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The Costs of Policies to Reduce Global Emissions of CO2: Initial Simulation Results with GREEN

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ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

The OECD Secretariat has developed a multi-region, multi-sector, dynamic general equilibrium model to quantify the economy-wide and global costs of policies to curb emissions of carbon dioxide (CO_2). The project is called the GeneRal Equilibrium ENvironmental model, hereafter referred to as GREEN. The purpose of this paper is to outline the main features of GREEN in a non-technical fashion and to present some preliminary results from three scenarios of alternative international agreements to cut CO_2 emissions. The paper also sets out a range of options for possible extensions to the model, with the explicit aim of improving its policy relevance.

* * *

Le Secrétariat de l'OCDE a mis au point un modèle d'équilibre général dynamique, multi-régional et multi-sectoriel, destiné à chiffrer les coûts macro-économiques et globaux des politiques visant à réduire les émissions de dioxyde de carbone (CO_2). Il s'agit du modèle environnemental d'équilibre général (GeneRal Equilibrium ENvironmental model), ci-après désigné comme le modèle GREEN. Cette note a pour objet de donner une brève description non-technique des principaux aspects du modèle GREEN et de présenter certains résultats préliminaires relatifs à trois scénarios possibles de réduction internationale des émissions de CO_2. Le document identifie également un certain nombre d'extensions du modèle envisagées afin d'en améliorer la portée en matière de politique économique.

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THE COSTS OF POLICIES TO REDUCE GLOBAL EMISSIONS OF CO_2: INITIAL SIMULATION RESULTS WITH GREEN

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The Costs of Policies to Reduce Global Emissions of CO_2: Initial Simulation Results with GREEN

I. Summary and Conclusions

In recent years there has been growing concern that human activities may be affecting the global climate through emissions of "greenhouse gases" (GHGs). These emissions will lead to a rise in average global temperature of several degrees centigrade over the next century (see box for a brief review of the scientific debate). Such warming could have major impacts on economic activity and society. As a result, policy makers have begun to consider various ways of curbing emissions of GHGs and the likely costs and benefits of such actions.

There is a rapidly growing literature quantifying the economic costs of various policies to reduce GHG emissions (see Hoeller *et al.*, 1991 for a survey). Such quantification should be world-wide, be able to take account of significant shifts in the patterns of production, consumption and trade and, because of the long-term nature of global warming, it should be based on a dynamic model.

The OECD Secretariat has developed a multi-region, multi-sector, dynamic applied general equilibrium (AGE) model to quantify the economy-wide and global costs of policies to curb emissions of carbon dioxide (CO_2). The project is called the GeneRal Equilibrium **EN**vironmental model, hereafter referred to as GREEN. The purpose of this paper is to outline the main features of GREEN in a non-technical fashion and to present some simulation results of alternative international agreements to cut emissions. It must be stressed at the outset that these results are preliminary.

A. Main features of GREEN

The key dimensions of GREEN are set out in Table 1. The present version of the model has a **medium-term** focus: it runs over a 35-year time horizon to 2020. A full description of the model's specification, its data base and its calibration and parametrisation is contained in Burniaux *et al.* (1991).

There are six detailed **regional** sub-models: three OECD regions -- North America, Europe and the Pacific -- and three non-OECD regions -- USSR, China and the energy-exporting LDCs. Because of the global nature of the GHG problem, specific attention was paid to modelling some key non-OECD regions. In that regard, it was deemed a high priority to model China and the USSR separately. It was also judged important to group together the major energy-exporting developing countries. Finally, the model contains a residual aggregate for the Rest of the World (RoW).

Since the main man-made source of CO_2 emissions arises from the burning of fossil fuels such as coal, oil and natural gas, the sectoral disaggregation of GREEN highlights the main interrelationships between energy production, energy consumption and the rest of the economy. The main sources of fossil-fuel energy are treated separately, with one source of non-fossil energy. Shifts in the structure of production in response to changes in

THE GREENHOUSE EFFECT (1)

The Earth's climate is determined by a complex array of factors. One key factor is the so-called "greenhouse effect" which is due to the presence of heat-trapping gases in the lower atmosphere. The expression stems from the fact that "greenhouse gases" (GHGs) act as a jacket that keeps warmth (infrared rays) from escaping the Earth's atmosphere, in much the same way as glass traps heat in a greenhouse. Without GHGs, the Earth's average temperature would be -18°C, instead of the current 15°C.

The main GHG is carbon dioxide (CO_2). Other important GHGs are chlorofluorocarbons (CFCs), methane (CH_4) and nitrous oxide (N_2O). Over the last hundred years, emissions of GHGs have grown dramatically due to the burning of fossil fuels, deforestation and the production of food. The atmospheric concentration of most GHGs is dependent not only on cumulative emissions, but also on the amount of natural absorption of these gases. This is particularly the case for Earth's carbon balance, as most carbon on earth is stocked in natural sinks, and not in the atmosphere. These sinks consist mainly of carbon stocked in plants on land (such as forests), in unused fossil fuels (mainly coal) and in the oceans, which are the largest carbon sink.

Atmospheric concentrations of GHGs adjust slowly to changes in emissions. Continued emissions at present rates would lead to increased concentrations for centuries ahead. Two questions arise: will the Earth warm up significantly? If it does so, what are the likely effects?

There is a growing consensus among scientists that the answer to the first question is yes. The Intergovernmental Panel on Climate Change (IPCC) estimates that the average rate of increase of global mean temperature during the next century will be about 0.3°C per decade (with an uncertainty range of 0.2°C to 0.5°C), if no actions are taken to reduce GHG emissions. Even if GHG emissions are stabilised at present levels, the temperature is predicted to rise at about 0.2°C per decade for the first few decades. Note that this warming rate is about ten times the one observed after the last Ice Age. Temperature increased then at the rate of 0.02°C per decade over a 2 000 year period, with major consequences upon the Earth's surface. Since then, global surface temperatures have probably fluctuated by little more than 1°C.

This rate of warming is associated with an expected rise in sea level of about 6 cm per decade (with an uncertainty range of 3-10 cm per decade), about three to six times faster than over the last 100 years or so. Other effects (rain patterns, frequency of storm and droughts, effects on agricultural yields, trees and other plants) are much more uncertain.

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1. See OECD (1991, pp. 20-30) and IPCC (1990) for more detailed, non-technical reviews of the evidence.

Table 1. **Key dimensions of the GREEN model**

PRODUCER SECTORS

1) Agriculture
2) Coal mining
3) Crude oil
4) Natural gas
5) Refined oil
6) Electricity, gas and water distribution
7) Energy-intensive industries
8) Other industries and services

CONSUMER SECTORS

1) Food, beverages and tobacco
2) Fuel and power
3) Transport and communication
4) Other goods and services

REGIONS

1) North America
2) Europe (EC and EFTA)
3) Pacific area (Australia, Japan, New Zealand)
4) Energy-exporting developing countries (b)
5) China
6) USSR
7) Rest of the World (RoW)

PRIMARY FACTORS (a)

1) Labour [1]
2) Sector-specific "old" capital [8]
3) "New" capital [1]
4) Sector-specific fixed factors for each fuel [4]
5) Land in agriculture [1]

a. Figures in brackets represent the number of each primary factor in each regional sub-model.

b. This grouping includes the OPEC countries as well as other oil-exporting, gas-exporting and coal-exporting countries. For a full listing of the countries, see Table 4 in Burniaux *et al.* (1991).

relative energy prices are captured by treating agriculture as a separate sector and by grouping the rest of the economy into two broad aggregates. energy-intensive industries and other industries and services. Changes in relative prices also affect the structure of consumer demand, with consumer goods grouped into four broad aggregates.

Over time, saving adds to the economy's capital stock. Capital, in turn, is assumed to be imperfectly mobile between sectors. It should be noted, however, that in GREEN there is no separate investment function nor are expectations about the future assumed to affect present saving decisions.

Particular attention is paid to the **depletion** of oil and natural gas reserves -- coal is assumed to be in infinite supply over the model's time horizon. The resource base is assumed to be in part price-sensitive: the level of oil and natural gas resources is a positive function of the world oil price, which is treated as exogenous.

All regions are linked by trade flows so that the model is able to quantify the effects of policies to curb CO_2 emissions in one or more regions on trade flows and the terms of trade of all regions. Imports from different regions are treated as imperfect substitutes, with the exception of crude oil which is assumed to be a homogeneous good. This treatment of imports implies that each region faces downward-sloping demand curves for its exports. Trade in emission rights between regions is also considered.

In assessing the preliminary results, it is important to bear in mind several limitations of the version of GREEN used to produce the results in this paper:

-- The potential benefits of curbing CO_2 emissions are not taken into account (1).

-- Other greenhouse gases -- CFCs, methane and nitrous oxide -- have not been modelled.

-- The Rest of the World (which includes most of Africa, Latin America, Asia and Eastern Europe) is not modelled with a detailed general equilibrium structure. There is no mechanism in the model as yet whereby a carbon tax can be levied in RoW to restrain the growth of its emissions.

-- The time horizon only runs to 2020 and no account is taken of the potential of back-stop technologies in curbing emissions. The horizon is also too short for a proper analysis of the links between emissions, atmospheric concentration and climate change.

For these reasons, it must be stressed that the simulation results reported in the paper are preliminary. The final section of the paper sets out a range of options for possible extensions to the model, with the explicit aim of improving its policy relevance. The OECD Secretariat is currently working to incorporate some of these extensions into a new version of GREEN.

In the absence of any actions to curb global CO_2 emissions, they could continue to grow at an annual rate of around 2 per cent a year over the period 1990-2020. A comparison of this **baseline** (unconstrained emissions) scenario with those from four other models indicates that the GREEN emissions path is not an outlier. The only major exception concerns China where GREEN has a higher growth rate of emissions than the other models. (Note, however, that the GREEN growth rate is closer to the trend observed over the past two decades.)

B. Alternative international agreements to curb CO_2 emissions

This paper presents the results of three scenarios of alternative international agreements. In the first scenario of a so-called "Toronto-type agreement", the industrialised countries -- the OECD countries and the USSR -- cut their emissions by 20 per cent below their 1990 levels by the year 2010. and stabilise them thereafter. A less stringent constraint is applied in China and the energy-exporting LDCs. The second scenario extends this global agreement to include a provision for **trade in emission rights**. In the third scenario, only the industrialised countries curb emissions. The chosen policy instrument to achieve the emission reduction targets in all three scenarios is a "carbon tax" -- a set of taxes levied on fossil-fuel use in proportion to the carbon content of the fuels.

Under the first scenario, the level of the carbon tax in the year 2020 averages $215 per ton of carbon (in 1985 prices and exchange rates) over all six regions. The equivalent OECD average tax is over $300; this corresponds to a tax of $36 per barrel of oil. The tax varies widely across regions, from a low of over $60 per ton of carbon in China in 2020 to a high of over $950 in the Pacific region. The wide dispersion across regions reflects differences in economic growth, the relative structure of fossil-fuel prices and the mix of fossil fuels in energy demand. These carbon taxes have a major impact on relative prices and government revenues. Consequently, they also affect trade flows, the terms of trade and the structure of production.

The costs, averaged over all six regions, of meeting these emission reduction targets, in terms of lower household real income (a measure of economic welfare) and real GDP, are estimated at 2 1/4 and 1 3/4 per cent, respectively, in the year 2020. The welfare costs are less than 1 per cent for North America and Europe, but are much larger -- of the order of 7 1/2 per cent -- for the energy-exporting LDCs and almost 2 1/2 per cent for the Pacific and China.

The regional spread of carbon taxes suggests that any international agreement which sets **uniform** targets should also include a provision allowing participating countries to trade emission rights. In the second scenario, all countries are assumed to have an initial endowment of emission rights. As a result of trading these rights, household real income, averaged across the six regions, would fall by only 1 per cent. The main beneficiaries from this trading would be the non-OECD regions, especially China and the energy-exporting LDCs, with lesser gains for the USSR and the Pacific. Allowing for trade in emission rights enables the world to cut the demand for coal more drastically, coal being the "dirtiest" fossil fuel in terms of carbon content. In consequence, China would be required to cut its CO_2 emissions more drastically than under the first scenario. In return for this, it would sell emission rights to OECD regions, mainly the Pacific, and derive substantial revenues -- over $60 billion in 2020 (in 1985$) -- from such trade. As a result, China would experience a welfare gain of 2.4 per cent in 2020 compared with a loss of 2 1/2 per cent in the no-trade case. The OECD regions consume more oil than they would have in the no-trade case, to the benefit of the energy-exporting LDCs.

If the industrial countries were to take action to curb emissions on their own, the costs to their economies would be virtually unchanged from what it would have been under a global agreement. But global CO_2 emissions would continue to grow at around 1 1/2 per cent a year and the non-participating regions, notably the energy-exporting LDCs, would suffer losses due to the carbon taxes in the industrialised countries.

If the industrialised countries were to attempt to achieve the same reduction in global CO_2 emissions as under the first scenario, the required carbon taxes would be enormous -- the OECD average tax in 2020 would be around $2 200 per ton of carbon. Taxes of this order of magnitude would lead to very large welfare losses: household real income in the OECD area in 2020 would be over 7 per cent below baseline and the energy-exporting LDCs would lose almost 10 per cent.

This suggests that any international agreement will have to include many non-OECD countries, especially large CO_2 emitters like China, if it is to be successful in curbing global emissions. But since many of these countries could expect to suffer non-negligible losses from participating in any such agreement, there would need to be incentives to encourage them to adhere to it.

A lower tax is needed to meet a given emissions constraint in the major coal-producing regions, reflecting the fact that coal is a relatively cheap fossil fuel, whose domestic price is heavily subsidised in some regions. These regions may be able to achieve a major part of the cut-back in global CO_2 emissions at a lower cost than the OECD regions; allowing for trade in emission rights could help secure their willing participation in such an agreement. The counterpart is that the coal industry -- which is very small in terms of its share of total output in all regions -- would be virtually wiped out.

C. Robustness of GREEN results

The results in the first three scenarios depend upon the exogenous values of the key parameters used to calibrate the model to its benchmark data. A limited amount of sensitivity analysis has focused on the three parameters: i) the price elasticities of import and export demand; ii) the inter-energy elasticity of substitution; and iii) autonomous energy efficiency improvement (AEEI). This shows that lowering the values of the export and import elasticities appears to make little difference to the broad magnitude of the costs in terms of lower real income across regions.

However, this reassuring conclusion does not hold with respect to the two energy-related parameters. If the inter-energy elasticity of substitution is raised from 1.2 -- its value in the GREEN baseline -- to 2, which is towards the high end of the range of econometric estimates, the estimated carbon taxes decline sharply in almost all regions. The average tax in 2020 declines to

$109 per ton of carbon and the welfare costs of meeting the target reduction in CO_2 emissions are halved. Thus, if substitution possibilities among different kinds of energy inputs are large over several decades, relatively small carbon taxes will be needed to ensure compliance with emission reduction targets.

AEEI is also a crucial parameter. The GREEN baseline assumes a common value for AEEI of 1 per cent in **all** periods and in **all** regions. A simulation was run in which its value was halved to 0.5 per cent in all regions. With a lower AEEI, CO_2 emissions grow faster than in the baseline case. Since emissions grow faster, higher carbon taxes are required to meet the target reduction, thereby leading to larger welfare and GDP losses.

II. An Overview of GREEN (2)

In GREEN, saving decisions affect future economic outcomes through the accumulation of productive capital. Investment decisions are not modelled and investment is computed residually. In each region, the model is calibrated on exogenous growth rates of GDP and neutral technical progress in energy use. The current version is simulated over the period 1985-2020, using time intervals of five years. Given the recursive structure of the model, the evolution over time of the economy can be described as a sequence of single-period temporary equilibria. The main characteristics of these equilibria are outlined next.

A. Single-period equilibrium

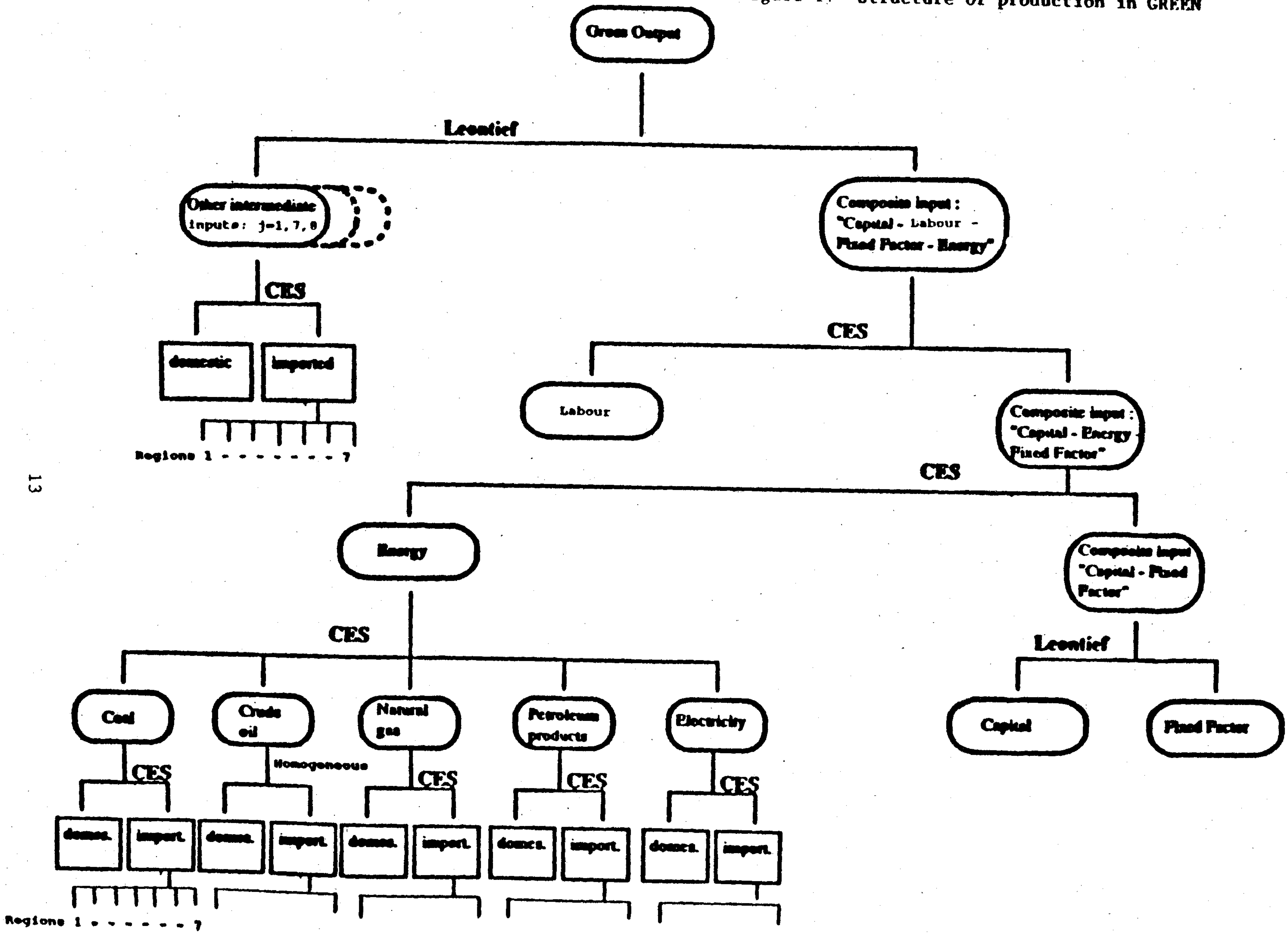
1. Production

There are eight producing sectors in GREEN, chosen to highlight the relationships between resource depletion, energy production and use, and CO_2 emissions. The main focus is on the energy sector. Three sources of fossil-fuel energy -- oil, natural gas and coal -- and one source of non-fossil (so-called "carbon-free") energy -- nuclear, solar and hydro power -- are distinguished. The production side of each regional model describes the supply of fossil fuels and the use of fossil and non-fossil energy inputs in the productive process. Allowance is also made for shifts in the composition of production by treating agriculture as a separate sector (3), and by distinguishing between two other broad sectors, energy-intensive industries and other industries and services.

All sectors are assumed to operate under constant returns to scale and share a common production structure (Figure 1). The quantities of all inputs are chosen optimally by producers in order to minimise costs given the level of sectoral demand and relative after-tax prices. Simplifying assumptions on the available technology make it possible to separate the decisions of producers into several stages, as indicated in Figure 1. The energy bundle is allocated among the alternative energy sources in the model, assuming a constant elasticity of substitution among them. This inter-energy substitution is a crucial factor in determining the level of CO_2 emissions.

Once the optimal combination of inputs is determined, sectoral output prices are calculated for each period assuming competitive supply (zero-profit)

Figure 1. Structure of production in GREEN



conditions in all markets except crude oil in the energy-exporting LDCs. The real world price of crude oil is exogenous. Since each sector supplies inputs to other sectors, output prices -- which are the cost of inputs for other sectors -- and the optimal combination of inputs are determined simultaneously in all sectors, conditional on the exogenous oil price.

2. Consumption

Consumer demand is split between four broad consumption aggregates (food and beverages, fuel and power, transport and communication, other goods and services) and saving (Figure 2). The consumption/saving decision is completely static: saving is treated as a "good" and its amount is determined simultaneously with the demands for the other four goods (4). Assumptions on preferences make it possible to separate consumer decisions into three stages, as indicated in Figure 2.

3. Carbon tax

The carbon tax is expressed as a **fixed** absolute amount of US$ per ton of carbon (5). In each region, it is computed as the equilibrium shadow price that would be paid for an additional ton of CO_2 emissions when a given constraint on total emissions is imposed. The tax is fuel-specific i.e. it varies in proportion with the CO_2-emission coefficients of oil, coal and natural gas. It is applied at the level of consumers of **primary** fuels, thereby avoiding distortions between domestic and imported fuels; it is also applied prior to any indirect taxation included in the model.

4. Government

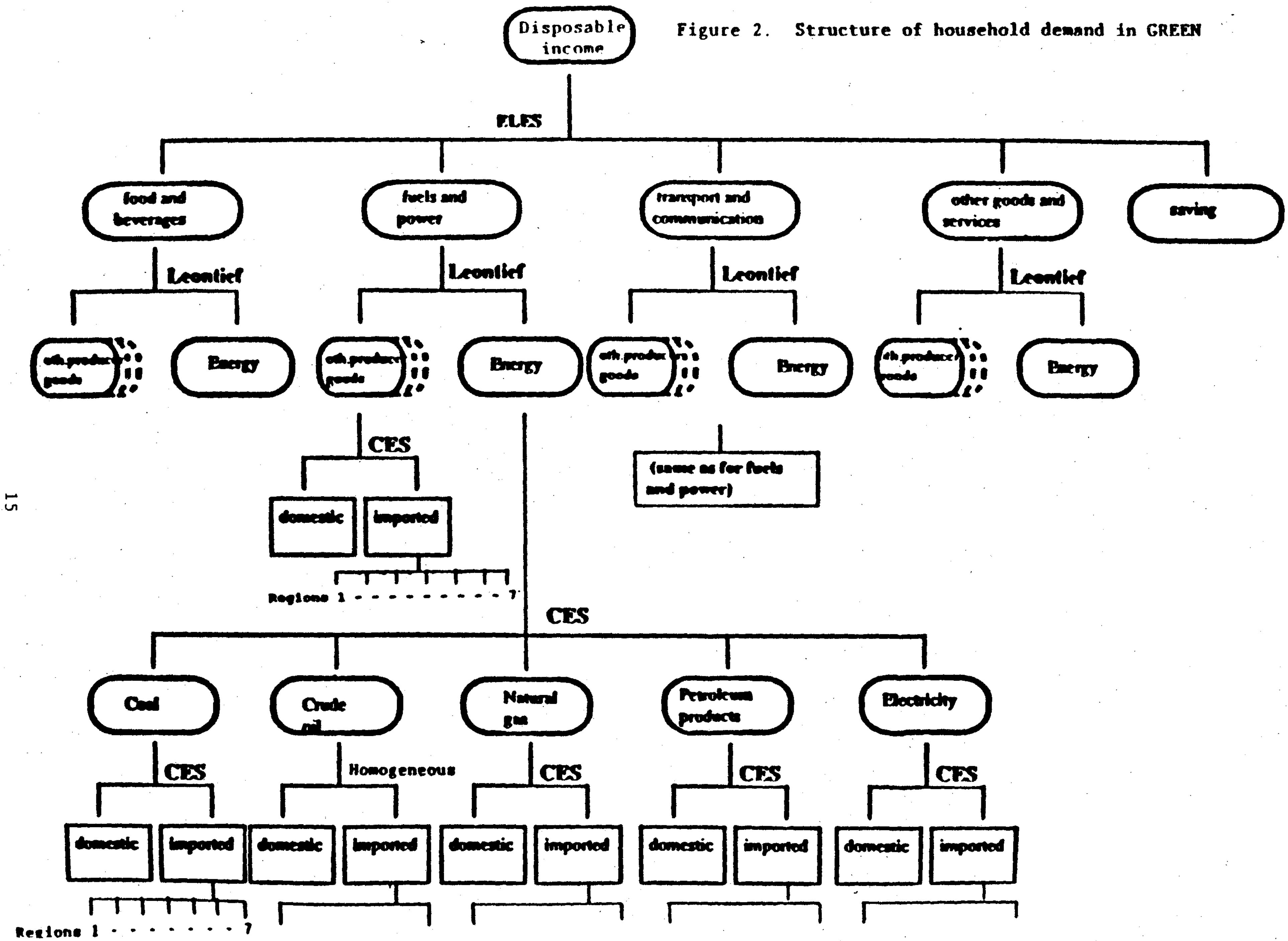
The government collects carbon taxes, income taxes and indirect taxes on intermediate inputs, outputs and consumer expenditures. Tax revenues depend on the level of economic activity. In addition, income-tax rates are adjusted to compensate for variations in the budget caused by changes in carbon tax revenues. Government expenditures are allocated among transfer and non-transfer expenditures. Both types of expenditures are exogenous in real terms, growing at the same rate as GDP.

5. Foreign trade

A set of bilateral trade matrices describes how price and quantity changes in each region affect world markets. Imports originating in different regions are treated as imperfect substitutes. In each region, total import demand for each good is allocated across trading partners according to the relationship between their export prices. This specification of imports -- commonly referred to as the Armington specification -- implies that each region faces downward-sloping demand curves for its exports.

The Armington specification is implemented for all goods except crude oil, which is assumed to be a homogeneous commodity (6). The energy-exporting LDCs are assumed to fix the price in the world oil market and the other regions behave as price-takers. Flows of oil between regions are the outcomes of the balance between domestic demand and supply of oil at given world prices, with the energy-exporting LDCs acting as a residual supplier.

Figure 2. Structure of household demand in GREEN



Each region runs a current-account surplus (deficit). The net outflow (inflow) of capital is subtracted from (or added to) the domestic flow of saving. To satisfy the world current-account constraint, the counterpart of this net flow is reallocated exogenously among the other regions. No account is taken of international income flows associated with changes in stocks of net foreign assets.

6. Trade in emission rights

Any international agreement to curb CO_2 emissions could include a provision allowing countries to trade emission rights. In the current version of GREEN, countries are endowed with an initial allocation of emission rights, set arbitrarily equal to the upper bounds on emissions imposed in the no-trade case. A constraint on CO_2 emissions is imposed at the world level, a world price of emissions is determined as the equilibrium carbon tax associated with this constraint, and regions can trade emission rights freely at this price. Regions with a lower carbon tax in the no-trade case will want to sell permits, while those in the opposite situation will want to buy them. Trade in emission rights, therefore, gives rise to flows of income between regions which are taken into account in the current account constraint. It is assumed that these income flows accrue to the government.

7. Closure

In each period, gross investment equals net saving (the sum of saving by households, the net budget position of the government and foreign capital inflows). The government budget as a share of GDP is held constant at its benchmark-year value, while the current account is fixed in nominal terms (7). Changes in the government budget induced by carbon taxation are assumed to be automatically compensated by changes in marginal income tax rates-- the carbon tax is revenue-neutral. Since government and foreign trade imbalances are exogenous, this particular closure implies that investment is driven by saving. Alternative closure rules would almost certainly give different welfare outcomes.

B. Dynamics

The intertemporal dimension of GREEN is recursive. Agents base their decisions on static expectations about prices and quantities. There are two stocks: fossil-fuel resources and capital. A resource depletion sub-model is specified for oil and natural gas. Production depends upon the initial levels of proven and unproven (so-called "yet-to-find") reserves, the rate of reserve discovery and the rate of extraction. The sum of proven and unproven reserves is predetermined in each period. The rate of reserve discovery is the rate at which unproven reserves are converted into proven reserves. The rate of extraction is the rate at which proven reserves are converted into output. Whether output increases or decreases over time depends on whether extracted resources are balanced by newly discovered resources. The levels of unproven reserves of oil and gas are assumed to be sensitive to the prices of oil and gas.

In the aggregate, the current capital stock is equal to the depreciated stock inherited from the previous period plus gross investment. At the sectoral level, industries are allowed to disinvest faster than their (sector-specific) depreciation rates, when their demand for capital is less than their depreciated stock. The extent of disinvestment (sale of second-hand capital goods to other sectors) is determined by the ratio of the sector-specific rental of old capital to the economy-wide rental of new capital. In each period, the capital available to expanding industries is equal to the sum of disinvested capital in contracting industries plus total saving generated by the economy, consistent with the closure rule of the model.

In the baseline scenario, model dynamics are calibrated in each region on exogenous growth rates of GDP by imposing the assumption of a **balanced growth** path. This implies that the capital-labour ratio (in efficiency units) is held constant over time (8). When alternative scenarios are simulated, the growth of capital is endogenously determined by the saving/investment relation.

C. The benchmark data sets

The "benchmark" year in GREEN is 1985, the year for which the latest input-output (I-O) tables are available for most OECD countries. Since I-O tables were not available for most non-OECD countries, a "minimum information" procedure was developed to estimate a consistent data set for these countries. This involved combining data from UN and IEA sources with coefficients from another country's I-O table -- for full details, Burniaux *et al.* (1991).

I-O tables were available for China and the USSR. The Chinese data set is based on a 1981 I-O table prepared for the World Bank (9); an incomplete official I-O table for 1988 was used to construct the Soviet data set (10). There is an important **caveat** about these two I-O tables. They are based on **domestic** price structures which are very different from world prices. These price distortions are very large in the energy sector. As will be noted in the next section, they play an important role in accounting for some of the differences in model outcomes across regions.

Table 2 presents benchmark data on some key indicators which will prove useful in understanding the simulation results in the next section. The first indicator expresses CO_2 emissions relative to household real income (in 1985 U.S.$). China and the USSR are the most emission-inefficient regions on this indicator, while the Pacific is the most efficient region.

The second indicator measures fossil-fuel use. In China and RoW (mainly India and Eastern Europe), the vast bulk of CO_2 emissions arises from coal burning. Natural gas is a significant source of CO_2 emissions in the USSR, while oil is the main source in Europe, the Pacific and the energy-exporting LDCs. The third indicator measures relative prices of fossil fuels by computing unit values per terajoule from the available I-O tables and comparing them with the average unit value in North America. Averaged over the six regions, coal and gas prices per terajoule are significantly lower than oil prices. Fossil fuel prices are particularly low in both China and the USSR: 46 and 75 per cent below the world average, respectively. All fossil fuel prices are very low in the USSR compared with world prices, whereas in China only coal has a very low price. Relative prices of fossil fuels are high in Europe and especially in the Pacific, where they are 60 per cent higher than the world average.

Table 2. **Some key indicators in the benchmark data sets by country/region, 1985**

	North America	Europe	Pacific	Energy-exporting LDCs	China	USSR	ROW	Total
1. **Ratio of CO_2 emissions to household income** (ton C./10^6 85$)	455	502	274	481	1 590	1 252		542
2. **Share in total CO_2 emissions (%)**:								
Coal	34	28	34	20	87	38	70	42
Oil	47	59	57	67	11	33	22	42
Gas	19	13	9	14	1	29	8	16
3. **Relative fossil fuel prices** (1) (**average price in North America** = 100):								
Coal	34.7	62.5	102.7	31.9	21.3	25.5	..	51.6
Oil	147.5	175.0	170.7	107.1	159.3	24.7	..	117.7
Gas	95.0	130.1	132.8	117.2	109.6	17.4	..	80.1
Average	100.0	131.8	144.3	98.7	48.7	22.3	..	90.6
4. **Net import penetration ratio in** crude oil (2)	22.1	57.5	94.1	-267.9	-30.4	-35.4	..	..
5. **Net import penetration ratio in** natural gas (2)	-0.5	20.4	84.2	-94.5	1.3	-33.7	..	..
6. **Share of fossil fuels in total exports**	4.4	4.5	1.7	65.5	17.7	20.1	..	..
7. **Share of fossil fuels in total imports**	11.8	31.8	33.7	2.7	0.8	0.7	..	..

1. **Defined as the unit value of one terajoule relative to the average unit value of fossil fuels in North America. Fossil fuel demands are converted into a common energy unit** (1 terajoule = 10^{12} joules): this facilitates the conversion into tons of carbon emitted with the help of widely-used conversion factors: 1 terajoule of coal = 23.3 tons of carbon, 1 terajoule of oil = 19.2 tons of carbon and 1 terajoule of gas = 13.7 tons of carbon.

2. Defined as the ratio (M - E)/(X + M - E), where M = imports, E = exports and X = domestic output.

The final four indicators provide data on net import penetration ratios for oil and natural gas and the shares of fossil-fuel trade flows in total exports and imports. The OECD regions were all energy-importing economies in 1985: the Pacific and, to a lesser extent, Europe were especially dependent on imported oil and gas. Fossil fuel exports accounted for two-thirds of total exports of the energy-exporting LDCs and around one-fifth of total exports in China and the USSR.

D. Selection of exogenous parameters

Values of certain exogenous parameters must be such that the benchmark data set is an equilibrium solution to the model (see box for a listing of these parameters). A literature search was undertaken to find "plausible" values for these parameters. Particular attention was paid to estimates of inter-energy elasticities of substitution, AEEI, and the foreign trade elasticities. The results of this literature search are described in detail in Burniaux *et al.* (1991).

Identical values for substitution elasticities in production and foreign trade are used for all regions. This is not very realistic, but the literature review provided little useful guidance on country-specific values. In line with the typical finding in the econometric literature, income elasticities of consumer demand are set at higher values in the non-OECD regions than in the OECD regions.

The production paths for oil and natural gas in most regions were calibrated to replicate projections for the year 2005 coming from the IEA's model of world energy markets. The sole exceptions were the USSR and China: the IEA model does not have gas projections for these countries. Production of oil and gas in both countries was calibrated on the projections for the year 2020 from the Edmonds and Reilly model (11).

III. Baseline Path of CO_2 Emissions

Deriving a plausible **baseline** path, i.e. the path that CO_2 emissions would be expected to take in the absence of policy actions to curb their growth, is a key element in estimating the costs of any such interventions. Once the baseline has been established, it is possible to answer the following kind of "what if" question: "What would be the impacts on both OECD and non-OECD countries if they, individually or jointly, took actions to curb the growth of CO_2 emissions?"

A. The baseline scenario

The assumptions about both GDP growth rates and the world oil price underlying the baseline scenario are taken from the Stanford-based Energy Modelling Forum Study No. 12 (EMF12) entitled "Global Climate Change: Energy Sector Impacts of Greenhouse Gas Emission Control Strategies" (12) (Table 3). The GDP growth rates in these projections are assumed to decline slowly after the year 2000 in all regions due to structural change and slower population growth.

KEY EXOGENOUS PARAMETERS IN GREEN

In GREEN, the following parameters are exogenous:

-- Elasticities of substitution between capital and energy;
-- Elasticities of substitution between labour and the capital-energy bundle;
-- Elasticities of inter-energy substitution, e.g. between coal, oil, natural gas and electricity;
-- Estimates of autonomous energy efficiency improvement (AEEI) by region;
-- Estimates of autonomous labour- and capital-augmenting technical progress;
-- Supply elasticities of "old" capital in declining sectors relative to their return differentials between declining and expanding sectors;
-- Supply elasticities of agricultural land, coal, natural gas and the carbon-free resource;
-- Price elasticities for unproven reserves of oil and natural gas;
-- Price elasticities for imports for intermediate use and for final demand;
-- Price elasticities for export demand;
-- Income elasticities of consumer demand;
-- Marginal tax rates on household items;
-- Elasticities of substitution between types of government expenditure.

Since GREEN is a consistent world trade model, the foreign trade elasticities are one crucial set of parameters. Given that the basic time interval is five years, **medium-term** values of the price elasticities of export and import demand by sector were chosen to calibrate the model rather than long-run values:

	Price elasticities of export demand	Substitution elasticities between domestic and imported goods
Fossil fuels (excluding crude oil)	-5	-4
Agricultural goods	-4	-3
Other manufactures and services	-3	-2

The elasticity of inter-energy substitution is a second key crucial parameter. The econometric evidence on this is not very reliable -- see Burniaux *et al.* (1991) for a survey of the literature. Some estimates suggested that a plausible range might be from 0.9 to 1.5, although others pointed to estimates of 2 or more. For the GREEN baseline, the value of 1.2 was used. The supply elasticity of the carbon-free resource was set at 0.2, reflecting a fairly conservative view of the expansion of nuclear power.

AEEI is another crucial parameter since the higher its value, *ceteris paribus*, the lower is the growth of CO_2 emissions. It has proved extremely difficult to pin down plausible values of the AEEI parameter in econometric estimation. Indeed, a recent study of U.S. experience by Hogan and Jorgenson (1990) suggests that AEEI may even have been slightly negative over the period 1958-79. This view has been strongly contested by Williams (1990) who argues that not only is AEEI likely to be positive but there are sound reasons for expecting it to increase over time. Faced with this uncertainty, we have chosen to follow the conventional wisdom in energy forecasting that the energy/output ratio will decline by 1 per cent a year in all regions.

The results of some limited sensitivity analysis with these three sets of parameters are reported in Section V.

Table 3. **Assumptions for the exogenous variables in the GREEN baseline scenario**

a) GDP growth rate

Period	North America	Europe	Pacific	Energy-exporting LDCs	China	USSR	RoW	Total
1990-2000	2.5	2.1	3.6	3.7	4.5	2.5	3.8	2.9
2000-2020	2.0	1.6	2.6	3.3	4.0	2.0	3.3	2.4

b) World oil price

The world oil price fell from $27.6 per barrel in 1985 to $22 per barrel in 1990. Thereafter, it is assumed to increase by $6.50 per barrel in each decade until 2020.

Baseline world CO_2 emissions are projected to grow at an annual average rate of almost 2 per cent a year: the level of emissions increases from 5.2 billion tons in 1985 to almost 10 billion tons in 2020. The share of the OECD countries in global emissions declines from 52 per cent in 1985 to 40 per cent in 2020 (Figure 3), while China's share increases from 9 per cent in 1985 to 19 per cent in 2020. The shares of the USSR and RoW are very stable over the whole period (13).

Figure 4 shows the contributions of the three fossil fuels to total world emissions. Emissions from coal increase from 42 per cent of total emissions in 1985 to 53 per cent in 2020, partly in response to shifts in relative prices: real oil prices grow much faster than real coal or gas prices after the year 2000 (14). The major reason for the shift to coal is above-average growth in China, the main coal consumer with the lowest coal price.

Baseline outcomes for some key variables are given in Table 4. Given the twin assumptions that exporters face a downward-sloping demand curve on the world market and the current account balance is exogenous, a region can grow faster than world demand only if its real exchange rate and terms of trade fall over time (15). In China, above-average growth rates of GDP are associated with a depreciation of the real exchange rate of almost 1 per cent per year (16). In Europe and North America, on the other hand, the real exchange rate appreciates slowly as their growth rates are lower than in most of the other regions.

Both the average real fossil fuel price and the real price of electricity grow faster after the year 2000. In two regions -- the Pacific and the energy-exporting LDCs -- fossil fuels become cheaper relative to electricity for several reasons. First, in both regions the electricity sector relies more on oil as an input than in the other regions and, as noted above, the real oil price rises rapidly from 1990 on. Second, energy demand relies more heavily on limited supplies of "carbon-free" sources of electricity as real coal prices grow slightly faster. Finally, as the technical progress coefficients applied to labour and capital in production decline over time as a result of the calibration, the opportunity costs of using the "carbon-free" resource in the electricity sector increase (17).

Growth rates of total demands for fossil fuels are mainly determined by GDP growth rates, AEEI coefficients and movements in the price of fossil fuels relative to electricity. Since the relative price is rather stable in most regions, the main effect on fossil-fuel demands comes from the decline in GDP growth rates combined with a shift in the mix of fossil fuels towards coal, especially in China. CO_2 emission growth rates are very closely linked to the growth rates of total primary fossil-fuel demands. They tend to be slightly higher, reflecting the shift to coal which has a higher carbon content per terajoule than oil or natural gas.

B. Comparison with other models and past trends

To put the GREEN baseline into perspective, two comparisons have been made: i) with baseline projections from the Global 2100 model of Manne and Richels (MR), the Edmonds and Reilly Model (ER) and the IEA model,

Figure 3. Regional shares of global CO_2 emissions in the baseline scenario

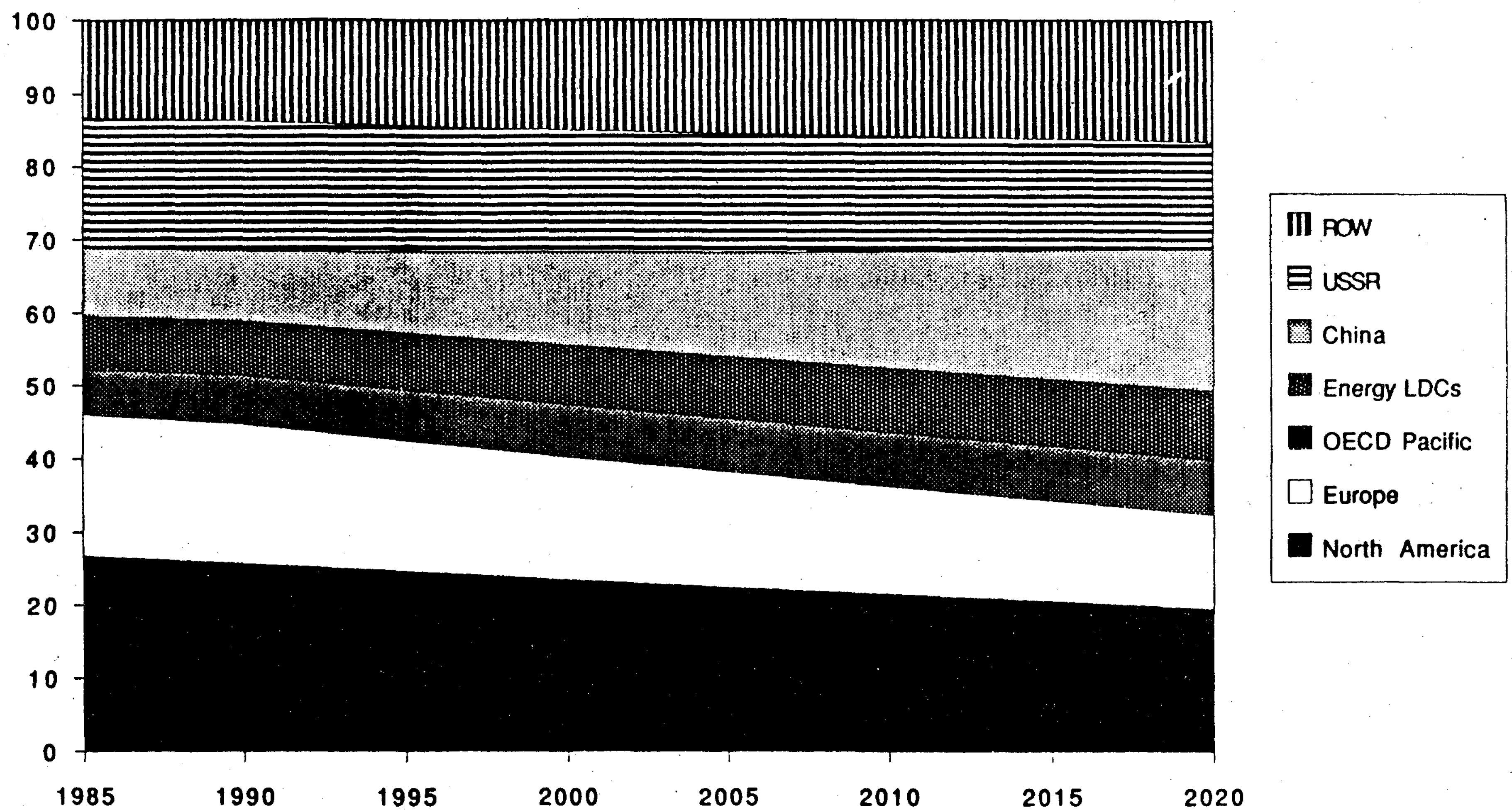


Figure 4. CO_2 emissions shares by fossil fuel source in the baseline scenario, 1985-2020

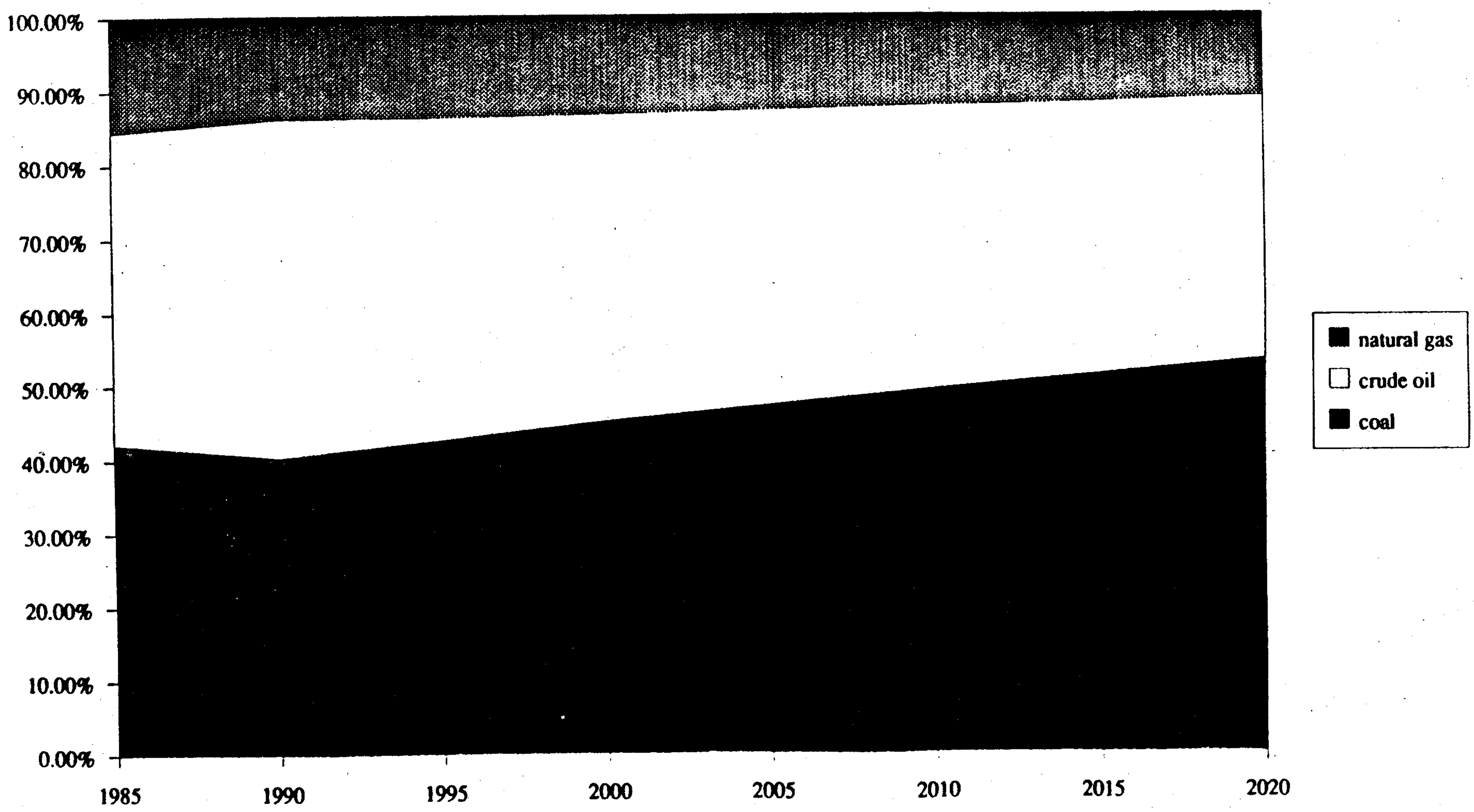


Table 4. Some key variables in the baseline scenario

Annual average per cent changes

	Real exchange rate (1)		Terms of trade (2)		Average real fossil fuel price (3)		Real electricity price (3)		Demands for total primary fossil fuels (4)	
	1985-2000	2000-2020	1985-2000	2000-2020	1985-2000	2000-2020	1985-2000	2000-2020	1985-2000	2000-2020
North America	0.0	0.1	-0.2	-0.3	0.0	1.2	-0.6	0.5	0.9	0.8
Europe	0.4	0.3	0.3	0.0	-0.3	1.0	-0.4	0.6	0.9	0.4
Pacific	-0.2	-0.3	-0.1	-0.4	0.1	1.5	0.7	2.5	2.8	1.9
Energy-exporting LDCs	0.2	0.2	0.2	1.1	-0.2	1.3	0.0	2.1	2.6	2.5
China	-0.9	-0.7	-1.0	-1.2	0.5	1.5	0.0	1.2	4.0	4.0
USSR	-0.2	-0.2	0.1	0.2	0.3	1.3	0.5	1.5	1.4	1.0

1. Defined as the weighted average factor price in a given country/region relative to the weighted average factor price for the world (excluding RoW).

2. Defined as the weighted average export price relative to the weighted average import price.

3. Deflated by the real exchange rate.

4. In terajoules.

standardising as far as possible the different regional breakdowns of each model (18); and ii) with historical trends since 1950 in CO_2 emissions. However, since the assumptions about growth rates of GDP and AEEI are not identical across the models, this comparison is illustrative rather than a standard evaluation of baselines (19).

The results of these comparisons are shown in Table 5. At the global level, all four models produce similar growth rates of emissions over the period 1985 to 2000, at around 2 per cent a year. Over the subsequent period to 2020, emission growth rates in GREEN and the IEA model (which refers to the period 2000-2005 only) are close, but both have slightly faster growth than the other models. In terms of **levels** of emissions in 2020, Figure 5 shows that GREEN is very close to the MR model, but has about 10 per cent more emissions than the ER model.

When the regional breakdown of the baseline projections is examined, the main difference between the models concerns China. GREEN projects an average growth rate of emissions in China of 4 per cent a year over the period 2000 to 2020 compared with 3.1, 2.6 and 2.2 per cent in the IEA, ER and MR models, respectively. But the historical data in Table 5 indicate that the GREEN projections for China are closer to recent trends.

IV. Curbing CO_2 Emissions: Three Alternative International Agreements

A. A Toronto-type agreement

Suppose that a global agreement was reached under which i) CO_2 emissions in the OECD regions **and** in the USSR would be restricted to 80 per cent of their 1990 levels by 2010, and stabilised thereafter; and ii) emissions in the energy-exporting LDCs and China would be restricted to be 50 per cent higher than their 1990 levels by 2010, and stabilised thereafter. What would such an agreement imply for carbon taxes and economic welfare?

1. Carbon tax and energy prices

The levels of carbon taxes required to meet these targets are given in Table 6. Since the baseline projects a continued growth in CO_2 emissions in all regions, the carbon tax rises steadily over the period in all regions. By 2020, the tax, averaged over all six regions, is $215 per ton of carbon (the equivalent average for the OECD area is $308) -- all taxes are expressed in 1985$. The level of the tax varies widely across regions, from a low of over $60 in China to a high of over $950 in the Pacific. There are several reasons for the high tax in the Pacific. In the baseline, CO_2 emissions in the Pacific grow faster than in the other OECD regions. The Pacific also has the highest relative energy prices, particularly for coal (see Table 2), and domestic demand for coal is almost wiped out as a result of the imposition of the carbon tax -- both factors serve to push the carbon tax into a region of sharply diminishing returns (20). Finally, the Pacific is the most CO_2-efficient region. It, therefore, requires a much larger carbon tax than the other OECD regions to satisfy a **uniform** cut in emissions.

North America and the USSR have similar carbon taxes in the 1990s despite the fact that domestic fossil fuel prices in the USSR are on average

Table 5. **Comparison of average growth rates of CO_2 emissions across models, 1950-2020**

Annual average percentage changes

	Historical data				Baseline projections		
	1950/75	1975/80	1980/85		1985/90	1990/2000	2000/2020
North America	2.3	1.4	-1.0	GREEN	1.1	1.0	0.9
				MR		1.6	1.2
				ER (1)	-----1.8-----		0.7
				IEA	1.5	1.5	0.7 (2)
Other OECD	2.7	1.8	-1.2	GREEN	2.3	1.1	1.0
				MR		1.6	1.0
				ER (1)	-----1.9-----		0.3
				IEA	1.7	1.3	1.0 (2)
USSR	5.9	2.5	1.9	GREEN	1.9	1.3	1.1
				MR		1.6	0.9
				ER (1)	-----1.3-----		0.1
				IEA	2.2	1.9	0.2 (2)
China	11.2	5.3	5.4	GREEN	2.6	4.7	4.0
				MR		2.5	2.2
				ER (1)	-----2.9-----		2.6
				IEA	4.5	3.3	3.1 (2)
RoW	4.7	5.4	2.4	GREEN	2.7	2.7	2.3
				MR		2.3	2.2
				ER (1)	-----2.8-----		3.5
				IEA	3.0	3.0	2.8 (2)
World	3.6	2.6	0.8	GREEN	2.0	1.9	1.8
				MR		1.9	1.5
				ER (1)	-----2.0-----		1.5
				IEA	2.4	2.2	1.7 (2)

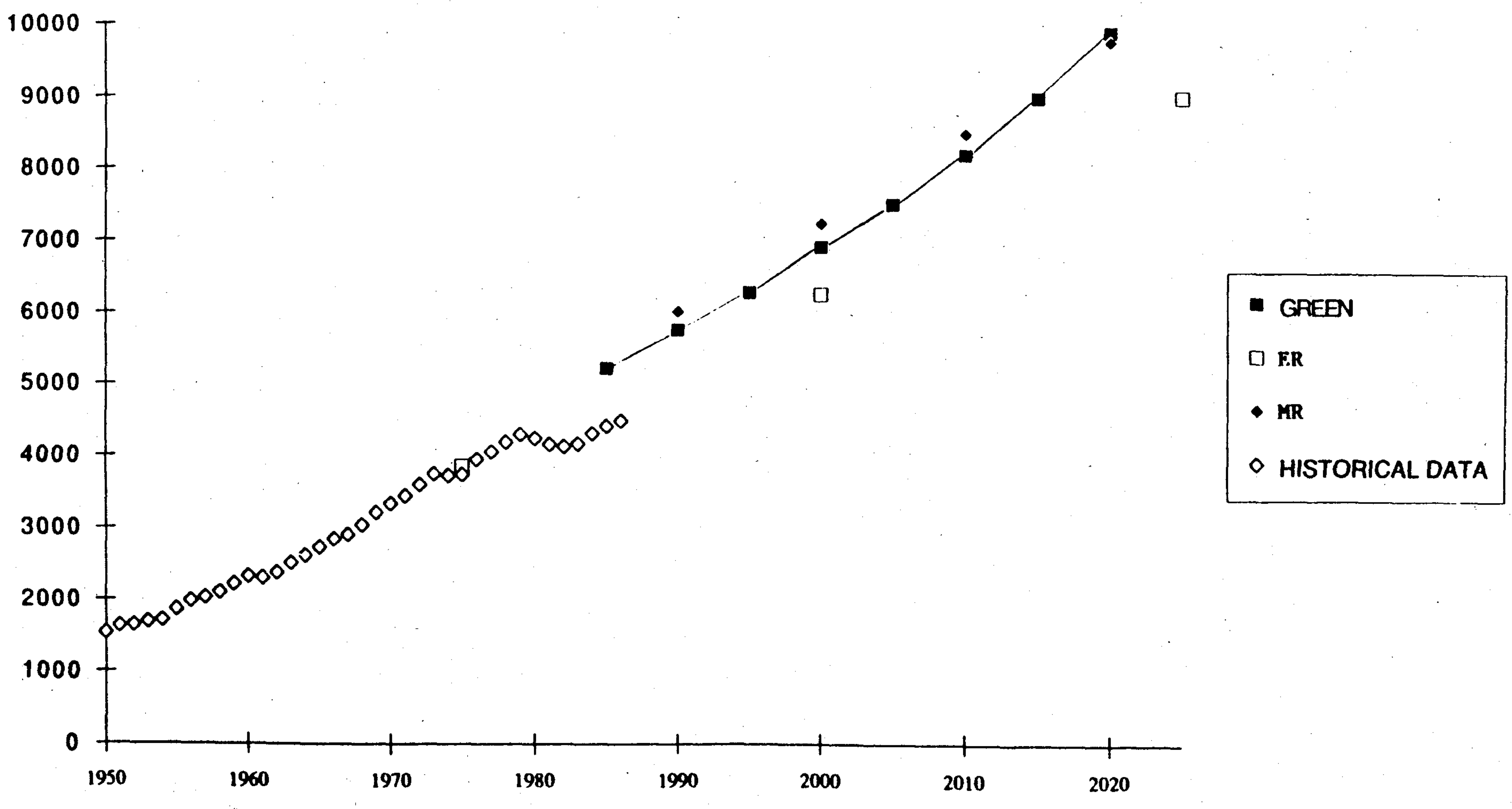
1. 1975-2000 and 2000-2025.

2. 2000-2005.

Sources: Historical data on emissions as well as the ER projections are from Edmonds and Barns (1990); MR projections were supplied directly to the OECD Secretariat by Alan Manne; the IEA projections are provisional. For details on the IEA model, see Kouvaritakis (1989).

Figure 5. World emissions of CO_2 in the baseline scenarios of three models, 1950-2020

Millions of tons of carbon



Note: Historical data are taken from *Edmunds and Burns* (1990). *This source* does not have a complete world coverage.

Table 6. **Carbon taxes and increases in real energy prices by country/region under a Toronto-type agreement**

i) Carbon taxes

1985 $/ton carbon

	North America	Europe	Pacific	Energy-Exporting LDCs	China	USSR	Total (1)
1995	3	7	41	7	5	5	9
2000	14	16	104	15	11	12	21
2010	139	168	549	24	23	69	123
2020	209	213	955	209	63	101	215

ii) Increases in real domestic energy prices (2) by source in 2020

Percentage increases compared with baseline

	North America	Europe	Pacific	Energy-Exporting LDCs	China	USSR
Coal	531	299	759	569	245	332
Crude oil	72	68	263	112	18	193
Natural gas	88	68	281	86	24	157
Refined oil	59	64	229	77	16	167
Electricity	41	36	83	49	49	75

1. Weighted average of the six regions where the weights are the share of each region in total CO_2 emissions.
2. Deflated by the real exchange rate.

only one-fifth of the North American level. This follows from the fact that domestic energy demand in the USSR relies much more on natural gas -- which has a lower carbon content than either coal or oil -- than the other regions (see Table 2). The carbon tax rises faster after the year 2000 in North America than in the USSR as the demand for coal in the former region dries up.

The lower part of Table 6 converts the carbon taxes into relative domestic energy price increases. Coal prices are three (China) to six times (North America, Pacific, energy-exporting LDCs) higher in the year 2020 compared with the baseline. The carbon tax has a much smaller effect on oil and gas prices than on coal in all regions.

The much larger increases in coal prices relative to oil and gas prices are important in explaining inter-energy substitutions. In regions where this price differential is greatest (China, North America and Europe), the resulting substitution towards oil and gas will tend to offset partly the substitution towards the "carbon-free" energy source, with the net result that domestic oil and gas demands are only reduced slightly or may even increase. In China, the electricity sector relies massively on coal. Therefore, the electricity price increases more than oil and gas prices, inducing a switch in demand towards oil and gas. In regions where the initial domestic price structure results in a lower price differential between coal, on the one hand, and oil and gas, on the other -- as is the case in the Pacific and the USSR -- the substitution towards the carbon-free energy leads to substantial cuts in domestic demand for oil and gas.

Finally, it must be emphasised that the levels of the carbon tax are likely to be very sensitive to changes in model specification. For instance, the version of GREEN used to produce these results contains no backstop technologies. Simulations with the Global 2100 model of Manne and Richels show that the time profile and levels of the carbon tax across regions are sensitive to the introduction of such technologies.

2. *Effects on real income, absorption and GDP*

Meeting these emission targets via a carbon tax gives rise to costs, in terms of lower welfare and GDP. But some countries could conceivably benefit from a carbon tax via terms-of-trade gains. Estimates of the real income and GDP effects under this scenario are reported in Table 7. Three indicators are reported: i) a measure of economic welfare, the change in household real income -- the so-called "Hicksian equivalent variation"; ii) the change in real domestic absorption (defined as the sum of household consumption, government consumption, investment and stock change); and iii) real GDP.

The typical pattern across regions is for welfare losses to increase over time in line with the carbon tax (21). By the year 2020, household real income, averaged across all regions, is 2.2 per cent lower compared with the baseline (22). The estimated costs are less than 1 per cent in North America, Europe and the USSR. The largest real income loss is recorded by the energy-exporting LDCs: by the year 2020 real income is 7.5 per cent lower. Table 7 also reports cumulated losses as shares of cumulated real income over the period 1995-2020: averaged over the six regions, real income is 1 per cent lower.

Table 7. **Effects of the carbon tax on real income and GDP in selected years**

Percentage changes relative to the baseline

	North America			Europe			Pacific			Energy-exporting LDCs		
	Household real income (1)	Real domestic absorption (2)	Real GDP	Household real income (1)	Real domestic absorption (2)	Real GDP	Household real income (1)	Real domestic absorption (2)	Real GDP	Household real income (1)	Real domestic absorption (2)	Real GDP
2000	-0.0	-0.1	-0.0	0.0	0.0	-0.0	0.1	-0.2	-0.3	-1.1	-0.9	-0.7
2010	-0.3	-0.4	-0.5	-0.5	-0.3	-0.5	-1.0	-1.5	-2.0	-4.4	-3.5	-2.2
2020	-0.8	-0.7	-0.8	-0.9	-0.4	-0.7	-2.4	-2.4	-3.7	-7.5	-5.2	-3.6
Cumulated effect over the period 1995-2020 (3)	-0.3	-0.3	-0.4	-0.4	-0.2	-0.4	-1.1	-1.4	-2.0	-4.4	-3.2	-2.1

	China			USSR			Total		
	Household real income (1)	Real domestic absorption (2)	Real GDP	Household real income (1)	Real domestic absorption (2)	Real GDP	Household real income (1)	Real domestic absorption (2)	Real GDP
2000	-0.3	-0.4	-0.3	0.4	-0.0	-0.1	-0.1	-0.2	-0.2
2010	-1.1	-1.0	-0.6	0.4	-0.8	-1.1	-1.0	-1.0	-1.0
2020	-2.3	-2.1	-1.5	-0.6	-1.6	-2.2	-2.2	-1.8	-1.8
Cumulated effect over the period 1995-2020 (3)	-1.3	-1.2	-0.8	0.1	-0.8	-1.1	-1.0	-0.9	-0.9

1. Hicksian equivalent variation, i.e. the increase in income a consumer would need before the imposition of a carbon tax to allow him to reach the welfare level he actually achieves after the change.

2. Defined as the sum of household consumption, government consumption, investment and stock changes, expressed in 1985 US$.

3. The sum of the annual gains and losses relative to the sum of annual real income, real absorption and GDP, respectively.

Real GDP falls compared with the baseline as the deadweight losses from the carbon tax lead to lower capital accumulation over time via the saving/investment relationship. Averaged across all regions, real GDP is almost 2 per cent lower in 2020; the largest losses are in the energy-exporting LDCs, the Pacific and the USSR. The large decline in the Pacific compared with the other OECD regions reflects not only the magnitude of the distortion induced by the carbon tax but also the fact that North America and Europe have lower ratios of saving relative to the capital stock in the benchmark year (1.3 and 2.0 per cent, respectively, compared with 3.7 per cent in the Pacific) (23).

3. *Terms of trade*

Levying a carbon tax will affect the terms of trade differently, depending on whether the region in question is an energy importer or an energy exporter, and this, in turn, will have an effect on welfare. Table 8 summarises the main mechanisms at work in these two types of region. The carbon tax cuts the demand for imported fossil fuels in energy-importing regions, thereby producing an energy trade surplus. Given the closure rule in GREEN, this has to be balanced by a corresponding trade deficit on non-energy goods and services. This is achieved by a rise in relative export prices (an improvement in the terms of trade). As a result, international markets for fossil fuels contract and energy-exporting regions suffer a terms-of-trade loss. The carbon tax also affects the competitiveness of exports of non-energy goods and services in both regions: their export price will increase in line with their energy content, thereby tending to improve the terms of trade.

Energy-importing regions are, therefore, likely to experience a terms-of-trade gain from a carbon tax whereas the effect is ambiguous in energy-exporting regions. The terms of trade could improve in those energy-exporting regions where the trade balance relies less on energy exports -- such as the USSR.

The simulated outcomes for the terms of trade under a Toronto-type agreement generally confirm these expectations:

(Annual average changes compared with baseline)

	1985-2010	2010-2020
North America	0.1	0.9
Europe	1.1	2.7
Pacific	2.6	7.2
Energy-exporting LDCs	-2.3	-6.5
China	-1.5	-3.9
USSR	1.6	4.8

The terms of trade improve in the OECD regions and in the USSR in response to the carbon tax, leading to gains in household real income which tend to offset the deadweight losses arising from the tax. Indeed, the terms-of-trade gains in the USSR outweigh the deadweight losses until after the year 2010. The USSR's terms of trade benefit from the relative price increase of its

Table 8. **Effects of a carbon tax on the real exchange rate and terms of trade in energy-importing and energy-exporting regions**

Effects of the carbon tax on:	Energy-importing regions	Energy-exporting regions
Energy trade:	1. Cuts in energy imports	2. Cuts in energy exports
	+	-
Non-energy trade:	3. Cuts in exports of non-energy goods and services	
	+	+
Total effect	+	?

non-energy exports; it is the only region which experiences a rising share of fossil-fuel exports in total exports **after** the imposition of a carbon tax -- the share rises by 26 per cent compared with baseline (24).

The energy-exporting LDCs experience a large terms-of-trade loss. China also experiences a terms-of-trade loss, mainly from shifts in the pattern of energy trade. On the export side, the fall in price and quantity of its coal exports leads to a decline in the relative export price of non-energy goods and services. There is also a sharp increase of crude oil imports as a result of inter-energy substitution away from coal towards oil; the existence of binding supply constraints for crude oil means that the additional demand for oil has to be met entirely by imports.

4. *Structure of production*

The carbon tax also gives rise to major shifts in the structure of production in all regions. These changes are dominated by the substitution of the "carbon-free" electricity source for fossil fuels. Table 9 shows that, in line with expectations, the coal industry would be hardest hit by the imposition of a carbon tax: on average across all six regions, its output is cut by almost two-thirds compared with baseline. At the same time, this is a very small sector: its share of total output in the benchmark year never exceeds 1 per cent in any country/region.

Oil production also declines on average by almost 15 per cent, but virtually all of this decline is concentrated in the energy-exporting LDCs. This latter outcome follows from the assumption that this region sets the international oil price and varies its output as the residual supplier. In regions where electricity production relies almost entirely on coal, as in China, the real price of electricity increases more than the price of gas; the substitution effect **within** fossil fuels prevails and gas output increases sharply. In the OECD regions, on the other hand, electricity generation relies more on oil and gas than on coal. Substitution from primary fossil fuels to the "carbon-free" electricity source dominates, and electricity supply increases while gas output declines slightly.

Finally, the output of energy-intensive industries is virtually unchanged in China and North America where a relatively small carbon tax is required in order to meet the emissions targets. Much larger declines are recorded in the Pacific where the carbon tax is high and also in the USSR. These results follow from the trade reallocation effects discussed above.

B. A Toronto-type agreement with trade in emission rights

Specific curbs on CO_2 emissions can be considered as initial endowments of emission rights. We now report the results of a Toronto-type agreement which imposes the **same** global constraint on CO_2 emissions as the first scenario, but allows for trade in emission rights. Under this scenario, emission cuts are optimally distributed across regions given that a common equilibrium tax is applied in **all** regions (excluding RoW).

The common tax amounts to \$152 (in 1985\$) per ton of carbon in 2020, implying that trade in emission rights serves to lower the tax in the OECD

Table 9. **Changes in the country/region structure of output by sector in 2020**

Percentage changes compared with baseline

	North America	Europe	Pacific	Energy-exporting LDCs	China	USSR	Total
Agriculture	-3.4	-1.5	-6.4	1.9	-0.7	-2.7	-1.6
Coal mining	-68.4	-67.1	-77.7	-76.3	-59.3	-45.3	-64.5
Crude oil	-0.4	-0.1	2.6	-17.4	0.8	0.0	-14.5
Natural gas	-13.2	-8.5	0.2	8.6	9.8	-0.4	-0.0
Refined oil	-11.2	-12.1	-40.3	-30.5	10.4	-35.2	-19.4
Electricity	2.1	2.3	6.0	1.1	-11.6	0.7	2.1
Energy-intensive industries	0.2	-2.9	-13.9	-3.6	0.1	-7.6	-4.5
Other industries and services	-0.9	-0.9	-4.0	-2.4	-1.8	-3.5	-1.8
Total	-1.2	-1.3	-5.6	-4.4	-1.8	-4.2	-2.6

regions and the energy-exporting LDCs compared with a no-trade agreement. The tax triples in China and increases by 50 per cent in the USSR. The optimal allocation of emission cuts implies that the OECD regions and the energy-exporting LDCs want to buy emission rights from China and the USSR. By the year 2020, 8 per cent of annual global CO_2 emissions are traded.

Allowing for trade in emission rights permits the world to cut coal emissions even more than under the first Toronto-type agreement. With the burden of adjustment to the CO_2 constraint shifted more from oil and gas towards coal under this scenario, oil exports of the energy-exporting LDCs are less affected than in the no-trade case: oil production falls by less than 10 per cent in 2020 compared with a fall of over 17 per cent in the no-trade scenario. China sells emission rights to the OECD regions, mainly to the Pacific, and uses the resulting revenues to buy more oil imports from the energy-exporting LDCs. China earns $62 billion (in 1985$) from selling emission rights to the OECD regions -- these revenues amount to 5 per cent of household real income in 2020. In return, it has to cut its yearly emissions by over 70 per cent below baseline.

The welfare gains from trading emission rights are expected to be important in China, the Pacific, the USSR and the energy-exporting LDCs. There should only be marginal effects in the other regions since none is a major trader in the market for emission rights. Real income effects, however, reflect not only gains from trading emission rights but also induced changes in the terms of trade. Regions which are large purchasers of emission rights -- such as the Pacific -- will experience a deterioration in their terms of trade compared with a situation of no trade in emissions.

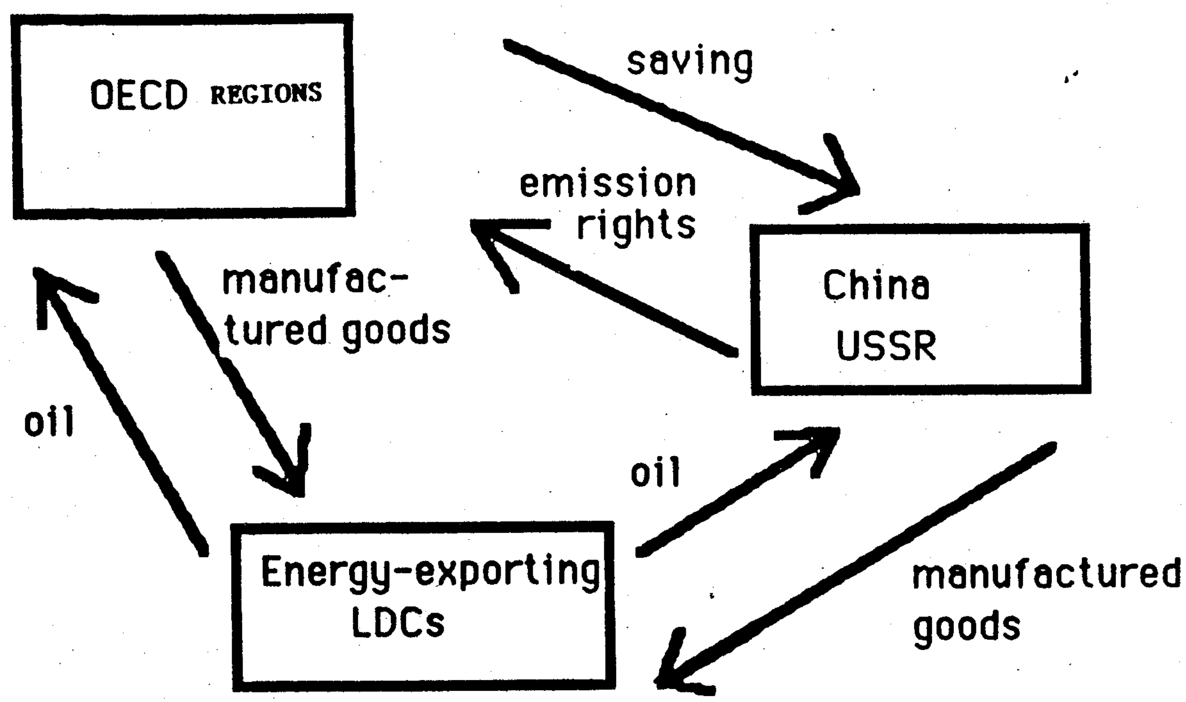
The efficiency gains from allowing for trade in emission rights are computed by comparing the magnitude of the change in household real income under the two scenarios. In terms of the cumulated effects over the period 1995-2020, the gains from trade are:

Percentage changes relative to baseline

North America	Europe	Pacific	Energy-exporting LDCs	China	USSR	Total
+0.0	+0.0	+0.4	+2.0	+3.0	+0.6	+0.6

China, the Energy-exporting LDCs, USSR and the Pacific are the main winners from allowing trade in emission rights. All four regions still record real income losses from meeting the CO_2 constraint, but in each case the losses are smaller when the global agreement contains a provision for trade in emission rights. The gains from trading emission rights are negligible for North America and Europe. The trade in emission rights leads to a new set of balanced flows of saving and goods between the regions (see Figure 6).

Figure 6. International flows from trade in emission rights



C. Curbing CO_2 emissions in industrial economies alone

Suppose that a Toronto-type agreement was adopted only by the industrialised economies, i.e. the OECD regions and the USSR. Global CO_2 emissions in 2020 would be cut by 23 per cent relative to baseline compared with a cut of 37 per cent in the global agreement. In addition, global CO_2 emissions would continue to grow at an annual rate of 1.6 per cent after 2010. This shows that any agreement which aims to curb CO_2 emissions at the global level must involve the major non-OECD countries if it is to be effective.

Levels of the carbon tax and the magnitude of the real income losses in the OECD regions and the USSR are virtually unchanged compared with the global scenario. The non-participants -- the energy-exporting LDCs and China -- do suffer losses, however, from the actions taken by the industrialised economies. For example, by the year 2020 their losses are:

(Percentage changes compared with baseline)

	Household Real income	Real domestic absorption	Real GDP
Energy-exporting LDCs	-6.0	-4.9	-3.0
China	-0.6	-0.3	-0.2

China's welfare loss is small compared with its loss of over 2 per cent under the global scenario. But the losses to the energy-exporting LDCs are almost as high as under the global agreement, implying that the main source of welfare losses in this region arises as a result of carbon taxes being applied in the industrialised economies.

A variant of this simulation was also run in which the industrialised economies agreed to achieve the same reduction in **global** emissions as under a Toronto-type agreement. In order to achieve this target, the OECD regions and the USSR have to reduce their emissions in 2020 by two-thirds compared with the baseline level. This requires enormous carbon taxes: the average tax in the OECD area in 2020 would be $2 200 per ton of carbon and over $500 in the USSR.

Carbon taxes on this scale lead to very large welfare losses: by 2020, real household income is 7 per cent below baseline in the OECD area and 4 1/4 per cent lower in the USSR. Once again, the energy-exporting LDCs are a major loser from the imposition of carbon taxes by the industrialised economies: their welfare loss is almost 10 per cent.

V. Sensitivity Analysis

Simulation results from AGE models are usually sensitive to the values of a few key parameters. Since there is often little consensus about "reasonable" values for these parameters, the standard way to assess the robustness of results is to undertake sensitivity analysis over a wide range of parameter values. Given time constraints, it was not possible to undertake extensive sensitivity analysis. Instead, a more limited exercise was undertaken with three key parameters: i) the foreign trade elasticities; ii) the elasticity of inter-energy substitution; and iii) AEEI. In each case, this involved running a new unconstrained emissions scenario -- called the reference case to distinguish it from the baseline case in Sections III and IV -- and the first Toronto-type agreement scenario.

A. Foreign trade elasticities

World trade models which are based on the Armington specification tend to generate large terms-of-trade effects in response to policies which affect trade flows. With large industry groupings -- such as "energy-intensive industries" or "other goods and services", it is reasonable to consider goods from different countries of origin as imperfect substitutes. But there is much uncertainty about the appropriate degree of substitution between domestic goods and imports and between goods from different regions.

The value of the substitution elasticity between domestic and imported goods in the non-energy sectors was set at 2 in the GREEN baseline and at 3 for the substitution elasticity between goods from different regions of origin. Such values would lie typically towards the upper end of the range of econometric estimates. Consequently, it was decided to reduce these substitution elasticities arbitrarily to 1.5 and 2, respectively, to assess the model's sensitivity to "low" trade elasticities. With lower trade substitution elasticities, the expectation is that changes in the terms of trade will be magnified relative to the reference case.

B. Inter-energy substitution

The literature survey in Burniaux *et al.* (1991) shows that there is great uncertainty about the value of this parameter. A value of 1.2 was selected for the baseline as being close to the mid-point of the range of econometric estimates, but some studies show a much greater potential for inter-energy substitution, especially in the long run.

Therefore, a more optimistic stance on technological adjustment was simulated by setting the inter-energy elasticity in all regions equal to 2, and the supply elasticity of the "carbon-free" energy resource equal to 0.5 (instead of 0.2). The latter change corresponds to an assumption that the supply of nuclear power over the next three decades will be less constrained by political concerns over reactor safety. The expectation is that these changes would result in lower carbon taxes by making it easier to substitute between the various energy sources. This, in turn, should give rise to lower costs of curbing CO_2 emissions.

C. AEEI

There has been much controversy over the value of this parameter. Some studies have argued that it is zero or even negative, while others have argued that it is positive. In the GREEN baseline, it was set equal to 1 per cent per year in all regions. For the sensitivity analysis, the value of AEEI was halved in all regions. Cutting AEEI implies a faster growth of CO_2 emissions in the reference case, requiring larger carbon taxes to meet any given emissions constraint.

D. Effects of these changes on carbon taxes and welfare costs

The effects of these changes on both the level of carbon taxes in 2020 and the change in household real income are shown in Table 10. The first conclusion is that lowering the values of the trade substitution elasticities makes little difference to the broad pattern of the results. Terms-of-trade changes (not shown) are magnified relative to the reference scenario. This means that regions suffering terms-of-trade losses (the energy-exporting LDCs, China) will lose slightly more than in the baseline case, whereas regions which experienced terms-of-trade gains (Pacific) from the carbon tax will lose less than in the baseline.

This reassuring conclusion does not hold with respect to the other two parameters. Raising the elasticity of inter-energy substitution and the supply elasticity of "carbon-free" energy cuts the average tax in 2020 in half, to $109 per ton of carbon. The magnitude of the fall in the carbon tax is not uniform across regions. It falls by less than 30 per cent in China and the energy-exporting LDCs compared with a fall of over 60 per cent in North America.

The welfare costs of curbing CO_2 emissions are much lower in all regions, with the exception of China, when the ease of substitution between energy sources is raised. Since this change means that energy demands decline less than in the baseline, the real income loss in the energy-exporting LDCs is significantly lower. China is the only region which records a higher real income loss, which arises from a larger terms-of-trade loss.

When AEEI is halved, global CO_2 emissions grow faster than in the baseline. A lower AEEI puts additional supply pressures on natural gas and the carbon-free resource, tending to drive up their relative prices more. As a result, the total demand for fossil fuels may increase less than in the baseline, implying a less than proportionate increase in emissions growth in China (CO_2 emissions grow by 4.3 per cent per year compared with 4 per cent in the baseline), or there may be a shift towards coal, leading to a more than proportionate increase in emissions growth in North America (1.5 per cent per year compared with 0.9 per cent in the baseline scenario).

Carbon tax rates rise sharply in all regions: the average tax in 2020 almost doubles to $401 per ton of carbon. The largest increases occur in regions where emissions were projected to grow relatively slowly -- North America and Europe. The costs of meeting these emission constraints also rise sharply: the average real income loss in 2020 doubles to over 4 per cent compared with the baseline.

VI. Possible Directions for Future Work

The simulation results reported in this paper serve to illustrate some of the economic costs of policies to curb CO_2 emissions. The results are only preliminary at this stage. The policy relevance of this work could be enriched

Table 10. Impact of sensitivity analysis on carbon taxes and real income changes in 2020

	GREEN baseline		"Low" trade elasticities (1)		Higher inter-energy substitution elasticity (2)		Lower AEEI (3)	
	Carbon tax (1985$)	Percentage change in real household income	Carbon tax (1985$)	Percentage change in real household income	Carbon tax (1985$)	Percentage change in real household income	Carbon tax (1985$)	Percentage change in real household income
North America	209	-0.8	202	-0.9	81	-0.3	493	-1.7
Europe	213	-0.9	222	-0.9	97	-0.2	420	-2.1
Pacific	955	-2.4	969	-2.0	440	-0.6	1 427	-4.5
Energy-exporting LDCs	209	-7.5	204	-7.9	161	-4.4	425	-12.8
China	63	-2.3	67	-3.1	45	-2.9	81	-3.3
USSR	101	-0.6	100	-0.5	58	0.1	160	-1.7
Total	215	-2.2	216	-2.3	109	-1.1	401	-4.1

1. The values of the substitution elasticities in sectors 7 and 8 between domestic and imported goods and between imports from different regions of origin are set at 1.5 and 2, respectively, compared with values of 2 and 3, respectively, in the baseline.

2. The elasticity of inter-energy substitution is raised from its baseline value of 1.2 to 2 and the supply elasticity of the carbon-free resource from 0.2 to 0.5.

3. AEEI is set at 0.5 per cent a year in all regions compared with 1 per cent in the baseline.

by various extensions to GREEN and by carrying out a wider range of simulations.

The following extensions to the model specification are currently under investigation by the OECD Secretariat:

i) **Extending the time horizon:** given the long-term nature of the climate change issue, it could be useful to extend the time horizon to 2050. If this were to be envisaged, the treatment of back-stop technologies would become a major issue.

ii) **Extending the regional/sectoral disaggregation:** since the non-OECD regions play such an important role in any analysis of climate change, it would make sense to split up the RoW region more and give it more general equilibrium structure. In particular, it might be feasible to model India, the Dynamic Asian Economies and Eastern Europe as separate regions. It might also be possible to separate out transportation as an additional producing sector.

iii) **Putty-clay specification of technology:** the version of GREEN described in this paper has putty-putty technology. Shifting to a putty-clay specification would allow the incorporation of adjustment costs resulting from the premature scrapping of significant parts of the capital stock.

iv) **Improve the modelling of the energy sector:** given the assumed CES technology, additional nesting levels in the production structure could be introduced in order to take account of lower substitutability between sub-sets of energy inputs -- such as gas and coal.

v) **Intertemporal optimisation:** price expectations are assumed to be static in the present version. This assumption is not very realistic in the context of credible government commitments to curb CO_2 emissions involving carbon taxes and other policy instruments. It might be possible to develop a more simplified version of the model which incorporated perfect foresight.

vi) **Strategic behaviour in fossil fuel markets:** it would be interesting to assess how the gains and losses in some regions are sensitive to alternative assumptions about the market structure for fossil fuels, particularly oil and coal.

vii) **Other greenhouse gases:** it might be possible, in conjunction with on-going work in the Environment Directorate and the IEA, to extend the model to include other GHGs such as CFCs and methane. This obviously depends on compiling good data on the sources of emissions for such gases:

At the same time, the OECD Secretariat attaches a very high priority to undertaking the following work:

i) **Systematic sensitivity analysis**: it is essential to undertake extensive sensitivity analysis in order to assess the robustness of GREEN results to the key parameter values in production, consumption and foreign trade.

ii) **Simulating a wide range of possible international agreements on climate change**: since negotiations on a draft international convention on climate change are now underway, the model can be used to simulate the economic costs of alternative proposals.

iii) **The effects of existing implicit carbon taxes**: domestic fossil-fuel prices diverge from world prices in all regions, reflecting existing tax/subsidy policies. In particular, oil is typically taxed more heavily than gas which, in turn, is taxed more heavily than coal. It would be important to explore the impact on CO_2 emissions of evening out these implicit carbon taxes before imposing a new carbon tax.

Notes

1. The reason for this neglect is that very little data are available on the likely benefits. See Nordhaus (1990) for a pioneering attempt to quantify the benefits as well as the costs of climate change. The Environment Directorate and the Economics and Statistics Department have engaged William Cline (Institute for International Economics, Washington) to review the literature on the benefits side.

2. See Burniaux *et al.* (1991) for a full description of the specification of GREEN, its data base and parametrisation.

3. Agriculture is treated as a separate sector since most analysts agree that this is the sector where the direct economic effects of climate change would be mainly concentrated -- see DOE (1990). In addition, if, in future extensions of GREEN, it were possible to include other GHGs such as methane, it makes sense to include agriculture as a separate sector since estimates suggest that over half of global emissions of methane are produced in agriculture.

4. The demand system in GREEN is a version of the Extended Linear Expenditure System (ELES) which was first developed by Lluch (1973). The formulation of the ELES is based on an atemporal maximisation of a Stone-Geary utility function by treating saving as a good with zero "subsistence quantity" -- see Howe (1975). This formulation assumes away any dependence of saving on the opportunity cost of current consumption (i.e. the rate of return on assets) by implicitly embodying the latter in the **constant** marginal propensity to consume. This implies that it is impossible to derive a consistent intertemporal welfare measure with the current version of GREEN.

5. Since increases in the atmospheric concentrations of CO_2 arise from the quantity of carbon that is generated by the burning of fossil fuels, the carbon tax is a specific (or excise) tax.

6. Natural gas and coal are assumed to be heterogeneous goods across regions due to transportation costs which are much higher than for oil.

7. This assumption implies that current account/GDP ratios converge to zero in the long-run.

8. This involves computing in each period a measure of Harrod-neutral technical progress in the capital/fixed factor bundle as a residual, given that the growth of the labour force (in efficiency units) is equal to the exogenous growth in GDP. This is a standard calibration procedure in dynamic AGE modelling -- see Ballard *et al.* (1985).

9. For details, see Martin (1990).

10. It was possible to complete the Soviet I-O table on the basis of a study by Professor Gérard Duchene (University of Lille II). For details, see Duchene and Scenik-Leygonie (1990).

11. The original version of the model is documented in Edmonds and Reilly (1985). For a recent application of the model, see Edmonds and Barns (1990).

12. The population growth projections are based on a recent World Bank study while the GDP growth projections are an average of the "higher" and "lower" growth cases included in the recent report of the IPCC's Response Strategy Working Group.

13. RoW has no general equilibrium structure in GREEN but it does produce CO_2 emissions. These arise as a result of the assumption that the level of emissions is proportional to GDP, adjusted by the exogenous increase of end-use energy efficiency:

$$Em_t^{RoW} = \frac{\prod_{t=1}^{n} (1+g_t)^t}{\prod_{t=1}^{n} (1+a_t)^t} \cdot Em_0, \text{ where } Em_0 = \text{initial level of } CO_2 \text{ emissions;}$$

g = growth rate of GDP;

and a = growth rate of AEEI.

14. All fossil-fuel prices are deflated by the real exchange rate. In each country, the real exchange rate is defined as the ratio of a weighted average of domestic primary factor prices to the numéraire of the model, which is the export price of non-energy goods and services in RoW.

15. As a general rule, there is a positive correlation (see Table 4) between changes in the real exchange rate and changes in the terms of trade. However, as the international oil price is exogenous in GREEN, the two variables can move differently over time. For instance, oil-exporting regions, such as the energy-exporting LDCs or the USSR, experience terms-of-trade gains as the international oil price increases post-1990. The opposite effect occurs in North America and in China (after 2000) as the depletion of domestic oil reserves leads to a growing share of oil imports in total imports; this in turn leads to a faster growth of import prices and a deterioration in the terms of trade in both regions.

16. There is an additional source of downward pressure on the real exchange rate in China over the period 2000-2020 from the depletion of its oil reserves. It shifts from being a net exporter of crude oil to a net importer. This imposes a further adjustment to the non-oil trade balance.

17. Supply of the "carbon-free" factor in the electricity sector is a positive function of its price relative to the regional average factor price, the latter being a "proxy" for the opportunity cost of using the

"carbon-free" resource. Lower labour and capital productivity growth increase their equilibrium prices and, therefore, the opportunity cost of investing in "carbon-free" energies.

18. Two problems remain after this adjustment. First, North America includes Canada in GREEN whereas it is included in the Other OECD region in the other models. Second, both ER and MR group eastern Europe with the USSR whereas GREEN treats the USSR as a single region and includes eastern Europe as part of the Row region. The bias is likely to be small in the case of North America as Canada accounts for only 8 per cent of total CO_2 emissions of the region, but more serious in the case of the USSR as eastern Europe accounts for about one quarter of total emissions of the combined Soviet Union plus Eastern Europe region.

19. The MR baseline was supplied to the OECD Secretariat by Alan Manne. Like the GREEN baseline, it incorporates the EMF12 assumptions about GDP growth but the growth rate of AEEI is around 0.5 per cent in all regions compared with 1 per cent in GREEN. While ER has the same AEEI assumptions as GREEN, its GDP growth rates are not identical to those laid down by EMF12. Instead, they are derived from assumptions about the growth rates of the labour force and labour productivity.

20. Bearing in mind that the tax is specified as an absolute $ amount per ton of carbon, a given relative energy price increase can be achieved by a lower carbon tax under the following conditions: i) when fossil fuel prices are initially lower relative to world prices (a $1 carbon tax has a larger impact in terms of relative price changes): and ii) when coal accounts for a large share of total energy demand, given that coal prices are lower than oil and gas prices in almost every region (see Table 2) and coal has a larger carbon content than either oil or gas. In addition, the carbon tax exhibits diminishing returns in terms of curbing emissions when coal use is eliminated and energy demand switches to more expensive fuels with lower carbon content.

21. For all regions except the USSR, the change in household real income is strongly correlated with the change in real absorption. Differences between these two indicators reflect the different energy intensities of private and public expenditures and investment. The closure used in the current version of GREEN implies that the public sector net balance is kept unchanged -- an assumption of revenue neutrality. Thus, carbon tax revenues are compensated by cuts in the marginal income tax rate. This closure has positive (negative) distributional implications for households when they consume relatively less (more) fossil fuels than the public sector. According to the benchmark data set for the USSR, government demand for energy accounts for over 20 per cent of total government consumption compared with less than 2 per cent of household consumption.

22. These deadweight losses are overstated for two reasons. First, the carbon tax is a "corrective" tax, i.e. it aims to raise the price of fossil fuels to reflect more adequately their social cost. Second, the revenues raised by the carbon tax are assumed to be returned to consumers in GREEN via a reduction in marginal income tax rates. Cutting other distortionary taxes should give rise to welfare gains but

there is no mechanism in the present version of the model for this to occur.

23. The current version of GREEN uses the following values of the capital/output ratio which are taken from the OECD Secretariat's Analytical Data Base:

North America	Europe	Pacific	Energy-exporting LDCs	China	USSR
2.6	3.3	2.4	3.0	3.5	3.4

24. The rising export share follows from cuts in domestic demand for crude oil and natural gas, combined with the assumption that fossil fuels are quasi-homogeneous products traded on perfectly competitive markets. This implies that any fall of domestic demand will induce producers to export what is not domestically consumed at a given world price.

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