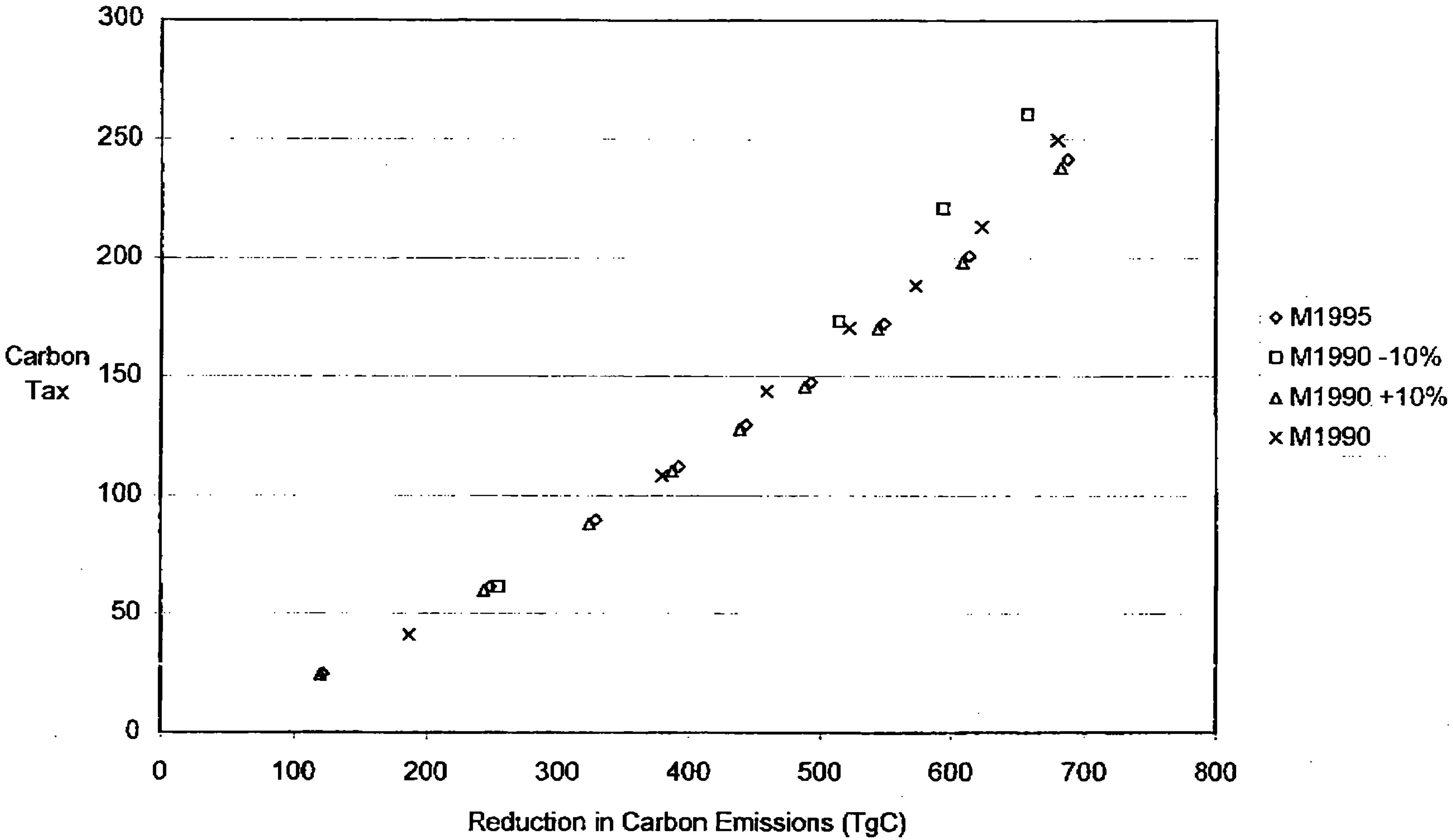


Figure 7. Cost of Emissions Mitigation
No Trading

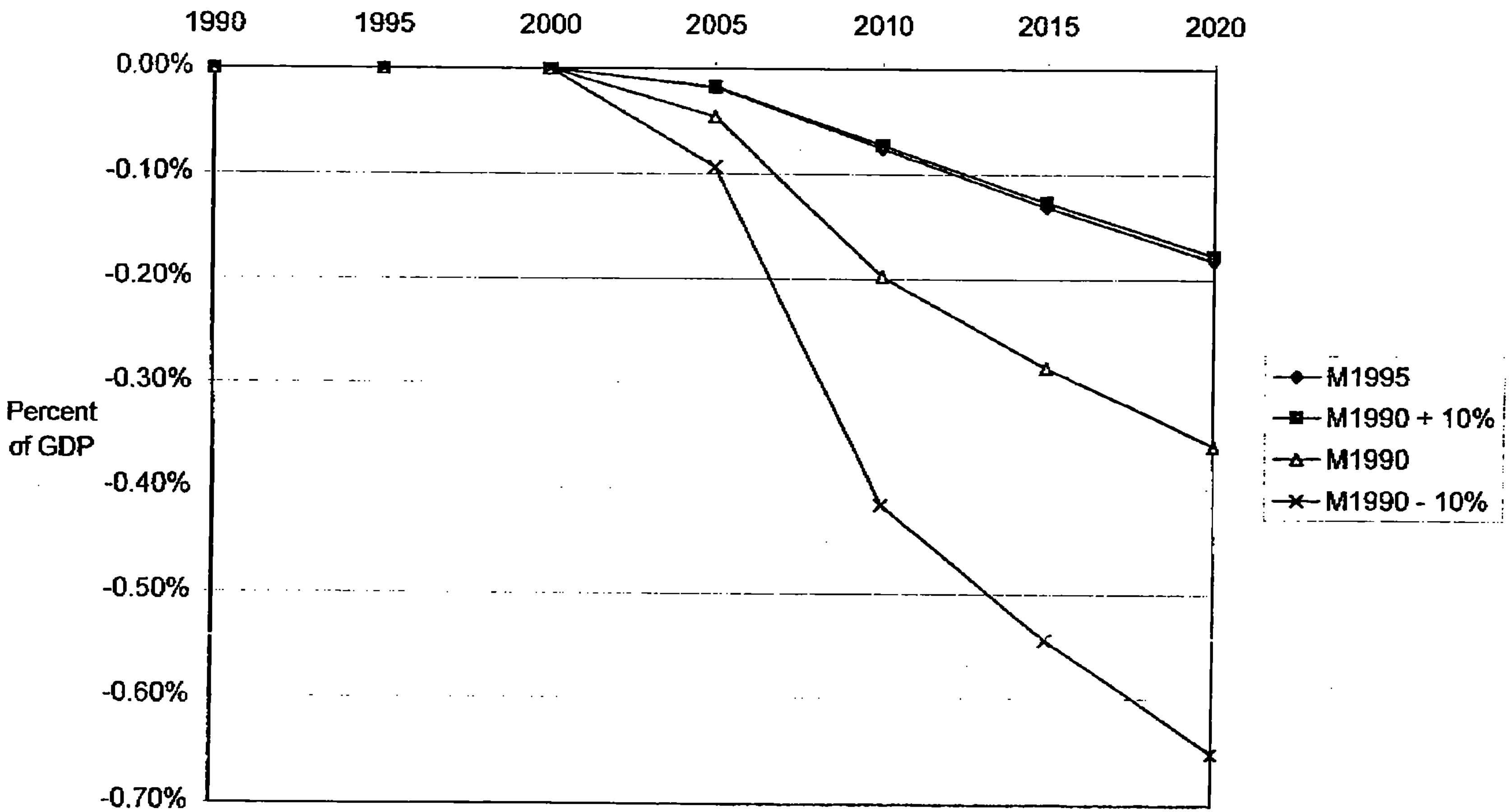


Figure 8. Illustration of 'Where' Flexibility Costs for M1990 Cases

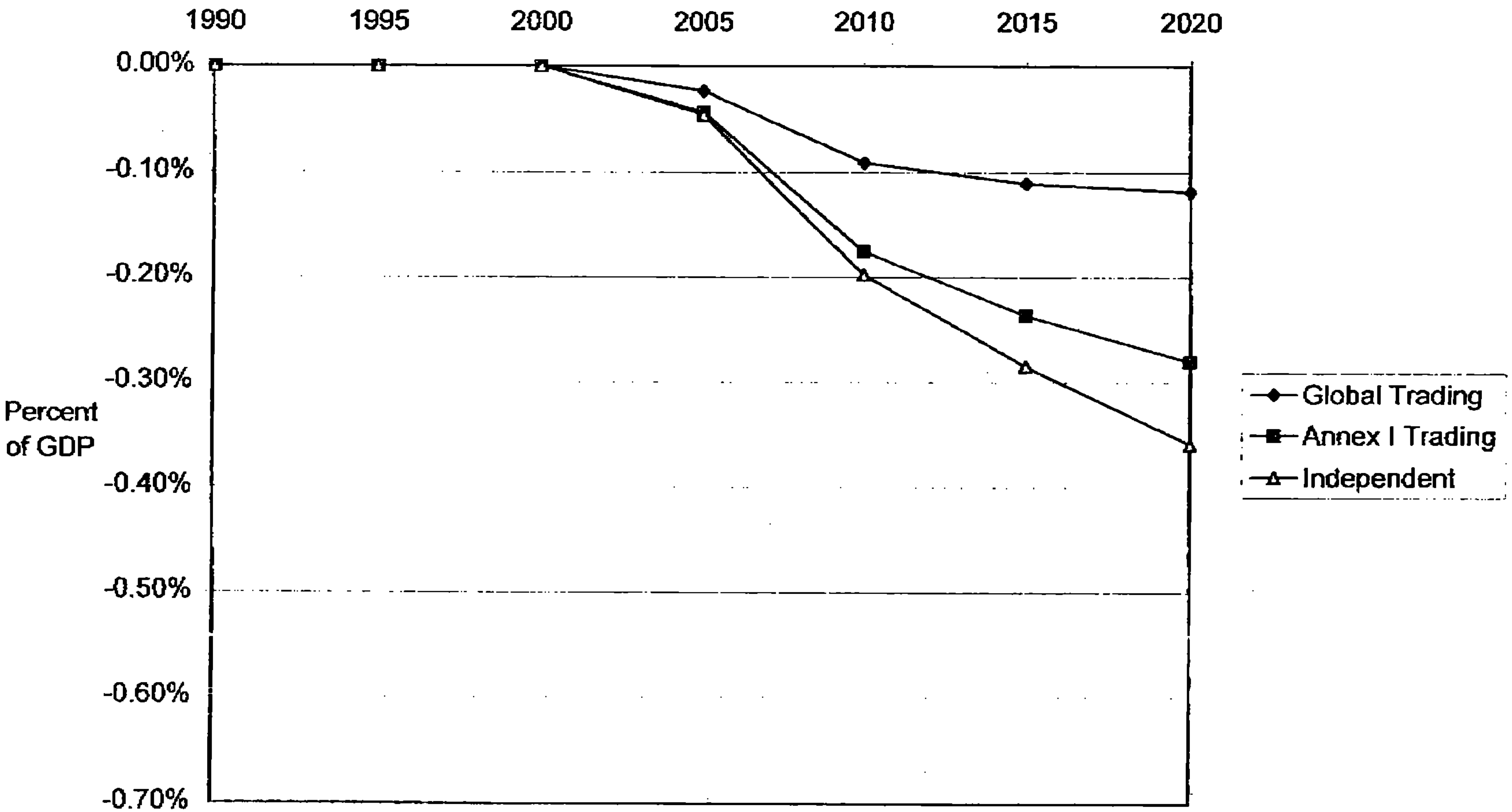
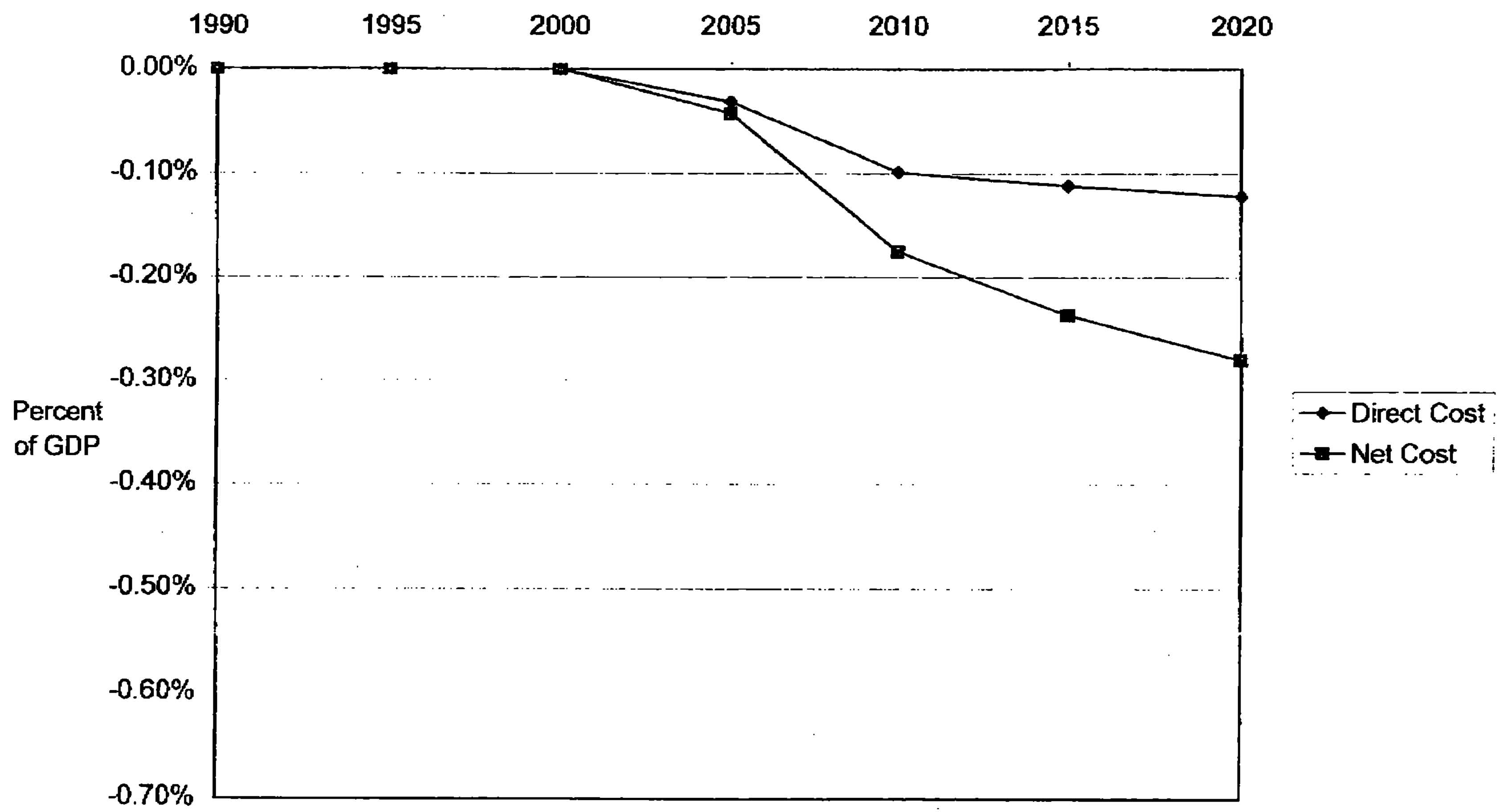


Figure 9. Cost Breakdown
M1990 Annex I Trading Case



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Review Draft – Comments Welcome

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Working Paper

Return to 1990: The Cost of Mitigating United States Carbon Emissions in the Post-2000 Period

JA Edmonds
SH Kim
CN MacCracken
RD Sands
MA Wise

October 1997

p12 "Direct cost" = integral of MC as share of GDP

p13 Trading. cost incl. permit purchases

p13 E Eur allowed 1990 levels (paper says as an alternative (to "reference-level") case

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ABSTRACT

The Second Generation Model (SGM) is employed to examine four hypothetical agreements to reduce emissions in Annex I nations (OECD nations plus most of the nations of Eastern Europe and the former Soviet Union) to levels in the neighborhood of those which existed in 1990, with obligations taking effect in the year 2010. We estimate the cost to the United States of complying with such agreements under three distinct conditions: no trading of emissions rights, trading of emissions rights only among Annex I nations, and a fully global trading regime.

We find that the cost of returning to 1990 emissions levels in the United States in the absence of trading opportunities is approximately $108 per metric ton carbon in 2010. The total cost in that year is approximately 0.2 percent of GDP. Emissions reductions are accomplished via energy conservation across a broad range of residential, commercial, industrial and transportation activities and by replacing coal fired power stations with natural gas facilities.

International trade in emissions permits lowers the cost of achieving any mitigation objective by equalizing the marginal cost of carbon mitigation among countries. This is sometimes referred to as "where" flexibility. "Where" flexibility allows least expensive emissions reductions to be undertaken first, regardless of where they occur among trade participants.

For the four mitigation scenarios in this study, economic costs to the United States remain below 1% of GDP through at least the year 2020. This was the case even in the scenarios where the United States met its mitigation targets without international trading of carbon permits.

Return to 1990
The Cost of Mitigating United States Carbon Emissions in the Post-2000 Period

James A. Edmonds
Son H. Kim
Christopher N. MacCracken
Ronald D. Sands
Marshall A. Wise

Pacific Northwest National Laboratory

More than 160 nations have signed the Framework Convention on Climate Change (FCCC). That agreement required Annex I nations,[1] the developed nations of the world plus economies of the Former Soviet Union and Eastern Europe, to undertake measures to return emissions to 1990 levels or below in the year 2000. The parties to the FCCC met in Berlin in the Spring of 1995 and determined that additional measures were required to implement the ultimate objective of the FCCC, "*to stabilize the concentration of greenhouse gases in the atmosphere at a level which would prevent dangerous anthropogenic interference with the climate system.*"

Subsequent to the Berlin discussions, nations of the world have begun to consider measures that would set quantifiable emissions limitation requirements in the post-2000 period for Annex I nations. Various measures have been considered. The purpose of this paper is to explore the economic consequences of efficient policy instruments—carbon taxes or tradable emissions permits—which might be employed to achieve a variety of targets in the post-2000 time frame.[2] Using the Second Generation Model (SGM), we estimate the costs to the United States of complying with of four Annex I mitigation scenarios under three permit trading regimes. Specifically, we examine the carbon taxes required for emissions mitigation and provide measures of the costs of mitigation.

We begin by describing the variety of policy options to be considered and our general approach to modeling those policies. We then review some of the necessary assumptions for this exercise, as well as the structure and calibration of the SGM. Finally, we discuss the results of our analysis, including time paths of emissions and measures of cost.

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[1] Australia, Austria, Belarus, Belgium, Bulgaria, Canada, Czechoslovakia, Denmark, European Economic Community, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Latvia, Lithuania, Luxembourg, Netherlands, New Zealand, Norway, Poland, Portugal, Romania, Russian Federation, Spain, Sweden, Switzerland, Turkey, Ukraine, United Kingdom of Great Britain and Northern Ireland, and the United States.

[2] In the United States, efforts were undertaken by the Interagency Analytical Team (IAT), and results were summarized in United States Government (1997). The Second Generation Modeling team was one of three modeling teams that participated in the evaluation of potential emission mitigation measures under discussion. Note that the results presented in this paper differ from SGM results presented under the auspices of the IAT. The IAT effort assumed higher rates of technical change induced by a response to policy implementation. This study does not make the same assumptions.

APPROACH

The SGM was used to simulate the impact of mitigation policies on the United States economy. The SGM is a computable general equilibrium economic model that projects economic activity, energy consumption, and carbon emissions for the United States and 11 other world regions. A more complete description of the SGM follows in the next section.

Four scenarios were constructed that reduce carbon dioxide emissions in Annex I countries by 2010. The four policies, designated 'M_', are listed below. Figure 1 shows United States emissions paths for the four scenarios and the reference case in million metric tons of carbon (MMTC). The reference case is a business-as-usual scenario, or what we project will happen in the absence of a mitigation policy. In each mitigation scenario, allowable emissions are reduced linearly from the reference level in 2000 to the emissions target in 2010.

M1990 — Emissions from Annex I regions must be no greater than 1990 emissions levels beginning in the year 2010.

M1990+10% — Emissions from Annex I regions must be no greater than 10% above 1990 emissions levels, beginning in the year 2010.

M1990-10% — Emissions from Annex I regions must be no greater than 10% below 1990 emissions levels, beginning in the year 2010.

M1995 — Emissions from Annex I regions must be no greater than 1995 emissions levels beginning in the year 2010.

[Figure 1. Carbon Dioxide Emissions Scenarios for the United States]

The four emissions mitigation scenarios each define a set of emissions rights for the Annex I regions. In a mitigation scenario, regions must possess permits, or rights to emit, for every million metric ton of domestic carbon dioxide emissions. Three emissions permit trading regimes were modeled under each mitigation policy: independent emissions mitigation, Annex I joint mitigation, and Annex I mitigation with global permit trading. The 12 SGM regions listed in Table 1 provide the necessary global coverage to simulate these trading systems. Carbon taxes were used to constrain emissions for each of the policy-trade combinations.

Table 1. Regions in the SGM

Annex I	Non-Annex I
United States	China
Canada	India
Western Europe	Mexico
Japan	South Korea
Australia	Rest of World[3]

[3] The Rest of World includes Latin America, Africa, and other Asian countries.

Former Soviet Union	
Eastern Europe	

In the independent mitigation case, each Annex I region must individually meet its required emissions targets without any trading of permits across regions. A time series of carbon taxes is determined for each region to reduce emissions to be equal to its allocated emissions rights.

With Annex I joint mitigation, a common carbon tax is applied to all Annex I regions to meet the overall Annex I emissions target. However, regions are allowed to trade permits amongst themselves so long as the total constraint is met in each time period. Regions may only emit more carbon than their allocated emissions rights allow if another Annex I region is willing to sell a corresponding number of its permits, thereby forcing the seller region to reduce its domestic emissions beyond the required target.

In the global trading case, emissions rights are allocated to Annex I regions at the same levels as in the Annex I trading case. Under global trading, however, the Annex I regions are allowed to purchase permits from each other and from non-Annex I regions so long as the global emissions constraint is met. The global constraint in each period is composed of the Annex I constraint and the sum of the non-Annex I regions' reference level emissions in that period. The SGM is used to determine a global carbon tax just large enough to meet the global emissions target.

In none of the above scenarios and trading combinations are non-Annex I regions forced to constrain their emissions below reference levels. No mitigation targets or emissions trajectories are imposed on those regions. Under the global permit trading regime, non-Annex I regions participate in the market for carbon permits only when it is to their economic benefit to do so. These regions are allocated permits equal to their projected reference emissions, so they are only required to reduce their emissions by an amount equal to the number of permits they wish to sell.

Eastern Europe and Former Soviet Union Permit Allocations

While carbon dioxide emissions in most regions are anticipated to continually increase over time beyond 1990 levels, this is not true for the Eastern Europe and Former Soviet Union regions. Emissions in these regions have declined since 1990. Their reference case emissions trajectories reflect this decline from 1990 to 1995 and then increase slowly from 1995 onward. The downturn in emissions poses a special problem when allocating emissions rights. Two approaches to permit allocations for the regions have been discussed in recent months. The first allocates permits based on the stated policy scenario (e.g., M1990 allocates permits based on 1990 emissions level) so that permits are allocated to them in the same way as they are to other Annex I regions. Because of the decline in emissions in those regions from 1990 to 1995, however, this approach results in emissions permits being granted to Eastern Europe and the Former Soviet Union in the policy years that are greater than their reference level emissions. These 'paper credits' are equal to the difference between the lower post-1990 emissions and the policy-level (i.e., 1990) emissions. For example, the Former Soviet Union's reference emissions level in 2010 is 836 TgC, significantly lower than its 1990 emissions of 1050 TgC. If granted permits equal to its 1990 emissions, it would receive 214 TgC worth of permits more in 2010 than its projected emissions, giving it 214 TgC worth of permits to sell without incurring any emissions reductions of its own.

The second approach to allocating permits to Eastern Europe and the Former Soviet Union is to grant permits equal to reference level emissions in each period until the projected path is constrained by the policy. For example, in the M1990 case, the Former Soviet Union would be granted permits equal to its projected reference emissions through 2020 because emissions in the policy years never recover to 1990 levels.

For the purpose of this exercise, we chose to emphasize the latter approach in allocating emissions to Eastern Europe and the Former Soviet Union. This reference allocation scheme ensures that the stated Annex I emissions targets are achieved in both the independent mitigation and permit trading scenarios. Because a final decision on the permit allocation method has yet to be made, however, we have also included a discussion of the impacts of the mitigation policies utilizing the first approach.

MODEL OVERVIEW

The SGM is designed specifically to address issues associated with global change. The model is designed to perform the following types of analysis:

1. Provide estimates of future time paths of environmentally important emissions associated with economic activity.

2. Provide estimates of the economic cost of actions to reduce greenhouse gas emissions.

Sectors

The SGM has nine producing sectors and twelve inputs to production. The inputs are land, labor, capital, and the nine produced goods. Economic detail is maintained in the energy supply and transformation sectors that are important for greenhouse gas emissions projections, but aggregated elsewhere into one large "everything else" sector.

Five different fuels are used for producing electricity, resulting in five subsectors for the electric generating sector. A separate economic production function, of the constant elasticity of substitution (CES) functional form, is used for each sector or subsector. Capital investment decisions depend on an assumed lifetime of capital for each sector or subsector. Capital lifetimes range from 15 years in the oil, gas, and coal production sectors to 70 years for hydroelectric power. The relative size of each production sector and subsector is shown in Table 2.

Table 2. Producing Sectors in the SGM

	Producing Sector	Gross Output in 1985 (millions of 1985 $)	
1	Agriculture	468,618	
2	Everything Else	5,086,486	
3	Oil Production	64,171	
4	Gas Production	45,804	
5	Coal Production	20,006	
6	Uranium Processing	2,195	
7	Electricity Generation	165,800	
	a. oil		10,959
	b. gas		34,152
	c. coal		85,930
	d. nuclear		21,370
	e. hydro		13,389
8	Petroleum Refining	145,015	
9	Gas Transmission and Distribution	105,330	

Market Clearing

In the SGM, markets are said to *clear*. In other words, the SGM solves for the set of prices for all markets (or sectors) in the modeled economy so that demands and supplies of each market are in equilibrium. The set of prices in which the equilibrium holds is called the *market-clearing* price set. In an equilibrium model like the SGM, markets are linked to other markets through the market-clearing process. For example, a change in the demand for coal will have an effect on not just the price of coal, but also the prices of oil, gas, and, at least indirectly, the prices of all markets in the economy.

Carbon permit prices and taxes are also solved by the SGM as part of the market equilibrium. Specifically, the SGM finds the carbon price such that the amount of carbon emitted is just equal to the carbon constraint of the region or group of regions under a carbon emissions limitation constraint.

Carbon Taxes and Revenue Recycling

The SGM uses a carbon tax within each region to provide an economic incentive for the economy to substitute away from carbon. Revenues obtained from the carbon tax can be very large, and how the revenues are recycled, or redistributed to the economy, makes a difference in the final economic cost. For this exercise, we assume that all carbon tax revenues are recycled back to consumers through a lump-sum government transfer.

For the cases where emissions rights are traded between countries, each SGM region is allocated an initial number of carbon emissions permits based on the stated mitigation policy (e.g., 1990 emissions levels for the M1990 scenario). Carbon permits can then be traded between countries at a price that clears the global market in these permits.

Modes of Operation

All of the SGM regions were initially developed as single-region models with a base year of 1985. Each regional model operates in five-year time steps generally through 2030, 2050, or 2100. Most of the single-region models were developed in collaboration with experts from that country. It is possible to run all of the regions individually or simultaneously in a global model with international trade. The three modes of operation for the SGM are:

1. Single Region
2. Global with Partial Market Clearing
3. Global with Full Market Clearing

Single-region operation. For each SGM region, all produced goods are classified as being tradable, nontradable, or traded at a fixed quantity. When SGM regions are operated independently, a fixed world price is assumed for certain tradable goods; regions may import or export as much of that good as desired at that fixed world price, subject to an overall balance of payments constraint. For all nontradable goods, the quantity of trade is fixed in advance. The following assignments are used when the United States model is operated independently:

Numeraire Sector:	everything else (price always equals 1)
Fixed World Price:	crude oil
Fixed Trade Quantities:	agriculture, coal, nuclear fuel, refined petroleum, electricity
Nontradables:	distributed gas, land, labor

For each region, the large 'everything else' sector is the numeraire, with its price fixed at 1 for all time periods. The prices of the other sectors in the economy are reported relative to this fixed value. The 'everything else' good is a tradable good for all regions. An exogenous balance-of-payments constraint is specified in advance for each region. Most regions are assumed to move linearly from a historical trade balance in 1985 to balanced trade by 2005.

Given a trial set of prices, the SGM computes supply and demand for all producing sectors and primary factors of production. Markets for the nontradables and goods traded at fixed quantities are brought into equilibrium by searching for a set of prices that equate supply and demand. Prices are adjusted until supply and demand are within 0.01% of each other.

Global model with partial market clearing. The global version of the SGM is used when there is at least one market that must clear globally. For the scenarios described in this paper, that market is tradable carbon emission permits. The model searches for a global carbon tax, which can be interpreted as a world carbon permit price, that clears the market for permits.

Each region is initially allocated a number of carbon permits and may trade those permits at the world permit price. Some regions will be sellers of permits and some will be buyers. After trading permits, all regions must hold permits equal to the domestic level of carbon emissions.

All regions are still subject to a period-by-period balance of payments constraint. The model does not allow borrowing to pay for carbon emissions permits. Imports of permits must be paid for with exports of some other good.

Global model with full market clearing. There are no longer any markets with a fixed world price. A set of world prices is found that clears all world markets. Also, world markets can be created for goods that were traded in fixed quantities in the single-region model.

All of the scenarios described in this paper were run in the second mode, global with partial market clearing. This mode was chosen for two reasons. The first is that we chose to adopt a fixed time path of world oil prices for SGM model runs that were completed for the United States Government during the spring of 1997. This meant that the world oil market would not be allowed to clear in the model. The second reason is that model results are often easier to interpret when some variables in the model remain predetermined over time.

Data Requirements

Three types of data are used to construct and calibrate each region of the SGM:

1. Economic and Demographic Data
2. Energy Balances
3. Technology Descriptions

Economic data include input-output tables and supplemental information from the national income accounts. Population projections were obtained from the World Bank. Energy balance tables were obtained either from the International Energy Agency or from government agencies within a region.

Input-output tables describe, in value terms, the flow of goods between industries and consumers in an economy. However, a model concerned with quantities of carbon emissions must also be concerned with quantities of energy. An input-output table alone is not sufficient to determine the quantities of oil, gas, coal, electricity, and refined petroleum that are produced and consumed. Supplemental information on energy quantities is required to map currency units from an input-output table to energy units needed to calculate levels of carbon emissions. We combine economic input-output tables with energy balance tables to create a hybrid input-output table with units of joules for energy products and real dollars for all other products. Miller and Blair (1985) provide a general description of, and the motivation for using, hybrid input-output tables.

Individual energy technologies are characterized by the annualized cost of providing an energy service. Data needed to determine the annualized cost include capital cost, equipment lifetime, annual fuel requirements, the interest rate, and other annual maintenance and operating costs.

REFERENCE CASE AND CALIBRATION

The cost of reducing greenhouse gas emissions is dependent on the reference case. The higher the growth rate of emissions in the reference case, the greater the cost of returning to 1990 emissions. Therefore, much effort is expended to create an acceptable reference case before running any of the mitigation scenarios.

Results for this study are reported for the years 1990 through 2020. The United States reference case was closely calibrated to the Annual Energy Outlook 1997 (AEO97). Since AEO97 projects only up to the year 2015, projections beyond 2015 are SGM model results and are not calibrated to any other established projections. Projections of carbon emissions, population, gross domestic product (GDP), energy consumption, and electricity generation for the United States are described below.

For the other global regions, economic and energy consumption growth rates were roughly calibrated to regional projections from the World Energy Outlook 1996 (WEO96). For the Eastern Europe and Former Soviet Union regions, projected energy consumption levels were adjusted downward from the WEO96 projection to reflect recent events. Population projections for all regions with the exception of the United States were set exogenously based on the World Population Projections 1994-1995, published by the World Bank. The United States population projection was set according to AEO97 projections. As mentioned earlier, the international crude oil price trajectory was also taken from the AEO97. Prices for all other fuels and goods in the model were determined endogenously.

The general calibration procedure was to first match GDP growth by adjusting parameters that control total factor productivity in the 'everything else' sector. Then energy consumption by fuel was calibrated by adjusting input-specific technical change parameters. Carbon emissions are an output of the model derived directly from primary energy consumption by applying fuel-specific emission factors.

Carbon Emissions

In 1990, total carbon dioxide emissions from the combustion of fossil fuels in the United States were 1,350 million metric tons of carbon. Model results show that total carbon dioxide emissions continue to rise as fossil fuel consumption increases and emissions reach 1,871 million metric tons by 2020. This amounts to a 39 percent increase in total emissions and an emissions growth rate of 1.1 percent per year. Reference case carbon emissions were shown earlier in Figure 1.

Gross Domestic Product

The two most important determinants of GDP are population growth and rates of change in productivity. Total population levels for the United States were taken directly from AEO97. United States population grows from 250 million in 1990 to 323 million in 2020. This represents an annual population growth rate of 0.85 percent per year.

GDP for the United States was matched to AEO97 projections by changing the total factor productivity parameter for the 'everything else' sector. Beginning with the 1990 GDP of 6.1 trillion dollars, the economy grows at nearly 2 percent annually to reach 10.6 trillion dollars by 2020.

Energy Consumption

Total energy consumption from 1990 to 2015 was calibrated to within 2 percent of projections from AEO97. Energy consumption by fuel is shown for the United States in Figure 2. Total consumption increases from 86 EJ in 1990 to 118 EJ in 2020. This increase represents an average annual growth rate of 1.1 percent over that period. The annual growth rate in energy consumption declines over time and by 2020 decreases to 0.5 percent per year.

Petroleum remains the major source of energy through 2020, but its share of total consumption declines over time, giving way to natural gas and, to a lesser extent, renewable energy sources. Coal is the third largest source of energy and its consumption grows steadily at slightly less than 1 percent per year. Nuclear energy's contribution to energy consumption declines over time.

[Figure 2. Energy Consumption – United States Reference Case]

Energy consumption does not grow as fast as GDP, which results in the energy-GDP ratio falling over time at an average annual rate of 1.0 percent per year. Figure 3 shows the energy-GDP ratio generated by the SGM for the United States reference case.

[Figure 3. Energy-GDP Ratio – United States Reference Case]

Electricity Generation

Projections of electricity generation are similar to those of the AEO97. SGM total electricity generation results are higher than the AEO97 projections by approximately 10 percent. Electricity generation from natural gas is the reason for the higher result. Total electricity generated in 1990 is nearly 11 EJ, which grows at 1.5 percent per year and expands to 17 EJ by 2020. The major source of electricity is the combustion of coal; however, electricity generation from natural gas plays a significantly larger role with time. In 1990, electricity generation from coal contributed 53 percent of the total generation, while that from natural gas combustion contributed 17 percent of the total. By 2020, the shares of electricity generation from coal and natural gas are closer. Electricity generation from coal and natural gas comprise 44 and 34 percent shares of the total, respectively. Highly efficient and low-cost natural gas combined cycle power plants incorporated into the SGM contribute to the growth of natural gas as the choice fuel for electricity generation. Nuclear power's contribution to the overall demand for electricity declines with time as existing power plants are retired and no new additional plants are constructed.[4] Renewable energy sources for electricity generation include hydroelectricity, solar photovoltaics and others. Generation of electricity from renewable sources increases slightly from 1990 to 2020; however, renewable energy's share of total electricity remains below 10 percent of the total.

COST OF EMISSIONS MITIGATION

[4] The assumption of no new starts reflects a de facto nuclear moratorium. Were nuclear power to be allowed to compete against other energy forms on the basis of price alone, the model would continue to build new facilities.

Although this exercise employed the 12-region version of the SGM, discussion of results in this paper will focus on the United States. The SGM provides output on regional GDP and its components and a detailed description of the composition of energy supply. In this analysis, we focus on the broad economic impacts to the economy. Specifically, we discuss the permit prices required to meet the various mitigation requirements and the costs to the United States economy of undertaking such policies. We also discuss the impacts of the domestic carbon taxes on energy consumption.

Permit Prices

Table 3 shows the permit prices by trading regime required for the United States to meet its emissions targets under the four mitigation scenarios. Permit prices in the United States must reach $108 per metric ton of carbon to reduce United States emissions to 1990 levels in 2010 in the independent mitigation case. This price increases significantly with the tighter constraint imposed under the M1990-10% case. Permit prices in the M1995 and M1990+10% scenarios are very similar as only 5 TgC separate the constraints in the two cases in 2010.

Table 3. United States Carbon Taxes Required to Meet Policy Goal Eastern Europe & FSU Allocated Reference Case Permits (1992 US$ per Metric Ton of Carbon)

	Independent Mitigation		Annex I Joint Mitigation		Annex I Mitigation with Global Trade	
	2010	2020	2010	2020	2010	2020
M1990	108	170	72	87	26	27
M1990+10%	60	110	42	58	16	18
M1990–10%	173	260	109	122	38	36
M1995	61	112	70	106	26	32

Permit prices fall as more regions are included in the market for carbon permits. In the independent emissions mitigation case, carbon emitters in the United States may undertake emissions mitigation options available only within the United States. In the Annex I joint and global permit cases, however, regions are included that have mitigation options with significantly lower costs, thereby lowering the marginal cost to the carbon permit market of meeting the desired emissions targets. As we will discuss, this 'where' flexibility in meeting emissions targets has a significant impact on costs as well as permit prices.

A fixed emissions level and an increasing reference case emissions level imply both a rising percentage emissions reduction and a rising price of meeting the fixed emissions target. Increasing population in the United States, and the economic growth that accompanies it, put upward pressure on emissions that, in turn, forces larger shifts away from coal toward natural gas and renewable energy sources. The availability of relatively inexpensive abatement options in the developing world allows the permit price to remain relatively constant over time in those cases.

As the permit prices decrease across trading regimes, the United States purchases increasing quantities of permits from abroad, thereby enabling it to emit more than its allocated permits alone would allow. Figure 4 shows United States emissions for the M1990 case across the three trading regimes. Under the independent emissions mitigation regime, the United States is limited to emitting only what it is allocated under the scenario, its 1990 emissions level. With Annex I trading, however, the United States purchases 209 TgC worth of permits in 2010 and 244 TgC in 2020 from the Former Soviet Union and Eastern Europe. The purchases increase to 316 TgC and 436 TgC in 2010 and 2020, respectively, under the global trading regime. Again, 'where' flexibility reduces the amount by which a permit-buying region must reduce its emissions and, therefore, reduces the cost to the region.

[Figure 4. United States Carbon Emissions – M1990 Cases]

The M1995 Annex I trading case is the only case in which the United States sells permits to other regions. The permit price under independent mitigation in 2010, as shown in Table 3, is less than that shown under Annex I trading. Because the United States can mitigate emissions less expensively in 2010 than other Annex I regions, it reduces its emissions beyond the required 1995 target and sells permits to other Annex I regions. By 2020, however, the United States begins to purchase permits from Eastern Europe and the Former Soviet Union.

Energy Consumption

Emissions mitigation is achieved primarily through two mechanisms: energy conservation - reduction in total energy consumption - and replacement of coal-fired capacity with less carbon-intensive fuels such as natural gas and renewables in the electricity sector. In the no-trading cases, fuel switching from coal to natural gas and renewable fuels in the electricity generation sector accounts for roughly 60 percent of the reduction in total emissions. Energy conservation makes up the remaining 40 percent of the reduction. The domestic carbon tax of $108 in 2010 in the M1990 case results in a reduction of total energy consumption by 14 percent relative to the reference case. Consumption of coal drops by 57 percent while consumption of petroleum drops by 7 percent. Consumption of natural gas, however, increases by 4 percent due to fuel switching. Figure 5 shows energy consumption by fuel in the year 2010 for the four mitigation scenarios. Note that even when emissions are returned to 1990 levels, the scale of the total energy system is not. The fuel switching mentioned above allows the emissions targets to be met without reducing total consumption by the same percentage as the required reduction in emissions.

[Figure 5. United States Energy Consumption in 2010]

Fuel substitution in the electricity sector results in the share of electricity generated from coal dropping from 45 percent in the reference case to 20 percent in the M1990 case. The reduction in electricity generation from coal is compensated for by increased generation from natural gas. The share of electricity generation from natural gas increases from 29 percent in the reference case to 51 percent M1990 case.

As discussed above, the domestic cost of stabilizing emissions at 1990 levels in 2010 without trade is \$108 per metric ton carbon. This cost roughly reflects the cost of abandoning existing coal-fired power generation capacity and replacing it with a new combined-cycle natural gas-fired unit. A \$108 per metric ton tax adds approximately \$0.02 per kilowatt-hour to the operations and maintenance (O&M) cost of power generation in a coal-fired plant. This additional cost makes the O&M cost of the coal plant higher than the levelized cost of installing a new gas-fired combined-cycle unit, roughly \$0.05 per kilowatt-hour. The \$108 tax, therefore, provides an emissions mitigation plateau for permit prices that is not exceeded until most of the existing coal capacity is replaced.

Certain caveats apply to the discussion above concerning the marginal cost of substituting natural gas-fired electricity generation capacity for existing coal-fired capacity. The cost analysis requires that the tax be levied indefinitely. If the tax policy is believed to be only temporary, the amount of substitution is likely to be much less substantial and the tax level required for stabilizing emissions could be higher. The tax level required for mitigation also depends on the cost of developing the infrastructure necessary to supply natural gas to potential new users. Extending pipelines to particular areas, for example, might increase the cost of gas enough so as to discourage switching from coal-fired plants in those areas.

Cost Calculations

A very convenient way to characterize the response of any SGM region to a carbon tax is by constructing a marginal cost of carbon curve. Figure 6 is a scatter plot of various carbon taxes applied to the United States economy and the corresponding reduction in carbon emissions. Data points plotted in Figure 6 are from the four independent mitigation scenarios for the United States. Note that a positive tax is required to achieve any reductions in carbon emissions.

[Figure 6. Marginal Cost of Carbon]

The marginal cost curve is used to calculate one measure of cost that we will call the *direct cost*. For any level of carbon emissions mitigation, the direct cost is defined as the area under the marginal cost curve up to that amount of mitigation.[5] While the first units of emissions reductions are very inexpensive; successive units become more and more expensive. So, as the constraints on emissions become tighter across cases and over time, the cost of mitigation increases. Figure 7 shows the direct costs for the United States for the four independent mitigation scenarios. Direct costs are shown at 5-year intervals through 2020 as a percentage of GDP. These costs are plotted as negative numbers.

[Figure 7. Cost of Emissions Mitigation – No Trading]

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[5] Note that these costs do not include the costs of establishing a domestic or international permit trading system nor do they include the transaction costs associated with permit trading among firms and/or regions.

Figure 8 focuses on the M1990 case and shows how costs to the United Sates are reduced with trade in emissions permits between countries. The 'independent' cost line shown in Figure 8 is the same as the M1990 cost line in Figure 7. In 2010, costs are reduced somewhat with Annex I trading and reduced by about one-half with global trading. In later years, the flexibility in where emissions reductions are undertaken impacts mitigation costs even more significantly.

[Figure 8. Illustration of 'Where' Flexibility – Costs for M1990 Cases]

Cost calculations for the emissions trading cases are different than in the independent case. Costs for the trading case take into account the value of permits traded. For a buyer of permits, such as the United States, net cost includes the direct cost plus expenditures on carbon permits. A breakdown of these two cost components is shown for the M1990 Annex I trading case in Figure 9. Direct cost is roughly half of the net cost. The remaining cost, the difference between the 'direct cost' and 'net cost' lines in Figure 9, is the value of emissions permits that would be purchased from other Annex I countries.

[Figure 9. Cost Breakdown – M1990 Annex I Trading Case]

Impact of Alternative Permit Allocation Approach

The results discussed thus far have been based on the assumption that Eastern Europe and the Former Soviet Union are allocated permits equal to the minimum of their reference-level emissions and the policy-level emissions. This section will discuss the impacts of an alternative permit allocation method in which Eastern Europe and the Former Soviet Union are granted permits equal to their policy-level emissions in every period. Recall that 'policy-level' refers to the emissions target set by the chosen mitigation policy. For example, the policy-level emissions in the M1990 case would be 1990 level emissions starting in 2010, and for the M1995 case they would be 1995 level emissions beginning in 2010. This assumption results in the 'paper credits' discussed earlier that significantly impact the permit prices required to meet Annex I emissions targets in the Annex I and global trading cases.

Table 4 shows the permit prices required to meet the policy goal under the policy-level permit allocation approach. The prices required for independent mitigation in the United States do not change from Table 3 above because the paper credits in those cases are not available for purchase outside Eastern Europe and the Former Soviet Union. Permit prices also remain unchanged under the M1995 case because by that time the two regions have already suffered the worst of their economic downturns so that emissions levels are at their lowest point in the 1990 to 2020 time frame. The permit prices under the other trading scenarios are significantly less under this allocation approach, however, because the regions are able to sell the paper credits without incurring any cost domestically. In the M1990 case in 2010, the paper credits allocated to Eastern Europe and the Former Soviet Union account for 37 percent of the emissions reductions necessary for the remaining Annex I regions to meet their target emissions. This addition of permits available for purchase reduces the permit price by $33, or by 46 percent, relative to the permit price under the reference-level allocation approach. Figure 10 shows the difference in permit prices for the M1990 case with Annex I trading between the two permit allocation approaches in 2010 and 2020.

Note that the difference decreases over time as emissions in Eastern Europe and the Former Soviet Union approach the policy goal.

Table 4. United States Carbon Taxes Required to Meet Policy Goal Eastern Europe & FSU Allocated Policy-level Permits (1992 US$ per Metric Ton of Carbon)

	Independent Mitigation		Annex I Joint Mitigation		Annex I Mitigation with Global Trade	
	2010	2020	2010	2020	2010	2020
M1990	108	170	39	73	15	22
M1990+10%	60	110	6	35	2	11
M1990–10%	173	260	88	124	31	36
M1995	61	112	70	106	26	32

[Figure 10. Permit Prices under Alternative Permit Allocation Methods for EE & FSU – M1990 Annex I Trading Case]

The lower permit prices under the policy-level approach result in lower total costs of emissions mitigation to the United States. In the M1990 Annex I trading case, costs as a percentage of GDP are reduced from 0.18 percent under the reference-level allocation approach to 0.12 percent under the policy-level approach in 2010. Figure 11 shows costs as a percentage of GDP for the M1990 Annex I trading case for both allocation methods.

[Figure 11. Cost of Emissions Mitigation under Alternative Permit Allocation Methods for EE & FSU – M1990 Annex I Trading Case]

DISCUSSION

In this section, we summarize some of the insights gained from our modeling activities using the SGM. First, economic costs depend a great deal on our assumptions about future carbon emissions. Second, several measures of cost are available from the SGM. Third, the distribution of costs among countries in a system of global permit trading is sensitive to assumptions on exchange rates as well as the initial allocation of permits. Fourth, any system of global trade in carbon permits implies potentially large transfers of wealth from one region to another. Finally, we discuss how some of our assumptions affect the results on costs.

Role of Reference Emissions in Shaping Marginal Mitigation Costs

All of the results in this study depend on assumptions used to create a reference emissions scenario from the present to 2020. The amount of mitigation required to return to 1990 levels depends directly on reference case emissions for each region. In the Annex I trading cases, carbon permit prices are particularly sensitive to reference scenarios for potential sellers of permits, especially Eastern Europe and the Former Soviet Union.

Among the Annex I countries, projecting future carbon emissions is especially uncertain for Eastern Europe and the Former Soviet Union. Of particular importance is when emissions in these regions will once again reach 1990 levels. If this point is reached before 2010, then we model EE and FSU just as any other Annex I country. If this point is reached after 2010, then emissions restrictions are not binding in EE and FSU until that point in time.

Measuring and Reporting Costs

At least two measures of cost are available from the SGM and from other models as well. The first measure, which we call the *direct cost*, can be thought of as either a deadweight loss or the integral under the marginal cost curve for carbon. Using either approach, direct cost is approximately equal to one-half of the carbon tax (or permit price) times the reduction in carbon emissions. For the permit trading cases, direct costs are then adjusted by the value of transfer payments required to purchase or sell permits. This measure of net cost is simple to construct and is comparable across models.

Of ultimate interest, however, is the net impact on some broader measure of economic activity (such as GDP) or on economic welfare (such as real consumption). There are many reasons why the change in GDP (or real consumption) is different than direct cost net of transfer payments. These other components of cost include the effects of pre-existing distortionary taxes, changes in terms of trade, and how tax revenues are recycled. In addition, measurement of GDP (or real consumption) depends on the choice of index and base year used to construct that index. This reflects real-world problems in constructing a quantity index for GDP when relative prices are changing.

Foreign Exchange Rates

Permit prices for the global permit trading cases are very sensitive to assumptions about exchange rates. And while the United States follows a largely free market approach to exchange rates, most developing nations do not. Therefore it may be perfectly reasonable to assume that over the long-term the United States exchange rate with other free market trading partners would tend toward the purchasing power parity rate, this assumption is questionable with other partners. This is particularly true for developing countries where market exchange rates, in local currency per U.S. dollar, can be three to five times the corresponding exchange rate based on purchasing power parity. A global permit price of $100 per metric ton translates, at market exchange rates, into a much higher relative price in the developing countries than in the United States.

Exchange rates based on purchasing power parity are usually used to compare income levels between countries, but market exchange rates must be used for goods actually traded between countries. This creates a potential problem for developing countries considering participation in a global permit trading program; carbon permits would be traded at market exchange rates, while GDP losses are better measured using purchasing power parity. For developing countries, losses in GDP could be greater than the value of carbon permits sold.

International Transfer Payments

We have modeled an international system of carbon permit trading that implies potentially large wealth transfers from buyers to sellers of permits. These transfers also change the pattern of other goods traded internationally. For a buyer of permits, this annual transfer of wealth is equal to the annual quantity of permits purchased times the world market price of the permits. The size of these transfers depends directly on the initial allocation of permits between countries. The initial allocation determines not only the amount of permits traded by each country, but also whether a country is a buyer or seller of permits.

For this study, the initial allocation of permits among Annex I countries is simply the emissions targets defined by the four mitigation scenarios. Non-Annex I regions were allocated permits equal to reference case emissions. These four mitigation scenarios represent only a few of the many possible ways of setting global emissions limits and allocating emissions rights among countries to meet those limits. Each allocation implies a different pattern of wealth transfers among countries.

Each region in the SGM is assigned a period-by-period balance of payments constraint. Buyers of carbon permits must, therefore, export more of other traded goods than otherwise to pay for the purchased permits. Conversely, sellers of permits use the permit revenues to increase imports of other goods.

Sensitivity of Costs to Model Assumptions

Economic costs reported by the SGM for the United States are sensitive to many of the model inputs. These include the choice of exchange rate, the inclusion of paper permits, and the method of revenue recycling.

If purchasing power parity exchange rates were used instead of market exchange rates for the developing countries, then any given world permit price would translate into a lower carbon tax in that country's local currency. For global trading cases, this would increase the global permit price needed to meet a global emissions limit, and the SGM would report higher costs for the United States.

For Eastern Europe and the Former Soviet Union, carbon permits were allocated based on their reference case, and not on 1990 emissions. If we had allocated permits based on 1990 levels, these extra 'paper credits' would create a less-stringent Annex I target. The model would then report a lower permit price for the trading cases, and a lower cost to the United States.

In this study, we assumed that all revenues from a carbon tax would be recycled as a lump sum to consumers. Another option is to use the carbon tax revenues to offset other taxes. This has the potential to reduce overall costs, since carbon tax revenues would displace other distortionary taxes.

KEY OBSERVATIONS

Economic costs are reduced with a permit-trading program that equalizes the marginal cost of carbon between countries. The least expensive emissions reductions are taken first, regardless of where they occur. Costs shown in Figure 8 provide a good example of the importance of this 'where' flexibility.

For the four mitigation scenarios in this study, economic costs to the United States remain below 1% of GDP through at least the year 2020. This was the case even in the scenarios where the United States met its mitigation targets without international trading of carbon permits.

Each region in the SGM can be characterized by a marginal cost of carbon curve, as was shown in Figure 6. This shows the approximate carbon tax required for any given level of carbon emissions reduction. For the amount of emissions reductions needed in 2010 to return to 1990 levels, a carbon tax of $108 per metric ton of carbon is required.

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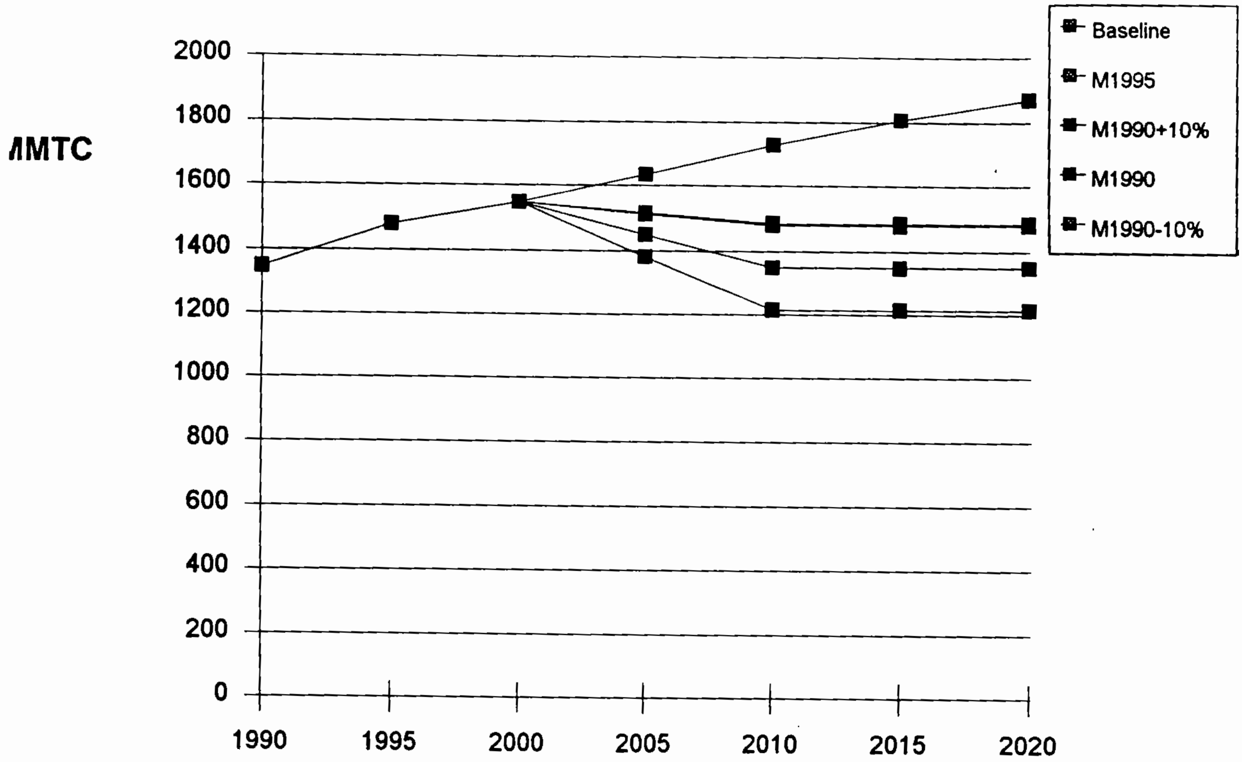
Figure 1. Carbon Dioxide Emissions Scenarios for the United States



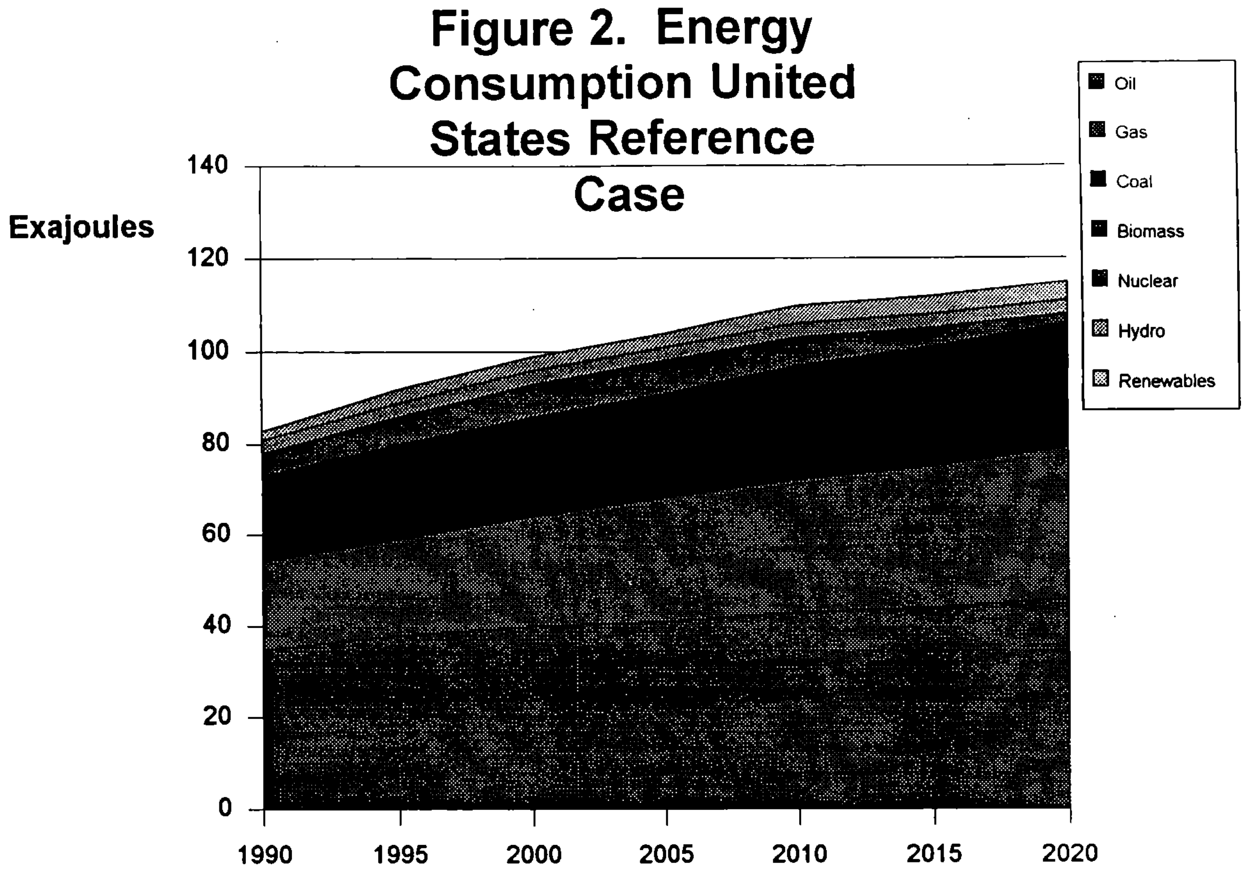


Figure 2. Energy Consumption United States Reference Case
Exajoules
140
120
100
80
60
40
20
0
1990
1995
2000
2005
2010
2015
2020
Oil
Gas
Coal
Biomass
Nuclear
Hydro
Renewables

Figure 3.
Energy-GDP Ratio
United States
Reference Case

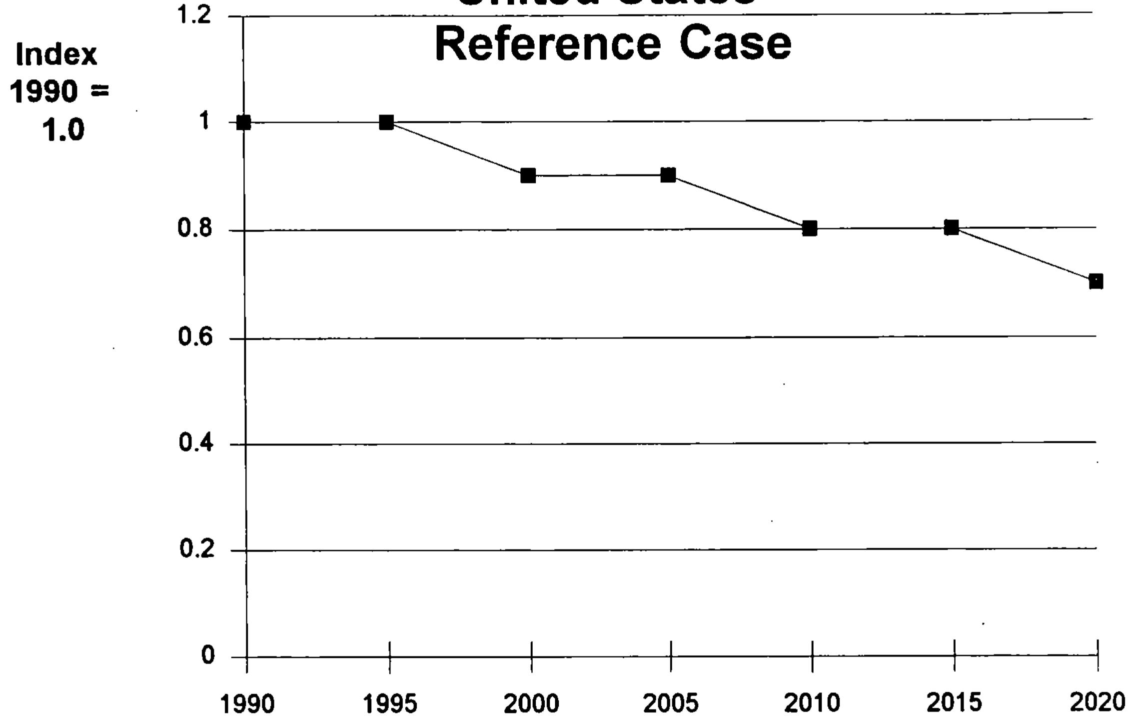
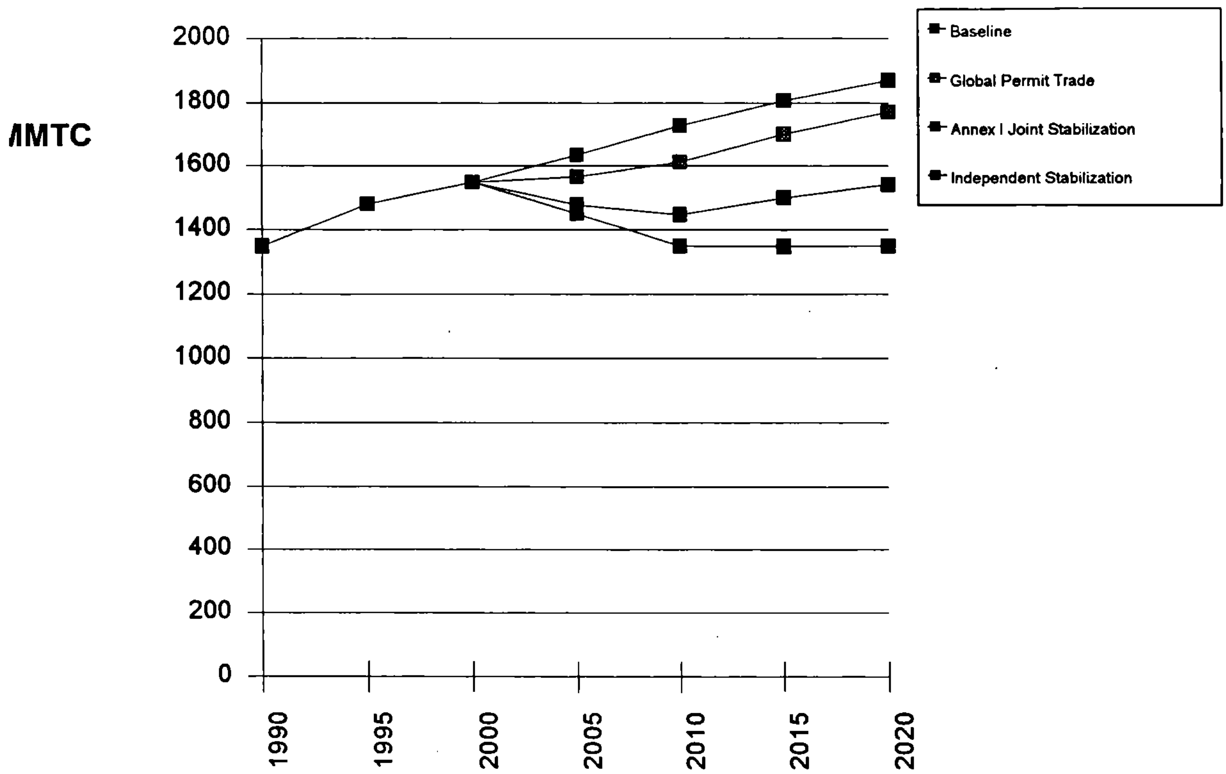


Figure 4. United States Carbon Dioxide Emissions M1990 Cases



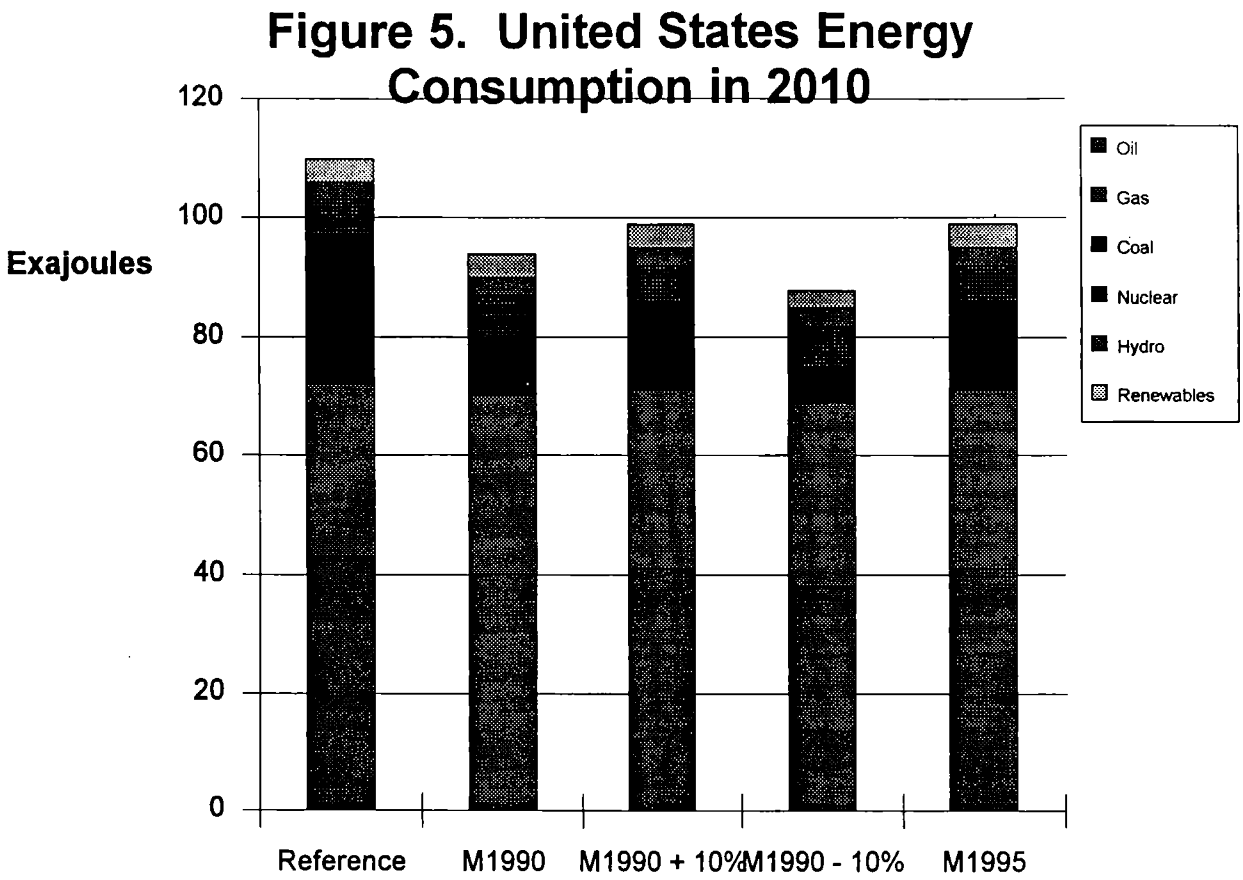


Figure 5. United States Energy Consumption in 2010
Exajoules
120
100
80
60
40
20
0
Reference
M1990
M1990 + 10%
M1990 - 10%
M1995
Oil
Gas
Coal
Nuclear
Hydro
Renewables

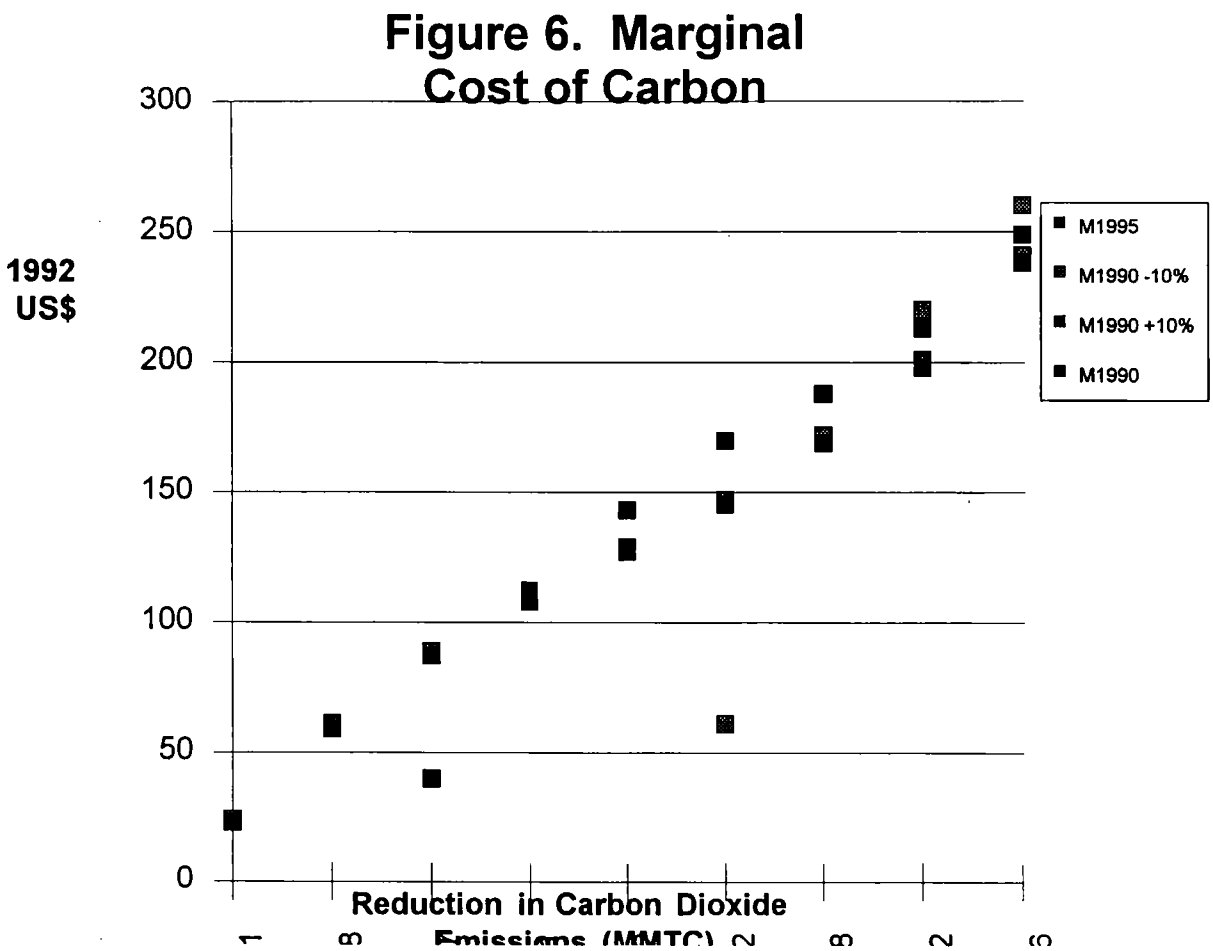


Figure 6. Marginal Cost of Carbon
1992 US$
300
250
200
150
100
50
0
Reduction in Carbon Dioxide Emissions (MMTC)
M1995
M1990 -10%
M1990 +10%
M1990

∫ M C

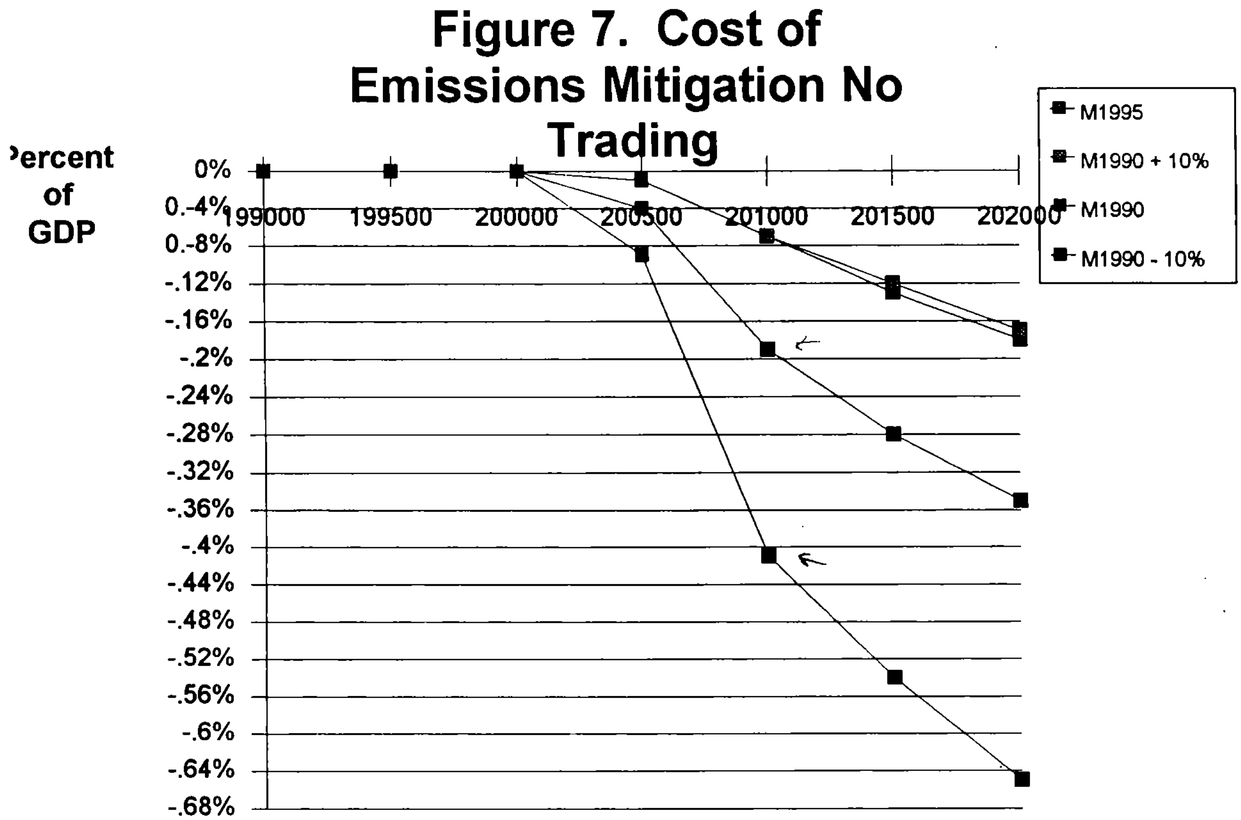


Figure 7. Cost of Emissions Mitigation No Trading
Percent of GDP
0%
0.-4%
0.-8%
-.12%
-.16%
-.2%
-.24%
-.28%
-.32%
-.36%
-.4%
-.44%
-.48%
-.52%
-.56%
-.6%
-.64%
-.68%
199000
199500
200000
200500
201000
201500
202000
M1995
M1990 + 10%
M1990
M1990 - 10%

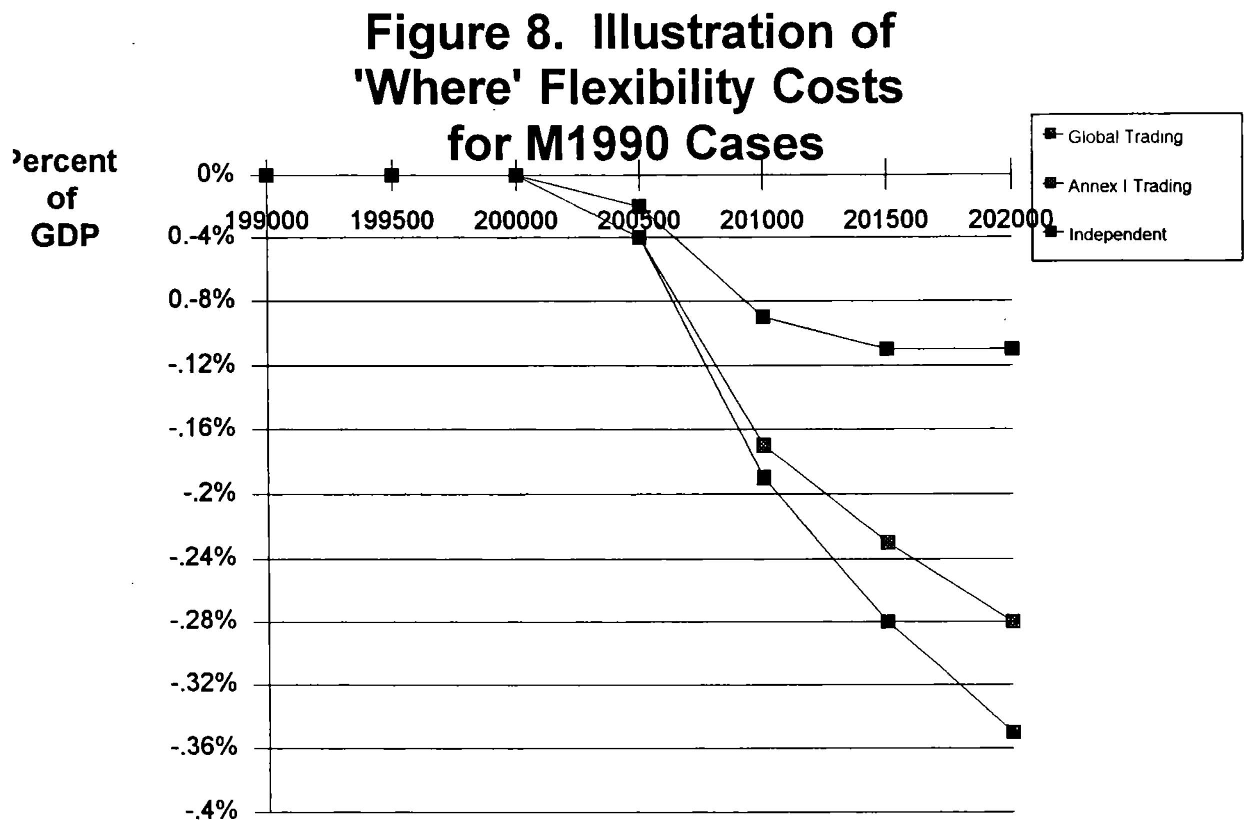


Figure 8. Illustration of
'Where' Flexibility Costs
for M1990 Cases
Percent
of
GDP
0%
0.-4%
0.-8%
-.12%
-.16%
-.2%
-.24%
-.28%
-.32%
-.36%
-.4%
199000
199500
200000
200500
201000
201500
202000
Global Trading
Annex I Trading
Independent

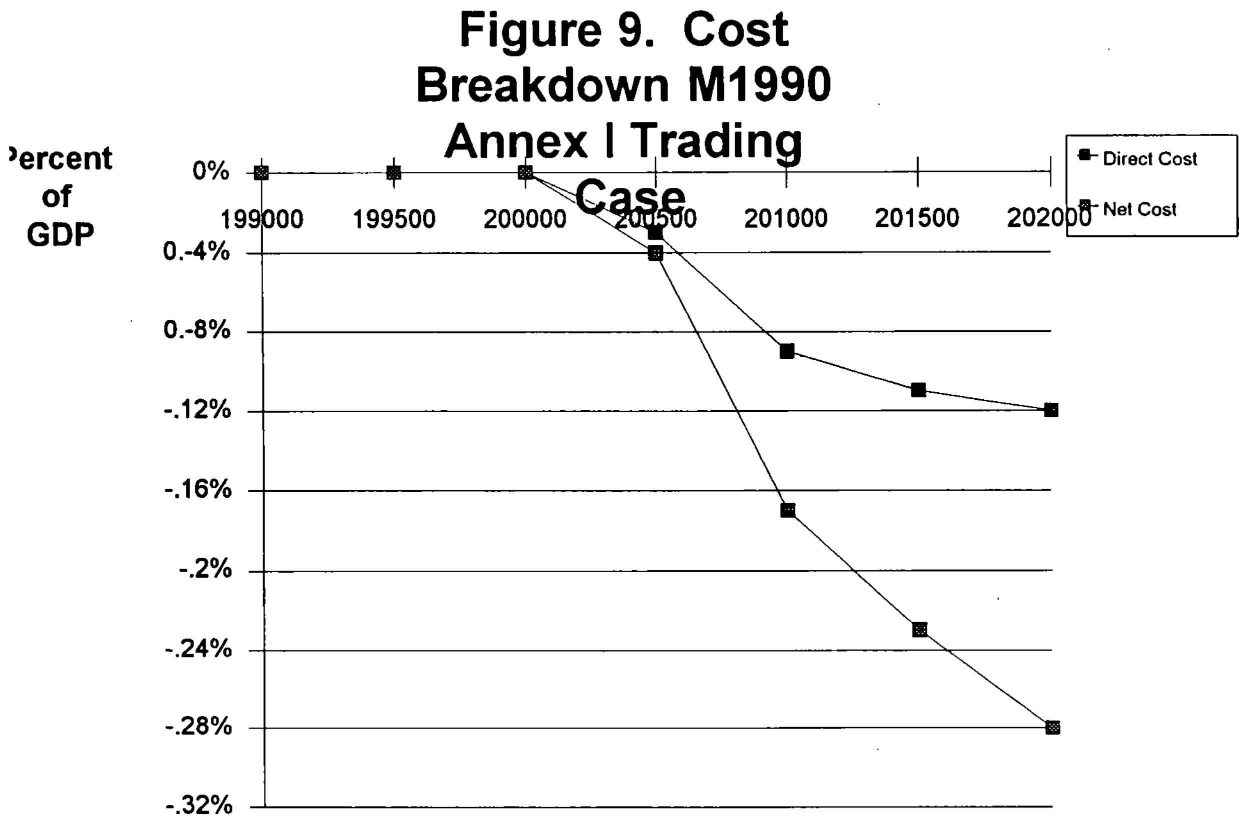


Figure 9. Cost Breakdown M1990 Annex I Trading Case
Percent of GDP
0%
0.-4%
0.-8%
-.12%
-.16%
-.2%
-.24%
-.28%
-.32%
199000
199500
200000
200500
201000
201500
202000
Direct Cost
Net Cost

Figure 10. Permit Prices under Alternative Permit Allocation Methods for EE & FSU: M1990 Annex I Trading Case

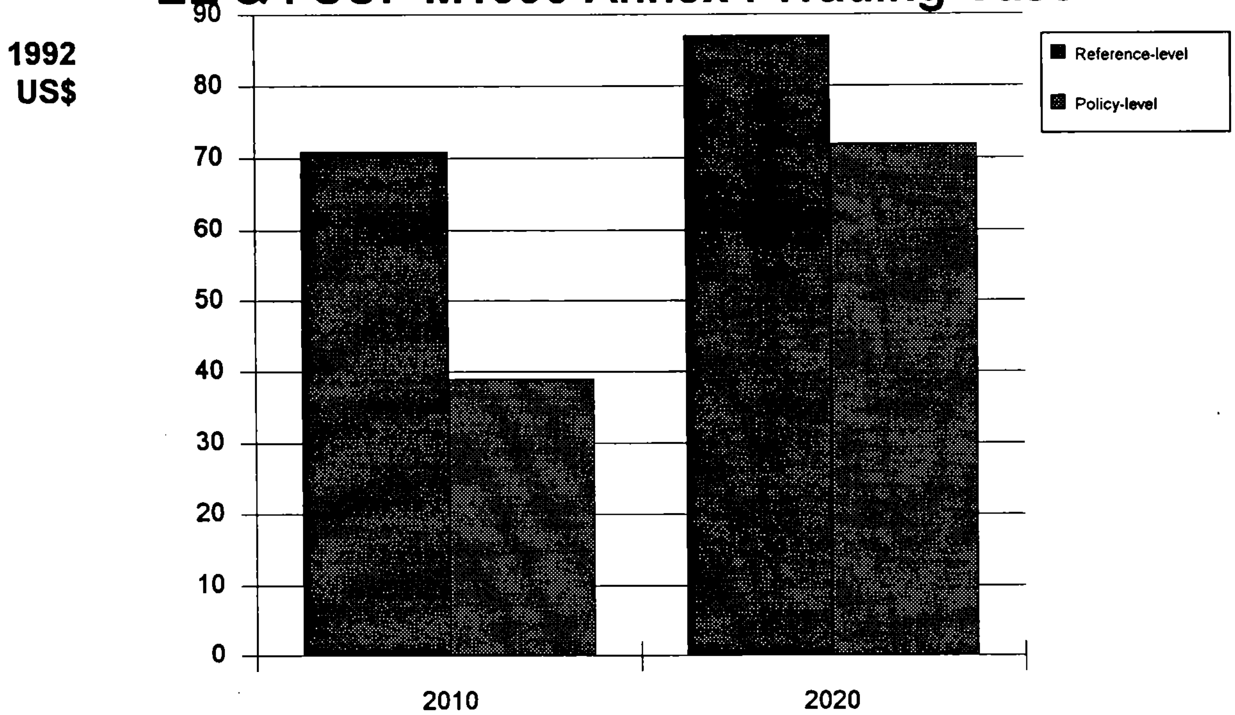


Figure 11. Cost of Emissions Mitigation under Alternative Permit Allocation Methods for EE & FSU – M1990 Annex 1 Trading Case