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[The Economics of Greenhouse Gas Emissions Abatement in China, A Preliminary Analysis] [Binder] [2]

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China has many options for improving efficiency in the energy sector with the continued use of coal. For example, Pressurized Fluidized Bed Combustion (PFBC) achieves thermal efficiency rates of about 40% by operating in combined cycle configurations, using both gas and steam engines. If a PFBC plant of 300 MW displaced a 300 MW pulverized coal plant that was part of China's base load, then 0.18 million metric tons of carbon (MMTC)[3] per year could be abated. Further, Integrated Gas Combustion Cycle (IGCC) is the state of the art in electricity generation from coal. IGCC employs coal gasification along with gas turbines to achieve efficiency rates of 38-45% with SO_2 removal technology in place (Fang 1998). Desulfurization efficiency can reach levels as high as 99%, and the technology can reduce levels of NO_x formation by 25% to 50% when compared to a traditional pulverized coal plant (Government of China 1996). An IGCC plant displacing the same pulverized coal plant discussed above could abate about 0.2 MMTC annually. (1) (2) (3) (4) 1A (5)

China has extensive potential for the development of wind power especially along the coastline and in the north. Large-scale wind projects could directly replace coal plants and can usually start generating electricity within a year of beginning construction. Two examples highlight the potential for wind power. One effort, begun in the 1980s to subsidize rural electrification in Inner Mongolia, has generated 140,000 small systems, employed 15,000 technicians, and fostered 42 Chinese enterprises engaged in wind power development. Another project imported medium scale turbines to create a wind farm in Dabancheng, Xinjiang. Overall, China has about 30 MW of grid-connected wind power in operation (Fang 1998). (6) 1A (7) 1A (8) 1A (9) 1V

In addition to technology investment opportunities in the energy sector, several technologies in industrial sectors could also have potential under the CDM. For example, the direct reduction technique for iron smelting could decrease energy use per unit of output. This process uses gas or liquid fuel and non-coking coal as a reducer to smelt iron. It achieves energy savings of 40-50% over blast furnace methods and can reduce carbon dioxide emissions by 50-60% per ton of steel produced (Government of China 1996). (10) (11) 1A (12) 1A

While the Clean Development Mechanism can serve as an important vehicle for investment and technology transfer, some economists believe that several characteristics of the CDM will cause it to result in fewer economic benefits than a well-functioning international trading system. The process of project review and certification, the adaptation fund, and accounting for administrative expenses will likely increase the transaction costs with a specific CDM project that would not likely occur under an efficient trading system. Further, the project-oriented approach of the CDM may not deliver least-cost abatement first like a tradable permit or tax system. Because of this, some have argued that the CDM will deliver fewer tons of emissions abatement at a given price of carbon than a trading system (MacCracken et al 1999). Indeed, because of the complexity of the CDM, Manne and Richels (13) 1A (14) 1A

3 All data on carbon dioxide emissions are presented in this document in terms of million metric tons of carbon equivalent. One ton of carbon dioxide is equal to 12/44 ton of carbon (this is based on the ratio of the molecular weights of carbon and carbon dioxide). All data on the price of a ton of carbon refer to carbon equivalent.

16 December 1996
ENGLISH/CHINESE ONLY

SUBSIDIARY BODY FOR SCIENTIFIC AND TECHNOLOGICAL ADVICE
Fifth session
Bonn, 25-28 February 1997
Item 7 of the provisional agenda

TECHNOLOGY AND TECHNOLOGY INFORMATION NEEDS

Comments from a Party

Note by the secretariat

By its decision 7/CP.2 (FCCC/CP/1996/15/Add.1), the Conference of the Parties, at its second session, requested the Convention secretariat to give high priority to the development and completion of a survey of the initial technology needs, as well as technology information needs, of Parties not included in Annex I to the Convention, with a view to providing a progress report to the Subsidiary Body for Scientific and Technological Advice at its fourth session. The COP also urged non-Annex I Parties to communicate initial information to the Convention secretariat not later than 1 December 1996 regarding technologies and know-how required to address climate change and its adverse effects that could be compiled by the secretariat into a detailed list of technology needs required by developing country Parties, taking into account that more elaborate technology needs would be included in their initial national communications.

In regard to the latter request, the secretariat has received a submission from China. In accordance with the procedure for miscellaneous documents, this submission is attached and reproduced in the languages in which it was received without formal editing. Any further submissions from Parties will be issued in an addendum to the present document.

In regard to the first request, the secretariat has initiated a survey of the technology needs of 20 Parties not included in Annex I, to obtain preliminary information and to test a survey instrument. The secretariat will provide information on the results of this survey at the fifth session of the SBSTA.

1. Integrated Gasification Combined Cycle

1.1 Technology Name

Integrated Gasification Combined Cycle

1.2 General Characteristics

Integrated Gasification Combined Cycle (IGCC) is an advanced power generation technology. The fundamental of IGCC is uses the cleaning gas produced from gasification and purification as fuel for the turbine, combines the gas turbine with steam turbine. It consists of coal pre-process, coal gasification, gas cleaning, and combined cycle power generation. The main advantages of IGCC are as follows: First, it offers high thermal efficiency, reached from 40 percent to 50 percent is 10 percent higher than of pulverized-coal (PC) fired power generation. The unit coal consumption is 310 gce/kWh. Second, it is relative insensitive to feedstock, allowing all types of coal to be fired. Third, it has a good commercial market.

1.3 Cost Information

The capital cost of early IGCC technology for the Cool Mater plant is much higher, and reached $2,538 /kW. Now for the commercial IGCC plants (500 Mw), the capital cost is approximately $900 /kW. The operating and maintenance cost for this plant amount to about 4 to 4.5 cents/kWh, which design lifetime expected 20 years.

1.4 Environmental Effects

The IGCC plant has low emissions of pollutants, and good environmental characteristics. Its desulphurization efficiency reached from 90 percent to 99 percent used a cleaning measure, and SO_2, NOx and particulate emissions had been controlled. It reduces the formation of NOx to levels from 25 percent to 60 percent lower than that from a conventional PC plant as the same of burning natural gas. Increased thermal efficiencies result in lower carbon dioxide emissions per unit electric generation, is about 0.8 kg/kWh.

(4)

1.5 Market Potential

With the development of society and economy of China, the present thermal power capacity will need to be expanded further. IGCC is an advanced power generation system that combines a higher coal-electricity production of efficiency with clean coal combustion technology. It is anticipated that IGCC technologies have the capacity to

2. Direct Reduction

2.1. Technology Name
Direct reduction

2.2 General Characteristics
The direct reduction technique of producing sponge iron is one of iron-smelting processes, which uses gas or liquid fuel and non-coking coal as energy and reducer, reduces metal iron at the temperature condition that iron ore (or include iron pellet) is solid. Considering the different reducer used, the direct reduction technique can be generally classified into two sub categories: gas-based process and coal-based process. Based on the difference reductive device, it can be divided into vertical furnace process, reaction pot process, fluidized-bed process, and rotary kiln process, etc. The output around the world in 1994 was 28.2 million tons and the average utilization rate of the device was 73 percent The widest processes used in industry now are Midrex and HYL in gas-based process, as well as SL/RN and DAVY's DRC in coal-based process. It was reported that the process used in DAVY's Direct Reduction Plant was rotary kiln, which reduce directly using coal-based as reducer. The metallization rate was 93 percent, iron rate was 96 percent, per ton direct reduction iron consumed 0.425 ton solid carbon, and 90-120 kWh electricity (of which 65 percent in direct reduction plant, 26 percent in material plant, 9 percent was auxiliary consumption). 11

2.3. Cost Information
The first direct reduction iron plant, named Kazuo County's Sponge Iron Smelting Plant in Liaoning province of China, invested 52.92 million yuan, the capacity was 25,000 tons, the average 10000 tons capacity investment was 2117 yuan, this number is $122.87 in Venezuela and $161.20 in Europe.

2.4 Environmental Effects
The energy consumption of the direct reduction technique is low, which is only from 40 percent to 50 percent of that of iron-melting in blast furnace, so it can reduce from 50 to 60 percent CO_2 emissions per ton steel. 12

2.5. Market Potential
The output of electric steel only occupies 22 percent of the whole steel output in China, while this share in developed country has reached from 30 percent to 40 percent, 56 percent in Italy. With the increase of steel accumulating in China, the retrieve amount of scrap steel will be going up, and electricity is relatively plenty, so

ENERGIZING CHINA

Reconciling Environmental Protection and Economic Growth

Edited by

Michael B. McElroy, Chris P. Nielsen, and Peter Lydon

Studies of Phase I of the Harvard University Committee on Environment China Project (1995–1998)

Harvard University Committee on Environment.

Distributed by Harvard University Press.

3

Strategic Options for Reducing CO_2 in China: Improving Energy Efficiency and Using Alternatives to Fossil Fuels

Fang Dong
Tsinghua University

Debra Lew
International Institute for Energy Conservation

Li Ping
DSC Communications Corp.

Daniel M. Kammen
Princeton University

Richard Wilson
Harvard University

Introduction

CHINA'S ECONOMIC GROWTH OVER the past fifteen years has been dramatic, with average annual increases in gross national product (GNP) of over 7%. In the next ten years, average annual growth is expected to remain at least at this level (Ho, Jorgenson, and Perkins, this volume). Associated with this economic expansion will be increased energy use. Table 1 lists the overall energy consumption in China by resource in 1993. We would expect that electricity use would rise faster than total energy use in China, as it has in other countries in comparable phases of their development (Bodansky 1991; Starr 1990; Wilson 1989), and in fact, Chinese leaders have decided to expand electricity production as fast as they can (11% per year in recent years).

In a perspective of concern about CO_2 emissions, it is equally or more important that it has been decided that the expansion of electricity production will be predominantly based on coal. The rapid increase in dematches among parts and equipment imported from different countries. An obstacle lies in the fact that China is unable to manufacture the heavy equipment of a nuclear reactor. Although a few such parts can be bought on the international market, this is a key issue that must be solved if costs are to be reduced by expansion of domestic production.

We conclude that cost, particularly capital financing, is the major restriction to nuclear power development. If costs are to be reduced by a learning curve, we recommend that China decide on one approach (preferably with strong domestic participation) and build several similar reactors. This contrasts with the present broad program with several different foreign and domestic suppliers.

Wind Power

Present situation. Worldwide grid-connected wind power capacity in 1994 was 3.7 GW. Although this is a small fraction of total installed electric capacity, wind power may play a large role in China's energy future for several reasons. In OECD countries, this emerging technology is often estimated to be cost-competitive with coal. If these costs can be transferred to China, especially in places where fossil fuel costs are high, the large demand for electricity in China could result in a rapid expansion of wind development. China has an extremely large wind resource, officially estimated to be 253 GW (Shi 1995). It is likely that use of modern turbines with high (50 meter) hub heights will further increase this potential. Wind power plants can be constructed quickly—typically in less than 7 a year—and part of the plant can be operational and generating revenue while the rest of the plant is being installed. China has extensive experience with small-scale wind turbines and appears to be committed to large-scale development of its wind resources to serve the electricity demand. A goal of 1 GW installed capacity by 2000 has been set.

Wind power has already begun to be exploited in China on the small- and medium-scales since the 1980s for rural electrification. Low-interest loans were given to wind turbine manufacturers and subsidies of 8 250 yuan (200 yuan per turbine and 50 yuan per battery, or about 10% of the system cost) were given to households in Inner Mongolia for the purchase of "wind-charger" systems. This has resulted in 140,000 small wind power systems in China, a domestic wind turbine industry of about forty-two various enterprises, and 15,000 technicians, who are trained in construction, installation, or maintenance of turbines (Zhu 1995). Of those 120,000 turbines that were installed in Inner Mongolia, 85% are reported to be in good condition and 78% in operation (Chen 1993).

TABLE 7
Installed Grid-Connected

Province or Region/Locality
Xinjiang
Dabancheng windfarm 1
Dabancheng windfarm 2
Inner Mongolia
Zhurehe
Shangdu
Guangdong
Nan'ao Island
Hebei
Zhanbei
Liaoning
Donggang
Hengshan (Dalian)
Zhejiang
Shengsi
Dachendao
Cangnan

The total installed capa
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TABLE 7
Installed Grid-Connected Wind Generating Capacity

Province or Region/Locality	MW	Number and Type	Year
Xinjiang			
Dabancheng windfarm 1	2.05	13 × Bonus 150	1989
		1 × Micon 100	1987
Dabancheng windfarm 2	9.9	4 × Bonus 300	1992
		23 × Nordtank/XWGP 300	1992
		4 × Bonus 450	1993
Inner Mongolia			
Zhurehe	4.2	5 × USW 100	1990
		6 × USW 100	1992
		4 × HSW 250	1993
		3 × Nordtank 300	1994
		10 × Bonus/HEEW 120	1994
Shangdu	3.875	5 × FD 15-55/11	1993
		12 × Nordtank 300	1994
Guangdong			
Nan'ao Island	4.7	2 × Nedwind 150	1989
		1 × Nedwind 90	1989
		3 × Nordtank 130	1991
		6 × Nordtank 150	1992
		15 × Nordtank 200	1994
Hebei			
Zhanbei	1.2	4 × Nordtank 300	1994
Liaoning			
Donggang	1.555	5 × Nordtank 300	1994
		1 × FD 55	
Hengshan (Dalian)	1.0	4 × HSW 250	1993
Zhejiang			
Shengsi	0.43	10 × Aeroman 30	1991
		1 × FD 11.2-30	1990
		2 × FD 16-22	1991
		1 × FD 16-22	1977
		1 × FD 16-30	1991
Dachendao	0.205	3 × Bonus 55	1988
		2 × FD 20	
Cangnan	0.055	1 × FD 55	

The total installed capacity of China's small turbines is 8.7 MW and annual production from them is 15.7 GWh (Wu 1995).

However, in order to replace coal power to a significant degree, large-scale grid-connected wind projects are needed. Installed wind power capacity costs about US$1,000 per peak kW. In the late 1980s medium-

TABLE 7 (CONTINUED)
Installed Grid-Connected Wind Generating Capacity.

Province or Region/Locality	MW	Number and Type	Year
Shandong			
Chang Island	0.11	2 × FD 15-55/11	1991
Rongcheng (Malan)	0.165	3 × Vestas 55	1986
Kongdongdao	1.06	1 × Windharvester 60	1988
Fujian			
Pingtan	0.955	4 × WindMaster 200	1986
		1 × FD 16-55	1989
		1 × FD 32-100	1993
Hainan			
Dongfang	0.055	1 × Vestas 55	1986

Note: By 1995, a total of 30.7 MW had been installed.
Source: Davidson 1994; Department of Hydropower and Rural Electrification 1995.

scale turbines were imported and the first MW-scale grid-connected wind farm was established in Dabancheng, Xinjiang. About 30 MW of grid-connected wind power is now operating in China; the details of these wind farms are listed in Table 7. Although the Eighth Five-Year Plan called for the development of the 100 kW turbine, Chinese domestic technology for this medium scale was not yet mature. Therefore, in order to achieve rapid expansion, the first medium-scale turbines and technology were imported. Now joint ventures have been set up between foreign and local companies to transfer the technology and allow cooperative production. For example, Husumer Schiffswerft of Germany has cooperatively produced their 250 kW machines with China's First Tractor and Construction Machinery Corporation. It is reported that the local content of these turbines is 20%, expected to increase to 80% as the Chinese learn to manufacture large turbine components. Ten Bonus 120 kW turbines of Danish design were partially manufactured by Hangzhou Generating Equipment Factory under a technology transfer agreement and installed in 1994 in Zhurehe, Inner Mongolia.

Resources. China is endowed with large wind resources in the north and along the coastline. Figure 3 shows the distribution of wind resources. The total exploitable electric potential capacity has been officially estimated to be 253 GW (Shi 1995). Winds in the northern parts of China are often fairly steady winds with little turbulence and few gales. The land is generally flat, uninhabited grassland which is conduera pacity.

Number and Type	Year
2 × FD 15-55/11	1991
3 × Vestas 55	1986
1 × Windharvester 60	1988
4 × WindMaster 200	1986
1 × FD 16-55	1989
1 × FD 32-100	1993
1 × Vestas 55	1986

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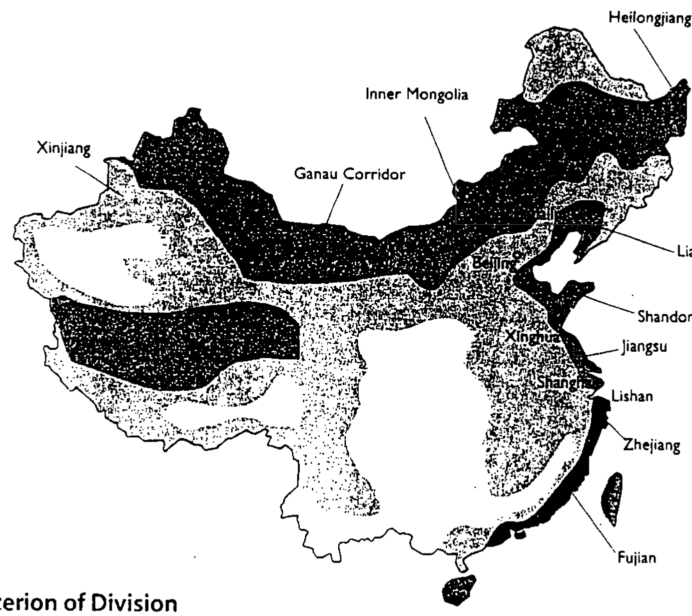
FIGURE 3
Wind Resources in China (1992)



Criterion of Division

	High	Moderate	Marginal	Poor
Wind Potential Region				
Time duration above wind speed of 3 m/s (hrs./yrs)	> 5000	5000–4000	4000–2000	< 2000
Time duration above wind speed of 6 m/s (hrs./yrs)	> 2200	2200–1500	1500–500	< 500
Wind energy density (w/m^2)	> 200	200–150	150–50	< 50

Source: Dai et al. 1992.

cive to easy access and transport of large equipment. This contrasts sharply with the monsoon winds of the southeast coast, which are generally confined to the islands and a strip of land a few tens of kilometers wide along the coastline, although these monsoon winds complement hydropower production, as they are strongest during the dry season when hydro can only operate at 20–25% of its capacity (Shen 1995).

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Note: By 1995, a total of 30.7 MW had been installed.
Source: Davidson 1994; Department of Hydropower and Rural Electrification 1995.

9

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The Economics of the Kyoto Protocol

*Christopher N. MacCracken, James A. Edmonds, Son H. Kim and Ronald D. Sands**

In this paper we use the Second Generation Model to 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. Our analysis shows that the cost of implementing the Protocol in the United States can vary by more than an order of magnitude. The marginal cost in 2010 could be as low as $26 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 mitigation obligations are not adequately anticipated by decision-makers.

INTRODUCTION

The Kyoto Protocol was completed on the morning of December 11, 1997, following more than two years of 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 150 delegations. Because the document is complex, its implications are not immediately obvious. If it enters into force, the Kyoto Protocol could have far-

The Energy Journal, Kyoto Special Issue.

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The Pacific Northwest National Laboratory is operated for the U.S. Department of Energy by Battelle Memorial Institute under contract DE-AC06-76RLO 1830. The views and opinions of the authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

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 create certified emission reduction credits beginning in the year 2000, and these credits can be applied to the 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.

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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 as well as 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 permit price just large enough to meet the global emissions target.

Non-Annex I regions are not required to constrain their emissions in the global trading scenario. 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 only reduce their emissions by an amount equal to the number of permits they wish to sell.

Expanding the supply of emissions mitigation through global permit trading results in significantly lower permit prices than those achieved under the

mo htly constrained
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The Kyoto Protocol: A Cost-Effective Strategy for Meeting Environmental Objectives?

Alan S. Manne and Richard G. Richels***

This paper has three purposes: 1) to identify the near-term costs to the United States of ratifying the Kyoto Protocol; 2) to assess the significance of the Protocol's "flexibility provisions"; and, 3) to evaluate the Kyoto targets in the context of the long-term goal of the Framework Convention. We find that the short-term U.S. abatement costs of implementing this Protocol are likely to be substantial. These costs can be reduced through international trade in emission rights. The magnitude of the costs will be determined by the number of countries participating in the trading market, the shape of each country's marginal abatement cost curve, and the extent to which buyers can satisfy their obligation through the purchase of emission rights. Finally and perhaps most important: unless the ultimate concentration target is well below 550 ppmv, the Protocol seems to be inconsistent with a long-term strategy for stabilizing global concentrations.

INTRODUCTION

The Kyoto Protocol represents a milestone in climate policy.[1] For the first time, negotiators have attempted to lay out emission reduction targets for the early part of the 21st century. The goal is for Annex 1 (developed countries plus economies in transition) to reduce their aggregate anthropogenic carbon dioxide equivalent emissions by at least 5 percent below 1990 levels in the commitment period 2008 to 2012. The Protocol, however, has yet to enter into force. To do so will require ratification by 55 countries representing 55 percent of total Annex 1 CO_2 emissions in 1990.

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1. Conference of the Parties (1997). "Kyoto Protocol to the United Nations Framework Convention on Climate Change," Third Session Kyoto, 1-10 December.

shall define the relevant principles, modalities, rules and guidelines ..."[7] Similar ambiguity surrounds the Clean Development Mechanism. Again, the elaboration of "modalities and procedures" is left to a future meeting of the Conference of the Parties.[8]

In this section, we explore three scenarios: 1) no trading, 2) Annex 1 trading plus CDM, and 3) full global trading. These three options are representative of alternative implementations of the Kyoto Protocol. Each has its own advocates and opponents, but we do not consider them equally likely. In our opinion, there is little likelihood of enticing all major countries to participate in a global market in emission rights during the initial commitment period (2008-2012).

The full global trading scenario represents an upper bound on the CDM's potential to reduce GDP losses. In calculating the potential size of the contribution from a CDM, we therefore calculate this upper bound on the export of emission rights from non-Annex 1 regions. Because of the difficulties in implementation of the CDM, however, we assume that only 15 percent of the potential would be available for purchase through this mechanism. This is a highly subjective estimate. Given the complexities of the CDM, however, we are not inclined to assign a higher value

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Figure 2 reports the incremental value of carbon emission rights to the US in 2010 and 2020. We focus first on 2010. In the most constrained scenario, the US must satisfy its emission reduction requirements within its own geographical boundaries. In this case, the value of emission rights approaches $240 per ton. With Annex 1 trading plus CDM, the value drops to slightly less than $100 per ton. As might be expected, the value of emission rights is lowest with full global trading. Here, it falls below $70 per ton.

For the two scenarios in which trading is permitted, the value of emission rights increases in 2020. This is because EEFSU's projected emissions lie below its negotiated constraint for 2010. It has been allocated more emission rights than it needs to satisfy its internal obligations. By 2020, however, EEFSU's economic growth is expected to be such that it no longer enjoys an excess of emission rights. As a result, there is more competition for emission rights in the international marketplace, and there is an increase in their price.

7. Conference of the Parties (1997). "Kyoto Protocol to the United Nations Framework Convention on Climate Change."

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(1999) assumed that a developing country would be able to generate emissions abatement through the CDM equal to 15% of what it would abate at the same carbon price in an international emissions trading system. See p. 13

C. International Emissions Trading

A variety of international energy-economic models have been used to evaluate the potential economic implications of the Kyoto Protocol. For example, the Stanford University Energy Modeling Forum coordinated a modeling comparison exercise involving 13 models developed by teams in Europe, the United States, Asia, and Australia. (1) 14 Further, the Organisation for Economic Cooperation and Development (OECD) hosted a workshop in 1998 where ~~9 modeling teams~~ ~~presented their~~ 16 papers with assessments of the Kyoto Protocol. were presented (2) 14

These models assess the projected marginal cost of abating carbon dioxide across countries and then estimate the extent of buying and selling in an international emissions market until no further economic gains can be achieved through additional trades – i.e., they find the market clearing price for an emissions allowance. For estimating the marginal cost within a country, most of these models evaluate a country's potential emissions abatement by assuming that such abatement occurs at least-cost. In the case of China, these models depict energy technologies – in terms of energy production, carbon emissions, and costs characteristics – across various sectors and they evaluate how firms modify their investment and consumption decisions in these technologies in response to the cost of emitting a ton of carbon. This incentive – pricing carbon emissions – could be provided through a carbon trading system, analogous to the U.S. sulfur dioxide trading system, or through a carbon tax system, analogous to some of China's current pollution discharge fees (Panayotou 1998). (3) 14 Such a policy approach would provide the incentive to attract greenhouse gas-efficient technologies like those discussed in the CDM section above, but at a higher volume than would be expected under the CDM. These models can then provide estimates of marginal cost (e.g., price of one ton of carbon abatement), emissions abatement by country, capital transfers by country, and measures of total economic costs or benefits.

In scenarios involving non-Annex I countries, these models assume that developing countries adopt emissions targets set at estimated 2010 business as usual emissions levels and participate in international trading. (4) 14 Figure 5 presents results from 12 models that participated in the Stanford University Energy Modeling Forum Kyoto Protocol exercise (EMF-16).

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INTRODUCTION AND OVERVIEW

*John P. Weyant and Jennifer N. Hill**

This Special Issue of *The Energy Journal* represents the first comprehensive report on a comparative set of analyses of the economic and energy sector impacts of the Kyoto Protocol on Climate Change. Organized by the Stanford Energy Modeling Forum (EMF), the objectives of this study were the same as for previous EMF studies: (1) identifying policy-relevant insights and analyses that are robust across wide ranges of models, (2) providing explanations for differences in results from different models, and (3) identifying high priority areas for future research. This study has produced a particularly rich set of results in all three areas, which is a tribute to the active participation of the modeling teams and the care each team took in preparing a paper for this volume.

The volume consists of a paper prepared by each modeling team on what it did and what it concluded from the model runs that were undertaken, proceeded by this introduction and summary paper. This summary focuses on the motivation for the study, the design of the study scenarios, and the interpretation of results for the four core scenarios, which all the teams ran. Each succeeding chapter contains ideas and insights drawn by the modeling teams from applying their models to issues they were able to address selected from a small set of important areas on which the group had mutually agreed to focus.

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The studies of the Energy Modeling Forum are sponsored by the U.S. Department of Energy, the U.S. Environmental Protection Agency, the Electric Power Research Institute, Mitsubishi Corporation, the New Energy and Industrial Technology Development Organization of Japan, and about 20 corporate affiliates. Besides the authors of the other papers in this volume, we would especially like to thank Campbell Watkins for his enthusiasm about the idea of doing this special issue and his insightful advice at each step in the production process. In addition, we would like to thank Geoff Pearce of the Energy Journal and Dave Williams of the IAEE for going above and beyond the call of duty in making this special issue a reality.

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1. Conference of the Parties (1997). "Kyoto Protocol to the United Nations Framework Convention on Climate Change," Third Session Kyoto, 1-10 December.

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The Economics of the Kyoto Protocol

*Christopher N. MacCracken, James A. Edmonds, Son H. Kim and Ronald D. Sands**

In this paper we use the Second Generation Model to 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. Our analysis shows that the cost of implementing the Protocol in the United States can vary by more than an order of magnitude. The marginal cost in 2010 could be as low as $26 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 mitigation obligations are not adequately anticipated by decision-makers.

INTRODUCTION

The Kyoto Protocol was completed on the morning of December 11, 1997, following more than two years of 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 150 delegations. Because the document is complex, its implications are not immediately obvious. If it enters into force, the Kyoto Protocol could have far-

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3

Adjustment Time, Capital Malleability and Policy Cost

*Henry D. Jacoby and Ian Sue Wing**

The cost of meeting Kyoto-style emissions reductions is heavily dependent on the malleability of an economy's stock of capital and the number of years available for adjustment. Each year of delay introduces more emission-producing activities that must be squeezed out of the system and shortens the time horizon for change, raising the carbon price required to produce the needed changes in capital structure. The MIT Emissions Prediction and Policy Assessment model is used to explore the effects of uncertainty in the degree of capital malleability in the short run, and to analyze how implied carbon prices vary depending on the time of credible commitment to emissions targets.

INTRODUCTION

Emissions reductions of the magnitude foreseen in the Kyoto Protocol would require large changes in the structure of production and consumption in Annex I countries, a challenging task even if attempted over a period of decades. With each succeeding year of dispute, deliberation and negotiation, the window to achievement of these proposed targets progressively closes. The shorter the time period over which the control task would be undertaken the higher the expected short-run cost, until at some point the targets lose credibility even with strong political commitment. One key influence on the level of difficulty is the rate at which the capital stock can be either replaced or retrofit, in order to sustain economic activity with a less carbon-intensive input mix.

For analysis of greenhouse gases, especially CO_2, our focus naturally is on energy as an input to economic activity, and in particular on the various forms of fossil energy. Energy is not used by itself, of course, but in the form of energy services supplied with the aid of some capital device. To some degree these two inputs can be substituted for one another in providing these services (e.g., a more costly but more efficient air conditioner). Further substitution is possible among the various sources of primary energy (oil, gas, coal, nuclear,

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Requiem for Kyoto:
An Economic Analysis of the Kyoto Protocol

William D. Nordhaus and Joseph G. Boyer***

This paper uses the newly developed RICE-98 model to analyze the economics of the Kyoto Protocol. It analyzes versions of the Kyoto Protocol that have different approaches to trading emissions rights and compares these with efficient approaches. The major conclusions are: (a) the net global cost of the Kyoto Protocol is $716 billion in present value, (b) the United States bears almost two-thirds of the global cost; and (c) the benefit-cost ratio of the Kyoto Protocol is 1/7. Additionally, the emissions strategy is highly cost-ineffective, with the global temperature reduction achieved at a cost almost 8 times the cost of a strategy which is cost-effective in terms of "where" and "when" efficiency. These conclusions assume that trading in carbon permits is allowed among the Annex I countries.

1. CLIMATE-CHANGE POLICY AND THE KYOTO PROTOCOL

Governments have struggled to find policies that can at the same time satisfy the demands of electoral politics and meet the needs for responsible stewardship of the globe. The initial response of nations to the threat of global warming was the Framework Convention on Climate Change (FCCC), which issued from the Rio Summit of 1992. Under the FCCC, Annex I countries (high-income nations plus the former Soviet Union and Eastern European countries) committed on a voluntary basis to limit their concentrations of greenhouse gases (GHGs) to 1990 levels. This commitment left open almost all the important questions, such as the environmental, economic, and political components of such a commitment.[1]

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Kyoto, Efficiency, and Cost-Effectiveness: Applications of *FUND*

*Richard S.J. Tol**

In this paper various emission reduction scenarios are evaluated with FUND—the Climate Framework for Uncertainty, Negotiation, and Distribution model. The aim is to help international negotiators improve upon the Kyoto Protocol. International cooperation in greenhouse gas emission reduction is important, and the more of it the better. The emission reduction targets as agreed in the Kyoto Protocol are irreconcilable with economic rationality. If the targets nevertheless need to be met, it is better to start emission reduction sooner than later in order to minimise costs. Methane emission reduction may be an important instrument to reduce costs.

INTRODUCTION

The Kyoto Protocol signifies the first serious attempt of the international community to take concrete action on greenhouse gas emission reduction. Time will tell whether the attempt will be a successful one. This paper looks at some of the economic implications of the agreement, and sheds some light on the issues unresolved in the Kyoto Protocol. It thus hopes to inform the negotiations on extending and refining the Kyoto Protocol. The first opportunity for this was in Buenos Aires, at the end of 1998, but little progress was made there.

The analyses in this paper are based on the *Climate Framework for Uncertainty, Negotiation, and Distribution (FUND)*, an integrated assessment model of climate change (Tol, 1997, 1998). Section 2 presents the model. Weyant et al. (1996) classify *FUND* as a policy-optimization model, that is, a model which selects the best policy strategy given certain constraints. In this paper, however, the constraints (inspired by the Kyoto Protocol) are so strict that there is often little room for (assumed) preferences to play a substantial

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Analysis of Carbon Emission Stabilization Targets and Adaptation by Integrated Assessment Model

Atsushi Kurosawa, Hiroshi Yagita, Weisheng Zhou, Koji Tokimatsu** and Yukio Yanagisawa****

This paper proposes a new framework for integrated assessment models of global environmental issues, including energy, climate, land use, macroeconomics, and environmental impacts. We conducted simulations on carbon emission stabilization in regions specified at the Third Conference of the Parties to the United Nations Framework Conventions on Climate Change (UNFCCC/COP3). Adaptation strategies including technology choice, conservation and carbon emission certificate trade are evaluated. We find that carbon certificate trade is potentially effective in averaging relative impact in macroeconomic activity.

INTRODUCTION

It is difficult to find a fundamental solution for global climate change issues, although experts in environmental science and policy-making discuss international agreements. Integrated assessment studies for evaluating comprehensive strategies are conducted by combining interdisciplinary knowledge such as climate change, energy, land use, etc. (IPCC, 1996). Integrated assessment can be summarized by three key terms, namely, "interdisciplinary characteristics," "uncertainties" and "long-term aspects." Mitigation and adaptation of climate change impacts are interdisciplinary by nature. If we take a simple example, global circulation of the atmosphere and

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Clubs, Ceilings and CDM: Macroeconomics of Compliance with the Kyoto Protocol

Johannes Bollen, Arjen Gielen**, and Hans Timmer****

The Kyoto Protocol suggests that imposing restrictions on emission trade among Annex I countries may force domestic action in each country. The Protocol also mentions the Clean Development Mechanism (CDM) as an instrument to extend trade to countries outside Annex I. We analyze both restrictions on and extensions of permit trade among Annex I countries. We use the applied general equilibrium model WorldScan in this analysis. We show that, compared to unrestricted trade, the USA tends to gain from restrictions on emission trade while other OECD countries are likely to be harmed. We further show that restrictions probably do not prevent so-called hot air in the former Soviet Union from being used. On the contrary, restrictions tend to increase global emissions. Finally, we conclude that CDM can be an efficient option to reduce abatement costs, but certain conditions should be fulfilled to avoid severe carbon leakage.

INTRODUCTION

The Kyoto Protocol was adopted during the third Conference of Parties to the Framework Convention on Climate Change (FCCC) in December 1997. The Protocol defines commitments for Annex I Parties (OECD countries and Economies in Transition) to reduce their overall greenhouse gas emissions by on average 5.2% below their 1990 levels in the five years after 2008. The commitments differ among the Annex I Parties—each party has a different level of so-called 'Assigned Amounts' (AA's) of greenhouse gas emissions. The EU committed to 8%, the USA to 7% and Japan to 6%, while Australia, Norway and Iceland committed to levels about 1990 emissions and New Zealand

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Analysis of Post-Kyoto Scenarios: The Asian-Pacific Integrated Model

Mikiko Kainuma, Yuzuru Matsuoka** and Tsuneyuki Morita**

The AIM/top-down model is a recursive general equilibrium model used to analyze the post-Kyoto scenarios presented by EMF16. Differences among scenarios mainly arise from the setting of emission trading. Japan's marginal cost is the highest among the Annex I countries except New Zealand, where a relatively high emission reduction is necessary, while the highest GDP loss is observed in the USA in 2010 in the no trading case. The marginal costs are much less in the global trading case. The countries of the former Soviet Union sell emission rights and the USA buys the largest amount of them. Emission reductions by trading will account for a large part of the total emission reductions if there is no restriction on trading. The GDP gain of the former Soviet Union is the largest in 2010 in the trading cases. The GDP change in Middle East Asia is negative, and reaches the highest level in the no trading case. Carbon leakage is particularly observed in the no trading case.

INTRODUCTION

The Asian-Pacific Integrated Model (AIM) estimates the emission and absorption of greenhouse gases in the Asia-Pacific region and judges their impact on the natural environment and socio-economy. It aims to contribute to policymaking with respect to global warming and its evaluation.

The AIM model consists of a greenhouse gas emissions model (AIM/emission) that forecasts the amount of anthropogenic greenhouse gas emissions, a warming phenomenon model (AIM/climate) that forecasts the concentration of greenhouse gases in the atmosphere and estimates the temperature increase, and a warming impact model (AIM/impact) that estimates the influence that climate change has on the natural environment and socio-economy of the Asia-Pacific region (Matsuoka et al. 1995).

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Effects of Restrictions on International Permit Trading: The MS-MRT Model

Paul M. Bernstein, W. David Montgomery*, Thomas F. Rutherford** and Gui-Fang Yang**

This paper assesses the economic impacts of carbon abatement programs proposed under the Kyoto protocol: the distribution of economic burden across countries and regions, the implications for international competitiveness, and the consequences of international permit trading. Our analysis is based on a dynamic global trade model which accounts for systematic differences in the energy efficiency of production in industrial and developing countries. Emission limits adversely affect the welfare of industrial and some developing countries, including all of the oil-exporting countries. Imports from Annex-B countries become more costly while demand for most developing country exports is reduced. Oil prices simultaneously fall, so the net impact on oil-importing developing countries is ambiguous. Energy-intensive industries have a strong economic incentive to relocate production to low-energy cost developing countries. Global trading in emission rights provides the lowest cost path to Kyoto, but it is unclear whether there are incentives for all non-Annex B countries to participate.

INTRODUCTION

The Kyoto Protocol, signed in December 1997 but not yet ratified by a majority of countries including the United States, defined the next steps to be taken to reduce global greenhouse gas emissions. It also left unsolved a wide range of questions about the future course of climate change policy. The Protocol calls for the majority of industrialized countries to limit their emissions of greenhouse gases by the first decade of the next century, and includes several "flexibility mechanisms" that could significantly reduce costs for some countries. Developing Countries undertook no commitments to limit their

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The Kyoto Protocol: An Economic Analysis Using GTEM

*Vivek Tulpulé, Stephen Brown, Jaekyu Lim, Cain Polidano, Hom Pant and Brian S. Fisher**

In this paper ABARE's Global Trade and Environment Model (GTEM) is used to analyse the potential of international emissions trading as a mechanism for helping to achieve the abatement commitments agreed to in the Kyoto Protocol. The prospect of two emission trading blocs, one consisting of the European Union and eastern Europe and the other consisting of many of the remaining Annex I regions, is also considered. The analysis shows that the carbon penalty varies significantly across regions when no emissions trading is allowed. In aggregate, the cost of abatement to Annex I regions falls with emissions trading. Under the assumption of the two trading blocs, the carbon penalty in the European bloc is higher than with full Annex I trading. The paper also considers the impact on developing countries and the role of carbon leakage in determining the economic impacts on Annex I regions.

INTRODUCTION

Negotiations for the Kyoto Protocol to the UN Framework Convention on Climate Change concluded on 11 December 1997. Parties listed in Annex I to the protocol agreed to reduce their aggregate greenhouse gas emissions to at least 5.2 percent below 1990 levels over the commitment period 2008-12. Significantly, the use of so-called 'flexibility mechanisms' that could reduce the economic costs of achieving emission reduction targets was agreed to in the protocol. These mechanisms include: joint implementation (Article 6), the clean development mechanism (Article 12) and international emissions trading (Article 17). While the Kyoto Protocol provides a legal basis for the introduction of such mechanisms, negotiations are now underway to determine the principles and guidelines that could govern their implementation.

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The authors are grateful to John Weyant, Kate Woffenden and Jennifer Noel Hill for helpful comments and suggestions.

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Emissions Trading, Capital Flows and the Kyoto Protocol

Warwick J. McKibbin, Martin T. Ross**, Robert Shackleton** and Peter J. Wilcoxen****

We use an econometrically estimated multi-region, multi-sector general equilibrium model of the world economy to examine the effects of the tradable emissions permit system proposed in the 1997 Kyoto Protocol, under various assumptions about the extent of international permit trading. We focus, in particular, on the effects of the system on international trade and capital flows. Our results suggest that consideration of these flows significantly affects estimates of the domestic effects of the emissions mitigation policy, compared with analyses that ignore international capital flows.

INTRODUCTION

As part of an effort to reduce global emissions of greenhouse gases (GHGs) that are expected to contribute to a significant warming of the earth's climate, the Kyoto Protocol to the United Nations Framework Convention on Climate Change, signed in Kyoto in December 1997, includes binding GHG emissions targets for the world's industrial economies ("Annex I" countries) for the period 2008-2012. The Protocol also provides for international trading of emission allowances among the countries that accept binding targets, in recognition of the theoretical efficiency benefits of allowing emission reductions

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The views expressed in this paper are those of the authors and should not be interpreted as reflecting the views of the organizations with which they are affiliated.

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The Economic Implications of Reducing Carbon Emissions

A Cross-Country Quantitative Investigation using the Oxford Global Macroeconomic and Energy Model

*Adrian Cooper, Scott Livermore, Vanessa Rossi, Alan Wilson and John Walker**

This paper presents the results of a series of simulations analysing the implications of measures to reduce carbon emissions in Annex 1 countries, conducted using the Oxford Global Macroeconomic and Energy Model. It shows that the GDP costs of reducing carbon emissions vary significantly across countries and that the cost depends on a number of critical factors including energy intensity, the rise in emissions in the base case and the amount of coal used especially in electricity generation. Moreover, it illustrates that a combination of macroeconomic rigidities and monetary policy responses to higher energy prices means that the output losses are likely to be substantial in the years immediately following the introduction of a carbon tax or similar emissions abatement policy.

INTRODUCTION

This paper reports the results of a series of simulations analysing the implications of measures to reduce carbon emissions in Annex 1 countries, conducted using the Oxford Global Macroeconomic and Energy Model. It is organised as follows. In section I we define some of the key economic concepts in the global warming debate and outline the theory behind abatement costs. We also describe how these economic concepts are embedded in the Oxford Model, and illustrate their importance by means of numerical simulations. In Section II we present quantitative analysis of the_GDP costs of meeting the emissions reduction targets agreed under the Kyoto Protocol, under a variety of policy options:

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CO_2 Emissions Control Agreements: Incentives for Regional Participation

Stephen C. Peck and Thomas J. Teisberg***

This paper explores the incentives for participation in international CO_2 control agreements using tradable emission permits. We employ a welfare analysis in a two-region model to explore these incentives. The two regions are Annex-I (A-I) and Non-Annex I (Non-A-I). A key insight underlying the analysis is that emission permit allocations must not depart too far from optimal emissions paths, to avoid creating future incentives to drop out of the agreement. We find a range of permit allocations that improves the welfare of both the Annex-I and the Non-Annex I, and compare them with allocations based on regional population or GDP. In addition, we examine the implications of the Kyoto agreement in the context of this welfare analysis. We find that the Kyoto agreement transfers wealth from A-I to the Non-A-I, while failing to realize the efficiency gains to be hoped for from an agreement to control CO_2 emissions.

INTRODUCTION

In this paper, we use a version of the CETA model to consider the implications of alternative rules for allocating tradable emission permits between two regional aggregations of the world. The two regional aggregations are the Annex I countries (A-I) and the Non-Annex I countries (Non-A-I). Alternative rules for allocating tradable emission permits produce different distributions of the net benefits of emission control between these two regions. Of particular interest are rules that provide higher net benefits to both regions than would be achieved in the absence of an agreement to control emissions; we refer to such rules as being in the "bargaining range." If the allocation rule of an agreement is in the bargaining range, then the agreement is more likely to be signed in the first place and more likely to be upheld over time. Conversely, if the rule is not in the bargaining range, there is no reason to expect the agreement to be signed or to expect it to last, if it is signed.

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Economic Modelling of Climate Change

OECD Workshop Report

Held at OECD Headquarters, 17-18 September, 1998

The ideas expressed in this volume are those of the authors and not necessarily those of the OECD or its Member countries.

ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT
PARIS, FRANCE

- Other greenhouse gases are specifically included in the agreement. They include methane, nitrous oxide, HFCs, PFCs, and SF_6.

- Allowance for emission credits through carbon sink enhancement.

- Ability of regional groups to cooperate to achieve targets through the concept of bubbles.

- Explicit introduction of mechanisms to achieve cost-efficient GHG reductions among the different Annex I countries, namely joint implementation (JI), and international trading of emission permits.

- Introduction of a mechanism for cooperation with non-Annex I countries, namely the clean development mechanism (CDM).

While some of these options have been the focus of past quantitative analyses, particularly regional bubbles and international emission trading, other features have received relatively little or no treatment. Most research groups are taking a two-pronged approach in their analysis of the Kyoto Protocol. The first and short term approach is to use existing tools to undertake a quick, yet incomplete analysis of the implications of the Protocol. In a second phase, existing tools will be modified to take on board the various new facets of the Protocol, and provide a better picture of its implications. Eventually, analysis of these new features can play a crucial role in the forthcoming negotiations on the precise implementation of the Protocol.

The OECD plays a notable role in the climate change debate. Different parts of the OECD (and its affiliates—the IEA and NEA) have studied various aspects related to climate change—for example, greenhouse gas inventories, new technologies, implementation mechanisms, and economic assessment. The latter was mostly undertaken in the OECD Economics Department and relied largely on the development and use of the GREEN model. The signing of the Kyoto Protocol has been a catalyst to renew the study of the economic impacts of policies to deal with GHG reductions. As part of the first phase of this new program, a workshop composed of modeling teams located in various OECD Member countries was organized to share recent results.[2] It was held at OECD headquarters in Paris on 17-18 September, 1998. The purpose of the workshop was three-fold: 2

- Review the state of the art of the economic modeling of climate change, including top-down versus bottom-up approaches[3], and integrated assessment models (IAM).

- Compare current analyses of the Kyoto Protocol, focusing, whenever available, on some of the specific features of the Protocol, for example, non-CO_2 GHGs, and the new mechanisms.

- Discuss longer term climate change issues, so-called "beyond Kyoto", for example the future role of non-Annex I countries, and the compatibility of the Kyoto Protocol with long-term stabilization of atmospheric GHG concentration.

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2 The agenda is provided in the annex to this summary.

3 Top-down models are broadly based on economic theory. They have varying levels of detail, but typically represent economies with sufficient structural detail to capture the main interactions between energy markets and the remainder of the economy. Bottom-up models are broadly based on energy-based technology models. They model the energy side of an economy with significant detail. At their origin, they had limited inclusion of other sectors of the economy. More recent bottom-up models are more inclusive of the rest of the economy (so-called E3 models—energy, economy, and environment).

(2)

TESTIMONY OF DR. JANET YELLEN
CHAIR, COUNCIL OF ECONOMIC ADVISERS
BEFORE THE
U.S. SENATE
COMMITTEE ON ENERGY AND NATURAL RESOURCES

MARCH 25, 1999

Thank you, Mr. Chairman. I appreciate having this opportunity to discuss with you the economics of climate change and the Administration's efforts to address this significant environmental challenge. As you know, the Administration released a report last July, entitled "The Kyoto Protocol and the President's Policies to Address Climate Change: Administration Economic Analysis." The report states that, in the Administration's view, the costs of achieving our Kyoto target would be modest if we can succeed in implementing international trading, joint implementation, and the Clean Development Mechanism in an efficient manner and we achieve meaningful developing country participation. In addition, since the 1997 Kyoto Conference, a variety of research on the economics of Kyoto, and especially on the economics of Kyoto's flexibility mechanisms, has been undertaken. Today, I will provide a brief summary of the Administration's Economic Analysis and review several of the key findings in the recent economic literature on climate change.

The Potential Impact of Climate Change

The Intergovernmental Panel on Climate Change (IPCC) concluded in 1995 that "the balance of evidence suggests that there is a discernible human influence on global climate." Current concentrations of greenhouse gases have reached levels well above those of preindustrial times. If growth in global emissions continues unabated, the atmospheric concentration of carbon dioxide (CO_2) will likely double relative to its preindustrial level by midway through the next century and continue to rise thereafter. As a result of the increased concentration of CO_2, the IPCC estimates that global temperatures will increase by between 2 to 6 degrees Fahrenheit in the next 100 years, with a best guess of about 3.5 degrees Fahrenheit. Potential consequences associated with this shift in climate include a rise in sea levels, greater frequency of severe weather events, shifts in agricultural growing conditions from changing weather patterns, threats to human health from increased range and incidence of diseases, changes in availability of freshwater supplies, and damage to ecosystems and biodiversity. Further discussion of the costs of climate change is contained in the Administration Economic Analysis.[1]

[1] Please refer to the attached paper copy or http://www.whitehouse.gov/WH/New/html/kyoto.pdf for a PDF version of this document.

Recent Research on the Economics of Climate Change

Since December 1997, many economists have conducted and made available their analyses of the Kyoto Protocol. I have noted in previous appearances before Congressional Committees that there are limitations to relying on one or a small set of models and that we were eager to see assessments of the Kyoto Protocol by other models. Two large efforts have been undertaken to coordinate and compile modeling results on the Kyoto Protocol. First, the Stanford University Energy Modeling Forum (EMF), a long-running model comparison exercise involving many of the leading climate and energy models, has coordinated full scale analyses of the Kyoto Protocol. Second, the Organisation for Economic Co-operation and Development (OECD) held an economic modeling workshop this past fall, and has since published the proceedings of this workshop which includes 16 papers.[i] In addition, several research teams have undertaken work in evaluating the potential for intergas trading and the cost-savings of a six-gas target relative to a carbon dioxide-only target. I would like to take this opportunity to provide an overview of this recent research.

Kyoto Modeling Analyses

The Energy Modeling Forum comparison exercise of the Kyoto Protocol has included ten modeling teams from the United States, Europe, and Asia. In evaluating the Kyoto Protocol, all of the participating teams used economic models that incorporate the potential for international trading in greenhouse gas permits. The OECD workshop included presentations by 10 modeling teams, 9 of which had global models as well.[3,4] By explicitly incorporating international trading, these models can evaluate the opportunities for cost-savings through trading among Annex I nations and among Annex I and developing countries were they to adopt emissions targets. Since the Kyoto Protocol enables all countries with emissions targets to trade emissions allowances among other countries with targets, these models are well-suited to assess the economic implications of the international trading component of the agreement.

While the models used in the EMF exercise and the OECD workshop can assess international trading, there are several other flexibility mechanisms of the Kyoto Protocol that they cannot, at present, readily assess. For example, these models did not incorporate the effects of sinks. While several modelers did assess the economic costs of achieving the Kyoto targets with "off-line" assumptions about sink activity, none incorporated an integrated energy-land use model. Further, most of the modelers did not evaluate opportunities to reduce costs by trading across greenhouse gases. These models are primarily energy models and are focused on the economics of reducing carbon emissions from fossil fuel combustion. Again, some modelers

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[3] Please note that several modeling teams participating in the EMF exercise made presentations at the OECD workshop.

[4] PDF-formatted files of the OECD workshop proceedings can be downloaded from the OECD webpage at http://www.oecd.org//dev/news/Environment/Modelling.htm.

3

ENERGIZING CHINA

Reconciling Environmental Protection and Economic Growth

Edited by
Michael B. McElroy, Chris P. Nielsen,
and Peter Lydon

Studies of Phase I of the
Harvard University Committee on Environment
China Project (1995–1998)

Harvard University Committee on Environment.

Distributed by Harvard University Press.

13

The Effectiveness and Efficiency of Environmental Policy in China

Theodore Panayotou
Harvard Institute for International Development

Introduction

THE PRE-REFORM ERA IN CHINA before 1978 was marked by forced industrialization, emphasis on heavy industry, and general environmental neglect. That command economy has left a legacy of poor environmental conditions, an energy-intensive industrial structure, and large point sources of pollution. Unlike the reforming economies of Eastern Europe and the former Soviet Union, which experienced industrial contraction and associated pollution reduction on the order of 25–50% with the introduction of market reforms, China has recently registered unprecedented rates of economic and industrial growth. Nonetheless, China also experienced a significant reduction in energy use intensity (and therefore, in pollution) from 13.4 tons of coal equivalent (tce) per 10,000 yuan of GNP in 1980 to 9.4 tce by 1990 (*Financial Times* 1992).

Thus we know that pollution per unit of output has greatly declined in China over the past fifteen years. This is partly due to incentives for cost reduction, improved production efficiency, and structural change in the economy, all three being factors brought about by the reforms. It is also partly due to active environmental management. Yet ambient environmental quality in Chinese cities and the countryside does not show

3

Chongqing and Yichang) and marketable pollution permits (e.g., in Shanghai). Experimentation in a few demonstration or testing sites is followed by gradual extension of implementation to other cities, and, eventually, to the entire nation. For example, the pollution levy system was tried first in Suzhu in 1979 and extended to the rest of China in 1981. The water discharge permit system was tried first in seventeen cities in 1987, expanded to 107 cities in 1990, to 260 cities in 1992, and nationwide implementation was planned for late-1995 (Zhong et al. 1994). The pollution permit system began on a trial basis in sixteen cities in 1991 and is now extended nationwide.

The central government sets uniform national standards and pollution charges, but in recognition of the vastness and diversity of the country, allows considerable flexibility to local governments in determining compliance schedules and exemptions as they implement the policy. Over 2,700 counties (or 90% of the total) in all of China's twenty-two provinces, five autonomous regions, and four autonomous municipalities are now levying charges on 200,000 enterprises for 113 pollutants.

The greatest accomplishments of the existing system of environmental management have been:

- the general increase in environmental awareness among the public and acceptance of the polluter pays principle by industry;
- a legal framework that allows the introduction and escalation of pollution charges and other economic instruments;
- a nationwide network of regional and local environmental protection bureaus, with personnel trained in environmental management;
- the raising of substantial resources (20 billion yuan in the past fifteen years) from pollution levies (see Table 2 for fee revenues during 1979–1991), substantially channeled to environmental investments for point source pollution control (see Table 3);
- the building of a considerable body of knowledge and experience through experimentation with a variety of regulatory, economic, and suasive instruments, able to form the foundation for the development of an integrated system of environmental management.

TABLE 2
Sources of Pollution Dis

Unit: 10,000 Yuan

Year	Number of Collected Units	Total Charge
1979 –1985	88,646	343,348
1986	108,645	119,007
1987	135,837	142,783
1988	160,383	160,898
1989	183,256	167,395
1990	188,142	175,156
1991	205,892	200,597
Total		1,309,184

Source: NEPA 1993.

TABLE 3
Uses of Pollution Discha

Unit: 10,000 Yuan

Year	Use of Total PDF
1979–1985	235,753
1986	95,596
1987	125,355
1988	145,058
1989	157,597
1990	160,352
1991	259,373
Total	1,179,084

Source: NEPA 1993.

TABLE 2
Sources of Pollution Discharge (Fees) in the PRC, 1979 to 1991

Unit: 10,000 Yuan

Year	Number of Collected Units	Total Charge	Pollution Charge of: Waste-water	Waste Gas	Solid Waste	Noise	Radia-tion	Indus-trial Sewage	Four Small Parts
1979–1985	88,646	343,348							
1986	108,645	119,007	71,147	32,903	2,528	1,887	66	765	9,711
1987	135,837	142,783	82,065	38,019	3,382	2,244	114	2,075	14,684
1988	160,383	160,898	86,875	44,087	3,262	3,064	58	2,949	20,603
1989	183,256	167,395	85,818	45,255	3,344	3,592	39	3,223	26,124
1990	188,142	175,156	89,978	44,776	3,076	3,399	32	5,175	28,721
1991	205,892	200,597	99,636	49,448	4,021	4,125	27	6,176	37,164
Total		1,309,184	515,519	254,488	19,613	18,510	336	20,363	137,007

Source: NEPA 1993.

TABLE 3
Uses of Pollution Discharge Fees (PDF) in the PRC, 1979 to 1991

Unit: 10,000 Yuan

Year	Use of Total PDF	Pollution Source Control Investment from PDF: Total	Subsidies	Loans	Subsidies for Environ. Agencies
1979–1985	235,753	165,753			70,000
1986	95,596	75,030	71,231	3,799	20,566
1987	125,355	99,053	85,879	13,174	26,302
1988	145,058	110,028	72,302	37,726	35,030
1989	157,597	118,445	69,260	49,185	39,152
1990	160,352	114,724	64,961	49,763	45,628
1991	259,373	196,049	63,156	132,893	63,325
Total	1,179,084	879,082	426,789	286,540	300,003

Source: NEPA 1993.

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vith climate change was adopted in untries have signed, but only eight had ɔcol participants is one thing; achieving

·on dioxide emissions from fossil fuels. ;ion levels to be reached about a decade ıctual economic growth since 1990 and ld be as much as 30 percent from base

require prodigious efforts. Hence the magnitude, severity and incidence of ssue of *The Energy Journal*, edited by assistance from Henry Jacoby of MIT, chels of EPRI, provides international ree using several different models. st h. The results provide both

ıat this volume is the longest *Energy* ld not have been produced without :ctric Power Research Institute, the US ɔnmental Protection Agency. We are in

G. Campbell Watkins
Joint Editor
The Energy Journal

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INTRODUCTION AND OVERVIEW

*John P. Weyant and Jennifer N. Hill**

This Special Issue of *The Energy Journal* represents the first comprehensive report on a comparative set of analyses of the economic and energy sector impacts of the Kyoto Protocol on Climate Change. Organized by the Stanford Energy Modeling Forum (EMF), the objectives of this study were the same as for previous EMF studies: (1) identifying policy-relevant insights and analyses that are robust across wide ranges of models, (2) providing explanations for differences in results from different models, and (3) identifying high priority areas for future research. This study has produced a particularly rich set of results in all three areas, which is a tribute to the active participation of the modeling teams and the care each team took in preparing a paper for this volume.

The volume consists of a paper prepared by each modeling team on what it did and what it concluded from the model runs that were undertaken, proceeded by this introduction and summary paper. This summary focuses on the motivation for the study, the design of the study scenarios, and the interpretation of results for the four core scenarios, which all the teams ran. Each succeeding chapter contains ideas and insights drawn by the modeling teams from applying their models to issues they were able to address selected from a small set of important areas on which the group had mutually agreed to focus.

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The studies of the Energy Modeling Forum are sponsored by the U.S. Department of Energy, the U.S. Environmental Protection Agency, the Electric Power Research Institute, Mitsubishi Corporation, the New Energy and Industrial Technology Development Organization of Japan, and about 20 corporate affiliates. Besides the authors of the other papers in this volume, we would especially like to thank Campbell Watkins for his enthusiasm about the idea of doing this special issue and his insightful advice at each step in the production process. In addition, we would like to thank Geoff Pearce of the Energy Journal and Dave Williams of the IAEE for going above and beyond the call of duty in making this special issue a reality.

COMPARISONS OF ALTERNATIVE EMISSION TRADING REGIMES

Although the Kyoto Protocol does explicitly mention the possibility of international trading of carbon emission rights, the negotiators have yet to agree on the extent of participation in any trading regime and whether there will be constraints on how many emissions rights can be bought or sold by individual participants. In our scenario design we started with some relatively simple implementations of the trading provisions in the Protocol in order to get a rough idea for what is at stake in the determination of the rules governing the trading regime. Here we look at carbon tax results for four alternative scenarios: (1) No Trading of international emission rights, (2) full Annex 1 (or Annex B) Trading of emissions rights, (3) the Double Bubble, which considers separate EU and rest of Annex 1 emissions trading blocks, and (4) Full Global Trading of emissions rights, with the non-Annex 1 countries constrained to their reference case emissions.

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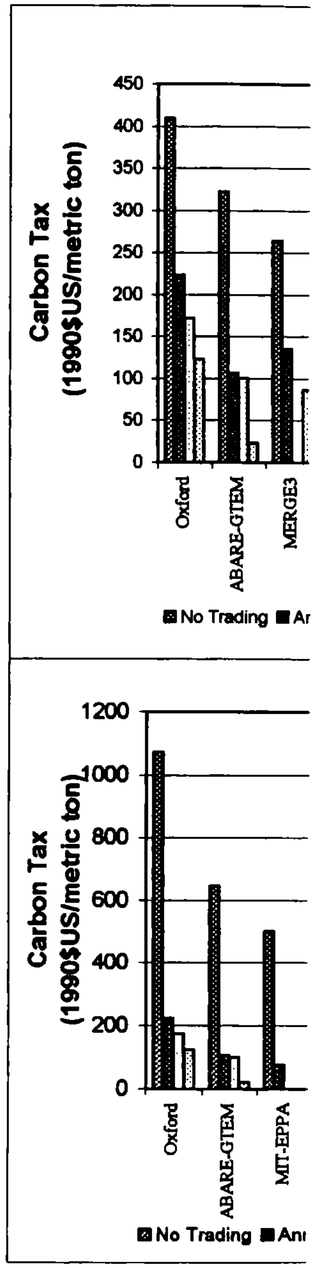
Several conclusions emerged from running these scenarios. First, virtually all of the modeling teams were uncomfortable running the Full Global Trading scenario as a realistic outcome of the current negotiating process; there is simply not enough time between now and the first budget period to agree on and design a trading regime involving all the participants in the United Nations Framework Convention on Climate Change. Thus, this scenario was run only as a benchmark for what ultimately might be achieved only. Second, in many of the models carbon taxes in the No Trade scenario rise to levels that make the modeling teams question whether the macro-economic constraints left out of most of the models (except the Oxford model, and parts of G-Cubed) might lead to economic impacts that are on the order of the equilibrium impacts that are considered. Despite these limitations a number of general conclusions can be drawn from the model results.

Figure 8 shows carbon tax results for the U.S., EU, Japan, and CANZ for four alternative trading regimes (here we add results for the Double Bubble scenario to those for the three "core" trading scenarios). The potential advantages of expanding the scope of the trading regime are evident in the figures. Moving from the No Trade to the Annex 1 Trading case lowers the carbon tax required in the four regions by a factor of two as a result of equalizing the marginal abatement cost across regions. This effect is particularly significant in this case because almost all models project a significant amount of "hot air" will be available from Russia. This represents reductions in Russia's Reference Case carbon emissions by 2010 relative to its 1990 level baseline allocation. Figure 9 shows projected GDP loss results for the U.S., EU, Japan, and CANZ for the four alternative trading regimes. The GDP losses are generally adjusted for payments for the purchase of carbon emission rights (a deduction) or receipts for the sale of carbon emission rights (an addition). The pattern of these results is similar to that for the carbon tax comparisons.

Figure 8. Year 2010 Carbo



Clinton Presidential Records
Digital Records Marker

This is not a presidential record. This is used as an administrative marker by the William J. Clinton Presidential Library Staff.

This marker identifies the place of a tabbed divider. Given our digitization capabilities, we are sometimes unable to adequately scan such dividers. The title from the original document is indicated below.

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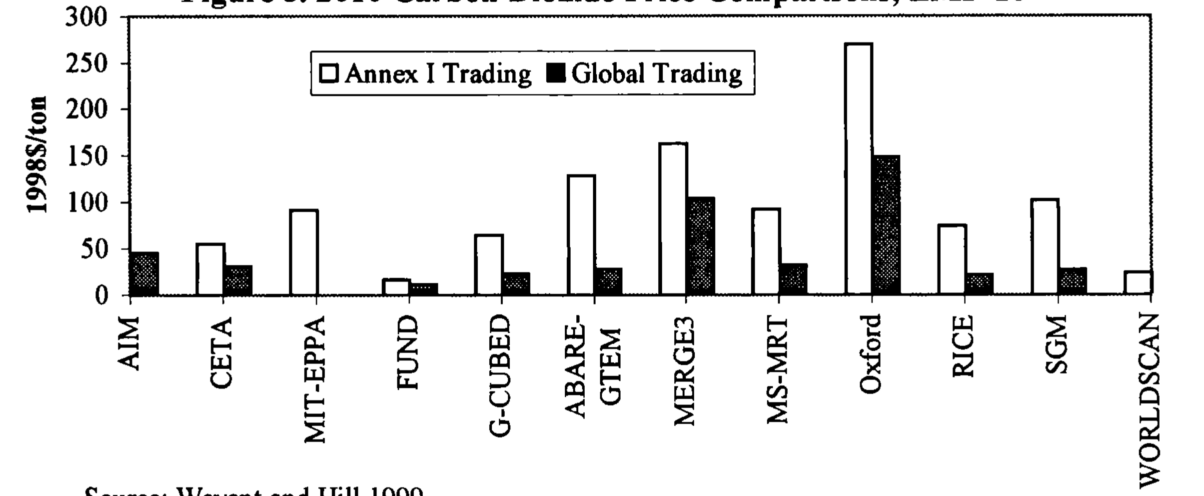
Figure 5. 2010 Carbon Dioxide Price Comparisons, EMF-16



Source: Weyant and Hill 1999

While the price of a ton of carbon emissions may vary across models, three key lessons can be drawn from these results. First, projected gains from trade, especially in expanding trading from Annex I countries to all countries, can be substantial. All the models found that marginal and total costs fell substantially going from Annex I to global trading, because developing countries can undertake low-cost emissions abatement and sell their emissions abatement to Annex I countries. Second, higher rates of economic growth in Annex I countries increase demand for emissions allowances, while higher rates of economic growth in developing countries tend to create more opportunities to substitute greenhouse gas-lean technology, and thus increase supply of low-cost emissions abatement. Third, countries with larger coal shares of total energy have more opportunities to abate emissions through energy efficiency and fuel switching than countries with smaller coal shares.

These model results provide illustrations of the possible characteristics of an international emissions market. What kind of role can China play in this emissions market? Analyses based on the MIT-EPPA model developed by researchers at the Massachusetts Institute of Technology indicate that China may have the lowest marginal abatement cost of any country or region in the world (figure 6). To abate emissions to 10% below 2010 projected business as usual levels, Japan realizes marginal costs 16 times greater than China. The European Community would experience marginal costs more than 6 times greater than China, while the United States would witness marginal costs nearly 4 times greater. The relative differences in marginal costs increase as countries move from abatement of 10% below 2010 BAU to 20% below 2010 BAU. Further, in the EPPA model, no developing or transition economy countries or regions have marginal costs lower than China's marginal cost. Thus, in this representation of the international emissions market, China would be the lowest-cost producer of emissions abatement. Tol (1999) also reports that China (as the dominant economy in the Centrally Planned Asia component of his FUND model) has the lowest abatement costs of any region or country in his global model. These results are based on the specific technology configurations in

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Kyoto, Efficiency, and Cost-Effectiveness: Applications of *FUND*

*Richard S.J. Tol**

In this paper various emission reduction scenarios are evaluated with FUND—the Climate Framework for Uncertainty, Negotiation, and Distribution model. The aim is to help international negotiators improve upon the Kyoto Protocol. International cooperation in greenhouse gas emission reduction is important, and the more of it the better. The emission reduction targets as agreed in the Kyoto Protocol are irreconcilable with economic rationality. If the targets nevertheless need to be met, it is better to start emission reduction sooner than later in order to minimise costs. Methane emission reduction may be an important instrument to reduce costs.

INTRODUCTION

The Kyoto Protocol signifies the first serious attempt of the international community to take concrete action on greenhouse gas emission reduction. Time will tell whether the attempt will be a successful one. This paper looks at some of the economic implications of the agreement, and sheds some light on the issues unresolved in the Kyoto Protocol. It thus hopes to inform the negotiations on extending and refining the Kyoto Protocol. The first opportunity for this was in Buenos Aires, at the end of 1998, but little progress was made there.

The analyses in this paper are based on the *Climate Framework for Uncertainty, Negotiation, and Distribution (FUND)*, an integrated assessment model of climate change (Tol, 1997, 1998). Section 2 presents the model. Weyant et al. (1996) classify *FUND* as a policy-optimization model, that is, a model which selects the best policy strategy given certain constraints. In this paper, however, the constraints (inspired by the Kyoto Protocol) are so strict that there is often little room for (assumed) preferences to play a substantial

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iteratively; without co-operation between regions, convergence is rapid (i.e., 4 or 5 iterations); with global co-operation, convergence is much slower (i.e., over 10 iterations). The distinction between generations of decision makers has two implications. Firstly, in a cost-benefit analysis, a decision-maker not only has to match her decisions with those of other regions, but also with the decisions of other generations. Secondly, the definition of intertemporal cost-effectiveness vanishes, as there is no decision-maker controlling the entire time-period. Explicitly distinguishing generations of decision makers recognises the sovereignty of each generation. In a cost-benefit analysis, this implies that emission reductions are individually rational at all times. Collective decision-making over generations and targeted capital transfers between generations are impossible in the model as in reality. Cost-effectiveness also implicitly assumes that targeted intergenerational capital transfers are possible (such transfers are needed to make an actual Pareto improvement of a potential one). In addition, cost-effectiveness analysis usually places undue weight on the preferences in the first periods (unless the pure rate of time preference is zero).

Table 4. Parameters of the CO_2 Emission Reduction Cost Function[a]

6

OECD-A	2.0789	CEE&fSU	2.0488	S&SEA	2.1268
OECD-E	2.3153	ME	2.1041	CPA	1.9544
OECD-P	2.2171	LA	2.1253	AFR	2.0931

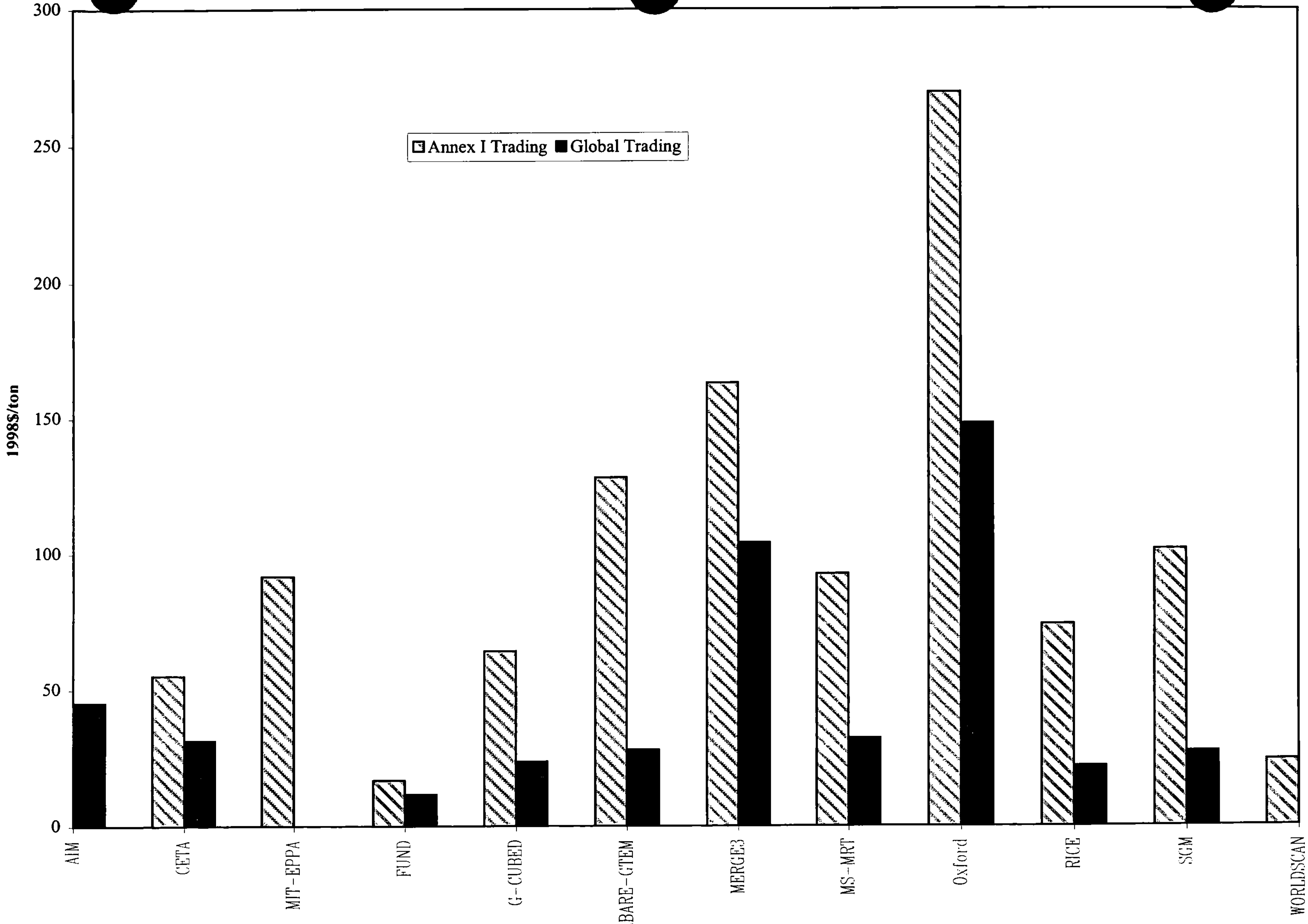
[a]The proportional loss of GDP C in year t of proportional emission reduction R in year t follows: $C_t = \alpha R_t^2$. The costs to GDP are modelled as a dead-weight loss to the economy. Emission reduction is brought about by a permanent shift in energy- and carbon-intensity.
Source: After Hourcade et al. (1996) and Rose and Stevens (1993).

3. THE GAINS FROM SPATIAL FLEXIBILITY

Annex I countries agreed to greenhouse gas emission reduction in the Kyoto protocol. For the regions of *FUND*, the agreed reductions are -7% for OECD-A, -8% for OECD-E, -6% for OECD-P, and 0% for CEE&fSU, all relative to the 1990 emissions (as modelled). These targets are to be met in the year 2010, and maintained thereafter. The other regions are restricted to their business-as-usual emissions. Note that, at the short term, there is little to no leakage in *FUND*.[3] These emission reductions can be achieved at various levels of international cooperation. At the one extreme, all regions should meet their regional target. At the other extreme, the emissions target is a global one, and

3. Recall that the only link between the regions is climate.

Figure 5. 2010 Carbon Diox[illegible]rice Comparisons, EMF-16



Source: Weyant and Hill 1999

Carbon Permit Price in 2010 (1990$s/metric ton)

Model	Annex I Tra	Global Trading
AIM	64.88 [1]	37.53 [13]
CETA	45.80 [2]	26.00 [14]
MIT-EPPA	76.20 [3]	
FUND	13.94 [4]	9.64 [15]
G-CUBED	53.32 [5]	19.59 [16]
ABARE-GT	106.50 [6]	23.14 [17]
MERGE3	135.40 [7]	86.49 [18]
MS-MRT	76.92 [8]	26.64 [19]
Oxford	223.73 [9]	123.00 [20]
RICE	61.50 [10]	18.17 [21]
SGM	84.46 [11]	22.43 [22]
WORLDSC	19.82 [12]	

1998 $

Model	Annex I Tra	Global Trading
AIM	78.12	45.18
CETA	55.14	31.30
MIT-EPPA	91.74	
FUND	16.79	11.61
G-CUBED	64.20	23.59
ABARE-GT	128.22	27.86
MERGE3	163.02	104.13
MS-MRT	92.61	32.08
Oxford	269.37	148.09
RICE	74.05	21.88
SGM	101.69	27.01
WORLDSC	23.86	

These are adjusted using GDP implicit price deflator from July 1999 Economic Indicators

Values
1990: 93.60
1998: 112.70

From excel File recieved from John Weyant at Stanford.

US	Carbon Tax in 2010 (1990$s)			
Model	No Trading	Annex I Trading	Double Bubble	Global Trading
AIM	152.773	64.88[1]	45.489	37.525[13]
CETA	167.71	45.8[2]		26[14]
MIT-EPPA	192.96	76.2[3]		
FUND		13.9423[4]		9.6425[15]
G-CUBED	$75.92	53.32[5]	$27.73	19.59[16]
ABARE-GTEM	322.2952732	106.4978483[6]	100.4321004	23.14019409[17]
MERGE3	264.466	135.399[7]		86.485[18]
MS-MRT	236.2192863	76.92017574[8]		26.64042684[19]
Oxford	409.9242144	223.7298122[9]	172.0541979	123[20]
RICE	131.9944	61.504[10]		18.17[21]
SGM	187.68108	84.456486[11]	58.5011	22.433381[22]
WORLDSCAN	84.53401838	19.81974874[12]		

US	Carbon Tax in 2010 (1990$s)			
Model	No Trading	Annex I Trading	Double Bubble	Global Trading
Oxford	409.9242144	223.7298122	172.0541979	123
ABARE-GTEM	322.2952732	106.4978483	100.4321004	23.14019409
MERGE3	264.466	135.399		86.485
MS-MRT	236.2192863	76.92017574		26.64042684
MIT-EPPA	192.96	76.2		
SGM	187.68108	84.456486	58.5011	22.433381
CETA	167.71	45.8		26
AIM	152.773	64.88	45.489	37.525
RICE	131.9944	61.504		18.17
WORLDSCAN	84.53401838	19.81974874		
G-CUBED	$75.92	53.32	$27.73	19.59
FUND		13.9423		9.6425

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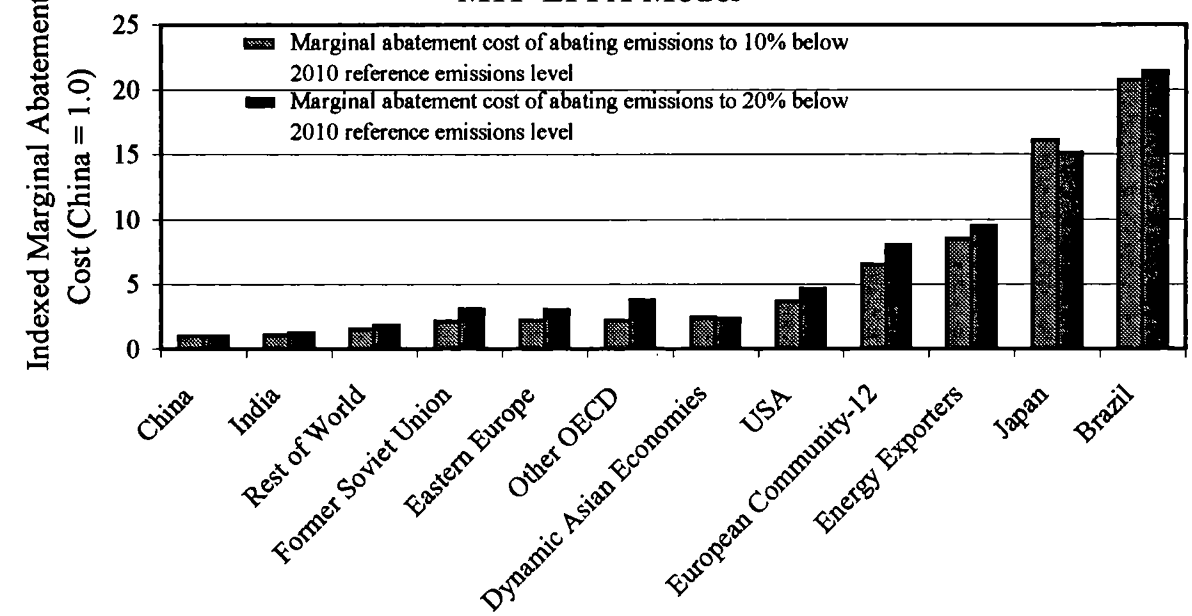
these models, and such technology representations vary across models.

Figure 6. 2010 Marginal Abatement Costs Across Countries in MIT-EPPA Model

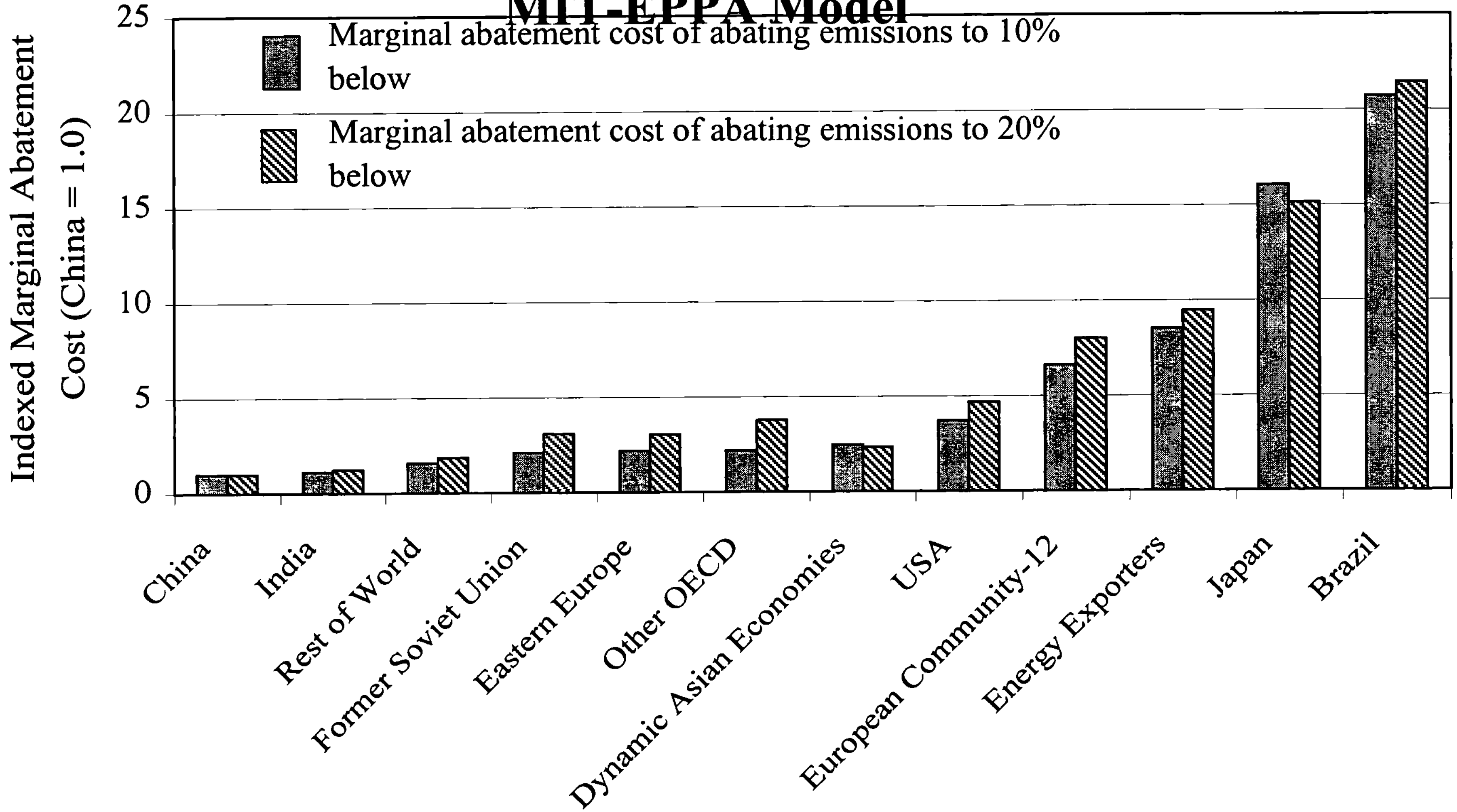


In addition to having the lowest abatement cost, as the largest non-Annex I economy, these modeling results illustrate the potential for China to be the largest producer of emissions abatement. Several of the EMF-16 modeling analyses also confirm the potential for China to produce the largest quantity of emissions abatement. (1)

Ellerman et al (1998) have estimated the marginal abatement cost curve for China with the MIT-EPPA model presented below (figure 7).[4] With this marginal abatement cost curve, or emissions abatement supply curve, one can estimate the number of tons abated in 2010 at a given price of carbon. In their assessment of global trading, they found that the market price would be $34/ton of carbon.[5] At this price, China would find it economic to abate approximately 430 MMTC in 2010. This estimate of emissions abatement is larger in absolute terms than the some other estimates, but because Ellerman et al project a higher emissions growth rate for China, the projected abatement as a percentage of BAU is similar to other models. If China had a target set at 2010 BAU, Ellerman et al estimate that it could sell more than $14 billion per year in emissions allowances which would generate gains from trade of about $9 billion per year during the first commitment period.

4 The equations in figures 7 and 8 take the form: price of carbon (in 1998 U.S. dollars per metric ton of carbon) is equal to the first coefficient multiplied by the quantity of emissions abated below 2010 BAU (in million metric tons of carbon) plus the second coefficient multiplied by the square of the quantity of emissions abated below 2010 BAU (MMTC).
5 All estimates of carbon prices are in 1998 U.S. dollars per ton of carbon equivalent, unless specified otherwise.

Figure 6. 2010 Marginal Abatement Costs Across Countries in MIT-EPPA Model



MIT-EPPA		5% below BAU		10% below BAU		15% below BAU		20% below BAU	
Country	2010 BAU	Q	P	Q	P	Q	P	Q	P
USA	1838[1]	91.9	7.880425	183.8	24.20646	275.7	48.97811	367.6	82.19536
Japan	424[2]	21.2	45.46552	42.4	104.8637	63.6	178.1945	84.8	265.4579
EEC	1064[3]	53.2	14.78854	106.4	43.16222	159.6	85.12106	212.8	140.6651
Othr OECD	472[4]	23.6	2.4072	47.2	14.28272	70.8	35.62656	94.4	66.43872
EE	395[5]	19.75	4.041344	39.5	14.24568	59.25	30.61299	79	53.1433
FSU	763[6]	38.15	3.507702	76.3	13.71035	114.45	30.60794	152.6	54.20047
Enry Exprt	927[7]	46.35	20.91405	92.7	55.57736	139.05	103.9899	185.4	166.1518
China	1792[8]	89.6	2.703411	179.2	6.530765	268.8	11.48206	358.4	17.5573
India	486[9]	24.3	2.798145	48.6	7.36776	72.9	13.70885	97.2	21.8214
DAE	308[10]	15.4	6.926612	30.8	16.08253	46.2	27.46775	61.6	41.08227
Brazil	97[11]	4.85	54.41322	9.7	135.2281	14.55	242.4446	19.4	376.0628
ROW	532[12]	26.6	3.627176	53.2	10.2261	79.8	19.79678	106.4	32.33922

Quantity of Reduction (Q) is set by X% of 2010 BAU.
Marginal Abatement cost (P) is calculated as
$aQ^2 + bQ$ where a + b are taken from page 9.

p. 15

1

	2010 BAU - 10%	2010 BAU - 20%
China	1.0	1.0
India	1.1	1.2
Rest of World	1.6	1.8
Former Soviet	2.1	3.1
Eastern Europ	2.2	3.0
Other OECD	2.2	3.8
Dynamic Asia	2.5	2.3
USA	3.7	4.7 (3)
European Com	6.6	8.0 (3)
Energy Export	8.5	9.5
Japan	16.1	15.1 (2)
Brazil	20.7	21.4

China=1.0

These are prices from previous page indexed to China's price.

(1)

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Massachusetts Institute of Technology

September 1998

ANALYSIS OF POST-KYOTO CO_2 EMISSIONS TRADING USING MARGINAL ABATEMENT CURVES

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We are greatly indebted to many colleagues and associates for consistent encouragement and critical comment. Foremost among these are the faculty and research staff associated with MIT's Joint Program on the Science and Policy of Global Change, particularly the EPPA Working Group. Particular thanks are due to Henry Jacoby, Dick Eckaus, Loren Cox and David Reiner for their careful comments on earlier drafts of this paper and to Ian Sue Wing for invaluable help in running the model. The encouraging response of participants of the RIIA/MIT Global Change Forum held at London in June 1998 gave much direction to the paper; and we are grateful to Nathalie Kosciusko-Morizet, Jean-Charles Hourcade, Thierry Le Pesant and Ken Chomitz for their subsequent interest and helpful comment. Finally, this research would not have been possible without the funding made available to the Joint Program by a number of corporations in the U.S., Europe and Japan, by EPRI, and by agencies of the Norwegian and U.S. Governments.

NB: all the prices in the following tables are in [illegible]. NAB = Non-Annex B regions

I and II. BACKGROUND, METHODOLOGY

TABLE 1 - bis: Reference emissions and Kyoto commitments

Reference emissions	USA	JPN	EEC	OOE	EET	oecd+eet	FSU	NAB	World	EEX	CHN	IND	DAE	BRA	ROW
Ref 1990 (Mton)	1362	298	822	318	266	3066	891	2022	2022	508	833	183	115	63	320
Ref 2010 (Mton)	1838	424	1064	472	395	4193	763	4142	4142	927	[illegible]	486	308	97	532
Kyoto	0.93	0.94	0.92	0.95	1.04		0.98								
Emissions in 2010 (Mton)	1267	280	757	301	277	2881	873	4142	7896	927	1792	486	308	97	532
Reductions / ref 2010 (Mton)	572	144	307	171	118	1312	-111	0	1202	0	0	0	0	0	0
Marginal Costs ($/ton)	$186	$584	$273	$233	$116										

TABLE 3 - bis: MACs approximations coefficients (P = aR^2+bR)

	USA	JPN	EEC	OOE	EET	FSU	EEX	CHN	IND	DAE	BRA	ROW
a	5.0E-04	1.6E-02	2.4E-03	8.5E-03	7.9E-03	2.3E-03	3.2E-03	7.0E-05	1.5E-03	4.7E-03	5 6E-01	2 1E-03
b	0.0398	1.816	0.1503	-0.0986	0.0486	0.0042	0.3029	0.0239	0.0787	0.3774	8.4974	0.0805

III. BASIC CASES

TABLE A: Kyoto OECD only no trading

	USA	JPN	EEC	OOE	Oecd
Reductions / ref 2010 (Mton)	572	144	307	171	1194
Marginal Costs ($/ton)	$186	$584	$273	$233	
Cost of Abatement ($billion)	37.62	34.37	30.29	12.81	115.09

TABLE B: Kyoto OECD only OECD trading

	USA	JPN	EEC	OOE	Oecd
Reductions / ref 2010 (Mton)	655	79	287	174	1194
Market Price of Permits ($/ton)	$240	$240	$240	$240	$240
Cost of Abatement ($billion)	55.28	8.22	25.02	13.44	101.96
Permits exp(-)/imp(+) (Mton)	-83	65	21	-3	0
i.e % of commitment (import)		*45%*	*7%*		
Flows exp(-)/imp(+) ($billion)	-19.95	15.66	4.94	-0.64	0.01
Total Cost ($billion)	35.33	23.88	29.96	12.80	101.97
Gains from trade ($billion)	2.30	10.49	0.33	0.01	13.12

TABLE C: Kyoto no trading

	USA	JPN	EEC	OOE	EET	oecd+eet	FSU	World
Reductions / ref 2010 (Mton)	572	144	307	171	118	1312	0	1312
Marginal Costs ($/ton)	$186	$584	$273	$233	$116			
Cost of Abatement ($billion)	37.62	34.37	30.29	12.81	4.67	119.76	0.00	119.76

TABLE D: Annex B trading

	USA	JPN	EEC	OOE	EET	oecd+eet	FSU	World
Reductions / ref 2010 (Mton)	466	49	201	128	124	968	234	1202
'Hot air' (Mton)						0	111	111
Market Price of Permits ($/ton)	$127	$127	$127	$127	$127	$127	$127	$127
Cost of Abatement ($billion)	21.16	2.82	9.51	5.16	5.36	44.01	9.95	53.96
Permits exp(-)/imp(+) (Mton)	106	95	106	43	-6	345	-345	0
i.e % of commitment (import)	*19%*	*66%*	*35%*	*25%*		*26%*		
Flows exp(-)/imp(+) ($billion)	13.44	12.06	13.51	5.49	-0.73	43.77	-43.77	0.00
Total Cost ($billion)	34.60	14.88	23.02	10.64	4.64	87.78	-33.82	53.96
Gains from trade ($billion)	3.03	19 49	7.27	2.17	0.03	31.99	33.82	65.81

TABLE E: Annex B trading, No hot air

	USA	JPN	EEC	OOE	EET	oecd+eet	FSU	World
Reductions / ref 2010 (Mton)	509	56	220	139	135	1058	254	1312
'Hot air' (Mton)						0	0	0
Market Price of Permits ($/ton)	$150	$150	$150	$150	$150	$150	$150	$150
Cost of Abatement ($billion)	27.10	3.73	12.21	6.60	6 86	56.51	12.73	69.23
Permits exp(-)/imp(+) (Mton)	63	88	87	33	-17	254	-254	0
i.e % of commitment (import)	*11%*	*61%*	*28%*	*19%*		*19%*		
Flows exp(-)/imp(+) ($billion)	9.40	13.23	13.00	4.90	-2.48	38.05	-38.05	0.00
Total Cost ($billion)	36.50	16.96	25.21	11.50	4.38	94.55	-25.32	69.23
Gains from trade ($billion)	1.12	17 41	5.08	1.31	0.29	25.21	25.32	50.53

TABLE F: World trading

	USA	JPN	EEC	OOE	EET	oecd+eet	FSU	NAB	World	EEX	CHN	IND	DAE	BRA	ROW
Reductions / ref 2010 (Mton)	182	12	73	59	52	378	101	723	1202	51	437	102	42	2	89
'Hot air' (Mton)						0	111	0	111						
Market Price of Permits ($/ton)	$24	$24	$24	$24	$24	$24	$24	$24	$24	$24	$24	$24	$24	$24	$24
Cost of Abatement ($billion)	1.66	0 14	0 71	0 41	0.43	3.36	0.81	6.99	11.15	0.54	4.22	0.95	0 44	0 03	0.81
Permits exp(-)/imp(+) (Mton)	390	132	234	112	66	935	-211	-723	0	-51	-437	-102	-42	-2	-89
i.e % of commitment (import)	*68%*	*92%*	*76%*	*66%*	*56%*	*71%*									
Flows exp(-)/imp(+) ($billion)	9.27	3.15	5.57	2.67	1.57	22.24	-5.03	-17.21	0.00	-1.21	-10.40	-2.44	-0.99	-0.06	-2.12
Total Cost ($billion)	10.94	3.29	6.29	3.09	2.01	25.60	-4.22	-10.22	11.15	-0.68	-6.17	-1.49	-0.55	-0.03	-1.31
Gains from trade ($billion)	26.69	31.08	24.00	9 73	2.66	94.16	4.22	10.22	108.61	0.68	6.17	1.49	0.55	0.03	1.31

1

The Economics of the Kyoto Protocol

*Christopher N. MacCracken, James A. Edmonds, Son H. Kim and Ronald D. Sands**

In this paper we use the Second Generation Model to 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. Our analysis shows that the cost of implementing the Protocol in the United States can vary by more than an order of magnitude. The marginal cost in 2010 could be as low as $26 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 mitigation obligations are not adequately anticipated by decision-makers.

INTRODUCTION

The Kyoto Protocol was completed on the morning of December 11, 1997, following more than two years of 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 150 delegations. Because the document is complex, its implications are not immediately obvious. If it enters into force, the Kyoto Protocol could have far-

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The Pacific Northwest National Laboratory is operated for the U.S. Department of Energy by Battelle Memorial Institute under contract DE-AC06-76RLO 1830. The views and opinions of the authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

...rtified emission reductions
...nex I parties can use these
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...bject to the authority of the
su...ed by an executive board.

...its can be created by projects as long

...rm benefits related to the mitigation

...at are in addition to any that would
...project activity.

...certified emission reduction credits
...credits can be applied to the budget

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...e a cost of mitigation that lies between
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...hey wish to sell.
...ons mitigation through global permit
...it prices than those achieved under the

Annex I permit trading scenarios. Table 9 shows the 2010 permit price under global trading as compared to the no trading and Annex I trading regimes.

Table 9. Emissions Taxes/Permit Prices Required to Meet Policy Goal in 2010 (1992 US$ per tonne of carbon equivalent)

Region	No Trading	Annex I Trading		Global Trading
		Monopolistic	Competitive	
Canada	350			
former Soviet Union	--			
Japan	458			
United States	168	105	73	26
Western Europe	130			
Australia	117			
Eastern Europe	--			

Table 10 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 308 MMTCe of permits sold by the former Soviet Union, however, include 247 MMTCe of "base mitigation credits."

Table 10. Composition of the Emissions Permit Market in the Global Trading Case (million tonnes of carbon equivalent)

Region	Permits Traded (MMTCe)	
	Purchased	Sold
Canada	61	
former Soviet Union		308
Japan	121	
United States	470	
Western Europe	134	
Australia	25	
Eastern Europe		49
China		341
India		37
Korea		3
Mexico		19
Rest of the World		54
Total	811	811

Emissions Trading, Capital Flows and the Kyoto Protocol

Warwick J. McKibbin, Martin T. Ross**, Robert Shackleton** and Peter J. Wilcoxen****

We use an econometrically estimated multi-region, multi-sector general equilibrium model of the world economy to examine the effects of the tradable emissions permit system proposed in the 1997 Kyoto Protocol, under various assumptions about the extent of international permit trading. We focus, in particular, on the effects of the system on international trade and capital flows. Our results suggest that consideration of these flows significantly affects estimates of the domestic effects of the emissions mitigation policy, compared with analyses that ignore international capital flows.

INTRODUCTION

As part of an effort to reduce global emissions of greenhouse gases (GHGs) that are expected to contribute to a significant warming of the earth's climate, the Kyoto Protocol to the United Nations Framework Convention on Climate Change, signed in Kyoto in December 1997, includes binding GHG emissions targets for the world's industrial economies ("Annex I" countries) for the period 2008-2012. The Protocol also provides for international trading of emission allowances among the countries that accept binding targets, in recognition of the theoretical efficiency benefits of allowing emission reductions

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The views expressed in this paper are those of the authors and should not be interpreted as reflecting the views of the organizations with which they are affiliated.

ón is slightly better off in
han under Annex I trading.
ey fall slightly less), fuel
ital outflows are smaller.
the ROECD region adopts carbon
s to shift some investment to other
Annex I trading, other countries are
s and are attempting to do the same
eciate substantially, rising by 23%
ider the double umbrella, however,
other than the ROECD so there is
ed States. There is less appreciation
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owever. Once the policy is actually
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that the non-Annex I developing
ties of domestic emission permits
to allow these permits to be traded
ar tained in Table 9. The
ie he trading regime is that
wa m owners in developing
willing to sell allowances to Annex
ed the marginal cost to the owners
e developing countries. The market
ctions on a global scale: emission
re cheapest, but Annex I countries

developing regions sell a fixed number of
nues to households as a lump-sum payment.

Table 9. Annex I Commitments With Global Permit Trading

	United States	Japan	Australia	Other OECD	China	LDC's
2005						
Permit price ($95)	--	--	--	--	--	--
Annual permit sales (Bil $95)	--	--	--	--	--	--
Carbon emissions	0.6%	-1.2%	-0.1%	-0.9%	0.9%	0.8%
Coal consumption	0.2%	-0.3%	0.0%	-0.3%	0.9%	0.4%
Oil consumption	1.0%	-1.7%	-0.4%	-1.3%	1.2%	1.1%
Gas consumption	0.7%	-0.3%	-0.4%	-0.8%	1.8%	0.7%
GDP	0.1%	-0.1%	0.0%	-0.1%	0.4%	0.1%
Investment	1.0%	-0.2%	-0.3%	-1.0%	2.4%	1.1%
Exports	-2.9%	1.5%	1.0%	4.1%	-27.2%	-8.7%
Exchange rate	3.7%	-3.1%	-0.6%	-7.0%	12.4%	6.1%
Net foreign assets (Bil. $95)	-$54	-$8	$12	$106	-$38	$25
GNP	0.1%	-0.1%	0.0%	0.0%	0.3%	0.2%
2010						
Permit price ($95)	$23	$23	$23	$23	$23	$23
Annual permit sales (Bil $95)	-$8.9	-$1.2	-$1.0	-$9.3	$7.0	$4.5
Carbon emissions	-7.4%	-4.2%	-4.9%	-3.4%	-19.1%	-7.9%
Coal consumption	-13.3%	-8.9%	-7.0%	-4.5%	-22.0%	-13.3%
Oil consumption	-3.6%	-2.8%	-2.4%	-3.3%	-3.3%	-5.6%
Gas consumption	-3.0%	-1.0%	-2.9%	-2.2%	-10.4%	-2.0%
GDP	-0.1%	-0.1%	-0.3%	-0.3%	-0.6%	-0.2%
Investment	0.4%	-0.3%	-0.2%	-1.0%	0.6%	0.1%
Exports	-3.4%	0.8%	-0.3%	3.6%	-22.6%	-9.7%
Exchange rate	3.6%	-2.8%	-0.6%	-7.2%	10.9%	6.5%
Net foreign assets (Bil. $95)	-$115	-$2	$20	$208	-$71	$51
GNP	-0.2%	-0.1%	-0.4%	-0.2%	-0.4%	0.0%
2020						
Permit price ($95)	$37	$37	$37	$37	$37	$37
Annual permit sales (Bil $95)	-$21.1	-$3.9	-$2.5	-$25.2	$24.3	$17.1
Carbon emissions	-11.4%	-6.1%	-6.5%	-4.6%	-24.9%	-11.1%
Coal consumption	-19.2%	-12.8%	-9.7%	-6.3%	-28.7%	-17.8%
Oil consumption	-6.2%	-4.2%	-3.1%	-4.4%	-4.9%	-8.2%
Gas consumption	-5.5%	-1.5%	-3.5%	-3.0%	-13.5%	-3.6%
GDP	-0.1%	-0.2%	-0.3%	-0.3%	-0.7%	-0.3%
Investment	0.3%	-0.4%	-0.1%	-1.0%	0.3%	0.0%
Exports	-3.9%	0.7%	-0.7%	3.3%	-20.0%	-9.0%
Exchange rate	3.6%	-3.4%	-0.4%	-7.5%	15.0%	7.0%
Net foreign assets (Bil. $95)	-$155	-$13	$25	$263	-$66	$78
GNP	-0.3%	-0.2%	-0.4%	-0.3%	-0.1%	0.0%

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ANALYSIS OF POST-KYOTO CO_2 EMISSIONS TRADING USING MARGINAL ABATEMENT CURVES

ACKNOWLEDGEMENTS

We are greatly indebted to many colleagues and associates for consistent encouragement and critical comment. Foremost among these are the faculty and research staff associated with MIT's Joint Program on the Science and Policy of Global Change, particularly the EPPA Working Group. Particular thanks are due to Henry Jacoby, Dick Eckaus, Loren Cox and David Reiner for their careful comments on earlier drafts of this paper and to Ian Sue Wing for invaluable help in running the model. The encouraging response of participants of the RIIA/MIT Global Change Forum held at London in June 1998 gave much direction to the paper; and we are grateful to Nathalie Kosciusko-Morizet, Jean-Charles Hourcade, Thierry Le Pesant and Ken Chomitz for their subsequent interest and helpful comment. Finally, this research would not have been possible without the funding made available to the Joint Program by a number of corporations in the U.S., Europe and Japan, by EPRI, and by agencies of the Norwegian and U.S. Governments.

NB. all the prices in the following tables are in 1985$. NAB = Non-Annex B regions

I and II. BACKGROUND, METHODOLOGY

TABLE 1 - bis: Reference emissions and Kyoto commitments

Reference emissions	USA	JPN	EEC	OOE	EET	oecd+eet	FSU	NAB	World	EEX	CHN	IND	DAE	BRA	ROW
Ref 1990 (Mton)	1362	298	822	318	266	3066	891	2022	2022	508	833	183	115	63	320
Ref 2010 (Mton)	1838	424	1064	472	395	4193	763	4142	4142	927	1792	486	308	97	532
Kyoto	0.93	0.94	0.92	0.95	1.04		0.98								
Emissions in 2010 (Mton)	1267	280	757	301	277	2881	873	4142	7896	927	1792	486	308	97	532
Reductions / ref 2010 (Mton)	572	144	307	171	118	1312	-111	0	1202	0	0	0	0	0	0
Marginal Costs ($/ton)	**$186**	**$584**	**$273**	**$233**	**$116**										

TABLE 3 - bis: MACs approximations coefficients (P = aR^2+bR)

	USA	JPN	EEC	OOE	EET	FSU	EEX	CHN	IND	DAE	BRA	ROW
a	5.0E-04	1.6E-02	2.4E-03	8.5E-03	7.9E-03	2.3E-03	3.2E-03	7.0E-05	1.5E-03	4.7E-03	5.6E-01	2.1E-03
b	0.0398	1.816	0.1503	-0.0986	0.0486	0.0042	0.3029	0.0239	0.0787	0.3774	8.4974	0.0805

III. BASIC CASES

TABLE A: Kyoto OECD only no trading

	USA	JPN	EEC	OOE	Oecd
Reductions / ref 2010 (Mton)	572	144	307	171	1194
Marginal Costs ($/ton)	**$186**	**$584**	**$273**	**$233**	
Cost of Abatement ($billion)	37.62	34.37	30.29	12.81	**115.09**

TABLE B: Kyoto OECD only OECD trading

	USA	JPN	EEC	OOE	Oecd
Reductions / ref 2010 (Mton)	655	79	287	174	1194
Market Price of Permits ($/ton)	**$240**	**$240**	**$240**	**$240**	**$240**
Cost of Abatement ($billion)	55.28	8.22	25.02	13.44	101.96
Permits exp(-)/imp(+) (Mton)	-83	65	21	-3	0
i.e % of commitment (import)		*45%*	*7%*		
Flows exp(-)/imp(+) ($billion)	-19.95	15.66	4.94	-0.64	0.01
Total Cost ($billion)	35.33	23.88	29.96	12.80	**101.97**
Gains from trade ($billion)	2.30	10.49	0.33	0.01	**13.12**

TABLE C: Kyoto no trading

	USA	JPN	EEC	OOE	EET	oecd+eet	FSU	World
Reductions / ref 2010 (Mton)	572	144	307	171	118	1312	0	1312
Marginal Costs ($/ton)	**$186**	**$584**	**$273**	**$233**	**$116**			
Cost of Abatement ($billion)	37.62	34.37	30.29	12.81	4.67	119.76	0.00	**119.76**

TABLE D: Annex B trading

	USA	JPN	EEC	OOE	EET	oecd+eet	FSU	World
Reductions / ref 2010 (Mton)	466	49	201	128	124	968	234	1202
'Hot air' (Mton)						0	111	111
Market Price of Permits ($/ton)	**$127**	**$127**	**$127**	**$127**	**$127**	**$127**	**$127**	**$127**
Cost of Abatement ($billion)	21.16	2.82	9.51	5.16	5.36	44.01	9.95	53.96
Permits exp(-)/imp(+) (Mton)	106	95	106	43	-6	345	-345	0
i.e % of commitment (import)	*19%*	*66%*	*35%*	*25%*		*26%*		
Flows exp(-)/imp(+) ($billion)	13.44	12.06	13.51	5.49	-0.73	43.77	-43.77	0.00
Total Cost ($billion)	34.60	14.88	23.02	10.64	4.64	87.78	-33.82	**53.96**
Gains from trade ($billion)	3.03	19.49	7.27	2.17	0.03	31.99	33.82	**65.81**

TABLE E: Annex B trading, No hot air

	USA	JPN	EEC	OOE	EET	oecd+eet	FSU	World
Reductions / ref 2010 (Mton)	509	56	220	139	135	1058	254	1312
'Hot air' (Mton)						0	0	0
Market Price of Permits ($/ton)	**$150**	**$150**	**$150**	**$150**	**$150**	**$150**	**$150**	**$150**
Cost of Abatement ($billion)	27.10	3.73	12.21	6.60	6.86	56.51	12.73	69.23
Permits exp(-)/imp(+) (Mton)	63	88	87	33	-17	254	-254	0
i.e % of commitment (import)	*11%*	*61%*	*28%*	*19%*		*19%*		
Flows exp(-)/imp(+) ($billion)	9.40	13.23	13.00	4.90	-2.48	38.05	-38.05	0.00
Total Cost ($billion)	36.50	16.96	25.21	11.50	4.38	94.55	-25.32	**69.23**
Gains from trade ($billion)	1.12	17.41	5.08	1.31	0.29	25.21	25.32	**50.53**

TABLE F: World trading

	USA	JPN	EEC	OOE	EET	oecd+eet	FSU	NAB	World	EEX	CHN	IND	DAE	BRA	ROW
Reductions / ref 2010 (Mton)	182	12	73	59	52	378	101	723	1202	51	437	102	42	2	89
'Hot air' (Mton)						0	111	0	111						
Market Price of Permits ($/ton)	**$24**	**$24**	**$24**	**$24**	**$24**	**$24**	**$24**	**$24**	**$24**	**$24**	**$24**	**$24**	**$24**	**$24**	**$24**
Cost of Abatement ($billion)	1.66	0.14	0.71	0.41	0.43	3.36	0.81	6.99	11.15	0.54	4.22	0.95	0.44	0.03	0.81
Permits exp(-)/imp(+) (Mton)	390	132	234	112	66	935	-211	-723	0	-51	-437	-102	-42	-2	-89
i.e % of commitment (import)	*68%*	*92%*	*76%*	*66%*	*56%*	*71%*									
Flows exp(-)/imp(+) ($billion)	9.27	3.15	5.57	2.67	1.57	22.24	-5.03	-17.21	0.00	-1.21	-10.40	-2.44	-0.99	-0.06	-2.12
Total Cost ($billion)	10.94	3.29	6.29	3.09	2.01	25.60	-4.22	-10.22	**11.15**	-0.68	-6.17	-1.49	-0.55	-0.03	-1.31
Gains from trade ($billion)	26.69	31.08	24.00	9.73	2.66	94.16	4.22	10.22	**108.61**	0.68	6.17	1.49	0.55	0.03	1.31

Region	a	B	R^2	Region	a	b	R^2
USA	**0.0005**	**0.0398**	0.9923	**EEX**	**0.0032**	**0.3029**	0.9983
JPN	**0.0155**	**1.816**	0.9938	**CHN**	**0.00007**	**0.0239**	0.9992
EEC	**0.0024**	**0.1503**	0.9951	**IND**	**0.0015**	**0.0787**	0.9970
OOE	**0.0085**	**- 0.0986**	0.9981	**DAE**	**0.0047**	**0.3774**	0.9996
EET	**0.0079**	**0.0486**	0.9973	**BRA**	**0.5612**	**8.4974**	0.9997
FSU	**0.0023**	**0.0042**	0.9938	**ROW**	**0.0021**	**0.0805**	0.9967

Table 3: Coefficients of the Approximations of the MACs of the Form: $P = aQ^2 + bQ$

In using these approximations, analysts should keep in mind that the price of this simplicity is some loss of the details of the general equilibrium features of the underlying model. The robustness of the curves assures us that the relation between price and quantity of abatement is relatively fixed, but the curves do not capture all the effects of emissions trading. Since the EPPA model remains our primary analysis tool, we have run the model in every policy case we studied not only to ensure that the approximations are not misleading, but also to check for any significant side effects. The prices and quantities for abatement were all very close to the approximations, but there is a side effect that the MACs do not show: "leakage." As will be discussed more extensively later, when only some regions' carbon emissions are constrained, carbon emissions tend to leak to non-constrained regions. Nevertheless, these effects are not essential to the analysis, and the analytical approximations are a powerful computational shortcut to particular results. They provide a convenient way to graphically represent the results of the analysis of trading, and we use them extensively for that purpose in the remaining sections.

f) Aggregate Supply and Demand Curves (Fig. 7)

Marginal abatement curves are the basis for determining the demand and supply for emission permits in any given market. Emission permits represent 'rights to emit' and these rights can be produced by some party abating more than it is required to do, or undertaking some abatement when not required to do so. The willingness of any party to purchase or to sell these permits is illustrated by Fig. 7. The vertical dotted line represents the amount of abatement required for a region to meet its Kyoto commitment. In the absence of any emissions trading it would

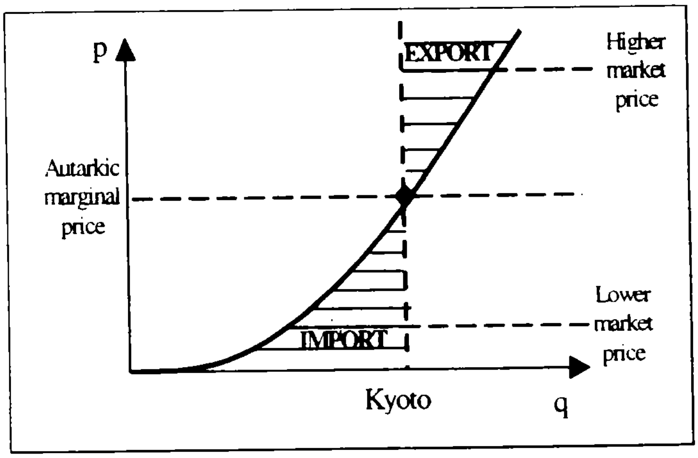

Fig. 7: Willingness to Import / Export with Regard to Market Price of Permits

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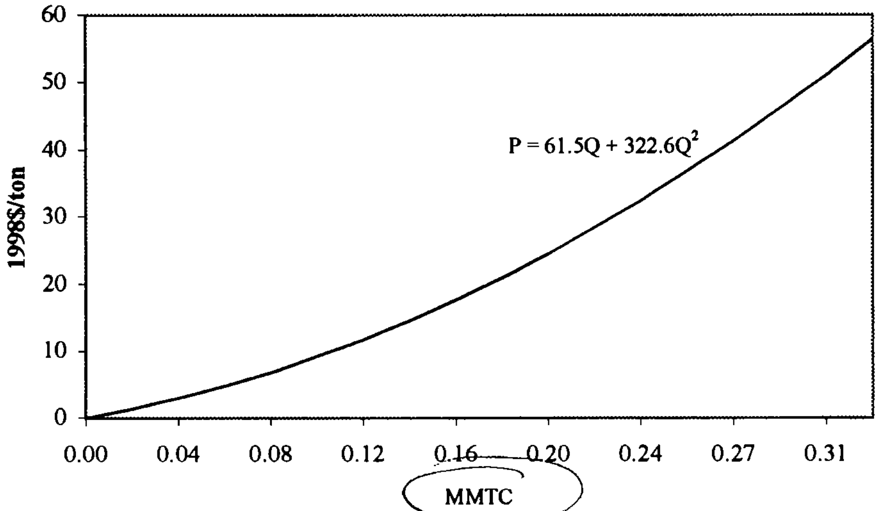
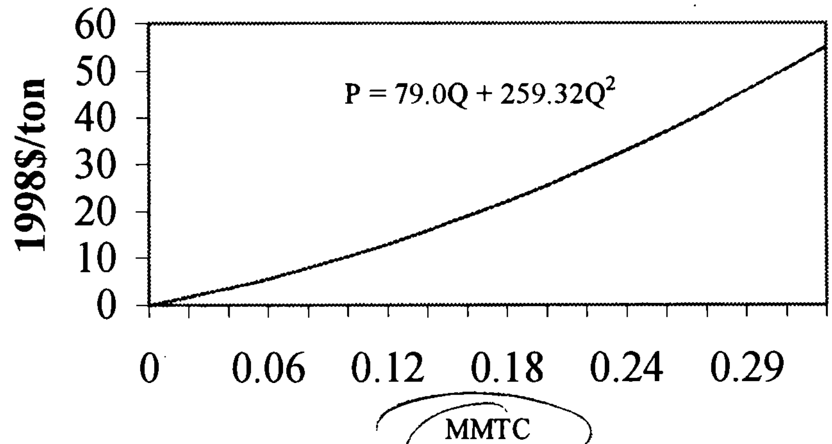
Figure 7. China 2010 Marginal Abatement Cost Curve, MIT-EPPA



Note: Q measured as fraction reduction from BAU
Source: Ellerman et al 1998

MacCracken et al (1999) employed the Second Generation Model (SGM) to evaluate the international emissions market assuming global participation. The SGM includes a China module, developed in coordination with Chinese energy-economic experts. The marginal abatement cost curve for China has then been estimated with SGM model outputs (figure 8). They found that under global participation in the international emissions market, the price for a ton of carbon would be \$29/ton, and China would find it profitable to abate about 340 MMTC in 2010. With a target assumed to be set at 2010 business as usual, exporting emissions allowances representing the emissions abatement

Figure 8. China 2010 Marginal Abatement Cost Curve, SGM



Note: Q measured as fraction reduction from BAU

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ADMINISTRATION ECONOMIC ANALYSIS

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estimates of the economic costs of actions to reduce carbon dioxide emissions.[14] SGM models the energy sector in greater detail than other sectors, so it can provide information on the trade-offs in the consumption of different fuels under a policy to reduce carbon dioxide emissions. It also serves the purpose of evaluating the effects of international emissions trading, because it includes twelve countries and regions (see Table 3). The capacity of the SGM model to take into account international trading is an obvious virtue of this model relative to the other two models used in the Interagency Analytical Team process, both of which only modeled the economic effects of emissions reductions in the United States. The SGM, like all models used to assess economic effects, has strengths and weaknesses. Therefore, the results from this analysis should be considered illustrative. However, the results of the Stanford EMF's investigation of the implications of international trading suggest that the conclusion that effective international trading can significantly reduce costs is robust (Weyant 1997).

Table 3. Countries/Regions in Second Generation Model

Annex I	**Non-Annex I**
United States	China
Western Europe	India
Former Soviet Union	Korea
Eastern Europe	Mexico
Japan	Rest of the World
Canada	
Australia	

Source: Second Generation Model

(1)

Abatement Cost Functions in Industrialized Countries

Drawing on results of more than 60 model runs from the SGM, the Administration developed country- and region-specific cost functions for carbon dioxide abatement by matching prices and emissions reductions in different model runs. For a given country or region, at a given emissions allowance price, the country/region reduces carbon emissions by a specified amount. Over a wide range of prices, the

(2)

14 For more information about the Second Generation Model, refer to Edmonds et al. 1992.

The Economics of the Kyoto Protocol

*Christopher N. MacCracken, James A. Edmonds, Son H. Kim and Ronald D. Sands**

In this paper we use the Second Generation Model to 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. Our analysis shows that the cost of implementing the Protocol in the United States can vary by more than an order of magnitude. The marginal cost in 2010 could be as low as $26 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 mitigation obligations are not adequately anticipated by decision-makers.

INTRODUCTION

The Kyoto Protocol was completed on the morning of December 11, 1997, following more than two years of 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 150 delegations. Because the document is complex, its implications are not immediately obvious. If it enters into force, the Kyoto Protocol could have far-

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Annex I permit trading scenarios. Table 9 shows the 2010 permit price under global trading as compared to the no trading and Annex I trading regimes.

Table 9. Emissions Taxes/Permit Prices Required to Meet Policy Goal in 2010 (1992 US$ per tonne of carbon equivalent)

Region	No Trading	Annex I Trading		Global Trading
		Monopolistic	Competitive	
Canada	350			
former Soviet Union	--			
Japan	458			
United States	168			
Western Europe	130	105	73	26
Australia	117			
Eastern Europe	--			

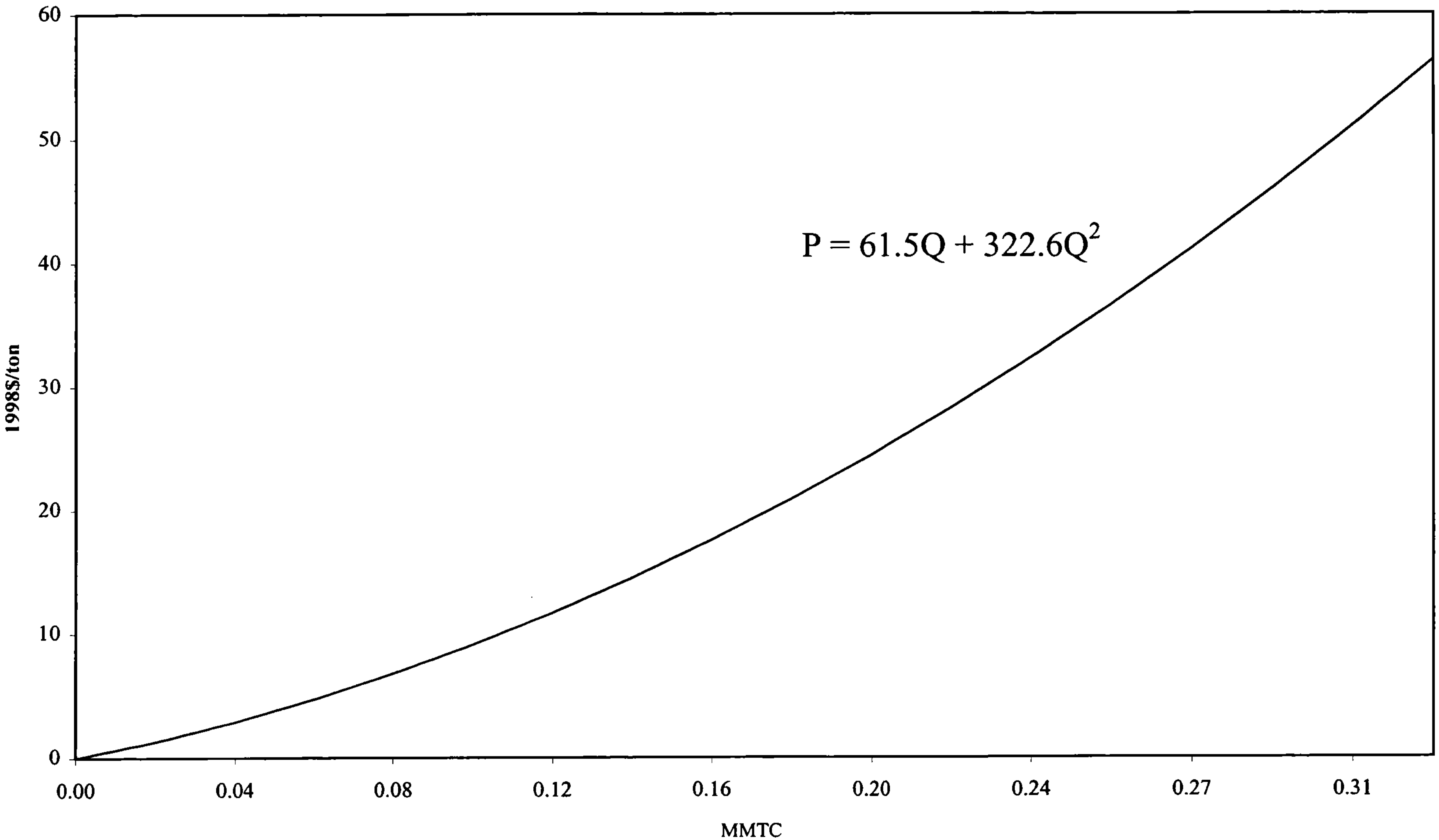
Table 10 shows the composition of the permit market in the global trading case. As mentioned above, permits sold by the non-Annex I regions are generated by equivalent emissions reductions in those regions. The 308 MMTCe of permits sold by the former Soviet Union, however, include 247 MMTCe of "base mitigation credits."

(3)

Table 10. Composition of the Emissions Permit Market in the Global Trading Case (million tonnes of carbon equivalent)

Region	Permits Traded (MMTCe)	
	Purchased	Sold
Canada	61	
former Soviet Union		308
Japan	121	
United States	470	
Western Europe	134	
Australia	25	
Eastern Europe		49
China		341
India		37
Korea		3
Mexico		19
Rest of the World		54
Total	811	811

Figure 7. China 2010 Marginal Abatement Cost Curve, MIT-EPPA



Note: Q measured as fraction reduction from BAU
Source: Ellerman et al 1998

China 2010 Marginal Abatement Cost Curve

Q	SGM	MIT-EPPA
0	0	0
0.019608	1.623222	1.329912
0.039216	3.445829	2.907882
0.058824	5.46782	4.73391
0.078431	7.689196	6.807997
0.098039	10.10996	9.130142
0.117647	12.7301	11.70035
0.137255	15.54963	14.51861
0.156863	18.56855	17.58493
0.176471	21.78685	20.89931
0.196078	25.20454	24.46175
0.215686	28.82161	28.27224
0.235294	32.63806	32.3308
0.254902	36.6539	36.63741
0.27451	40.86913	41.19208
0.294118	45.28374	45.99481
0.313725	49.89773	51.0456
0.333333	54.71111	56.34444

Also 1998 $

1998 $

Q	SGM	MIT-EPPA
0	0	0
0.019608	1.623222	1.329912
0.039216	3.445829	2.907882
0.058824	5.46782	4.73391
0.078431	7.689196	6.807997
0.098039	10.10996	9.130142
0.117647	12.7301	11.70035
0.137255	15.54963	14.51861
0.156863	18.56855	17.58493
0.176471	21.78685	20.89931
0.196078	25.20454	24.46175
0.215686	28.82161	28.27224
0.235294	32.63806	32.3308
0.254902	36.6539	36.63741
0.27451	40.86913	41.19208
0.294118	45.28374	45.99481
0.313725	49.89773	51.0456
0.333333	54.71111	56.34444

For given marginal abatement cost curve, $P = a^* Q + b^* Q^2$ where Q is the fraction of reduction from BAU.

$a^* = b \cdot Q^T \cdot c$ where b is the parameter from page 9, c is the implicit GDP deflator (1985 from Table B7 1998 ERP, 1998 value from Jy 1999 Economic Indicators - values are 78.53 + 112.7 respectively), and Q^T is the total emissions under BAU from final page of report.

$b^* = a \cdot Q^T \cdot c$ where Q^T + c are defined as above and a is taken from page 9.

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only 10%. This fundamental question is that of the robustness of the MACs. And indeed, a drawing like Fig. 2 and the simple method we have deduced from it assume this robustness (one curve for each region, whatever the reductions in other regions). The answer: they are robust.

For example, Fig. 5 shows simultaneously the two sets of MACs corresponding to varying levels of OECD abatement assuming no emissions trading and fully efficient emissions trading.[6] The curves in both sets are similar (less than 10% variation in price for any given level of abatement), thus showing that the MACs are robust with regard to this change of policy. We have made similar comparisons for Annex B trading and global trading, and we have examined one region's MAC (the USA) when all other regions vary from reference to as much as a 60% reduction. In all cases, we have found the same fundamental result: whatever the trading scheme, whatever the extent of the market, the marginal abatement curves are almost identical. These model results indicate that abatement cost in a region is largely independent of abatement efforts in other regions.

Our conclusion is that MACs, and more generally, the costs associated with a given level of domestic abatement, are robust to different levels of abatement among regions and the scope of emissions trading. Whatever the reductions of other regions, a MAC for a region R at time T looks the same.

e) Analytical Approximations: a Simple Tool for Trade Studies (Fig. 6)

Robustness implies that each region at time T has a unique marginal abatement curve. This fundamental result validates the use of marginal abatement curves, and makes actual trade analysis straightforward and simple. Analysis can be simplified even further if each curve could be described by a single mathematical expression because, once we have the equations of the MACs, the cost calculations (i.e. integration under the curves) are extremely simple and rapid.

Fig. 6 shows, for the OECD regions, that we can fit simple analytical curves to the sets of plots resulting from the EPPA runs, and that those fits are very good (for each curve, R^2 is very close to 1). This result is true for all the other regions as well. The curves that best fit the EPPA-generated plots are of the form: $P = aQ^2 + bQ$, where Q is the amount of abatement in million metric tons of carbon (Mton) and P is the marginal cost, or shadow price, of carbon in 1985 US\$.[7] By integration, the total cost of abatement is: $C = 1/3*aQ^3 + 1/2*bQ^2$). The table below displays the coefficients a and b for each region in 2010, as well as the coefficient of determination, R^2.

[6] Note that, compared to figs. 3 and 4, the x-axis has been re-scaled to quantities.

[7] Multiplication by 1.5 converts all price and cost data in this paper into current (1998) USdollars.

Region	a	B	R^2	Region	a	b	R^2
USA	**0.0005**	**0.0398**	0.9923	**EEX**	**0.0032**	**0.3029**	0.9983
JPN	**0.0155**	**1.816**	0.9938	**CHN**	**0.00007**	**0.0239**	0.9992
EEC	**0.0024**	**0.1503**	0.9951	**IND**	**0.0015**	**0.0787**	0.9970
OOE	**0.0085**	**- 0.0986**	0.9981	**DAE**	**0.0047**	**0.3774**	0.9996
EET	**0.0079**	**0.0486**	0.9973	**BRA**	**0.5612**	**8.4974**	0.9997
FSU	**0.0023**	**0.0042**	0.9938	**ROW**	**0.0021**	**0.0805**	0.9967

Table 3: Coefficients of the Approximations of the MACs of the Form: $P = aQ^2 + bQ$

In using these approximations, analysts should keep in mind that the price of this simplicity is some loss of the details of the general equilibrium features of the underlying model. The robustness of the curves assures us that the relation between price and quantity of abatement is relatively fixed, but the curves do not capture all the effects of emissions trading. Since the EPPA model remains our primary analysis tool, we have run the model in every policy case we studied not only to ensure that the approximations are not misleading, but also to check for any significant side effects. The prices and quantities for abatement were all very close to the approximations, but there is a side effect that the MACs do not show: "leakage." As will be discussed more extensively later, when only some regions' carbon emissions are constrained, carbon emissions tend to leak to non-constrained regions. Nevertheless, these effects are not essential to the analysis, and the analytical approximations are a powerful computational shortcut to particular results. They provide a convenient way to graphically represent the results of the analysis of trading, and we use them extensively for that purpose in the remaining sections.

f) Aggregate Supply and Demand Curves (Fig. 7)

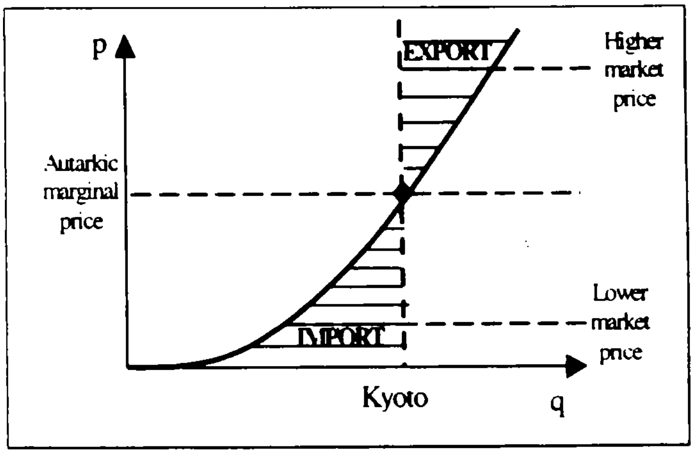


Fig. 7: Willingness to Import / Export with Regard to Market Price of Permits

Marginal abatement curves are the basis for determining the demand and supply for emission permits in any given market. Emission permits represent 'rights to emit' and these rights can be produced by some party abating more than it is required to do, or undertaking some abatement when not required to do so. The willingness of any party to purchase or to sell these permits is illustrated by Fig. 7. The vertical dotted line represents the amount of abatement required for a region to meet its Kyoto commitment. In the absence of any emissions trading it would

NB: all the prices in the following tables are in 1985$. NAB = Non-Annex B regions

I and II. BACKGROUND, METHODOLOGY

TABLE 1 - bis: Reference emissions and Kyoto commitments

Reference emissions	USA	JPN	EEC	OOE	EET	oecd+eet	FSU	NAB	World	EEX	CHN	IND	DAE	BRA	ROW
Ref 1990 (Mton)	1362	298	822	318	266	3066	891	2022	2022	508	833	183	115	63	320
Ref 2010 (Mton)	1838	424	1064	472	395	4193	763	4142	4142	927	1792	486	308	97	532
Kyoto	0.93	0.94	0.92	0.95	1.04		0.98								
Emissions in 2010 (Mton)	1267	280	757	301	277	2881	873	4142	7896	927	1792	486	308	97	532
Reductions / ref 2010 (Mton)	572	144	307	171	118	1312	-111	0	1202	0	0	0	0	0	0
Marginal Costs ($/ton)	**$186**	**$584**	**$273**	**$233**	**$116**										

TABLE 3 - bis: MACs approximations coefficients (P = aR^2+bR)

	USA	JPN	EEC	OOE	EET	FSU	EEX	CHN	IND	DAE	BRA	ROW
a	5.0E-04	1.6E-02	2.4E-03	8.5E-03	7.9E-03	2.3E-03	3.2E-03	7.0E-05	1.5E-03	4.7E-03	5.6E-01	2.1E-03
b	0.0398	1.816	0.1503	-0.0986	0.0486	0.0042	0.3029	0.0239	0.0787	0.3774	8.4974	0.0805

III. BASIC CASES

TABLE A: Kyoto OECD only no trading

	USA	JPN	EEC	OOE	Oecd
Reductions / ref 2010 (Mton)	572	144	307	171	1194
Marginal Costs ($/ton)	**$186**	**$584**	**$273**	**$233**	
Cost of Abatement ($billion)	37.62	34.37	30.29	12.81	**115.09**

TABLE B: Kyoto OECD only OECD trading

	USA	JPN	EEC	OOE	Oecd
Reductions / ref 2010 (Mton)	655	79	287	174	1194
Market Price of Permits ($/ton)	**$240**	**$240**	**$240**	**$240**	**$240**
Cost of Abatement ($billion)	55.28	8.22	25.02	13.44	101.96
Permits exp(-)/imp(+) (Mton)	-83	65	21	-3	0
i.e % of commitment (import)		*45%*	*7%*		
Flows exp(-)/imp(+) ($billion)	-19.95	15.66	4.94	-0.64	0.01
Total Cost ($billion)	35.33	23.88	29.96	12.80	**101.97**
Gains from trade ($billion)	2.30	10.49	0.33	0.01	**13.12**

TABLE C: Kyoto no trading

	USA	JPN	EEC	OOE	EET	oecd+eet	FSU	World
Reductions / ref 2010 (Mton)	572	144	307	171	118	1312	0	1312
Marginal Costs ($/ton)	**$186**	**$584**	**$273**	**$233**	**$116**			
Cost of Abatement ($billion)	37.62	34.37	30.29	12.81	4.67	119.76	0.00	**119.76**

TABLE D: Annex B trading

	USA	JPN	EEC	OOE	EET	oecd+eet	FSU	World
Reductions / ref 2010 (Mton)	466	49	201	128	124	968	234	1202
'Hot air' (Mton)						0	111	111
Market Price of Permits ($/ton)	**$127**	**$127**	**$127**	**$127**	**$127**	**$127**	**$127**	**$127**
Cost of Abatement ($billion)	21.16	2.82	9.51	5.16	5.36	44.01	9.95	53.96
Permits exp(-)/imp(+) (Mton)	106	95	106	43	-6	345	-345	0
i.e % of commitment (import)	*19%*	*66%*	*35%*	*25%*		*26%*		
Flows exp(-)/imp(+) ($billion)	13.44	12.06	13.51	5.49	-0.73	43.77	-43.77	0.00
Total Cost ($billion)	34.60	14.88	23.02	10.64	4.64	87.78	-33.82	**53.96**
Gains from trade ($billion)	3.03	19.49	7.27	2.17	0.03	31.99	33.82	**65.81**

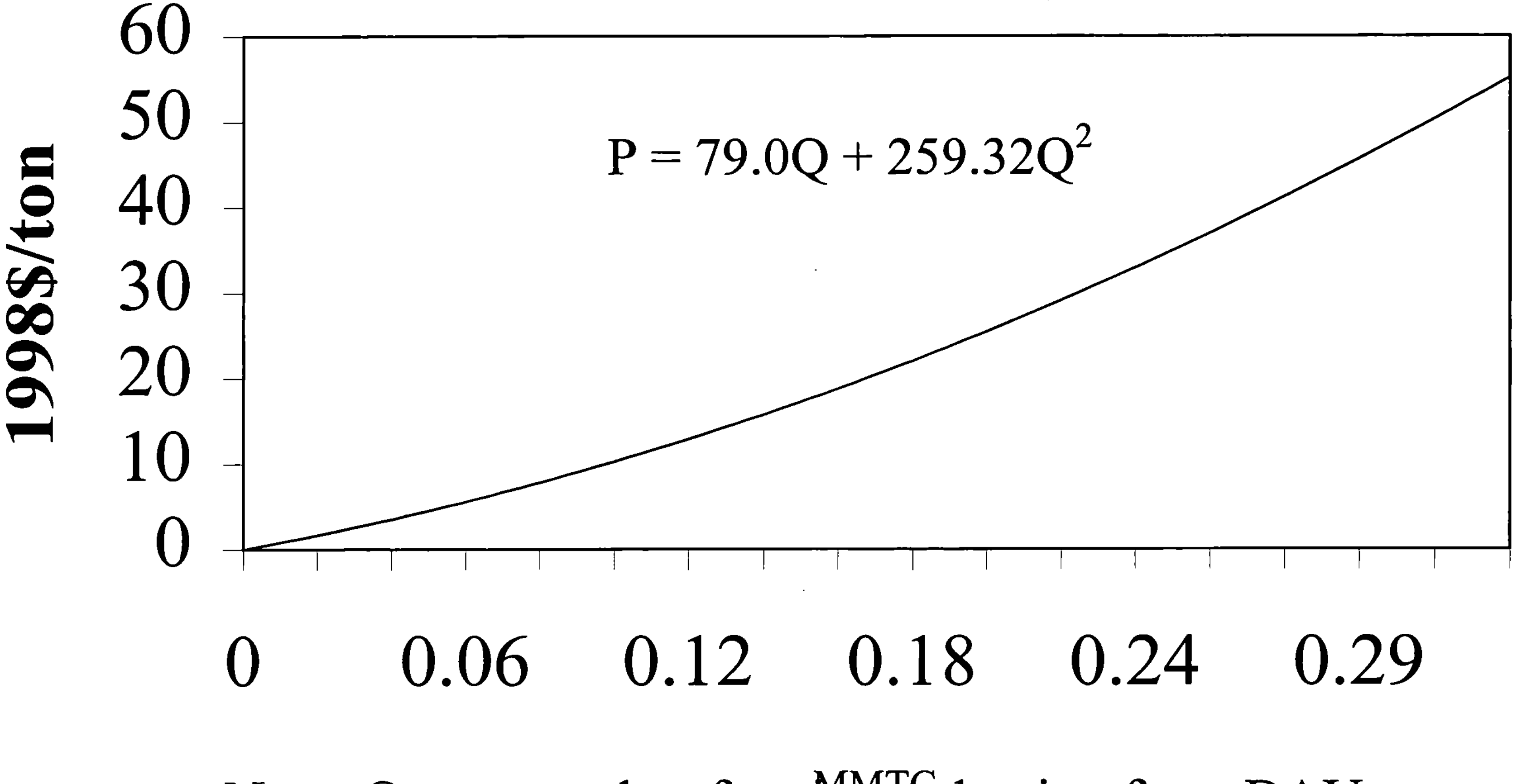
TABLE E: Annex B trading, No hot air

	USA	JPN	EEC	OOE	EET	oecd+eet	FSU	World
Reductions / ref 2010 (Mton)	509	56	220	139	135	1058	254	1312
'Hot air' (Mton)						0	0	0
Market Price of Permits ($/ton)	**$150**	**$150**	**$150**	**$150**	**$150**	**$150**	**$150**	**$150**
Cost of Abatement ($billion)	27.10	3.73	12.21	6.60	6.86	56.51	12.73	69.23
Permits exp(-)/imp(+) (Mton)	63	88	87	33	-17	254	-254	0
i.e % of commitment (import)	*11%*	*61%*	*28%*	*19%*		*19%*		
Flows exp(-)/imp(+) ($billion)	9.40	13.23	13.00	4.90	-2.48	38.05	-38.05	0.00
Total Cost ($billion)	36.50	16.96	25.21	11.50	4.38	94.55	-25.32	**69.23**
Gains from trade ($billion)	1.12	17.41	5.08	1.31	0.29	25.21	25.32	**50.53**

TABLE F: World trading

	USA	JPN	EEC	OOE	EET	oecd+eet	FSU	NAB	World	EEX	CHN	IND	DAE	BRA	ROW
Reductions / ref 2010 (Mton)	182	12	73	59	52	378	101	723	1202	51	437	102	42	2	89
'Hot air' (Mton)						0	111	0	111						
Market Price of Permits ($/ton)	**$24**	**$24**	**$24**	**$24**	**$24**	**$24**	**$24**	**$24**	**$24**	**$24**	**$24**	**$24**	**$24**	**$24**	**$24**
Cost of Abatement ($billion)	1.66	0.14	0.71	0.41	0.43	3.36	0.81	6.99	11.15	0.54	4.22	0.95	0.44	0.03	0.81
Permits exp(-)/imp(+) (Mton)	390	132	234	112	66	935	-211	-723	0	-51	-437	-102	-42	-2	-89
i.e % of commitment (import)	*68%*	*92%*	*76%*	*66%*	*56%*	*71%*									
Flows exp(-)/imp(+) ($billion)	9.27	3.15	5.57	2.67	1.57	22.24	-5.03	-17.21	0.00	-1.21	-10.40	-2.44	-0.99	-0.06	-2.12
Total Cost ($billion)	10.94	3.29	6.29	3.09	2.01	25.60	-4.22	-10.22	**11.15**	-0.68	-6.17	-1.49	-0.55	-0.03	-1.31
Gains from trade ($billion)	26.69	31.08	24.00	9.73	2.66	94.16	4.22	10.22	**108.61**	0.68	6.17	1.49	0.55	0.03	1.31

Figure 8. China 2010 Marginal Abatement Cost Curve, SGM



Note: Q measured as fraction reduction from BAU

China 2010 Marginal Abatement Cost Curve

Q	SGM	MIT-EPPA
0	0	0
0.019608	1.64872	1.329912
0.039216	3.49684	2.907882
0.058824	5.54436	4.73391
0.078431	7.79128	6.807997
0.098039	10.2376	9.130142
0.117647	12.88332	11.70035
0.137255	15.72844	14.51861
0.156863	18.77296	17.58493
0.176471	22.01689	20.89931
0.196078	25.46021	24.46175
0.215686	29.10293	28.27224
0.235294	32.94505	32.3308
0.254902	36.98657	36.63741
0.27451	41.2275	41.19208
0.294118	45.66782	45.99481
0.313725	50.30754	51.0456
0.333333	55.14667	56.34444

1998 $

Q	SGM	MIT-EPPA
0	0	0
0.019608	1.64872	1.329912
0.039216	3.49684	2.907882
0.058824	5.54436	4.73391
0.078431	7.79128	6.807997
0.098039	10.2376	9.130142
0.117647	12.88332	11.70035
0.137255	15.72844	14.51861
0.156863	18.77296	17.58493
0.176471	22.01689	20.89931
0.196078	25.46021	24.46175
0.215686	29.10293	28.27224
0.235294	32.94505	32.3308
0.254902	36.98657	36.63741
0.27451	41.2275	41.19208
0.294118	45.66782	45.99481
0.313725	50.30754	51.0456
0.333333	55.14667	56.34444

SGM results provide the MAC as

$$P = 0.050851\,\tilde{Q} + 0.000121\,\tilde{Q}^2$$

where $\tilde{Q}$ is total reduction from BAU & P is in 1992 \$. The equation was scaled to 1998 \$ using 1.127 (the 1998 implicit price deflator from the Jy 1999 Economic Indicators ~~and~~ (112.7) divided by 100 the value for 1992). If $\bar{Q}$ is 2010 BAU, then

$$P = \left[\frac{0.05085}{\bar{Q}^{-1}}\left(\frac{\tilde{Q}}{\bar{Q}}\right) + 0.000121\cdot\bar{Q}^2\left(\frac{\tilde{Q}}{\bar{Q}}\right)^2\right]1.127$$

$$= 0.05085\,\bar{Q}(Q) + 0.000121\cdot\bar{Q}^2(Q)^2$$

For SGM, $\bar{Q}$ = 1379 million MTCE.

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could generate nearly $10 billion in revenue annually.

In addition to the international economic models used in the EMF-16 exercise, some China specific assessments of abatement potential have been conducted. While these studies cannot explicitly illustrate the potential role of China in an international emissions market, they have the benefit of evaluating the Chinese economy in greater detail, and can provide additional insights about the abatement potential in China.

See rewrite from Garbaccio

For example, Garbaccio et al (1999) completed a recent evaluation of a carbon tax on the Chinese economy. Such a tax could mirror other emissions and pollutant charges in China. Garbaccio et al designed a 29-sector computable general equilibrium model based on China's 1992 input-output (I-O) tables. They estimated levels of carbon taxes necessary to abate emissions 5%, 10%, and 15% below business as usual over a 40-year period. Revenues from the carbon tax were recycled to the economy by proportional reductions in labor and capital taxes, which in their model promotes higher rates of investment. While GDP falls below projected business as usual in the first year of these three simulations, the investment induced by revenue recycling results in GDP growth above BAU after the first year in all scenarios. In this model, China's emissions could be abated by 15% below business as usual at a cost less than $10 per ton of carbon equivalent (approximately 30 yuan, in 1992 yuan), which is well below the estimated Annex I trading carbon prices in the EMF-16 model results. This analysis indicates that China can substantially reduce its greenhouse gas emissions while maintaining or even increasing its rate of economic growth. Participating in emissions trading and exporting emissions allowances would provide similar economic benefits and bring in additional capital that could also contribute to economic growth.

Table 2 summarizes some of the findings in the economic-energy modeling literature on the potential economic gains for China in participating in international emissions trading. These results assume that China has an emissions target for the first commitment period set at projected emissions for 2010 under business as usual. With the relatively significant emissions abatement below business as usual reflected in these modeling results, targets set slightly below business as usual could generate substantial gains from trade. However, more stringent targets would likely reduce these gains, and extremely stringent targets – for example, below 1990 levels for greenhouse gases in China – would likely result in direct abatement costs well in excess of sales revenues. Of course, these gains from trade are sensitive to both the international market price for a ton of carbon as well as the abatement opportunities within China. These scenarios assume that all developing countries adopt emissions targets set at 2010 BAU levels. Since some of these countries also have low abatement costs relative to developed countries, this assumption implies that China would have competition in "producing" emissions abatement. To the extent that other relatively large, low-cost developing countries do not adopt emissions targets, the supply of emissions abatement would be less than estimated in these global trading scenarios, and China would witness a higher market price for abating carbon and additional economic incentive to abate more emissions. This would increase both the volume of emissions abatement sold to other countries and the economic value of these sales.

See p. 14

Table 2. Potential Economic Effects of Chinese Participation in International Emissions Trading

Forthcoming in *Environment and Development Economics*, 1999.

2a

Controlling Carbon Emissions in China*

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ABSTRACT

We examine the use of carbon taxes to reduce emissions of CO_2 in China. To do so, we develop a dynamic computable general equilibrium (CGE) model of the Chinese economy. In addition to accounting for the effects of population growth, capital accumulation, technological change, and changing patterns of demand, we also incorporate into our model elements of the dual nature of China's economy where both plan and market institutions exist side by side. We conduct simulations in which carbon emissions are reduced by 5, 10, and 15% from our baseline. After initial declines, in all of our simulations GDP and consumption rapidly exceed baseline levels as the revenue neutral carbon tax serves to transfer income from consumers to producers and then into increased investment. Although subject to a number of caveats, we find potential for what is in some sense a "double dividend," a decrease in emissions of CO_2 and a long run increase in GDP and consumption.

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using inputs that are partly allocated through the plan and partly purchased in the market; (iii) the government which buys goods and services, imposes taxes, redistributes income, and sets down a central plan; and (iv) the foreign sector which purchases exports and supplies imports and foreign investment. The flow of payments among the various actors in the economy is summarized in the social accounting matrix (SAM) given in Figure 1. (The SAM is described more fully in section three.)

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The economy is divided into the 29 sectors listed in Table 1. Our plan-market formulation follows the theoretical work of Byrd (1989) and Sicular (1988) and the static CGE implementation of Garbaccio (1994, 1995). For those commodities and factors of production with both a market and plan component, there is a division between the two tracks. A fixed amount of total output is sold at the plan price, while the remainder is sold on the market. The market price equates demand and supply for all commodities. Marginal decisions are made on the basis of the market prices while changes in plan prices and quantities are inframarginal. In a single period, for those sectors in which both tracks exist, the net effect of the plan allocations is to create lump sum transfers between producers and consumers. However, over time, the plan allocations do affect sectoral retained earnings and investment.

The factors of production in the model are capital, labor, land, energy, and other intermediates. Given the unavailability of sectoral time-series data, we use Cobb-Douglas production functions, with the coefficients changing over time so that there is both technical progress (more output with the same inputs) and biased technical change (changes in input demands unrelated to prices). This exogenous technical change is projected such that the Chinese input demands resemble the U.S. 1992 structure in 40 years. 2d

The use of energy in China in recent years is discussed in Garbaccio, Ho, and Jorgenson (1998). Using the 1987 and 1992 input-output tables, we show that recent declines in the energy-GDP ratio have been due mostly to a fall in the use of energy per unit of output at the sectoral (roughly 2-digit) level. By contrast, very little of the change in the energy-GDP ratio has been due to changes in the composition of output. This fall in energy use cannot be plausibly explained by changes in relative prices alone and should be largely attributed to technical change (or change in sectoral composition below the 2-digit level). Our projections of biased technical change allow for this trend to continue in the simulations.

The capital input for each industry consists of a plan component that is not mobile across sectors and a market component that is rented from a common capital stock. The capital stock evolves over time with new investment and depreciation. The labor input is mobile across sectors with the total supply projected using a population model. For two industries, agriculture and crude petroleum, "land" is an input and its supply is fixed exogenously.

Consumers derive income from wages, dividends, and transfers. They make purchases at both plan and market prices. The pattern of consumption demands changes over time (due to effects other than just changes in relative prices) and this is again projected using 1992 U.S. data. Household savings are set as an exogenous share of income and form part of national savings together with enterprise retained earnings and (net) foreign investment. Savings are used for investment in domestic capital and to finance the government budget deficit.

The government imposes taxes on enterprise capital income, sales, and imports. On the expenditure side, the government buys goods, provides subsidies and investment grants, pays interest on government bonds, and makes transfer payments. The deficit is covered by domestic and foreign borrowing. The modeling of imports and exports follows the standard one-country treatment and the trade and current account deficits are set exogenously. The evolution of the stocks of domestic and foreign debts and interest payments are treated consistently.

3. Data and Exogenous Variables

The primary data set for the model is built around the official Chinese input-output tables for 1992.[4] The input-output tables have in turn been used to construct the SAM for the same year (Figure 1). The SAM provides a tabular snapshot of the economy for a single year. For each economic agent, there is a row that records incomes and a column that records expenditures. Our SAM allows for a distinction between commodities and activities (industries). Each activity can produce more than one commodity so that we can incorporate both the official USE (commodity by activity) and MAKE (activity by commodity) matrices.[5] 2c

[4] Details of the data construction and sources are given in Garbaccio, Ho, and Jorgenson (1997a). Details of the projections of many of the exogenous variables are also included.

[5] For example, the "petroleum refining" activity produces both the "petroleum refining" and "chemical" commodities.

and θ_i is the emissions coefficient by fuel type.[7]

After establishing the base case, we then run alternative simulations where emissions of carbon dioxide are constrained to be a fraction (γ) of the base case in every period:

(2) $$CAR_{alt}(t) \;=\; \gamma\, CAR_{base}(t) \quad , \quad t = 1, 2, ..., T.$$

All other exogenous variables and parameters are held constant. To achieve the carbon emissions target, we let the carbon tax be an endogenous variable which has the effect of raising the prices of coal and oil.[8] The imposition of the carbon tax raises additional revenue for the government. In order to keep the alternative simulations revenue neutral, we reduce all other taxes proportionately. With government deficits held constant, this means that we are keeping government spending the same as in the base case. To scale the original tax rates, we introduce an additional endogenous variable, λ_t, into the alternative system such that: Le

(3) $$t_t^k = \lambda_t t_o^k, \quad t_{it}^t = \lambda_t t_{io}^t, \quad \text{etc.} \quad ,$$

where t_t^k is the capital income tax rate and t_{it}^t is the indirect tax rate for sector i. The sectoral indirect tax rates (net of subsidies) are provided in the last column of Table 1. The government expenditure neutrality constraint is then set so that:

(4) $$GG_{alt}(t) \;=\; GG_{base}(t) \quad ,$$

where GG is the quantity index of government purchases (equation A15 in the appendix). This keeps aggregate spending constant. The quantity of specific commodities purchased will, of course, change. To summarize, in the alternative simulations there are two additional equations, (2) and (4), and two additional endogenous variables, the tax rate per ton of carbon and λ. GG, an endogenous variable in the base case is made an exogenous variable in the alternative solutions. Tax rates on capital income, sales, and tariffs are made endogenous in the alternative cases.

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[7] Net imports of refined petroleum are also calculated and included in the total.

[8] See equations A4 and A12 in the appendix.

We then compare the outcome of the alternative simulations with the base case solution. Although our base case may be of independent interest, we do not focus on it in this paper. The base case levels of output, emissions, etc., are driven by the assumptions about the exogenous variables, such as the rates of population growth and technological change. In Ho, Jorgenson, and Perkins (1998), we examined a number of plausible assumptions about the exogenous variables and produced a wide range of forecasts of the levels of output and emissions. Our assumptions about the exogenous variables in the current paper lead to fairly high average growth rates. In the base case, GDP rises at an average of 5.7 percent per year over the first 30 years. The growth rate is higher in the beginning but gradually declines as both population and productivity growth slow in the later years. The high rate of GDP growth leads to a high rate of growth of carbon emissions, averaging 3.8 percent per year over the first 30 years.

We ran three alternative scenarios: 5%, 10%, and 15% reductions in carbon emissions (i.e. $\gamma = 0.95$, 0.90, and 0.85). The impacts of these carbon reductions on some important variables are presented in Tables 2, 3, and 4 and graphed in Figures 2 through 7. The base case levels of total carbon emissions and the levels for the 5%, 10%, and 15% reduction cases are shown in Figure 2.[9] For each of the reduction scenarios, the percentage change in GDP relative to the base case is shown in Figure 3. In all of the alternative scenarios, there is a very small decline in GDP in the 1st year. However, in each case, there is an increase in the level of GDP in every year thereafter. In the 15% carbon reduction case, by the 30th year of the simulation, the level of GDP has increased by almost 1 percent over the baseline.

The unit carbon tax rates calculated for the three emissions reductions cases are shown in Figure 4. For the 5% emissions reduction case, a tax of about 9 *yuan* per ton of carbon is required in the 1st year of the simulation.[10] Increasing the percentage reduction in emissions requires a more than proportionate increase in the unit carbon tax. Offsetting the new revenue from the carbon tax is the reduction in all other taxes by the factor λ. The value for λ in each period is graphed in Figure 5. Each of the other tax rates is reduced by about 1 percent in the

[9] In the base case, carbon emissions in year 2032 are 2.16 billion tons. This figure is reduced by 5%, 10%, and 15% in the alternative simulations.

[10] There are 0.518 tons of carbon emitted per ton of average coal. The average price of coal output in 1992, derived by dividing the value in the input-output table by the quantity of coal mined, is about 68 *yuan* per ton. This implies a tax on coal of about 7 percent.

simulation period for the 5% carbon reduction case and by approximately 3 to 4 percent in the 15% case.

The imposition of the carbon tax increases energy prices and this in turn leads to increases in the prices of other goods (relative to the numeraire, the nominal wage rate). A decline in the real wage results in a fall in household income and, in the first few years of the simulations, a decline in aggregate consumption. This is shown in Figure 6. However, given our assumption that the labor supply in China is inelastic, the decline in the real wage does not have a distortionary effect on hours worked. At the same time, because of the offsetting reductions in enterprise taxes, enterprise retained earnings are increased. Households do not receive a similar benefit from the reduction in the taxes on labor income because these taxes are negligible in the base year. As shown in Figure 7, the increase in retained earnings is transferred into an increase in investment. Over time, this increased investment results in an increase in total output. This shows up within a few years in an increase in consumption over the baseline in all of the carbon tax simulations.

2f

We can now look at the effects on the individual primary energy sectors (see Tables 2, 3, and 4). After the imposition of the sectoral carbon tax on coal, in the 1st year of the 5% reduction simulation the purchaser's (market) price of coal increases by 6.1 percent. Because of its lower carbon content, the imposition of the sectoral carbon tax on oil causes the purchaser's price of oil to rise by only 1.0 percent. The increase in the price of coal results in a 6.0 percent reduction in coal output. In the 1st year, oil sector output falls by 0.8 percent while imports of oil and refined petroleum both fall by about 2 percent. Overall, these changes lead to a fall in total primary energy use of 4.7 percent, slightly less than the 5 percent decline in total carbon emissions.[11]

Increasing the percentage reduction in carbon emissions requires a more than proportionate increase in sectoral carbon tax rates. For coal, the 5%, 10%, and 15% reductions in carbon emissions require, respectively, 6.1, 12.9, and 20.7 percent increases in coal prices in the 1st year. Similar disproportionate increases in prices are required for oil. As shown in Table 2, this holds true for coal and oil in both the 1st and 30th years of the simulations.

[11] Total primary energy use is calculated as the simple sum of the standard coal equivalents of coal, oil, natural gas, and hydroelectricity.

The effects on other sectors are predictable. Changes in purchaser's (market) prices for the 1st year are given in Table 3. Because of the rise in primary energy prices, sectors that use energy intensively experience proportionate price increases. For example in the 5% reduction scenarios, the price of electricity increases by 0.8 percent, building materials by 0.3 percent, and primary metals by 0.3 percent. Figures for changes in sectoral output are given in Table 4. There are reductions in the output of electricity and refined petroleum. Agricultural output falls slightly because of the decline in demand due to the drop in real household income. At the same time, sectors that sell investment goods (transport equipment and construction) experience increases in demand and output.

Over time, as the GDP and capital stock rise relative to the base case, higher demand for energy requires that the carbon tax rates be increased in order to continue to achieve the same proportionate reduction in emissions. In the 5% carbon reduction case, this results in a 6.7 percent increase in the market price of coal in the 30th year compared to the 6.1 percent increase during the 1st year of the simulation (see Table 2). The effect is reversed for oil because of the assumed availability of oil imports at the projected world price. The assumption that government spending is fixed in real terms, coupled with an increasing tax base, results in the revenue from the carbon tax falling as a share of total revenue over time. In the 5% carbon reduction case, the share of revenue from the carbon tax falls from 1.2 percent in the 1st year to 0.6 percent in the 30th year. In the 15% reduction case, the share falls from 3.6 to 1.9 percent.

Two comments are in order on the pattern of carbon taxes over time in our model. The first concerns our assumptions about capital mobility. In the initial years of our simulations, the plan portion of capital dominates the total. The plan portion of capital is assumed to be immobile. Compared to models with completely mobile capital, this results in a much slower rate of substitution of capital for energy. Over time, the stock of mobile *market* capital rises in each industry and this results in more flexibility in later years. The second comment concerns the specification for the crude oil sector. The crude oil sector is one of two industries in the model with "land" (oil reserves) as an input and the quantity of domestic reserves is assumed fixed. The domestic price of oil therefore rises relative to most other prices and imports of oil rise faster in the carbon tax simulations than in the base case. Alternative specifications, such as including exploration costs into our model or different assumptions about future world oil prices, could alter our results.

Finally, we should emphasize what our assumptions about the production functions and technical change imply. As discussed previously, the share coefficients are projected exogenously. This affects the level of energy use and has a major influence on the "business as usual" baseline solution. However, the percentage change in energy use induced by the imposition of carbon taxes is determined by the elasticity of substitution between the various inputs. These elasticities are constant in our production functions and are therefore identical in both the base case and carbon tax simulations. The percentage change in input demands is not determined by the value of the share coefficients.[12]

5. Conclusions

Our results paint a rather optimistic picture of the use of carbon taxes to induce a reduction in CO_2 emissions in China. Although the imposition of a carbon tax results in a fall in consumption in the first few years of our simulations, in all of the emissions reduction scenarios analyzed, GDP rises above the baseline level after the first year. Within a few years, increases in investment also lead to increases in consumption above the baseline. Since we do not use an intertemporal utility function, we do not calculate discounted consumption. However, it would take an extremely high discount rate to produce a loss in the aggregate.

Recent work using analytical and computable general equilibrium models by Bovenberg and de Mooij (1994), Goulder (1995a), Parry (1995), Bovenberg and Goulder (1996), Böhringer, Pahlke, and Rutherford (1997) and others have cast doubt on the likelihood of a "double dividend" from environmental taxation. A review of this evolving literature is beyond the scope of this paper.[13] However, it is possible to point out a number of reasons why our results differ and in fact do not contradict those obtained in these studies. First, we should emphasize that our main result comes about because of the shift from consumption to investment brought about indirectly through the imposition of the carbon tax. Although GDP increases in every year after the first year, it drops below the baseline in the first year of all of our carbon tax simulations. Second, the most important element driving our results is our assumption that the labor supply in

[12] This comment applies to the other exogenous variables in the model as well. A different rate of technical progress, for example, would lead to a different path for the base case. However, the percentage change in variables (like GDP) resulting from the imposition of a carbon tax, would be only marginally affected. Assuming a more rapid rate of liberalization of the plan elements would have income, but not price effects.

[13] A good overview of the "double dividend" literature is given in Goulder (1995b).

China is inelastic. With this specification, the fall in the real wage brought about by increases in goods prices has no distortionary effect on hours worked. The assumption of a positive labor supply elasticity is one of the key assumptions that leads to the rejection of the "double dividend" hypothesis for developed country economies, but seems inappropriate in the context of China's transition economy.[14] Third, the fact that in China, taxes on labor are negligible means that households receive almost no benefit from the revenue neutral reduction in tax rates. This effect serves to further shift the burden of the carbon tax onto households. Fourth, most of the dynamic CGE models for developed economies have endogenously determined savings rates with perfect foresight, while the private savings rate in our model is exogenous (although not constant). Enterprise savings are affected by the revenue neutral reduction in the enterprise income tax, but there is no price effect on retained earnings. Hence the passive rise in investment. Finally, other distortions, like the two-tier price system and highly differentiated net output tax rates on intermediate and final goods, leave open the possibility for many welfare enhancing reforms, which may relate only coincidentally to environmental objectives.[15] Given that carbon taxes have the effect of reducing subsidies and raising prices for energy goods, our results are consistent with calls by the World Bank and others for China to increase efficiency by liberalizing energy markets.

Our results contrast with those of Zhang (1998a, 1998b) who found large decreases in output in his carbon tax simulations for China. Although Zhang also assumes an inelastic labor supply and an exogenous savings rate, there are a number of differences between the models which may account for the differing results. First, Zhang's model is based on data for 1987, while ours is based on data for 1992. As an example of the difference in base year data, Chinese imports of crude oil were negligible in 1987, but by 1992 had risen to 14 percent of the value of domestic oil consumption. Second, the economy in Zhang's model is completely marketized, while we incorporate a number of features that reflect the mixture of plan and market that still exists in China. Third, Zhang's model has 10 sectors while ours has 29. The more refined

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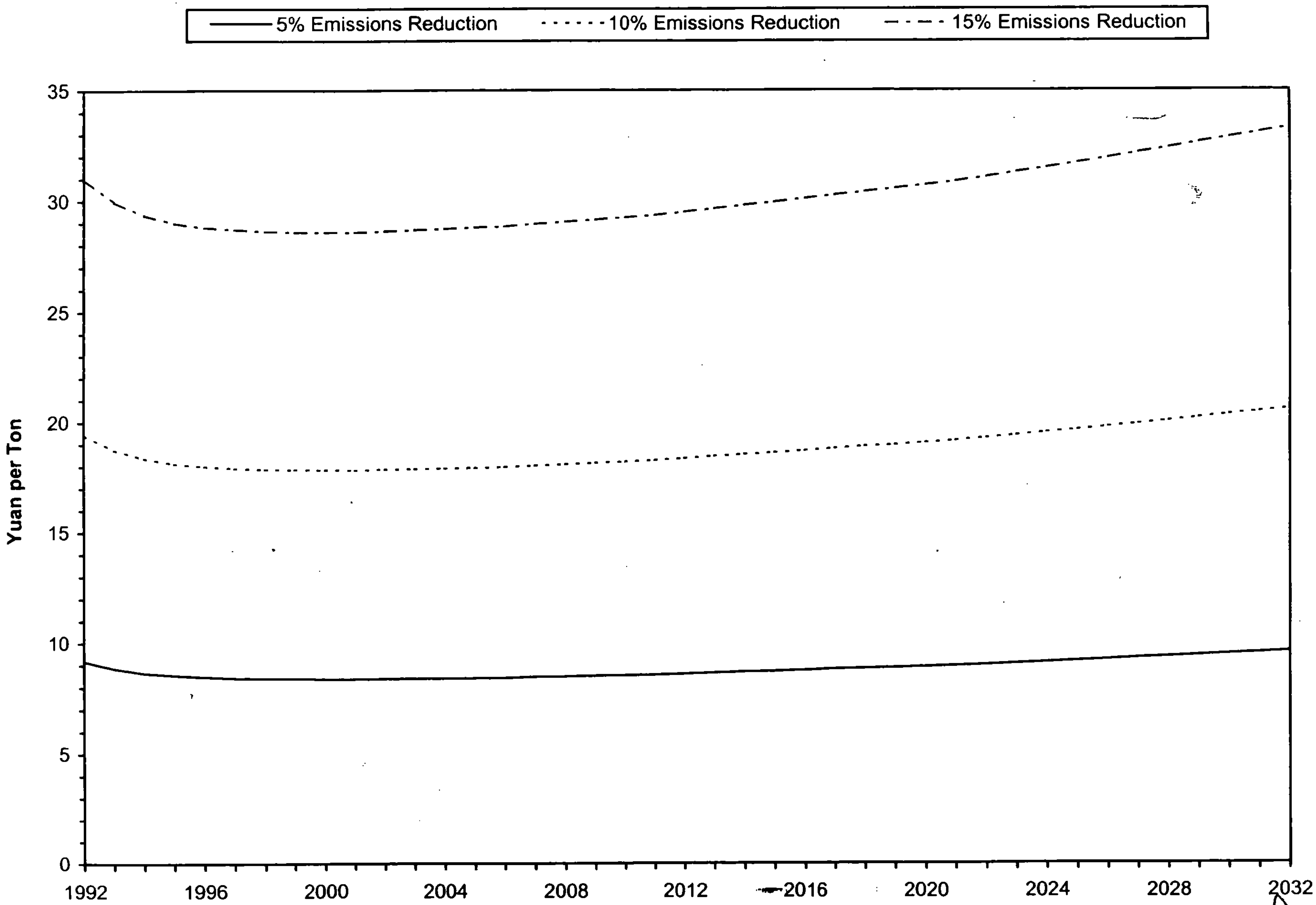
[14] At this time we are aware of no study that has estimated a labor supply elasticity for China. However, we should note that allowing for an elastic labor supply in our model would require the inclusion of leisure in the welfare function. Given the development of labor markets in China and the high rate of unemployment, we do not believe that this would be a useful complication of the model.

[15] Some of the sectoral inequality in commodity tax rates was reduced following the taxation system reforms that took place at the beginning of 1994.

Figure 4: Carbon Taxes Required to Attain a Given Reduction in Emissions



Clinton Presidential Records
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Divider Title: **19**

Model	2010 Price of Carbon (1998$)	Emissions Abatement (% below BAU)	Annual Revenues from Sales of Emissions Allowances, 2008-2012
MIT-EPPA (Ellerman et al 1998)	$34/ton	24%	$14 billion/year
SGM (MacCracken et al 1999)	$29/ton	24%	$10 billion/year
GREEN (van der Mensbrugghe 1998)	$27/ton	15%	$6 billion/year
RICE (Nordhaus and Boyer 1999)	$22/ton	14%	$4 billion/year
G-Cubed (McKibbin et al 1999)	$24/ton	19%	$7 billion/year
ABARE-GTEM (Tulpule et al 1999)	$28/ton	19%	$10 billion/year

In these scenarios, every ton of abatement undertaken by China under a 2010 BAU target would allow it to sell a one-ton emissions allowance to other countries with emissions targets. Because these models assume that emissions abatement occurs at least-cost, every ton abated costs less than the 2010 price of carbon – the price China would receive for selling emissions allowances internationally – except for the last ton abated. In addition to the revenues associated with the sale of emissions allowances, the abatement of emissions could have several other economic effects on China. This opportunity to act as one of the largest suppliers of emissions allowances in the international emissions market could serve to attract more FDI and advanced technology to the energy and industrial sectors that emit the majority of greenhouse gases.

Efforts to abate emissions could have two other countervailing effects on the economy. First, policies such as a carbon tax could provide revenues to the government and afford it the opportunity to reduce taxes on labor and investment. As noted above in the discussion of the Garbaccio et al analysis, such a policy could result in lower carbon dioxide emissions while stimulating investment and increasing GDP in the long run. However, some researchers have found that carbon taxes can exacerbate pre-existing tax distortions in markets, such as labor taxes, and this could have the effect of increasing the costs of abatement (Bovenberg and Goulder 1996). It should also be noted that carbon taxes can partially correct pre-existing subsidy distortions in energy markets, which would reduce the costs of abatement.

Finally, abating carbon dioxide emissions often results in the abatement of local air pollutants, such as sulfur dioxide, particulate matter, and nitrogen oxides that cause significant costs in terms of public health effects as well as agriculture and silviculture damage. The next section reviews the benefits in improving local air quality that accompanies carbon dioxide abatement.

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Joint Program on the Science and Policy of Global Change
Massachusetts Institute of Technology

September 1998

ANALYSIS OF POST-KYOTO CO_2 EMISSIONS TRADING USING MARGINAL ABATEMENT CURVES

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We are greatly indebted to many colleagues and associates for consistent encouragement and critical comment. Foremost among these are the faculty and research staff associated with MIT's Joint Program on the Science and Policy of Global Change, particularly the EPPA Working Group. Particular thanks are due to Henry Jacoby, Dick Eckaus, Loren Cox and David Reiner for their careful comments on earlier drafts of this paper and to Ian Sue Wing for invaluable help in running the model. The encouraging response of participants of the RIIA/MIT Global Change Forum held at London in June 1998 gave much direction to the paper; and we are grateful to Nathalie Kosciusko-Morizet, Jean-Charles Hourcade, Thierry Le Pesant and Ken Chomitz for their subsequent interest and helpful comment. Finally, this research would not have been possible without the funding made available to the Joint Program by a number of corporations in the U.S., Europe and Japan, by EPRI, and by agencies of the Norwegian and U.S. Governments.

NB: all the prices in the following tables are in 1985$ NAB = Non-Annex B regions

I and II. BACKGROUND, METHODOLOGY

TABLE 1 - bis: Reference emissions and Kyoto commitments

Reference emissions	USA	JPN	EEC	OOE	EET	oecd+eet	FSU	NAB	World	EEX	CHN	IND	DAE	BRA	ROW
Ref 1990 (Mton)	1362	298	822	318	266	3066	891	2022	2022	508	833	183	115	63	320
Ref 2010 (Mton)	1838	424	1064	472	395	4193	763	4142	4142	927	1792	486	308	97	532
Kyoto	0.93	0.94	0.92	0.95	1.04	\	0.98	\	\	\	\	\	\	\	\
Emissions in 2010 (Mton)	1267	280	757	301	277	2881	873	4142	7896	927	1792	486	308	97	532
Reductions / ref 2010 (Mton)	572	144	307	171	118	1312	-111	0	1202	0	0	0	0	0	0
Marginal Costs ($/ton)	**$186**	**$584**	**$273**	**$233**	**$116**	\	\	\	\	\	\	\	\	\	\

TABLE 3 - bis: MACs approximations coefficients (P = aR^2+bR)

	USA	JPN	EEC	OOE	EET	FSU	EEX	CHN	IND	DAE	BRA	ROW
a	5.0E-04	1.6E-02	2.4E-03	8.5E-03	7.9E-03	2.3E-03	3.2E-03	7.0E-05	1.5E-03	4.7E-03	5.6E-01	2.1E-03
b	0.0398	1.816	0.1503	-0.0986	0.0486	0.0042	0.3029	0.0239	0.0787	0.3774	8.4974	0.0805

III. BASIC CASES

TABLE A: Kyoto OECD only no trading

	USA	JPN	EEC	OOE	Oecd
Reductions / ref 2010 (Mton)	572	144	307	171	1194
Marginal Costs ($/ton)	**$186**	**$584**	**$273**	**$233**	\
Cost of Abatement ($billion)	37.62	34.37	30.29	12.81	**115.09**

TABLE B: Kyoto OECD only OECD trading

	USA	JPN	EEC	OOE	Oecd
Reductions / ref 2010 (Mton)	655	79	287	174	1194
Market Price of Permits ($/ton)	**$240**	**$240**	**$240**	**$240**	**$240**
Cost of Abatement ($billion)	55.28	8.22	25.02	13.44	101.96
Permits exp(-)/imp(+) (Mton)	-83	65	21	-3	0
i.e % of commitment (import)	\	*45%*	*7%*	\	
Flows exp(-)/imp(+) ($billion)	-19.95	15.66	4.94	-0.64	\ 0.01
Total Cost ($billion)	35.33	23.88	29.96	12.80	**101.97**
Gains from trade ($billion)	2.30	10.49	0.33	0.01	**13.12**

TABLE C: Kyoto no trading

	USA	JPN	EEC	OOE	EET	oecd+eet	FSU	World
Reductions / ref 2010 (Mton)	572	144	307	171	118	1312	0	1312
Marginal Costs ($/ton)	**$186**	**$584**	**$273**	**$233**	**$116**	\	\	\
Cost of Abatement ($billion)	37.62	34.37	30.29	12.81	4.67	119.76	0.00	**119.76**

TABLE D: Annex B trading

	USA	JPN	EEC	OOE	EET	oecd+eet	FSU	World
Reductions / ref 2010 (Mton)	466	49	201	128	124	968	234	1202
'Hot air' (Mton)	\	\	\	\	\	0	111	111
Market Price of Permits ($/ton)	**$127**	**$127**	**$127**	**$127**	**$127**	**$127**	**$127**	**$127**
Cost of Abatement ($billion)	21.16	2.82	9.51	5.16	5.36	44.01	9.95	53.96
Permits exp(-)/imp(+) (Mton)	106	95	106	43	-6	345	-345	0
i.e % of commitment (import)	*19%*	*66%*	*35%*	*25%*	\	*26%*	\	\
Flows exp(-)/imp(+) ($billion)	13.44	12.06	13.51	5.49	-0.73	43.77	-43.77	0.00
Total Cost ($billion)	34.60	14.88	23.02	10.64	4.64	87.78	-33.82	**53.96**
Gains from trade ($billion)	3.03	19.49	7.27	2.17	0.03	31.99	33.82	**65.81**

TABLE E: Annex B trading, No hot air

	USA	JPN	EEC	OOE	EET	oecd+eet	FSU	World
Reductions / ref 2010 (Mton)	509	56	220	139	135	1058	254	1312
'Hot air' (Mton)	\	\	\	\	\	0	0	0
Market Price of Permits ($/ton)	**$150**	**$150**	**$150**	**$150**	**$150**	**$150**	**$150**	**$150**
Cost of Abatement ($billion)	27.10	3.73	12.21	6.60	6.86	56.51	12.73	69.23
Permits exp(-)/imp(+) (Mton)	63	88	87	33	-17	254	-254	0
i.e % of commitment (import)	*11%*	*61%*	*28%*	*19%*	\	*19%*	\	\
Flows exp(-)/imp(+) ($billion)	9.40	13.23	13.00	4.90	-2.48	38.05	-38.05	0.00
Total Cost ($billion)	36.50	16.96	25.21	11.50	4.38	94.55	-25.32	**69.23**
Gains from trade ($billion)	1.12	17.41	5.08	1.31	0.29	25.21	25.32	**50.53**

TABLE F: World trading

	USA	JPN	EEC	OOE	EET	oecd+eet	FSU	NAB	World	EEX	CHN	IND	DAE	BRA	ROW
Reductions / ref 2010 (Mton)	182	12	73	59	52	378	101	723	1202	51	437	102	42	2	89
'Hot air' (Mton)	\	\	\	\	\	0	111	0	111	\	\	\	\	\	\
Market Price of Permits ($/ton)	**$24**	**$24**	**$24**	**$24**	**$24**	**$24**	**$24**	**$24**	**$24**	**$24**	**$24**	**$24**	**$24**	**$24**	**$24**
Cost of Abatement ($billion)	1.66	0.14	0.71	0.41	0.43	3.36	0.81	6.99	11.15	0.54	4.22	0.95	0.44	0.03	0.81
Permits exp(-)/imp(+) (Mton)	390	132	234	112	66	935	-211	-723	0	-51	-437	-102	-42	-2	-89
i.e % of commitment (import)	*68%*	*92%*	*76%*	*66%*	*56%*	*71%*	\	\	\	\	\	\	\	\	\
Flows exp(-)/imp(+) ($billion)	9.27	3.15	5.57	2.67	1.57	22.24	-5.03	-17.21	0.00	-1.21	-10.40	-2.44	-0.99	-0.06	-2.12
Total Cost ($billion)	10.94	3.29	6.29	3.09	2.01	25.60	-4.22	-10.22	**11.15**	-0.68	-6.17	-1.49	-0.55	-0.03	-1.31
Gains from trade ($billion)	26.69	31.08	24.00	9.73	2.66	94.16	4.22	10.22	**108.61**	0.68	6.17	1.49	0.55	0.03	1.31

The Economics of the Kyoto Protocol

*Christopher N. MacCracken, James A. Edmonds, Son H. Kim and Ronald D. Sands**

In this paper we use the Second Generation Model to 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. Our analysis shows that the cost of implementing the Protocol in the United States can vary by more than an order of magnitude. The marginal cost in 2010 could be as low as $26 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 mitigation obligations are not adequately anticipated by decision-makers.

INTRODUCTION

The Kyoto Protocol was completed on the morning of December 11, 1997, following more than two years of 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 150 delegations. Because the document is complex, its implications are not immediately obvious. If it enters into force, the Kyoto Protocol could have far-

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mit prices than those achieved under the

Annex I permit trading scenarios. Table 9 shows the 2010 permit price under global trading as compared to the no trading and Annex I trading regimes.

Table 9. Emissions Taxes/Permit Prices Required to Meet Policy Goal in 2010 (1992 US$ per tonne of carbon equivalent)

Region	No Trading	Annex I Trading: Monopolistic	Annex I Trading: Competitive	Global Trading
Canada	350			
former Soviet Union	--			
Japan	458			
United States	168	105	73	26
Western Europe	130			
Australia	117			
Eastern Europe	--			

Table 10 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 308 MMTCe of permits sold by the former Soviet Union, however, include 247 MMTCe of "base mitigation credits."

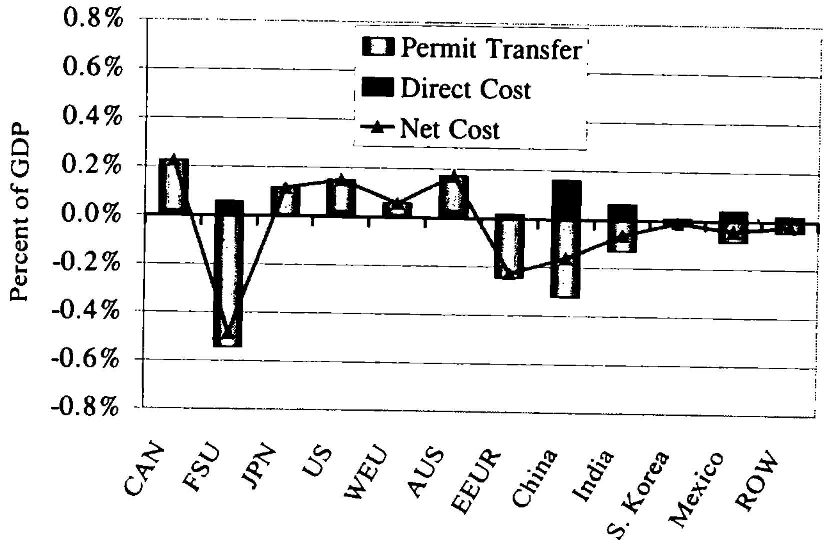
Table 10. Composition of the Emissions Permit Market in the Global Trading Case (million tonnes of carbon equivalent)

Region	Permits Traded (MMTCe): Purchased	Permits Traded (MMTCe): Sold
Canada	61	
former Soviet Union		308
Japan	121	
United States	470	
Western Europe	134	
Australia	25	
Eastern Europe		49
China		341
India		37
Korea		3
Mexico		19
Rest of the World		54
Total	811	811

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 24 percent in 2010 relative to the baseline consumption, with over 85 percent of that reduction coming from reduced coal consumption. The mitigation activities in China and the other non-Annex I regions are undertaken at significantly less cost than in the Annex I regions, however, thereby allowing the permit buying regions to emit more than in the Annex I trading or no trading cases for less cost. And although the non-Annex I permit sellers achieve mitigation primarily through conservation, their energy consumption and carbon equivalent emissions continue to grow.

Costs as a percentage of GDP are consequently 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 separated into the direct cost and net permit trading revenue components for the global trading case.

Figure 11. Cost by Component and Region in 2010 in Percentage of GDP - Global Trading



The lower permit price induces only minor changes in the Annex I regions' energy systems relative to the reference case. Energy consumption in the United States in 2010 increases by 26 percent over 1990 levels, as compared to an increase of only 17 percent under Annex I competitive permit trading, as

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SUMMARY OF PARTICIP

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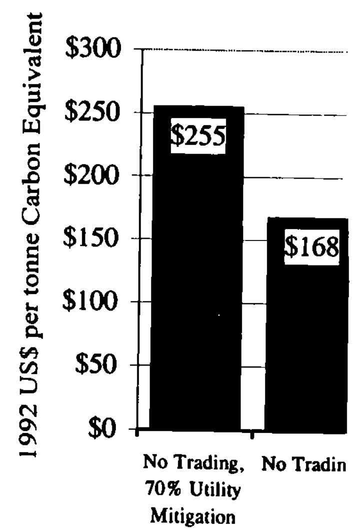
Figure 12. Range of Permit



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Economic Modelling of Climate Change

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ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT
PARIS, FRANCE

A (Preliminary) Analysis of the Kyoto Protocol: Using the OECD GREEN Model

by

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Table 12: **Quotas, Use, and Net Purchases – World Tradable Permits in 2010**

(mmt)

	Initial Quotas	*Carbon Emissions*	*Net Purchases*	*Net Purchase ($bn 1985)*
European Economic Community	791	990	200	3.8
Japan	326	397	70	1.3
Other OECD Countries	294	364	70	1.3
United States	1,271	1,535	264	5.0
European Economies in Transition	302	361	59	1.1
Baltic 3 — CIS	1,382	1,117	-265	-5.0
Brazil	136	132	-4	-0.1
China	1,513	1,285	-228	-4.3
India	325	280	-45	-0.9
Dynamic Asian Economies	278	261	-17	-0.3
Energy Exporting Countries	610	531	-79	-1.5
Rest of the World	604	580	-24	-0.5
OECD	2,984	3,647	662	12.6
Other	4,847	4,185	-662	-12.6
Total	7,832	7,832	0	0

(3)

The (global) permit price under this scenario is much lower than either the region-wide carbon tax of the Kyoto2 simulation, or the Annex I-wide permit price of the Kyoto3 simulation. In 2010, the permit price is $19, a bit more than one-third the price in the previous simulations. In 2010, all OECD regions are net purchasers of emission rights. Under this system of allocation, the OECD regions would purchase 662 mmt, to 18 percent of their final consumption, and 22 percent of their initial quotas. The non-Member economies (including the BCS) would sell about 14 percent of their initial (2010) quota. Given the relatively low price of the quota, the trade in permits would generate only around $13 billion, of which the lion's share would accrue to BCS and China. The total net revenue from selling permits, to domestic users would amount to about $90 billion in the Annex I region, and about $65 billion in the non-Annex I economies. For the Annex I countries, the tax burden is significantly less than in Kyoto3. The aggregate tax burden is down by about 31 percent.

The change in real income in the year 2010 is significant compared to the previous simulations. In aggregate, the world loss drops from –0.2 percent to –0.1 percent (or from –$50 billion to -$25 billion). All the OECD regions, except the EET, gain relatively from a global tradable permit scheme, with Europe and Japan halving their losses compared to Kyoto3. For the non-Annex I economies, the loss in real income drops from –0.4 percent to only –0.1 percent of GDP. In relative terms all the non-Member regions improve their well-being except for ROW. The greatest relative gains occur in China and India. The energy exporting region, though still suffering from an absolute decline, nevertheless significantly improves its position. It appears that with a somewhat different allocation of initial permits (or with additional exogenous transfers), all non-Member economies could gain from this type of mechanism compared to the business-as-usual scenario, and all OECD economies could gain compared to any of the three other Kyoto scenarios where the policies are limited to member countries alone. In particular, the energy exporting countries should strongly support an international framework for limiting carbon emissions since if the Annex I countries are determined to meet their targets, they stand to lose significantly (at least in the medium term).

V Conclusion

In its latest report, the IPCC concluded that there is incontrovertible evidence that human activities are having a measurable impact on the chemistry of the atmosphere, and by extension, that these atmospheric changes are leading to changes in climate at a global level. There is sufficient anecdotal evidence — warmer summers, more extreme weather, etc. — that the issue of global warming has caught the attention of the general public, even though there is no uniform call to action. There is a

4

Joseph Guenther Boyer <joseph.boyer@yale.edu>
09/01/99 10:41:02 AM

Record Type: Record

To: Joseph E. Aldy/CEA/EOP

cc:
Subject: RE: RICE results for China

Joseph:

Sorry to be so late on this. I put all my emails on the backburner last week, and then they slipped my mind. Here are the numbers you asked for. These represent the output of the RICE model that underlies the Energy Journal article you mentioned.

2010 China Reference case emissions: 1336.8 MMtC
2010 Carbon price with Kyoto Protocol, global trading: $18.17 per tonne
2010 China emissions with Kyoto Protocol, global trading: 1155.2 MMtC
2010 China GDP with Kyoto Protocol, global trading: $1643.09 billion. (This is in 1990 US dollars, converted using market exchange rates)

I will be happy to answer any further requests, and next time the reply will be more expeditious.

Joe Boyer
joseph.boyer@yale.edu

Department of Economics
Yale University
28 Hillhouse Ave
New Haven, CT 06511
(203) 432-3581

PS: I would be interested in hearing about any working paper or publication that you guys put together on the the economic effects of emissions abatement in China. I'd appreciate it if you could send me a notification by email if you produce a paper for circulation. Thanks.

-----Original Message-----
From: Joseph_E._Aldy@cea.eop.gov [mailto:Joseph_E._Aldy@cea.eop.gov]
Sent: Tuesday, August 24, 1999 9:57 AM
To: joseph.boyer@yale.edu
Subject: RICE results for China

5

Emissions Trading, Capital Flows and the Kyoto Protocol

Warwick J. McKibbin, Martin T. Ross**, Robert Shackleton** and Peter J. Wilcoxen****

We use an econometrically estimated multi-region, multi-sector general equilibrium model of the world economy to examine the effects of the tradable emissions permit system proposed in the 1997 Kyoto Protocol, under various assumptions about the extent of international permit trading. We focus, in particular, on the effects of the system on international trade and capital flows. Our results suggest that consideration of these flows significantly affects estimates of the domestic effects of the emissions mitigation policy, compared with analyses that ignore international capital flows.

INTRODUCTION

As part of an effort to reduce global emissions of greenhouse gases (GHGs) that are expected to contribute to a significant warming of the earth's climate, the Kyoto Protocol to the United Nations Framework Convention on Climate Change, signed in Kyoto in December 1997, includes binding GHG emissions targets for the world's industrial economies ("Annex I" countries) for the period 2008-2012. The Protocol also provides for international trading of emission allowances among the countries that accept binding targets, in recognition of the theoretical efficiency benefits of allowing emission reductions

The Energy Journal, Kyoto Special Issue.

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** United States Environmental Protection Agency, Mail Code 2126, 401 M Street S.W., Washington, DC 20460. E-mail: shackleton.robert@epa.gov

**** University of Texas at Austin, Department of Economics, Campus Mail Code C3100, Austin, TX 78712. E-mail: wilcoxen@eco.utexas.edu; and The Brookings Institution, Washington.

The views expressed in this paper are those of the authors and should not be interpreted as reflecting the views of the organizations with which they are affiliated.

ECD region is slightly better off in
ılation than under Annex I trading.
(th hey fall slightly less), fuel
r, a pital outflows are smaller.
n the ROECD region adopts carbon
is to shift some investment to other
Annex I trading, other countries are
ls and are attempting to do the same
eciate substantially, rising by 23%
nder the double umbrella, however,
other than the ROECD so there is
ed States. There is less appreciation
ıtive to the ROECD currency. This
rs to convert part of their portfolios

ıowever. Once the policy is actually
ı abatement costs under the double
terms of trade. By 2010, ROECD
they would have been under Annex

that the non-Annex I developing
ities of domestic emission permits
l to allow these permits to be traded
ar ntained in Table 9. The
rie he trading regime is that
owa from owners in developing
willing to sell allowances to Annex
led the marginal cost to the owners
ıe developing countries. The market
ıctions on a global scale: emission
ıre cheapest, but Annex I countries

t developing regions sell a fixed number of
enues to households as a lump-sum payment.

Table 9. Annex I Commitments With Global Permit Trading

	United States	Japan	Australia	Other OECD	China	LDC's
2005						
Permit price ($95)	--	--	--	--	--	--
Annual permit sales (Bil $95)	--	--	--	--	--	--
Carbon emissions	0.6%	-1.2%	-0.1%	-0.9%	0.9%	0.8%
Coal consumption	0.2%	-0.3%	0.0%	-0.3%	0.9%	0.4%
Oil consumption	1.0%	-1.7%	-0.4%	-1.3%	1.2%	1.1%
Gas consumption	0.7%	-0.3%	-0.4%	-0.8%	1.8%	0.7%
GDP	0.1%	-0.1%	0.0%	-0.1%	0.4%	0.1%
Investment	1.0%	-0.2%	-0.3%	-1.0%	2.4%	1.1%
Exports	-2.9%	1.5%	1.0%	4.1%	-27.2%	-8.7%
Exchange rate	3.7%	-3.1%	-0.6%	-7.0%	12.4%	6.1%
Net foreign assets (Bil. $95)	-$54	-$8	$12	$106	-$38	$25
GNP	0.1%	-0.1%	0.0%	0.0%	0.3%	0.2%
2010						
Permit price ($95)	$23	$23	$23	$23	$23	$23
Annual permit sales (Bil $95)	-$8.9	-$1.2	-$1.0	-$9.3	$7.0	$4.5
Carbon emissions	-7.4%	-4.2%	-4.9%	-3.4%	-19.1%	-7.9%
Coal consumption	-13.3%	-8.9%	-7.0%	-4.5%	-22.0%	-13.3%
Oil consumption	-3.6%	-2.8%	-2.4%	-3.3%	-3.3%	-5.6%
Gas consumption	-3.0%	-1.0%	-2.9%	-2.2%	-10.4%	-2.0%
GDP	-0.1%	-0.1%	-0.3%	-0.3%	-0.6%	-0.2%
Investment	0.4%	-0.3%	-0.2%	-1.0%	0.6%	0.1%
Exports	-3.4%	0.8%	-0.3%	3.6%	-22.6%	-9.7%
Exchange rate	3.6%	-2.8%	-0.6%	-7.2%	10.9%	6.5%
Net foreign assets (Bil. $95)	-$115	-$2	$20	$208	-$71	$51
GNP	-0.2%	-0.1%	-0.4%	-0.2%	-0.4%	0.0%
2020						
Permit price ($95)	$37	$37	$37	$37	$37	$37
Annual permit sales (Bil $95)	-$21.1	-$3.9	-$2.5	-$25.2	$24.3	$17.1
Carbon emissions	-11.4%	-6.1%	-6.5%	-4.6%	-24.9%	-11.1%
Coal consumption	-19.2%	-12.8%	-9.7%	-6.3%	-28.7%	-17.8%
Oil consumption	-6.2%	-4.2%	-3.1%	-4.4%	-4.9%	-8.2%
Gas consumption	-5.5%	-1.5%	-3.5%	-3.0%	-13.5%	-3.6%
GDP	-0.1%	-0.2%	-0.3%	-0.3%	-0.7%	-0.3%
Investment	0.3%	-0.4%	-0.1%	-1.0%	0.3%	0.0%
Exports	-3.9%	0.7%	-0.7%	3.3%	-20.0%	-9.0%
Exchange rate	3.6%	-3.4%	-0.4%	-7.5%	15.0%	7.0%
Net foreign assets (Bil. $95)	-$155	-$13	$25	$263	-$66	$78
GNP	-0.3%	-0.2%	-0.4%	-0.3%	-0.1%	0.0%

THE ENERGY JOURNAL

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IA EE

The Costs of the Kyoto Protocol: A Multi-Model Evaluation

Special Issue

International Association for Energy Economics **IAEE**

id suggestions from the participants in the EMF
Un nd Snowmass during 1998, as well
ns oping both consistent measures of
nal trade issues. We gratefully acknowledge
e Electric Power Research Institute, and the
dings are the sole responsibility of the authors.

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6

The Kyoto Protocol: An Economic Analysis Using GTEM

*Vivek Tulpulé, Stephen Brown, Jaekyu Lim, Cain Polidano, Hom Pant and Brian S. Fisher**

In this paper ABARE's Global Trade and Environment Model (GTEM) is used to analyse the potential of international emissions trading as a mechanism for helping to achieve the abatement commitments agreed to in the Kyoto Protocol. The prospect of two emission trading blocs, one consisting of the European Union and eastern Europe and the other consisting of many of the remaining Annex I regions, is also considered. The analysis shows that the carbon penalty varies significantly across regions when no emissions trading is allowed. In aggregate, the cost of abatement to Annex I regions falls with emissions trading. Under the assumption of the two trading blocs, the carbon penalty in the European bloc is higher than with full Annex I trading. The paper also considers the impact on developing countries and the role of carbon leakage in determining the economic impacts on Annex I regions.

INTRODUCTION

Negotiations for the Kyoto Protocol to the UN Framework Convention on Climate Change concluded on 11 December 1997. Parties listed in Annex I to the protocol agreed to reduce their aggregate greenhouse gas emissions to at least 5.2 percent below 1990 levels over the commitment period 2008–12. Significantly, the use of so-called 'flexibility mechanisms' that could reduce the economic costs of achieving emission reduction targets was agreed to in the protocol. These mechanisms include: joint implementation (Article 6), the clean development mechanism (Article 12) and international emissions trading (Article 17). While the Kyoto Protocol provides a legal basis for the introduction of such mechanisms, negotiations are now underway to determine the principles and guidelines that could govern their implementation.

The Energy Journal, Kyoto Special Issue.

The authors are grateful to John Weyant, Kate Woffenden and Jennifer Noel Hill for helpful comments and suggestions.

* Australian Bureau of Agricultural and Resource Economics, GPO Box 1563, Canberra, ACT 2601, Australia. Web site: http//www.abare.gov.au. E-mail: sbrown@abare.gov.au

ı **Reductions**

ies 0 and associated emission ›ho Table 6. With independent ties vary substantially from country penalty is related to the magnitude the ease of substitution between fuel ity, and the responsiveness of energy ›rgy costs.

tries are assumed to utilise the least ›t. Consequently, as the size of the ›arbon emission penalty will tend to ›ilities become increasingly scarce. ı abatement task (when considering el use) and this contributes to the ı under the Kyoto Protocol, without

·ion penalty will result in consumers less emission intensive fuel sources. t in the electricity sector. Substitution dy uses technologies in the electricity s implies a need to reduce emissions re substitution possibilities tend to be ›enalties are required to encourage the ricity sector to total carbon re in Figure 1. For example, and esser extent nuclear power) ›mission reductions in the electricity ›n hydroelectricity.

›n penalty for eastern Europe and the ndicate the existence of opportunities ı in other Annex I countries. For the ıissions do not rise above 1990 levels ›en abatement (contraction) sufficient Emissions in the former Soviet Union ario as production costs rise in Annex re binding, leading to some shift in ınex I countries to the former Soviet

Table 6. Carbon Emission Penalties and Projected Change in CO_2 Emission Reductions at 2010 under the Kyoto Protocol: Three Emissions Trading Scenarios

	Emission penalty per tonne of carbon			Change in CO_2 emissions (relative to the reference case)		
	No trading	Annex I trading	Double bubble	No trading	Annex I trading	Double bubble
	US$1992	US$1992	US$1992	%	%	%
Australia	455	114	108	-24.2	-6.4	-6.0
New Zealand	396	114	108	-30.4	-14.4	-13.7
United States	346	114	108	-27.6	-10.3	-9.7
Canada	835	114	108	-31.2	-9.0	-8.5
Japan	693	114	108	-21.8	-5.8	-5.4
European Union	714	114	176	-25.3	-6.3	-9.2
Former Soviet Union	0	114	108	1.6	-40.8	-37.1
Eastern Europe	40	114	176	-23.6	-46.2	-53.6
Annex I average	322	114	126	-19.7	-19.7	-19.7

(6)

SBrown@abare.gov.au
08/24/99 08:42:34 PM

Record Type: Record

To: Joseph E. Aldy/CEA/EOP

cc:

Subject: RE: ABARE-GTEM model results for China

Joe,

thanks for your Email. We've only run the global emissions trading scenario in the context of the EMF model comparison exercise so I can only provide you with results for the CO2 only version of GTEM. Here are the numbers you were after:

1) China's 1990 emissions of carbon dioxide were 2167 MT. At 2010 emissions are projected to be 6845 MT CO2.

2) The carbon price under the global trading scenario is $US 24.84.

3) China's emissions are projected to decline by 19 per cent relative to the reference case at 2010 under the global trading scenario.

4) Chnia's GDP is projected to decline by around 0.6 per cent relative to the reference case at 2010 under the global trading scenario.

If you need any other information just let me know.

Regards,

Steve Brown

-----Original Message-----
From: Joseph_E._Aldy@cea.eop.gov [mailto:Joseph_E._Aldy@cea.eop.gov]
Sent: Tuesday, 24 August 1999 23:52
To: sbrown@abare.gov.au
Subject: ABARE-GTEM model results for China

Stephen Brown,

We are pulling together research on the economic effects of emissions abatement in China for some of our climate change work. I noticed in your recent Energy Journal article that you have completed several Annex I trading scenarios, but you did not present any global trading cases (or other scenarios that would include abatement by China). In addition, I noticed in your report "Economic Impacts of the Kyoto Protocol: Accounting

9

Optimal Environmental Taxation in the Presence of Other Taxes: General-Equilibrium Analyses

By A. LANS BOVENBERG AND LAWRENCE H. GOULDER*

Most economies feature levels of public spending that require more tax revenues than would be generated solely from the pollution taxes set according to the Pigovian principle, that is, set equal to marginal environmental damages. As a consequence, tax systems generally rely on both environmental (corrective) and other taxes. However, economists typically have analyzed environmental taxes without taking into account the presence of other, distortionary taxes. The omission is significant because the consequences of environmental taxes depend fundamentally on the levels of other taxes, including income and commodity taxes.

This paper examines how optimal environmental tax rates deviate from rates implied by the Pigovian principle in a second-best setting where other, distortionary taxes are present. Previous investigations of this issue include the partial equilibrium analyses of Dwight R. Lee and Walter S. Misiolek (1986) and Wallace E. Oates (1991), who derive formulas linking the optimal rate for a newly imposed environmental tax to the marginal excess burden from existing taxes. In a general-equilibrium setting, Agnar Sandmo (1975) and Bovenberg and Frederick van der Ploeg (1994) have demonstrated how the well-known "Ramsey" formula for optimal commodity taxes is altered when one of the consumption commodities generates an externality.[1]

The present paper contributes to the analytical and empirical literature in three ways. First, it extends earlier analytical work on optimal environmental taxation in a general-equilibrium setting by considering pollution taxes imposed on intermediate inputs. This is a useful extension because many actual environmental regulations and taxes affect the costs of intermediate inputs.[2] Second, the paper investigates second-best optimal environmental taxes numerically. Here we expand on the analytical work by employing a numerical general-equilibrium model of the United States. The use of a numerical model enables us to employ a realistic specification of taxes and adopt a fairly detailed representation of production and demand. Our paper thus combines the strengths of analytical and numerical approaches: a stylized analytical model uncovers the major mechanisms at play, while a numerical model explores the empirical significance of these mechanisms in a more realistic setting. Despite considerable differences in the complexity of the analytical and numerical models, we find a strong coherence between the two models' results.

The third contribution of the paper is its numerical investigation of optimal environmental tax policies in the presence of realistic policy constraints. The constraints involve either the inability to alter all tax rates (so that much of the initial, suboptimal tax system re-

* Bovenberg: CPB Netherlands Bureau for Economic Policy Analysis, P.O. Box 80510, 2508 GM The Hague, The Netherlands, and CentER for Economic Research, Tilburg University; Goulder: Department of Economics, Landau Economics Building 335, Stanford University, Stanford, CA 94305-6072. The authors are grateful to Jesse David and Steven Weinberg for excellent research assistance, to three anonymous referees for helpful comments, and to the National Science Foundation (Grant SBR-9310362) and IBM Corporation for financial support.

[1] A closely related issue is the extent to which the costs of environmental taxes are lowered when revenues from such taxes are devoted to reductions in existing distortionary taxes. A key question is whether "recycling" the revenues in this way can make the overall cost of the revenue-neutral policy zero or negative. For general discussions of this issue see, for example, David W. Pearce (1991), James M. Poterba (1993), Oates (1995) and Goulder (1995a). For analytical treatments see, for example, Bovenberg and Ruud A. de Mooij (1994) and Ian W. H. Parry (1995). For numerical investigations see, for example, Robert Shackleton et al. (1996) and Goulder (1995b).

[2] For example, taxes on fossil fuels raise the costs of fuel inputs; similarly, specific excises such as taxes on gasoline raise the costs to producers of the transportation services they might employ.

TABLE 3—SENSITIVITY ANALYSIS[a]

	MCPF	Optimal tax implied by analytical model	Optimal tax from numerical model
1. Central case	1.252	60	52
2. Marginal rates for preexisting taxes:			
Lowered 50 percent	1.113	67	61
Raised 50 percent	1.410	53	46
3. Intertemporal elasticity of substitution in consumption:[b]			
Low (0.33)	1.198	63	55
High (0.66)	1.406	53	43
4. Uncompensated elasticity of labor supply:[c]			
Low (0.00)	1.121	67	61
High (0.26)	1.398	54	48
5. Energy substitution elasticities:[d]			
Lowered by 50 percent	1.233	61	54
Raised by 50 percent	1.366	55	48

[a] Marginal environmental benefits are assumed to be $75 per ton. Results for the numerical model are from simulations of a carbon tax with revenue-preserving reductions in marginal rates of the personal income tax.
[b] Central case value is 0.5.
[c] These simulations involve changes in ν, the goods-leisure elasticity of substitution. The central case value of ν is 0.77, implying an uncompensated labor supply elasticity of 0.15. ν is 0.62 and 0.90 in the low and high elasticity cases. The compensated elasticities in the low, central and high cases are 0.47, 0.94, and 5.90, respectively.
[d] In the low (high) elasticity simulation, $\sigma_{E,}$, the elasticity of substitution between composite energy (E) and composite materials (M), is lowered (raised) in all industries by 50 percent from its central case value of 0.7.

substitution elasticities raise the potential for distortions in capital, labor, or energy markets from a given configuration of taxes. The numerical model generates a higher MCPF with increases in these elasticities; hence the optimal rates prescribed by the analytical model are lower. Changes in these parameters also induce changes in the optimal rates derived directly from the numerical model. These changes are in the same direction as the changes in optimal rates prescribed by the analytical model.

Under central case values for parameters, the optimal rate from the numerical model is 69 percent of the Pigovian rate. By comparison, the optimal rate is 57 (73) percent of the Pigovian rate under high (low) values for the intertemporal elasticity of substitution in consumption. It is 64 (81) percent of the Pigovian rate under high (low) values for the labor supply elasticity.

IV. Conclusions

9

This paper has employed analytical and numerical models to examine the general-equilibrium interactions between environmentally motivated taxes and distortionary taxes. The analytical model extends earlier work by examining environmental taxes that, like carbon taxes, apply to intermediate inputs. This model indicates that in the presence of distortionary taxes, optimal environmental tax rates are generally below the rates suggested by the Pigovian principle—even when revenues from environmental taxes are used to cut distortionary taxes.

The numerical simulations support this analytical result. Under central values for parameters, optimal carbon tax rates from the numerical model (when the tax system is fully optimized) are between six and twelve percent below the marginal environmental damages.

In addition, the numerical model shows that in the presence of realistic policy constraints, optimal carbon tax rates are far below the marginal environmental damages—and may even be negative. Simulations based on the U.S. tax system indicate that if policy makers can only incrementally alter existing distortionary taxes (rather than globally optimize the tax system), the optimal carbon tax may be substantially below the marginal environmental damages. Moreover, if the revenue changes from carbon taxes are absorbed through changes in lump-sum transfers (rather than through changes in marginal rates of existing distortionary