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

by

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I Introduction

In December, 1997 the Parties to the United Nations Framework Convention on Climate Change (FCCC), met for the so-called Third Conference of the Parties (COP3) in Kyoto, Japan. The discussions leading up to COP3, and during the meeting were fraught with difficulty with different groups of countries proposing vastly different objectives. Some of the key disagreements were among OECD Member country governments — the European Union, Japan, and the United States — concerning the overall emission targets, but there also existed considerable discussion concerning the role of the developing countries and whether they should be subject to any targets at all.

On December 11th, 1997 a final agreement on the Kyoto Protocol was achieved. The industrialized countries agreed to a target reduction in emissions from 1990 levels which vary from 6 to 8 percent (with a handful of countries having less stringent targets). Other Annex I countries, essentially the countries of Central and Eastern Europe, the Baltic countries, and the Russian Federation have agreed to similar targets. No other country has committed to limiting their emissions. The implementation of policies to achieve the target reductions was not explicitly specified in the Protocol, though several different mechanisms involving international cooperation were cited (for example tradable permits and the concept of "bubbles"). The Protocol does not limit itself to carbon emissions, but also includes other greenhouse gases. In addition, removal of atmospheric carbon through the creation of carbon sinks is duly recognized by the protocol.

This paper attempts to assess the economic costs of achieving the proposed emission reduction targets. An economic model, known as the OECD GREEN model, is used to assess these costs. It has been slightly updated to reflect observed economic behavior through the 1990s. The model can only partially assess the costs of implementing the Kyoto Protocol, particularly since it only incorporates carbon emissions and not the other greenhouse gases. The main purpose of the paper will be to assess and compare several different policies to achieve the targets agreed to by the parties to the Kyoto Protocol. The Protocol does not specify the implementing policies, therefore there is a wide scope of policies for the signing countries. The emphasis of this paper is on coordinated approaches versus un-coordinated approaches. It will be shown that coordinated approaches are more cost effective. Furthermore, it will show that **global** coordination, i.e. involving countries with no target commitments, would be most cost effective, in particular for the non-OECD countries, depending on the design of carbon reduction program.

The next section of the paper will provide a more extensive description of the Kyoto Protocol. This section will be followed by a broad overview of the GREEN model. The subsequent section introduces the implementation of the Kyoto Protocol in terms of the model, i.e. it will describe the specific scenarios and discuss the results. The final section contains some concluding remarks.

II Kyoto Agreement

With all of the pre-conference haggling and competing pressures from certain quarters for significant emission limits, and from others for no limits, the final agreement represents a major initiative from the Annex I group of countries.[1] On average, the Annex I countries have agreed to reduce their aggregate emissions of carbon (equivalent) gas by 5 percent with respect to their 1990 level of emissions in the time range of 2008-2012. Table 1 provides a complete breakdown for all of the Annex I countries. For the Annex I countries as a whole, this could represent a reduction of 23 percent of total emissions in 2010 compared to what they might be in the absence of an agreement, and for the OECD it could mean as much as a 29 percent reduction (see section below for calculations).

While much of the focus on global warming has concentrated on CO_2 emissions (essentially generated by the use of fossil fuels), the Kyoto Protocol broadens the scope of emissions to

1 Refer to the abbreviations on page 28 for a description of some of the terms and acronyms referred to in this paper.

incorporate five other critical greenhouse gases (see Box 1, page 8) — methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride. While carbon emissions are essentially linked to the consumption of fossil fuels, the source of these other emissions is mainly linked to other human activities. Another important element in the accord is to account for growth in domestic carbon sinks, for example reforestation projects. The developed countries would also get credit for reducing net emissions in developing countries — either through projects to improve energy efficiency or by increasing carbon sinks.

The Protocol has left a number of loose ends, particularly in terms of the implementation of the commitments, though leaving specific allowance for tradable permits among the signatory countries.

The scope of this preliminary analysis is somewhat limited, mostly due to the limitations of the existing analytical framework. In particular, the model does not incorporate any of the other five greenhouse gases included in the agreement, though, with perhaps limited effort, it might be possible to include methane and/or nitrous oxides. The paper will assess a variety of different schemes to achieve the commitments — domestic carbon taxes, regional carbon taxes, tradable permits, etc. A further model restriction, but which should have limited impact on the assessment, is that it will be assumed that the commitments are achieved in 2010.

Table 1: **Annex I Countries and their Commitments**

(*Commitments are represented as percentage of 1990 emission levels to be achieved between 2008-2012*)

European Union		**Economies in Transition to a Market Economy**	
Austria	92	Bulgaria	92
Belgium	92	Croatia	95
Denmark	92	Czech Republic	92
Finland	92	Estonia	92
France	92	Hungary	94
Germany	92	Latvia	92
Greece	92	Lithuania	92
Ireland	92	Poland	94
Italy	92	Romania	92
Luxembourg	92	Russian Federation	100
Netherlands	92	Slovakia	92
Portugal	92	Slovenia	92
Spain	92	Ukraine	100
Sweden	92		
United Kingdom	92		
Other Europe		**Other Annex I**	
Iceland	110	Australia	108
Liechtenstein	92	Canada	94
Monaco	92	Japan	94
Norway	101	New Zealand	100
Switzerland	92	United States of America	93

The Implications of the Kyoto Protocol

While the overall reductions appear at first glance to be modest, on the order of 5 to 10 percent, they must be put in the context of where the signing countries would be in the absence of an agreement. Let E_0 represent the level of emissions in 1990, and E_1 be the level of emissions in the year 2010.

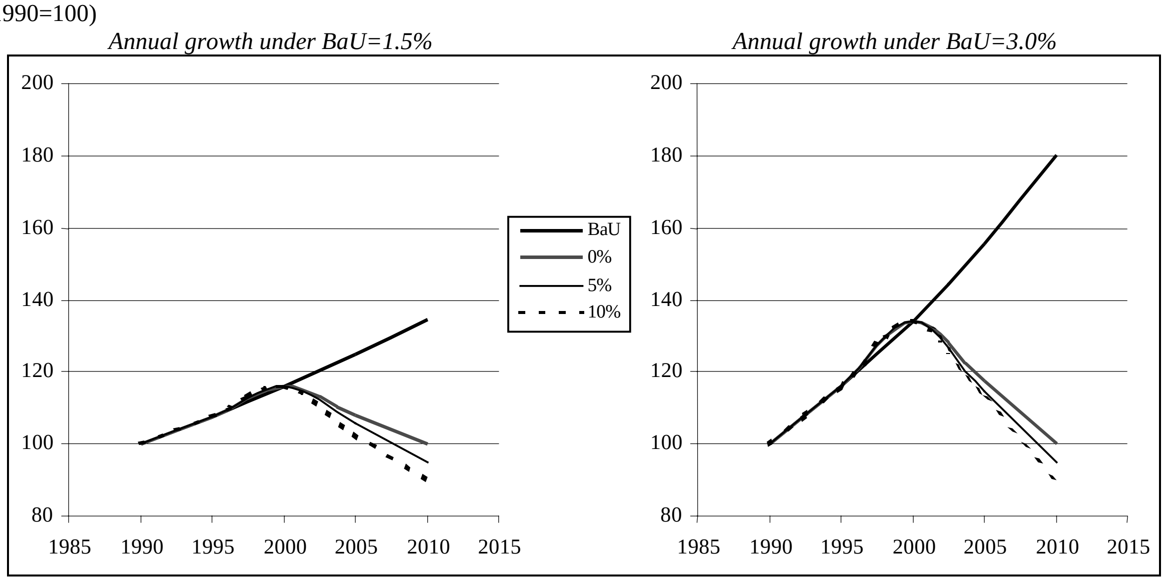
Assume that emissions grow at a constant rate of *g* percent per annum. (A good rule of thumb is that emissions grow at about 1 percent less on average than the growth of GDP. This is a combination of energy efficiency improvement, the move to services, and a different fuel mix.) Let χ represent the target reduction in the year 2010, with respect to the level of emissions in 1990. The percentage reduction in emissions in 2010, with respect to the baseline (or BaU) level of emissions is given by the following formula:

$$E_1^{BaU} = (1+g)^{20} E_0 \qquad E_1^* = (1-\chi) E_0 \qquad \frac{E_1^*}{E_1^{BaU}} - 1 = \frac{1-\chi}{(1+g)^{20}} - 1$$

The variable E^{BaU} represents the level of emissions in the baseline scenario, i.e. in the absence of policies to reduce emissions, and the variable E^* represents the target level of emissions. For example, if χ is equal to an 8 percent reduction target, and the average growth in emissions in the baseline scenario is 1.5 percent, then the targeted level of emissions needs to be 32 percent below where they would have been in the absence of carbon limitations. The economic problem is somewhat compounded by the transition to the target. The planning period is currently 10-14 years, not the 18-22 years which would have been available in 1990, i.e. the transition period is much shorter, including the fact that many countries have yet to implement any specific programs for limiting carbon emissions. The charts in Figure 1 provide graphical evidence for the effort required to limit emissions between now and 2010. The left graph shows a country with emissions growing at 1.5 percent per year, somewhat higher than the recent OECD average. Each graph has 4 scenarios. The top scenario is the baseline (or BaU) scenario. Under a 1.5 percent growth assumption, emissions would grow by about 35 percent in the period 1990-2010. Each subsequent scenario is a carbon limitation scenario (assuming a linear decline from 2000 onward). The first is stabilization at 1990 emission levels. The next two are a 5 and 10 percent reduction from 1990 emission levels respectively. The right graph shows the same scenarios except that the BaU scenario has emissions increasing at about 3 percent per annum, a scenario closer to the profile of the non-OECD economies, and a perhaps an under-estimate with respect to some of the quickest growing emerging economies. Under the BaU scenario, emissions almost double in 20 years time. Stabilization would obviously require a much greater effort.

Figure 1: **Emission Reduction Scenarios**

(1990=100)



Box 1: **Greenhouse gases**

The Kyoto Protocol is the first agreement to include other greenhouse gases than CO_2. The other greenhouse gases included in the protocol are: methane, nitrous oxides (N_2O), and three halocarbons — hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6) — which are substitutes for the ozone-damaging chlorofluorcarbons (CFCs). (CFCs, also greenhouse gases, are being phased out under the so-called Montreal Protocol, signed in September, 1987.) While the first three account for the bulk of greenhouse gas emissions, the emissions of the latter three are growing rapidly and their warming potential is 20,000 times greater than CO_2.

The table below indicates the relative importance of the six greenhouse gases. CO_2 and methane emissions account for a significant portion of greenhouse gas emissions.

Gas	*Greenhouse contribution* (percent)	*Annual rate of emissions* (ppbv/year)	*Atmospheric concentration* (ppbv)	*Warming potential*	*Atmospheric lifetime* (years)	*Source of emissions*
CO_2	64%	1,600	356,000	1	50-200	Burning of fossil fuels: transportation (23%), electricity generation (33%), other (44%).
CH_4	19%	8	1714	21	8-12	Livestock (30%), other agriculture (e.g. rice) (29%), resource extraction (26%), other (e.g. landfills) (15%).
N_2O	6%	0.8	275	206	120	Burning of fossil fuels, nitrogen fertilizer, deforestation
HFCs	<1%			1000-20,000	2-264	Aerosols, foamed plastics, refrigerants, solvents
PFCs	<1%	0.0012	0.004-0.07	5,500-25,500	2,600-50,000	Aerosols, foamed plastics, refrigerants, solvents
SF_6	<1%	0.0002	0.032	35,500	3,200	Aerosols, foamed plastics, refrigerants, solvents

Notes:
1. *ppbv stands for parts per billion (10^9) by volume.*
2. *Greenhouse gas contribution refers to the contribution of the individual emissions since pre-industrial times. The contribution of CFCs is about 10%, the residual attributed to other gases.*
2. *Warming potential shows the greenhouse impact for the same volume of gas with respect to CO_2 (which by definition has the value 1) over a 100 year time span.*
3. *Atmospheric lifetime refers to the normal life span of the gas in the atmosphere, before it is either absorbed by the oceans, plants, or the ground, or transformed into a different gas by atmospheric chemical reactions.*

Sources: IPCC (1996) and Masters (1991).

III The GREEN Model

The GREEN Model, originally developed by the OECD Economics Department in the early 1990s, has been used extensively to assess the impacts of reducing (energy related) carbon emissions.[2] The assessments are based on a baseline (or reference) scenario, sometimes referred to as the Business-as-Usual scenario (BaU). In other words, the BaU scenario is one where no active measures are undertaken to deal with carbon emissions (save perhaps no-regrets policies). Carbon limitation scenarios are thus compared to the BaU scenario. There are various ways to implement carbon limitation scenarios. Countries can implement carbon limits on an individual basis using country-specific carbon (or energy) taxes. Regions can implement carbon limits using a region-wide tax. Under this latter implementation, the level of reduction may vary by country within the region. Regions can also implement carbon limits using tradable permits. This will have similar impacts as a region-wide carbon tax, but the impact on each country's real income will depend on the initial allocation of emission rights.

Model Dimensions

GREEN consists of 12 economic regions, some of which are individual countries (see Annex A on page 30 for precise definitions). Four of the groups are exclusively OECD regions — Japan (JPN), the United States (USA), EEC-12 (EEC), i.e. the 12 member countries of the European Union prior to the accession of Austria, Finland, and Sweden, and a rest of OECD region OOE (prior to the accession of the most recent members, notably Mexico, the Czech Republic, Hungary and Poland). All four of these regions are part of the so-called Annex I countries. There are two other Annex I regions, the countries of Eastern and Central Europe (EET), and the three Baltic Republics and the CIS countries (BCS). (For the purposes of this paper, the EET region is included in the OECD aggregate region.) The non-Annex I countries are divided into three large countries — Brazil (BRA), China (CHN), and India (IND) — and three aggregate regions — the dynamic Asian economies (DAE), energy exporting countries (EEX), and the rest of the world (ROW). The energy exporting countries play a significant role in the model since they are assumed to be suppliers of last resort on the crude oil market, or in other words, they have some market power over the international price of oil.

The GREEN model is dynamic. In its current configuration the model has a base year of 1985 and projects forward to the year 2050, initially in steps of 5 years (1990, 1995, 2000, 2005, and 2010), and subsequently in steps of 20 years (2030 and 2050). The dynamic structure is recursive dynamic, i.e. the model is solved in sequential time steps and equilibrium within each time period only depends on past and contemporaneous variables. (While a forward-looking model has better theoretical properties, particularly in terms of determining savings and allocating investment, the computational costs are deemed excessive for these class of models.) Accumulation equations link the individual time periods. The capital stock is augmented by past investment. Population and labor grow at a given (exogenous) rate based on UN demographic projections. Natural resources exist in finite quantities and their supply is modeled using a (price sensitive) resource depletion module. Beyond changes in the availability of factors, economic growth is also generated by technological growth which is specific to labor, capital, and energy use. Labor productivity is exogenous, as is the so-called autonomous energy efficiency improvement (AEEI). Capital productivity in the baseline scenario is calibrated in order to achieve a given target for aggregate GDP growth. In subsequent scenarios, all productivity factors are exogenous, and the growth rate of GDP is endogenous.

Economic activity is divided into four broad activities — energy, agriculture, sectors intensive in energy use (e.g. iron and steel, pulp and paper), and all other goods and services (see Annex A). In OECD countries, the last sector clearly covers the lion's share of overall economic activity. Initially, energy is sub-divided into five components, and eventually an additional three components are

[2] See OECD (1993), OECD (1995), Lee et. al. (1994), and van der Mensbrugghe (1994) for more detailed documentation of the model and its results.

introduced. The initial energy components are coal, crude and refined oil, natural gas, and electricity. Demand for these five different sources of energy allows for different cross-substitution possibilities as a function of their relative price and technical possibilities.

Starting in 2010, three additional sources of energy are introduced, these are so-called backstop technologies. They include a) a relatively cheap but “dirty” oil substitute essentially shale oil and/or tar sands; b) a rather more expensive but “clean” synthetic fuel such as biomass; and c) a direct substitute for electricity such as solar, wind, fusion. The first two backstop fuels compete directly with coal, oil, and gas. The electric substitute competes directly with conventionally generated electricity. The backstops are introduced into the model through a set of exogenous prices (see Table 3 on page 12). The market penetration parameter of the backstop fuels is also exogenous, though market share will be a function of the price of the backstop fuels, relative to the conventional fuels. If the substitution parameter between conventional fuels and the backstop fuels is high, and the price of the backstops is lower than the price of the conventional fuels, then market penetration will be high. This implies that the price of the backstop fuels places on overall cap on carbon taxes. If carbon taxes push the price of conventional fuels beyond the price of the clean backstops, the latter would takeover the fuel markets. The backstops are assumed to be available in each region, in unlimited quantities, and therefore, there is no trade in the backstop fuels.

Model Specification

The GREEN Model is in a class of models referred to as applied (or computable) general equilibrium models. The strength of this class of economic models is consistency with generally accepted micro-economic theory, significant structural detail, and the nature of general equilibrium, i.e. that changes in any one area of economic activity may have measurable impacts in other areas. One of the key weaknesses is that the many model parameters are rarely corroborated with standard econometric estimates. This calls for undertaking significant sensitivity analysis to see which parameters are key in altering the results and their interpretation.

Production in each sector depends on a certain combination of intermediate inputs, labor, and capital. Amongst the intermediate inputs, the energy goods are given a distinguishing role. Each sector is modeled so as to reflect certain patterns of substitution possibilities between labor, capital, and energy (see Figures B1 and B2 in Annex B on page 31). The substitution possibilities differ according to the age of capital, i.e. GREEN incorporates a vintage capital production structure. Typically, substitution possibilities are greater with newer capital. In this way, GREEN can capture the possibility that energy and capital can be perfect complements in the short run (i.e. the substitution elasticity between capital and energy is zero), but that in the long run it may be possible to substitute capital for energy if the price of energy were to increase relative to the price of capital.

The model includes three sources of domestic demand (apart from intermediate demand) — a single representative household, government demand for goods and services, and investment demand for goods and services. All three allocate their demand for the different energy sources based on the relative price of the relevant fuels. There are two domestic closure rules. The first is that the government deficit (or surplus) is fixed. To achieve this target, the household direct tax rate is endogenous. This is an appropriate closure in a long term model since it avoids fiscal sustainability issues, i.e. the deficit to GDP ratio declines as income increases. The second domestic closure rule is that investment is savings driven. Net investment is the sum of household and government saving, adjusted by net foreign saving. Changes in any of these three components of saving has a direct impact on the level of investment.

Import demand is modeled using the ubiquitous Armington assumption which posits that demand for goods is differentiated by region of origin. Each agent of the economy determines demand for some aggregate level of consumption (the so-called Armington aggregate). In a separate step, demand for this aggregate good is decomposed into demand for a domestic component and an import component.

The flexibility of switching between domestic and import sources is governed by the Armington substitution elasticity. A low elasticity reflects a low degree of substitution. This is often the case with trade in services for example. A high elasticity reflects a high degree of competition. The more disaggregated the commodity description of a model, the higher one would anticipate the elasticity to be. The crude oil sector in GREEN is distinguished by an infinite elasticity, reflecting the high degree of homogeneity of crude oil internationally, and its relatively low transportation cost. Though natural gas, and perhaps to a lesser extent coal, are also relatively homogeneous goods, the more costly transportation margins leads these goods to be modeled as Armington goods. (Note that the demand for aggregate import demand is further allocated across the diverse trading partners using a second step Armington procedure.) The model has a fully consistent set of bilateral trade flows.[3] A global model like GREEN automatically captures *endogenous* changes to the terms of trade.

The foreign closure rule assumes that foreign saving flows are fixed in each time period. This closure rule implies that the aggregate trade balance is fixed in each time and in each region. The equilibrating mechanism is the real exchange rate. Similar to the government fiscal closure rule, the foreign closure rule avoids raising any sustainability issues.

The model only accounts for energy-related carbon emissions, i.e. the direct consumption of coal, oil, and gas (and the "dirty" backstop fuel), and their related emissions. The emission factors are given in Table 2. The synthetic fuel backstop option is the most polluting form of primary energy followed by coal, oil, and gas. This difference in carbon content partly explains the relatively good emission performance of certain European countries over the last decade. These countries have switched significantly from coal towards natural gas as a major source of primary energy.

Table 2: **Carbon Content of Primary Fuels**
(*Million tons of carbon emitted per exajoule*)

Coal	23.89
Natural gas	13.75
Crude oil	19.71
Synthetic fuels	39.00

IV The Scenarios

The Business-as-Usual Scenario

Prior to undertaking any policy simulations, a baseline, or Business-as-Usual scenario is developed. Policy simulations then reflect deviations from the BaU scenario. Table 3 summarizes the key policy and technical assumptions in the BaU scenario. Table 4 summarizes the key growth assumptions. All the other variables resulting from the BaU scenario are generated as endogenous outcomes conditional on the exogenous assumptions. From a technical point of view, the key endogenous parameter generated by the BaU scenario is the capital productivity factor which is in some sense a residual productivity parameter given the exogenous assumptions on labor and energy productivity, and the overall GDP growth rate. The capital productivity parameter is considered given in subsequent policy simulations, and the GDP growth rate is endogenous.

Macroeconomic aggregates

While the model is designed to for scenario analysis to the year 2050, the current paper will restrict the analysis to the year 2010. The average growth in GDP in the Annex I countries in the baseline scenario is assumed to be 2.3 percent per annum over the 20-year period 1990-2010. For the non-

3 Unlike some models, GREEN does not differentiate the allocation of domestic production by region of destination, i.e. domestic suppliers can transfer their supply from the domestic market to the export market, or vice versa, at no cost.

Annex I countries, the GDP growth rate is assumed to 4.4 percent per annum over the same 20 year period. However, population growth will be higher in the non-Annex I countries, averaging 1.6 percent, with only a 0.4 percent average increase in Annex I. Overall the world's population would increase from 5.3 billion in 1990 to 6.9 billion in 2010. In all regions, population growth is nonetheless declining. In per capita terms, the Annex I average income increases from $9,000[4] to $13,100 between 1990 and 2010, and in the non-Annex I countries the relevant figures are $850 and $1,460. There is some convergence in the overall income gap, where the Annex I to non-Annex I ratio decreases from 11 to 1, to 9 to 1, though the higher population growth rate in the non-Annex I regions forestalls further convergence.

Table 3: **Key Assumptions of the Business-as-Usual Scenario**

Energy price subsidies are reduced by 50 percent by the year 2010
Autonomous energy efficiency improvement (AEEI) increases by 1 percent per annum in all regions
Fiscal deficits (or surpluses) are fixed at base year levels in real terms
Foreign saving levels are fixed at base year levels in real terms
Backstop technologies come on stream beginning in 2010 under the following assumptions:

	Unit Cost	*Unit cost per TJ*	*Carbon Content*	*Substitution Elasticity*	*Penetration Coefficient*
Carbon based backstop	$50 per barrel	$8 473	39	10	0.3
Carbon-free backstop	$100 per barrel	$16 946	0	10	0.3
Electric backstop	7½¢ per Kwh	$28 126	0	5	0.1

Notes:

1. *All dollar amounts are 1985 dollars.*
2. *Carbon content is in units of million tons of carbon per exajoule.*
3. *The substitution elasticity determines the degree of substitution between the conventional fuel and its backstop substitute(s). The penetration coefficient determines the market share of each fuel at equal prices. For instance, the two primary fuel substitutes would each have a market share of 30 percent with their conventional counterpart having a 40 percent share at equal prices. The electric backstop would have a 10 percent share.*
4. *The price of the electric backstop is augmented by a region-specific transport margin.*

Energy and the Environment

Global primary energy use is estimated to increase from 323 EJ in 1990 to 453 EJ in 2010, a 40 percent increase. The average annual increase is 1.7 percent. About 60 percent of the increase in energy consumption, i.e. 79 EJ occurs in the non-Annex I regions. Figure 2 shows the increase for each of four regions, and the world total, between 1990 and 2010, and their decomposition by primary fuel source. Though the backstops come on line in 2010, their initial penetration is very low since their price, relative to conventional fuels, remains high in the absence of other energy price policies.

The growth in carbon emissions roughly parallels the growth in energy use. Total carbon emissions grow from a level of 6,332 million metric tons (mmt) of carbon to 9,129 mmt, a total increase of 44 percent, or an average annual increase of 1.8 percent. Roughly 61 percent of the increase of close to 2,800 mmt is accounted for by growth in the non-Annex I countries. While carbon emissions from coal and oil consumption are almost equal in 1990 (42-43 percent), in 2010 coal becomes more important with a 51 percent share, compared to oil's 37 percent share. High economic growth in the coal-dependent economies of India and China are partly to explain this result. Figures 3 and 4 show respectively the decomposition of carbon emissions by region of origin, and the growth and decomposition of regional carbon emissions by fuel source. Overall, the non-Annex I share in world emissions would increase from 27 percent to 38 percent.

[4] Unless otherwise stated, all dollar amounts are in 1985 US dollars. No conversion has been made to take into account different purchasing powers, hence all values are expressed in 1985 market exchange rates.

In the baseline simulation, the energy markets are assumed to be significantly affected by changes in energy price distortions. Significant energy subsidies — see Table 5 for the main sources of distortion — are reduced by 50 percent by the year 2010, leading to substantial reductions in energy use per unit of output, above and beyond energy savings from improved efficiency.

Table 4: **Growth Assumptions of the Business-as-Usual Scenario**

	Real GDP (*Billions of 1985 US Dollars*)				**Real GDP Growth Rates** (*percent per annum*)			
	1985	*1990*	*2000*	*2010*	*1985 /1990*	*1990 /2000*	*2000 /2010*	*1990 /2010*
European Economic Community	2,455	2,897	3,527	4,424	3.4	2.0	2.3	2.1
Japan	1,351	1,705	2,092	2,610	4.8	2.1	2.2	2.2
Other OECD Countries	874	1,010	1,276	1,602	2.9	2.4	2.3	2.3
United States	3,998	4,595	5,864	7,375	2.8	2.5	2.3	2.4
European Economies in Transition	209	212	251	385	0.2	1.7	4.4	3.0
Baltic 3 — CIS	468	715	681	1,077	8.8	-0.5	4.7	2.1
Brazil	182	198	273	414	1.7	3.3	4.2	3.8
China	427	626	1,366	1,911	8.0	8.1	3.4	5.7
India	188	257	388	584	6.4	4.2	4.2	4.2
Dynamic Asian Economies	282	437	740	1,114	9.2	5.4	4.2	4.8
Energy Exporting Countries	1,076	1,103	1,514	2,286	0.5	3.2	4.2	3.7
Rest of the World	678	777	1,173	1,762	2.8	4.2	4.2	4.2
OECD	8,887	10,419	13,011	16,397	3.2	2.2	2.3	2.3
Other Annex I	468	715	681	1,077	8.8	-0.5	4.7	2.1
Other	2,833	3,397	5,453	8,070	3.7	4.8	4.0	4.4
Total	12,189	14,532	19,128	25,518	3.6	2.8	2.9	2.9

	Population (*Millions*)				**Population Growth Rates** (*percent per annum*)			
	1985	*1990*	*2000*	*2010*	*1985 /1990*	*1990 /2000*	*2000 /2010*	*1990 /2010*
European Economic Community	322	328	336	336	0.4	0.3	0.0	0.1
Japan	121	124	126	127	0.4	0.2	0.0	0.1
Other OECD Countries	118	128	143	157	1.5	1.2	0.9	1.0
United States	239	251	275	296	1.0	0.9	0.7	0.8
European Economies in Transition	118	120	119	118	0.3	-0.1	-0.1	-0.1
Baltic 3 — CIS	278	290	294	296	0.9	0.1	0.1	0.1
Brazil	136	148	170	190	1.8	1.3	1.2	1.3
China	1,040	1,123	1,241	1,327	1.5	1.0	0.7	0.8
India	751	832	984	1,127	2.1	1.7	1.4	1.5
Dynamic Asian Economies	174	189	215	238	1.6	1.3	1.0	1.2
Energy Exporting Countries	655	741	915	1,106	2.5	2.1	1.9	2.0
Rest of the World	869	982	1,244	1,545	2.5	2.4	2.2	2.3
OECD	919	950	1,000	1,034	0.7	0.5	0.3	0.4
Other Annex I	278	290	294	296	0.9	0.1	0.1	0.1
Other	3,625	4,015	4,769	5,533	2.1	1.7	1.5	1.6
Total	4,821	5,255	6,062	6,863	1.7	1.4	1.2	1.3

Notes:
1. *Labor productivity is assumed to grow at the rate of GDP minus the rate of population growth.*
2. *Capital productivity is calculated in the BaU scenario to be consistent with the given rate of GDP, labor productivity, and AEEI assumptions.*

Table 5: **Base Year Energy Subsidies**

(*percent of world reference price*)

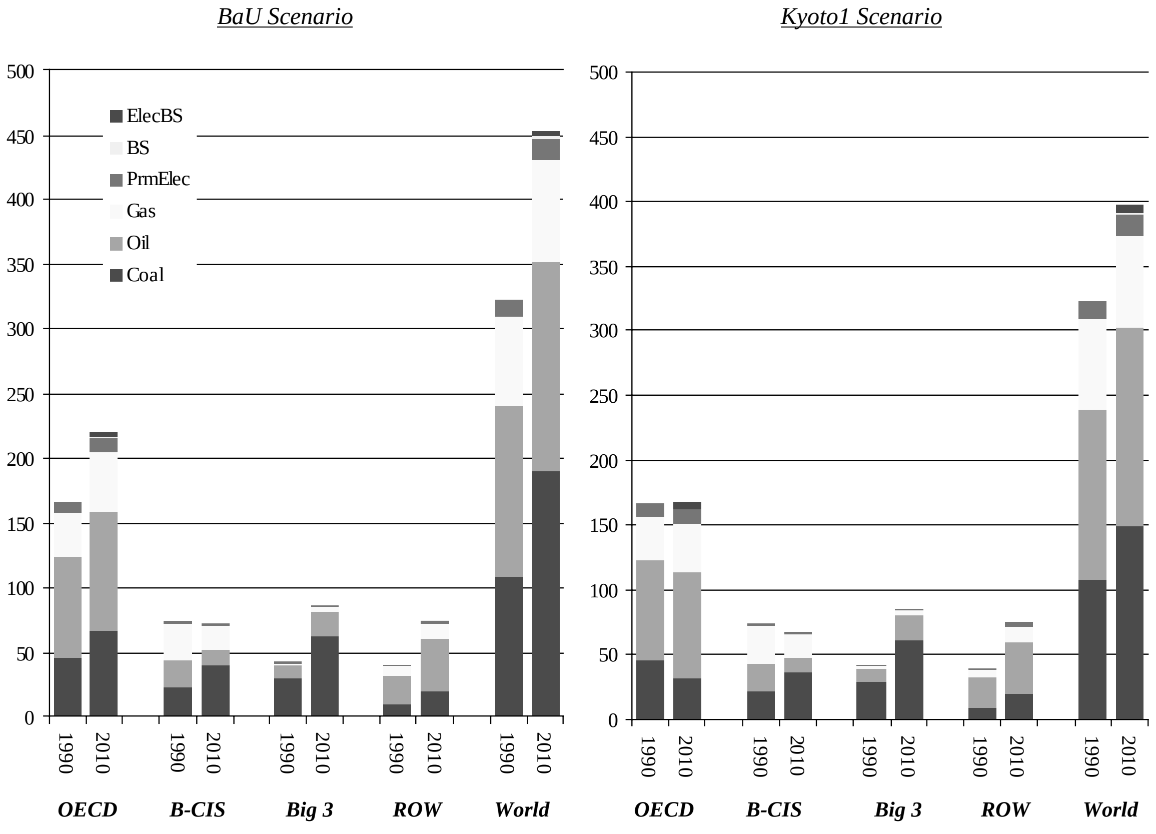
	Coal	*Crude Oil*	*Natural Gas*
European Economies in Transition	48.1	61.2	43.1
Baltic 3 — CIS	44.1	12.4	11.7
Brazil	..	75.6	58.5
China	45.0	98.3	88.8
India	58.5	58.3	49.9
Dynamic Asian Economies	..	82.7	..
Energy Exporting Countries	..	63.6	79.2
Rest of the World	..	81.7	..

Notes:

1. *Missing values indicate the relevant fuel has either a zero or positive tax applied.*

Figure 2: **Growth and Decomposition of Energy Demand**

(*Units in exajoules*)



Notes:

1. *BS and ElecBS represent respectively the backstop fuels substitutes (both carbon-based and carbon-free) for conventional fossil fuels, and the electric backstop option. PrmElec represents the generation of electricity from conventional non-fossil fuel sources, e.g. hydroelectricity, and nuclear.*
2. *The OECD region includes EEC, JPN, OOE, USA, and EET. The B-CIS region is only BCS. The Big3 region includes BRA, CHN, and IND. ROW includes DAE, EEX, and ROW. The World total is the aggregate over all regions.*

Figure 3: **Decomposition of Carbon Emissions by Region**

(*Units in million metric tons*)

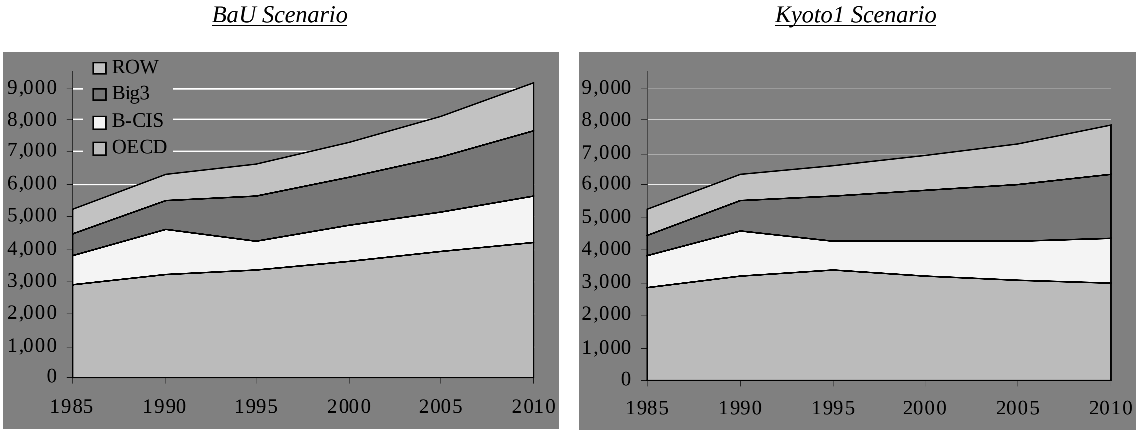
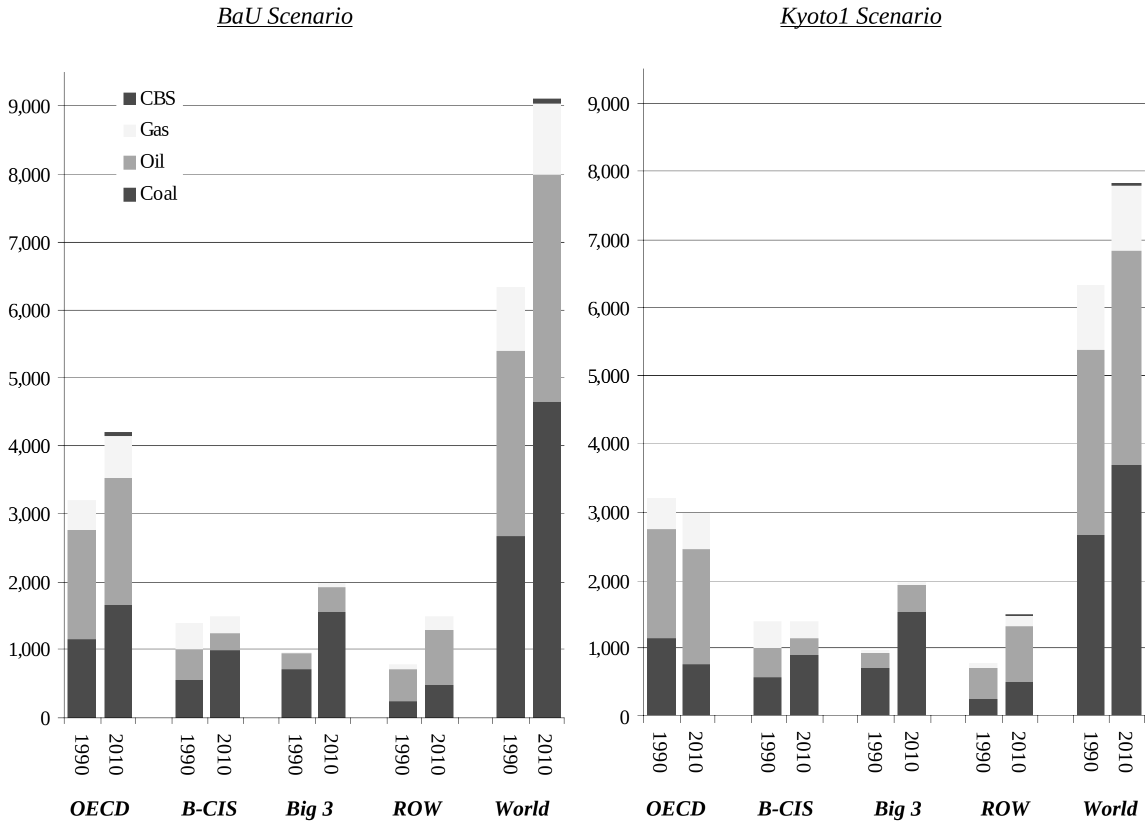


Figure 4: **Growth and Decomposition of Carbon Emissions by Source**

(*Units in million metric tons*)



Notes:

1. *CBS represents the carbon-based backstop fuel.*
2. *The OECD region includes EEC, JPN, OOE, USA, and EET. The B-CIS region is only BCS. The Big3 region includes BRA, CHN, and IND. ROW includes DAE, EEX, and ROW. The World total is the aggregate over all regions.*

The Kyoto Protocol

As described above, the Kyoto Protocol would lead to substantial reductions by the period 2008-2012 compared to the projected level of emissions within a group of Annex I countries. The results described below provide some rough idea about the economic costs of meeting these reduction levels. In many ways, these costs can be assumed to be upper bound estimates (with respect to the BaU scenario), since the implementation of the protocol in the GREEN model is less comprehensive than the agreement itself. GREEN only incorporates energy-related carbon emissions, not the other five greenhouse gases which are included in the protocol. Nor does GREEN make provision for carbon sinks. Adding either of these two elements could lead to lower cost estimates.[5] GREEN also has myopic foresight and therefore is not ideal for determining the optimal profile for achieving the targets. For example, the electric backstop option becomes available in 2010, and due to the relatively high electricity prices in Japan, it achieves a relatively high market share in Japan in 2010. If the availability and the price were known with certainty today, it would probably be advantageous for Japan to wait until 2010 to make the necessary changes in its energy mix.

There are many other uncertainties concerning the implementation of the accord. Each country is free to choose its own set of instruments, as well as the time profile for achieving the target. The remainder of the section describes four scenarios. The first three analyze three different implementation scenarios involving exclusively the six Annex I regions. The fourth scenario includes the non-Annex I regions in a potential tradable permit scheme. The table below summarizes all five scenarios:

BaU	Business-as-usual (or baseline) scenario. Note that this scenario includes a 50 percent reduction of energy subsidies by the year 2010 (which is maintained in all subsequent scenarios). All other energy policies are assumed constant.
Kyoto1	Each of the six Annex I regions implements its own carbon tax in order to achieve its target reduction by the year 2010.
Kyoto2	The six Annex I regions act in concert to limit their aggregate emissions, consistent with their announced targets. This implies that the overall Annex I target is met, though the individual regional targets will not necessarily be binding. A region-wide uniform carbon tax is implemented.
Kyoto3	The six Annex I regions set up a tradable permit scheme. The allocation of quotas matches their 2010 commitments.
Kyoto4	A global tradable permit scheme is implemented. Each Annex I region has the same quota as in the Kyoto3 scenario. The non-Annex I regions are given permits identical to their projected consumption patterns determined in the Kyoto3 scenario. In this case, they can be no worse off than in Kyoto3, and the global level of emissions is also capped at its Kyoto3 level.

Go-it-alone Emissions Reduction – Kyoto1

In the first simulation, designated by Kyoto1, the six Annex I regions in the GREEN model are assumed to start implementation of their carbon reduction profile in the year 2000, leading to achieving their target reduction by the year 2010. The profile assumes a linear decline between 2000 and 2010. Each region is assumed to act alone, and to implement a carbon tax. The emissions profile for the regions are provided in Table 6.

5 The addition of the other greenhouse gases could potentially make the estimates of the costs of reduction higher. It would depend on the baseline emission trends of the other gases and their relative costs of abatement.

Under Kyoto1, each of the six regions acts independently, i.e. they implement a carbon tax on their own emissions in order to achieve their individual designated targets. Since the cost of reducing emissions in each region varies, the level of the carbon tax will likewise vary. The level of the carbon tax is primarily a function of four factors:[6]

- It is positively related to the pre-tax price of fuels. The higher the pre-tax price, the higher the carbon tax, since it is implemented as an excise tax. (A 20¢ tax per gallon in the US would have a higher percentage impact than the equivalent tax in the average European country.)
- It is negatively related to the average carbon content of energy use at the outset. Countries with a high concentration of coal use, for example, will need a smaller tax, ceteris paribus.
- It is negatively related to the overall degree of energy substitution possibilities. The higher the level of substitution, the easier it is for an economy to switch to other resources. The level of substitution is a complex function of the CES nests, and it is also influenced by the percentage share of new capital.
- It is positively related to the level of the constraint. This is rather obvious. A more stringent constraint leads to a greater level of taxation.

The price and availability of the clean backstop substitute fuels also puts an overall cap on the level of the carbon tax. Once the price of "dirty" fuel reaches the price of the clean backstops, users will switch their demand to the "clean" fuels. This is more relevant to periods after 2010. After 2010, the price of conventional fuels may rise constantly as the existing supply of reserves declines. The current estimates of recoverable reserves of oil and gas are somewhere around 40 years for crude oil, and 60 years for natural gas.[7] The lifetime of coal reserves, and shale oil and tar sands, are estimated to be significantly longer. One could also anticipate that the price of clean backstop fuels may decline over time as technological innovation and scale economies reduce the price of production and utilization.

Table 6: **Emission Profile for Annex I Countries**

(*percent level – 1990=100*)

	2000	*2005*	*2010*
European Economic Community	100	96	92
Japan	106	100	94
Other OECD Countries	105	101	97
United States	102	98	93
European Economies in Transition	90	92	93
Baltic 3 — CIS	76	86	100

Notes:

1. *Due to their economic transformation, coupled with the reduction of significant energy price distortions, the EET and BCS regions' profile essentially impose no binding constraint until later in the target period.*

Figure 5 depicts the level of the carbon tax for the six implementing regions in the Kyoto1 scenario. Focusing on the year 2005 first, when the reductions really start to bite, but the backstops are as yet unavailable, we notice that the highest carbon tax is in Japan, at $223 per ton of carbon.[8] Principally, this is due to the existing relatively high price of energy in Japan. The next highest tax is in Europe, at $138 per ton of carbon. The US and the other OECD region (OOE) have a tax of about $87 per ton. The price of energy in these regions is significantly lower than in Europe. The situation in 2010 changes to some degree. In Europe, the US, and OOE, the tax increases (to $150, $114, and $177), as the reduction target becomes much tighter (almost 30 percent below baseline emissions). In Japan,

6 See Burniaux et. al. (1993), p. 68 for a more detailed explanation.

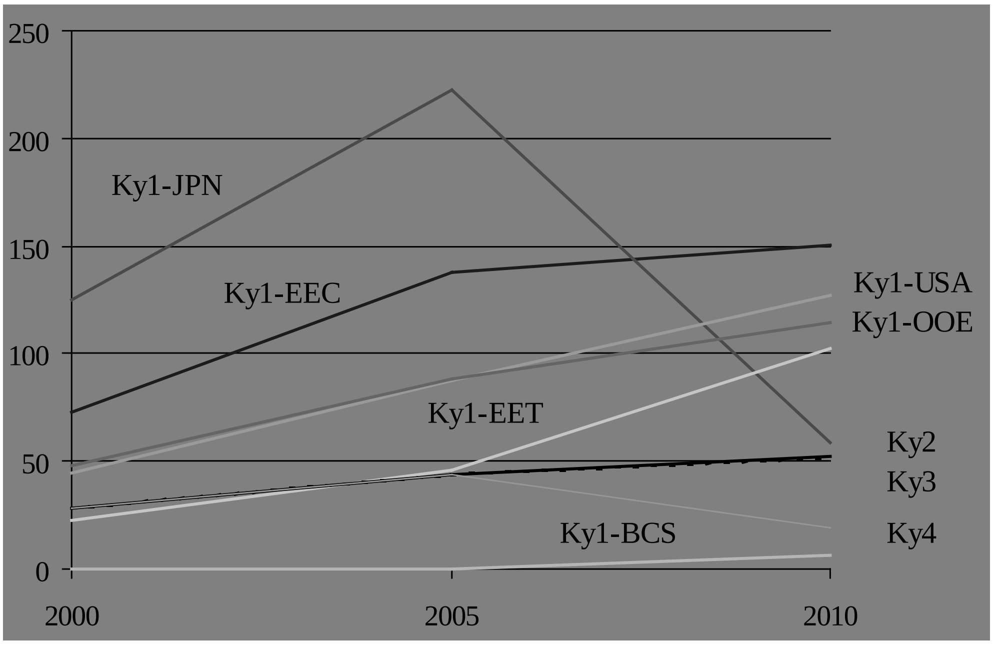
7 See British Petroleum (1997). The numbers suggested by BP refer to the ratio of current production from *proven* reserves. These estimates tend to vary significantly since the cost of discovering and producing oil and gas from previously non-economical reserves has continuously declined.

8 The carbon taxes are deflated by the unit cost of OECD manufacturing exports (which is the numéraire of the model).

the tax level decreases substantially, to $59, as the clean backstops are able to compete successfully due to the high price of energy in Japan. The backstops are not able to penetrate to any significant extent in the other OECD regions. In EET, the emissions constraint is binding and the tax is a non-negligible $102 in 2010. However, this must be considered in light of the remaining energy subsidies. The constraint in the BCS region is hardly binding, even in 2010.

Figure 5: **Carbon Tax Profiles**

($1985 *per ton of carbon*)



Notes:

1. *All four Kyoto scenarios are present in this chart. Ky1 has region-specific carbon taxes for each of the six Annex I regions. The Ky2 and Ky3 scenarios have a uniform Annex I-wide tax (or tradable permit price). The Ky4 scenario has a world-wide price for tradable permits.*
2. *The tax curves for the USA and OOE under the Kyoto1 scenario (Ky1), are virtually identical. Similarly, the Ky2 and Ky3 tax curves are virtually identical.*
2. *The dollar price is deflated by the numéraire of the model — the average price of OECD manufacturing exports.*

Though the carbon tax is implemented as an excise tax, it is possible to assess its ad valorem equivalent, or in other words, the wedge between the pre-tax price of energy and the post-tax price. Table 7 provides these wedges for the three conventional fossil fuels. As to be expected, the highest price wedge is imposed on coal since it has the highest carbon content per unit of energy. In the case of the US, for example, the post-tax price of coal would increase three-fold in 2010.

Table 7: **Ad Valorem Equivalent of the Carbon Tax in 2010**

	Kyoto1			Kyoto2			Kyoto3			Kyoto4		
	Coal	*Oil*	*Gas*	*Coal*	*Oil*	*Gas*	*Coal*	*Oil*	*Gas*	*Coal*	*Oil*	*Gas*
EEC	1.53	0.55	0.44	0.53	0.18	0.15	0.54	0.18	0.15	0.20	0.07	0.05
JPN	0.26	0.20	0.16	0.23	0.17	0.13	0.23	0.17	0.13	0.09	0.06	0.05
OOE	2.86	0.55	0.68	1.15	0.22	0.27	1.18	0.22	0.27	0.43	0.08	0.10
USA	2.10	0.44	0.52	0.95	0.19	0.23	0.97	0.19	0.24	0.35	0.07	0.09
EET	2.06	0.48	0.63	1.02	0.23	0.31	1.03	0.23	0.31	0.37	0.08	0.11
BCS	0.17	0.04	0.06	1.46	0.33	0.51	1.38	0.34	0.48	0.51	0.12	0.18
BRA										0.15	0.08	0.09
CHN										0.64	0.07	0.09
IND										0.55	0.09	0.15
DAE										0.24	0.07	0.06
EEX										0.34	0.08	0.07
ROW										0.60	0.07	0.04

Notes:

1. *The post-tax price is equal to the pre-tax price times the factor (1+t) where t is the ad valorem equivalent. If t is equal to 1, the tax rate is 100 percent and the post-tax price is double the pre-tax price.*

Global carbon emissions in 2010 drop from 9,100 mmt in the BaU scenario, to 7,800 mmt in the Kyoto1 scenario (see Table 8 and Figure 4). Virtually the entire drop originates in the six Annex I regions. In the non-Annex I regions, emissions drop by an imperceptible 7 mmt. There are increases in some of the non-Annex I regions as they benefit from lower international energy prices. Large countries, such as China and India, have significant domestic coal industries which are only marginally affected by changes in global coal prices. Use of cleaner fuels can be expected to the extent that oil and gas prices fall more relative to the domestic coal price. Even excluding the major energy producers, it appears that the phenomenon of carbon leakage is unlikely to be important in 2010.[9]

Table 8: **Carbon Emissions**

(million metric tons)

	1990	*2010*	*Carbon Emissions in 2010*				*Percent of BaU Emissions in 2010*			
	BaU		Kyoto1	Kyoto2	Kyoto3	Kyoto4	Kyoto1	Kyoto2	Kyoto3	Kyoto4
EEC	859	1,087	791	936	934	990	73	86	86	91
JPN	347	431	326	377	376	397	76	87	87	92
OOE	304	435	294	336	335	364	68	77	77	84
USA	1,366	1,794	1,271	1,426	1,423	1,535	71	79	79	86
EET	325	438	302	328	327	361	69	75	75	82
BCS	1,382	1,479	1,382	963	971	1,117	93	65	66	76
BRA	88	134	139	136	136	132	104	102	101	98
CHN	706	1,519	1,501	1,512	1,513	1,285	99	100	100	85
IND	164	326	325	326	325	280	100	100	100	86
DAE	131	274	282	278	278	261	103	101	101	95
EEX	361	608	599	603	604	580	98	99	99	95
ROW	299	606	614	610	610	531	101	101	101	88
Annex I	4,583	5,662	4,366	4,366	4,366	4,763	77	77	77	84
Other	1,749	3,467	3,460	3,465	3,466	3,069	100	100	100	89
World	6,332	9,129	7,826	7,831	7,831	7,832	86	86	86	86

9 However, there is more displacement of industrial production, particularly for the energy intensive sectors. On aggregate, production of the energy intensive good declines by 2.1 percent in the OECD regions, and increases by 2.2 percent in the non-OECD regions. Some of the decline can be attributed to lower overall economic activity, but a large portion of the decline is due to competitive factors. See Oliveira-Martins et. al. for more detailed analysis of the carbon leakage issue.

Figure 2 (from above) provides a picture of the change in the fuel mix for the OECD countries. In absolute terms, coal consumption drops by one-third in the Annex I countries, with more minor reductions in the oil and gas markets (11-12 percent). While coal and oil are not very different in terms of overall carbon emissions, the international oil market is much more flexible. Hence, the high carbon tax is counter-acted by a much larger drop in the wholesale price of oil than is the case for coal or natural gas. In other words, the tax-augmented price of oil makes it relatively more attractive than coal, even adjusting for the differences in carbon content. Natural gas is less taxed than oil, and hence should be relatively more attractive. However, the nature of the gas markets also tends to dampen the impacts of carbon taxation on gas, and therefore, the relative attractiveness of gas is only partially captured in the lower effective carbon tax.[10] There is virtually no penetration of the carbon-free backstop option for fossil fuels due to its high cost. The electric backstop option more than doubles its share in primary energy consumption in the Annex I countries, from 1.2 percent in 2010 in the baseline scenario, to 2.5 percent in 2010 in the Kyoto1 scenario.

In terms of the aggregate economic costs, the go-it-alone carbon tax scenario, leads to a drop in real income of 0.5 percent in the year 2010, relative to baseline GDP in 2010, for the Annex I aggregate region (see Table 9). The most significant costs occur in Europe and Japan at –0.8 and –0.9 percent respectively, with the USA and OOE at around –0.4 percent. Though surprising at first, the EET region actually benefits from imposing a carbon tax. This happens because the EET region heavily subsidizes energy and the carbon tax counteracts the negative effects of the subsidy. Though energy subsidies are assumed to be halved by 2010 in the BaU scenario, the carbon tax in the earlier period provides enough of a dynamic boost to these economies to allow them to achieve an overall gain in 2010. While the BCS region has even higher energy subsidies than the EET region, it is also a major energy exporter. Its losses can largely be attributed to a decline in its terms of trade. Furthermore, since the emissions constraint is barely binding for the BCS region, the small carbon tax has little impact on reversing the negative impacts of its energy subsidies. In monetary terms, the total losses amount to $93 billion (in 1985 dollars), or $100 billion if the EET gain is removed.

Table 9: **Change in Real Income**

	Kyoto1	*Kyoto2*	*Kyoto3*	*Kyoto4*	*Kyoto1*	*Kyoto2*	*Kyoto3*	*Kyoto4*
	(billion $1985)				(percent of BaU GDP in 2010)			
EEC	-35.5	-8.5	-18.4	-8.5	-0.8	-0.2	-0.4	-0.2
JPN	-23.3	-6.1	-9.6	-5.5	-0.9	-0.2	-0.4	-0.2
OOE	-5.6	-1.5	-3.6	-2.7	-0.3	-0.1	-0.2	-0.2
USA	-26.8	-12.0	-22.6	-16.3	-0.4	-0.2	-0.3	-0.2
EET	7.9	5.9	4.4	3.5	2.1	1.6	1.2	0.9
BCS	-10.3	7.8	32.0	13.9	-1.0	0.7	3.0	1.3
BRA	3.0	1.2	1.1	1.7	0.7	0.3	0.3	0.4
CHN	-1.4	-1.3	-1.0	7.5	-0.1	-0.1	-0.1	0.4
IND	0.5	-0.1	0.0	4.1	0.1	0.0	0.0	0.7
DAE	0.6	-0.3	-0.6	1.1	0.1	0.0	-0.1	0.1
EEX	-76.3	-32.6	-29.4	-21.4	-3.4	-1.4	-1.3	-0.9
ROW	-7.9	-3.7	-2.2	-3.3	-0.4	-0.2	-0.1	-0.2
Annex I	-93.4	-14.4	-17.8	-15.7	-0.5	-0.1	-0.1	-0.1
Other	-81.5	-36.8	-32.1	-10.2	-1.0	-0.5	-0.4	-0.1
World	-175.0	-51.2	-49.8	-25.9	-0.7	-0.2	-0.2	-0.1

The aggregate impact on the non-Annex I economies is relatively slight, with one major exception. The key energy-exporting region, EEX, would suffer a real income loss of -3.4 percent in 2010, relative to baseline GDP in 2010. Similar to the BCS region above, the main reason for the loss is the change in the terms of trade, i.e. the drop in the price of its key exports, notable oil and gas. In the

10 The current version of the model ignores recent changes to the natural gas market which has made it a much more traded commodity than in the past.

case of the EEX region, the export price index declines by 4.5 percent, while the import price index increases by 1.7 percent. The contrary is true for many of the other regions. Brazil's real income increases by 0.7 percent, largely because it relies heavily on imported energy, whose price is declining.

With the risk of sounding repetitive, it is to be noted that these losses in real income are assumed to be maximum range losses for the reasons cited above. Moreover, the impact on the average annual growth rates over the 20-year period is almost imperceptible. Of course, one of the key missing elements from this line of analysis is that it fails to measure the benefits from reducing carbon emissions (and perhaps complementary emissions such as SOx and particulates), though the benefits, in terms of reduced global warming, are likely to be realized by future generations.

In terms of fiscal analysis, the carbon taxes generate significant revenues (see Table 10). In the current version of the model, these revenues are transferred *in toto* to households (thereby reducing their direct tax liability). Aggregate carbon tax revenues for the Annex I could be as much as $183 billion in 2000 and rise to $350 billion by 2010, about 2 percent of aggregate Annex I GDP. Targeting even a small percentage of this towards research and development, in cooperation with the private sector and universities, could provide a lowering of the overall costs of achieving the emissions reduction targets.

Regional Coordination – Kyoto2

In the second simulation of the Kyoto Protocol, it is assumed that the six Annex I regions coordinate their actions to reduce emissions. Given that there are significant differences in the marginal cost of reducing emissions across countries, it is clear that a coordinated approach could reduce the overall cost to all six of the regions, though one or more of the regions could be worse off in the absence of any transfers. An overall Annex I emissions target of 4,366 mmt is imposed for the year 2010. This represents an aggregate reduction of –4.7 percent from the level of emissions in 1990, and a 23 percent reduction from the baseline emission level in 2010. A uniform Annex I-wide carbon tax is implemented which equalizes the marginal cost of abatement across the six regions.

Table 10: **Carbon Tax Revenues**

Billion $1985

	Kyoto1			*Kyoto2*			*Kyoto3*			*Kyoto4*		
	2000	2005	2010	2000	2005	2010	2000	2005	2010	2000	2005	2010
EEC	58.2	102.9	113.6	24.8	38.5	47.7	24.8	38.5	48.6	24.8	38.5	19.0
JPN	41.6	67.4	19.3	11.2	17.9	19.2	11.2	17.9	19.6	11.2	17.9	7.7
OOE	13.4	25.2	37.1	8.9	13.7	17.4	8.9	13.7	17.7	8.9	13.7	7.0
USA	62.7	109.3	141.2	38.5	58.8	72.1	38.5	58.8	73.5	38.5	58.8	29.1
EET	6.9	14.3	32.6	8.5	13.5	17.8	8.5	13.5	18.1	8.5	13.5	7.3
BCS	0.1	0.1	9.0	26.9	40.1	49.7	26.9	40.1	51.2	26.9	40.1	21.1
BRA										0.0	0.0	3.4
CHN										0.0	0.0	26.2
IND										0.0	0.0	5.5
DAE										0.0	0.0	6.0
EEX										0.0	0.0	14.1
ROW										0.0	0.0	11.2
Annex I	183.0	319.2	352.8	118.7	182.5	224.0	118.7	182.5	228.8	118.7	182.5	91.3
Other	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	66.5
World	183.0	319.2	352.8	118.7	182.5	224.0	118.7	182.5	228.8	118.7	182.5	157.8

Percent of GDP

	Kyoto1			*Kyoto2*			*Kyoto3*			*Kyoto4*		
	2000	2005	2010	2000	2005	2010	2000	2005	2010	2000	2005	2010
EEC	1.7	2.6	2.6	0.7	1.0	1.1	0.7	1.0	1.1	0.7	1.0	0.4
JPN	2.0	2.9	0.7	0.5	0.8	0.7	0.5	0.8	0.8	0.5	0.8	0.3
OOE	1.1	1.8	2.3	0.7	1.0	1.1	0.7	1.0	1.1	0.7	1.0	0.4
USA	1.1	1.7	1.9	0.7	0.9	1.0	0.7	0.9	1.0	0.7	0.9	0.4
EET	2.7	4.5	8.4	3.4	4.3	4.6	3.4	4.3	4.7	3.4	4.3	1.9
BCS	0.0	0.0	0.8	3.9	4.6	4.6	3.9	4.6	4.7	3.9	4.6	1.9
BRA										0.0	0.0	0.8
CHN										0.0	0.0	1.4
IND										0.0	0.0	0.9
DAE										0.0	0.0	0.5
EEX										0.0	0.0	0.6
ROW										0.0	0.0	0.6
Annex I	1.3	2.1	2.0	0.9	1.2	1.3	0.9	1.2	1.3	0.9	1.2	0.5
Other	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.8
World	1.0	1.4	1.4	0.6	0.8	0.9	0.6	0.8	0.9	0.6	0.8	0.6

The resulting carbon tax is respectively $29, $44, and $51 in the years 2000, 2005, and 2010. Focusing on the last year, the uniform tax is significantly lower for Europe than the go-it-alone strategy, and more than halved for OOE, the US, and EET. Japan comes out about even. This is not true during the transition period. Japan would benefit from the coordinated strategy prior to 2010. It is the competitiveness of the electric backstop option in Japan which sets an overall cap on the cost of abatement in Japan. Since the BCS region by and large has no problem in achieving its emission reduction target on its own, it would stand the most to lose, and in fact, the carbon tax in this region is close to zero in the Kyoto1 scenario. However, as will be shown below, it nevertheless gains a double dividend in this scenario.

The global impact on carbon abatement is virtually the same in both the Kyoto1 and Kyoto2 scenarios. Given that the Annex I emissions level is imposed in both, this signifies that the design of the implementation among the Annex I countries has relatively little impact on the level of emissions outside of the Annex I region. The emission profile across Annex I countries changes to some extent, even if the aggregate level of emissions is the same. In 2010, all the OECD regions increase their level of emissions significantly, compared to their 2010 commitments. The increases are respectively

18, 15, 14, 12, and 8 percent for the EEC, JPN, OOE, USA, and EET. The BCS region is the only region with a decline in its emissions (compared to its commitment), its emissions declining by a large -30 percent. This is a logical consequence of the equalization of the marginal cost of abatement. (The differences between Kyoto1 and Kyoto2 during the transition period may be less dramatic).

The aggregate economic cost is virtually eliminated in the year 2010 for the Annex I region. The drop in real income is –0.1 percent, rather than –0.5 percent, with the greatest relative impact occurring in Europe and Japan where the marginal cost of abatement is highest. As already alluded to above, the BCS region reverses its previous loss (-1.0 percent) into a significant gain (0.7 percent). It reaps a double dividend. First, the imposition of the carbon tax counteracts the negative effects of the remaining energy subsidies. The firmer international energy prices, coupled with a stronger (relative) performance of the European economies, generates significant improvement in its terms of trade (from –4.4 percent in Kyoto1 to only –1.6 percent in Kyoto2), and a more favorable trading environment. The aggregate impacts for the non-Member economies leads to a halving of its previous loss of –1.0 percent. There is less of a drop in energy prices, hence the energy exporters lose less, though some of the gains in the other regions are somewhat dampened. In summary, a coordinated strategy should be quite appealing to the Annex I regions, at least from a strictly economic point of view. The EET region is the only region with a relative loss (compared to Kyoto1), though with a significant absolute gain. The relative reduction in the carbon tax lowers its dividend from counteracting the remaining energy subsidies.

Tradable Permits for the Annex I – Kyoto3

In this implementation of the Kyoto Protocol, the Annex I regions again coordinate their efforts to limit emissions in 2010. However, instead of imposing a uniform region-wide tax, each individual region is assigned an emission quota, and the regions can trade among themselves so as to equalize the marginal cost of abatement. In microeconomic terms, this simulation is very similar to the region-wide uniform tax. The permit price will act in the same way as the regional carbon tax. There are two key differences. The first is that under a quota system there is no uncertainty concerning the terminal level of emissions (as long as there is adequate monitoring), though there may be uncertainty about the price of the permit. Under the tax system, the tax would be known (though governments could eventually let it vary), but the emissions target may be missed if the tax is either too high or low. The second difference is that the allocation of the net costs and gains will be determined by the initial apportionment of the emissions quota. Many different schemes have been proposed, but in the end, any adopted scheme will be a political decision.

Given the signature of the Kyoto Protocol, it seems reasonable to assign quotas for the year 2010 consistent with the agreed upon commitments. A more critical issue concerns the transition period. There are many potential schemes which could be designed during the transition period. In order to neutralize any impact from differences during the transition period, both this scenario, and the following one, assume that the regions of Annex I coordinate their strategies during the transition period, but do not implement a tradable permit market. In other words, the transition period for both scenarios is equivalent to Kyoto2, and hence the results for the years 2000 and 2005 are identical. The tradable permit scheme is only implemented in 2010. Table 11 provides the details concerning the quota allocation for the year 2010. The sum of the quotas in 2010 is equal to the aggregate Annex I commitment for that year, i.e. an average reduction of –4.7 percent with respect to the Annex I level of emissions in 1990. As in the Kyoto1 and Kyoto2 scenarios, there are no limits on the non-OECD countries.

Table 11: **Quotas, Use, and Net Purchases in 2010**

(*mmt*)

	Initial Quotas	*Carbon Emissions*	*Net Purchases*	*Net Purchases ($bn 1985)*
European Economic Community	791	934	143	7.3
Japan	326	376	50	2.5
Other OECD Countries	294	335	41	2.1
United States	1,271	1,423	152	7.8
European Economies in Transition	302	327	25	1.3
Baltic 3 — CIS	1,382	971	-410	-20.9
Total	4,366	4,366	0	0

Most of the structural results are identical with the results from the Kyoto2 simulation. The price of the tradable permit is virtually the same as the common tax rate determined in the Kyoto2 scenario (at around $51 per ton), as are the emission levels by region, (gross) permit receipts, etc. The aggregate change in real income for the Annex I region is also similar, however, the allocation of the changes in real income across regions is quite different. Those regions having to purchase emission permits, suffer a real income loss compared to the Kyoto2 simulation. The BCS region is the only net seller of tradable permits, hence all the other five regions lose somewhat from the tradable permit scheme compared to Kyoto2. However, all the regions of the OECD gain compare to the go-it-alone strategy, accept for EET, which though still gaining significantly, would be better off by essentially removing its remaining energy subsidies. Impacts in the non-OECD regions are marginal.

Gross sales of emission permits are respectively 410 mmt in 2010, about 9.4 percent of total emissions. The gross sales in value terms amount to roughly $20 billion (in 1985 dollars). This is only a small portion of total permit receipts of about $230 billion.

Tradable Permits on a Broader Scale – Kyoto4

It is obvious to most analysts that the marginal abatement costs are much lower in most of the non-Annex I countries than in the Annex I countries. However, many non-Member countries are reluctant to entertain any emission targets, arguing correctly, that the Annex I countries have been emitting carbon for 150 years and therefore should bear the greater burden of reducing emissions, while allowing them to catch up to Annex I income levels. It can be shown, nonetheless, that it is possible to achieve the same level of global reductions, while at the same time reducing the cost to the Annex I countries and (perhaps significantly) improving the aggregate gains of non-Annex I economies.

As mentioned above, there are many ways to implement these types of agreement. In this particular scenario, it is assumed that the Annex I countries are given quotas consistent with their commitments. The allocation of permits for the Annex I regions is exactly as in the Kyoto3 scenario. The non-Annex I countries are given quotas which are equivalent to their level of emissions from the Kyoto3 scenario, i.e. they can be no worse off than in the Kyoto3 scenario, and globally, the level of emissions will exactly match the level of emissions in the Kyoto3 scenario. Table 12 shows the allocation of permits, as well as the final level of emissions, and net trade in emissions.

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

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 significant amount of skepticism — among public officials, the private sector, and academics — that many are suggesting to take a wait-and-observe attitude while more evidence is collected, and new technologies are discovered which will mitigate the need for tougher measures. There are vocal advocates for so-called *no-regrets* policies. These are policies which should be undertaken in any case on purely economic grounds. Some of these policies are obvious on economic grounds, for example, the need for many countries to remove all subsidies on energy, though may be difficult to implement for political reasons. Estimates of the impact of removing energy subsidies show that these alone could reduce emissions by up to 30 percent. Other types of no-regrets policies are more directly linked to private energy consumption — for example energy conservation measures. If these truly are no-regret policies, a thorough analysis of why these policies are not being implemented needs to be taken.

Despite the many ongoing uncertainties concerning climate change, and the significant wrangling both prior to, and during, the Kyoto meeting, its successful conclusion must be considered a considerable achievement, even if its ratification proves to be difficult in a number of countries. If the countries meet the reduction targets within the next 15 years, it will be the first time since the beginning of the Industrial Revolution that economic growth in the industrialized countries would be decoupled from growth in carbon emissions on a broad and sustained basis. Depending on the estimate of the level of emissions in the period 2008-2012 in the absence of any policies, the total reduction at the global level could be around 14 percent, around 23 percent for the Annex I countries, and for the OECD region, it may represent a reduction of 29 percent. This level of reduction will be associated with an economic cost, and the purpose of this paper was to explore the level of the cost and ways to minimize it. (A longer term perspective should also assess the positive benefits from reducing greenhouse gas emissions.)

In the absence of any coordination among the Annex I countries, the aggregate economic cost would approach 0.7 percent of 2010 GDP compared to the BaU scenario, with the highest costs in Europe and Japan. The impacts on the rest of the world are varied. The energy exporting regions would lose significantly, mainly due to a deterioration in their terms-of-trade as world energy prices would fall. Some regions would benefit from lower energy prices, notably Brazil, but also many of the OECD countries. China and India, largely absent from world energy markets due to their significant coal resources, would witness little overall impact. In some regions there is a slight increase in carbon emissions, but on aggregate, non-Annex I carbon emissions are stable. At a more detailed level, it is obvious that some OECD industries are likely to suffer from a decline in competitiveness due to higher energy prices. However, the OECD economies have largely moved out of energy-intensive industries (as a share of total output), and the cost of energy, even in these sectors, tends to be a small share of total cost. The model suggests that output from energy-intensive sectors would decline by around 2.2 percent in the OECD in 2010 compared to the BaU scenario, and increase by about the same 2.2 percent in the non-Member economies. These results are of course subject to significant uncertainty and further sensitivity analysis would provide a broader understanding of international linkages.

Two of the four carbon abatement scenarios clearly indicate that coordinated action among the Annex I countries could lead to significant reductions in the cost of limiting emissions. In the two scenarios, the aggregate cost of abatement fell by 80 percent. The two differ in implementation of the coordinated policies. In the first case, a global target is set for the Annex I-wide region, and each country implements the same uniform carbon tax. This has the virtue of equalizing the marginal cost of abatement across the region as a whole. The second coordinated scenario involved allocating an initial quota of emission permit across the Annex I countries and allowing for trade in the permits. The structural results are virtually identical in the two scenarios since the price of the permit essentially mimics the carbon tax. The allocation of the gains and the costs across regions will differ and will depend strongly on the initial allocation of permits.

The final simulation incorporates the non-Member economies in a global tradable permits scheme. The quota allocations for the Annex I countries was the same as in the previous simulation, and the non-Annex I countries were given a quota similar to their actual emissions from that simulation (i.e. Kyoto3). At worse, this simulation would simply re-produce the results of the previous simulation. However, integrating the non-Member economies into an essentially Annex I-only scheme to reduce emissions, produces positive results for almost **all** countries, particularly the non-Annex I countries. The aggregate loss to the non-Annex I economies in the Annex I-only schemes varies from -0.4 to -1.0 percent. In participating with the Annex I countries, the net loss is virtually eliminated, and all regions gain in relative terms except perhaps for Brazil and ROW which lose somewhat due to a relative deterioration in their terms-of-trade. With a different quota allocation, or some other exogenous transfer mechanism, it would be possible to make all regions relatively better-off. The regions with the largest to gain from international coordination are the energy exporting regions.

These results are simply meant to be suggestive. First, the GREEN model needs to be developed in two directions — more regional and sectoral coverage, and incorporation of the other greenhouse gases (and perhaps carbon sinks). The analysis also calls for much more sensitivity analysis. There is a very long list of critical assumptions which requires more systematic review. Among them are:

- BaU GDP and population growth rates.
- Exogenous levels of energy efficiency improvement.
- Levels of non-renewable resources (proven and unproven).
- Supply elasticities of fossil fuels.
- Supply of non-fossil fuel generated electricity.
- Substitution and income elasticities, particularly with respect to energy.
- Price and market potential for backstop fuels.
- Import demand elasticities.
- Optimal transition paths.

Despite the limitations of the analysis in this paper, it shows that the cost of achieving the Kyoto Protocol emissions target will most likely only have a negligible impact on overall OECD economic growth rates, particularly if a coordinated approach to achieving the targets is implemented. The costs presented in the paper should be considered an upper bound, since the model neglects the other greenhouse gases, as well as the possibility of receiving credit for augmenting carbon sinks. A strong message also emerges from the final simulation, where it is clearly demonstrated that international coordination could provide a positive outcome for both the OECD countries as well as the non-Member countries. The EET and BCS regions may suffer a relative loss (though an absolute gain) compared to other scenarios, but modifications in permit allocations, or some other transfer scheme could generate a (relative) positive outcome for all Annex I regions.

Finally, it should be noted that the Kyoto Protocol is only the first step in what is likely to be a lengthy process to reduce greenhouse gas emissions. The most important determinant of future climate change is the concentration of greenhouse gases. Given the significant lifetime of CO_2 in the atmosphere, it will take decades of emission reductions before there is any noticeable reduction in CO_2 concentrations. However, the initiation of the Kyoto Protocol may spur research and investment in new technologies which will enable “clean” sustainable economic growth.

Abbreviations

AEEI	Autonomous energy efficiency improvement. The AEEI is a model parameter for expressing the exogenous annual growth in energy efficiency.
Annex I	Group of countries which consists of OECD Member countries, the countries of Central and Eastern Europe, the Baltic Republics, Belarus, the Russian Federation, and Ukraine. Annex I countries are signatories to the Framework Convention on Climate Change. (N.B. Korea Mexico, and Turkey, though OECD Member countries are not part of Annex I.) In the presentation of the model results, the Annex I group refers to the following regions (see Annex A): EEC, JPN, OOE, USA, EET and BCS.
BaU	Business-as-usual. Acronym used to describe reference (or baseline) scenario, in the absence of policies to reduce carbon emissions.
Billion	Equivalent to one-thousand million (or 10^9).
COP	Conference of the Parties. Name given to the periodic conferences of the parties to the FCCC. COP3 was held in Kyoto in December, 1997, and led to the so-called Kyoto Protocol.
FCCC	United Nations Framework Convention on Climate Change. (Web home page: http://www.unfccc.de.)
Exajoule	A measurement of energy equal to 10^{18} joules. One exajoule is equivalent to 23.88 million tons of oil equivalent (MTOE), or 174 million barrels of oil (mb).
GREEN	The OECD **G**ene**R**al **E**quilibrium **EN**vironmental Model for assessing the economic impacts of limiting carbon emissions.
IEA	International Energy Agency. (Web home page: http://www.iea.org.)
IPPC	Intergovernmental Panel on Climate Change. International panel of experts jointly established by the World Meteorological Organisation and the United Nations Environment Programme to assess climate change. (Web home page: http://www.ipcc.ch.)
Kwh	Kilo-watt hour is a measure of electricity consumption.
OECD	Organisation for Economic Co-operation and Development. (Web home page: http://www.oecd.org.) In the presentation of the results, the OECD region consists of five regions of the model (see Annex A): EEC, JPN, OOE, USA, and EET.

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Annex A: Model Dimensions

Regional Concordance

EEC European Union – 12
Belgium, Denmark, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, United Kingdom

JPN Japan

OOE Other OECD
Austria, Finland, Norway, Sweden, Australia, New Zealand, Canada, Turkey

USA United States of America

EET Central and Eastern Europe
Bulgaria, Czech Republic, Hungary, Poland, Romania, Slovakia, former Yugoslavia

BCS Baltic Republics and the Commonwealth of Independent States
Estonia, Latvia, Lithuania, Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kirgiztan, Moldava, Russia, Tajikistan, Turkmenistan, Uzbekistan

BRA Brazil

CHN China

IND India

DAE Dynamic Asian Economies
Hong Kong, South Korea, Philippines, Singapore, Taiwan, Thailand

EEX Energy Exporting Countries
OPEC – Algeria, Ecuador, Gabon, Indonesia, Iran, Iraq, Kuwait, Libya, Nigeria, Qatar, Saudi Arabia, United Arab Emirates, Venezuela. Non-OPEC oil exporters – Angola, Benin, Brunei, Cameroon, Columbia, Congo, Malaysia, Mexico, Oman, Peru, Trinidad and Tobago, Tunisia, Egypt. Coal – South Africa. Gas – Bolivia.

ROW Rest of the World
All other countries and territories

Sectoral Concordance

Agric Agriculture
ISIC – 11-13. SITC – 00, 034, 036, 041-045, 054, 057, 07, 2, 25, 266, 27-28.

Coal Coal
ISIC – 210. SITC – 322, 323.

Oil Crude oil
ISIC 220. SITC – 333.

Gas Natural gas
ISIC 220. SITC – 341.

RefOil Refined petroleum products
ISIC 353, 354. SITC – 334, 335.

Elec[1] Electricity, gas, and water
ISIC 4. SITC – 35.

EnerInt[2] Energy intensive industries
ISIC 341, 351, 352, 371, 372. SITC – 24, 64, 5, 67, 68.

OtherInd All other industries and services
ISIC 230, 290, rest of 3, 5-9. SITC – 1, 2, 4, 6-9, 64, 67, 68.

CBS Carbon-based backstops
There are three, one for each conventional fossil-fuel with the following three prefixes: Coal, Oil, Gas.

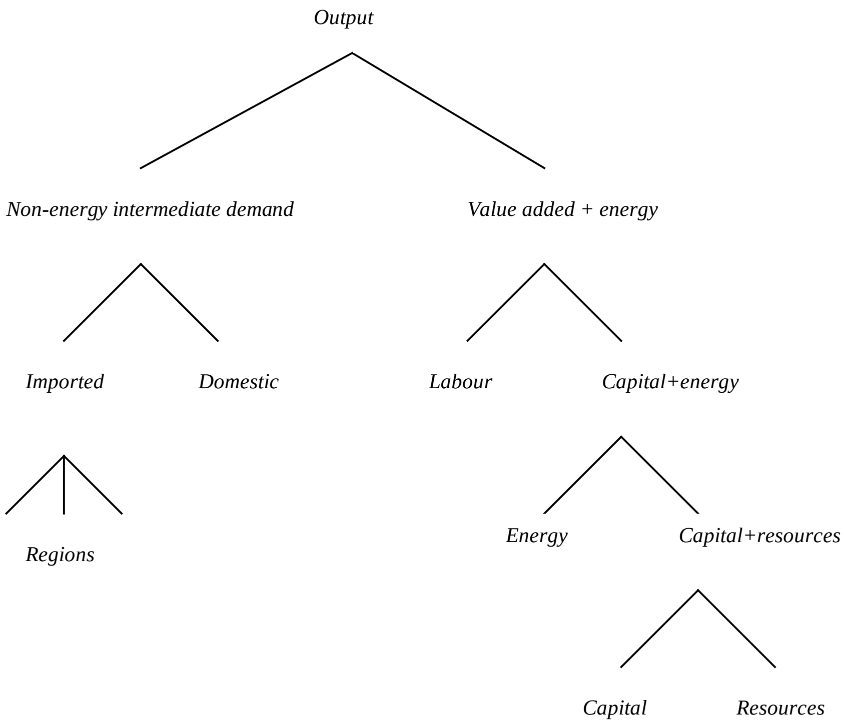
CFBS Carbon-free backstops
There are three, one for each conventional fossil-fuel with the following three prefixes: Coal, Oil, Gas.

ElecBS Electric backstop

Notes:
1. *Includes hydro-electricity, electricity produced by nuclear power and by the other carbon-free energy sources.*
2. *Includes paper and pulp products (ISIC 341), chemicals (ISIC 351 and 352), iron and steel (ISIC 371), and non-ferrous metals (ISIC 372).*

Annex B: Production Structure Figures

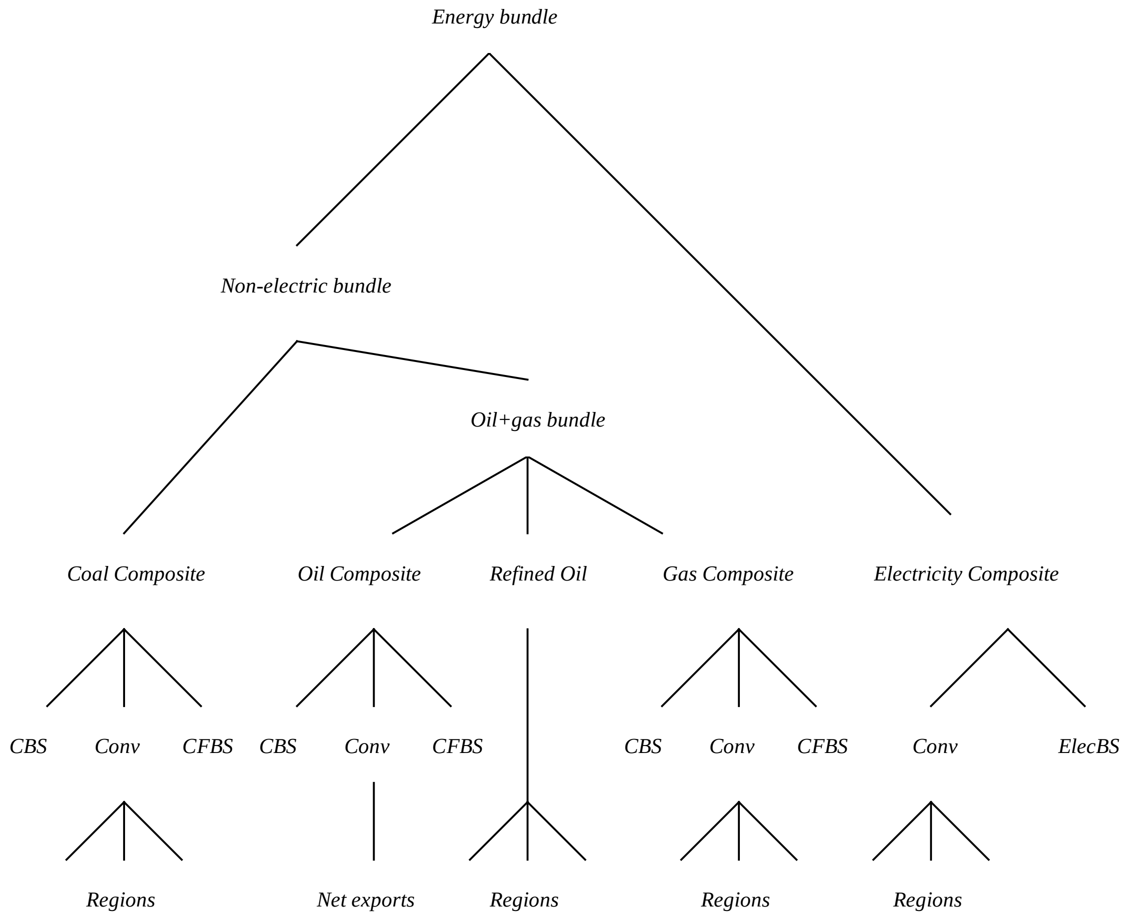
Figure B1: **Production Structure Nesting**



Notes:

1. *Resources are sector-specific resources associated with production, for example land in agriculture, and the non-renewable resources in coal, crude oil, and natural gas. Resources are included in the Capital compontent of the Capital+energy bundle.*
2. *The production substitution elasticities are specific to each region, sector, and capital vintage. Typically, the substitution elasticities for* ***old*** *capital are lower than for* ***new*** *capital. (See Burniaux et. al. for values and sources of substitution parameters).*
3. *Aggregate import demand is allocated across regions using a second-step Armington nest. (N.B. The number of regions in the model is 12.)*
4. *Productivity parameters are associated with the use of labor, capital, resources, and energy.*

Figure B2: **Energy Structure Nesting**



Notes:

1. *The nested energy structure is also applied to energy demand by households, government, and investment. The final demand activities have a single nest, i.e. one set of substitution elasticities, whereas in production, substitution elasticities are differentiated by capital vintage.*
2. *Prior to the introduction of the backstop fuels (in 2010), the demand for the composite energy good is equated to demand for the conventional component.*
3. *There are two backstop fuels which compete with the conventional fossil fuels — a carbon-based backstop (CBS), and a carbon-free backstop (CFBS). There is a single backstop substitute for conventional electricity designated by ElecBS.*
4. *Crude oil is the only commodity which is homogeneous at the world level. Net exports is determined as the difference between domestic production and domestic consumption. Production is limited by existing reserves, and is influenced by the contemporaneous oil price.*