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The Costs of Reducing CO2 Emissions: A Technical Manual

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THE COSTS OF REDUCING CO_2 EMISSIONS: EVIDENCE FROM GREEN

This paper presents simulation results using the OECD Secretariat's GREEN model to quantify the economic costs of possible international agreements to curb CO_2 emissions. These results supersede the initial GREEN results published in Working Paper no. 103 in June 1991.

The first section of the paper summarises the analysis and draws some conclusions for policy. Section II of the paper reviews the so-called Business-as-Usual scenario and presents some sensitivity analysis around it. Section III considers international agreements under which emission curbs are only applied by the OECD countries or the EC and no actions are taken by the non-OECD regions. Particular attention is paid to the possibility that unilateral action by the OECD countries might give rise to so-called "carbon leakages", i.e. higher emissions in the non-OECD regions. Section IV extends the coverage of the international agreements to embrace the non-OECD countries. It quantifies the gains from cost-effective agreements and explores how a common equilibrium carbon tax or tradeable permits affects the distribution of gains and losses across regions. The final section deals with eliminating existing distortions in energy prices.

* * *

Cette étude présente les résultats des simulations utilisant le modèle GREEN, construit par le Sécretariat de l'OCDE, qui a pour objectif la quantification des coûts économiques des éventuels accords internationaux pour réduire les émissions de CO_2. Ces résultats remplacent les résultats préliminaires obtenus avec GREEN, publiés dans le document de travail no. 103 en juin 1991.

La première partie de cette étude résume l'analyse et tire quelques conclusions de politique économique. La section II passe en revue le scénario de réference ainsi que les facteurs auxquels ce scenario est particulièrement sensible. La section III considère les accords internationaux pour lesquels les réductions d'émissions sont seulement appliquées dans les pays de l'OCDE ou dans la CE et aucune action est prise par les régions non-OCDE. Une attention particulière a été donnée à la possibilité que des actions unilatérales par les pays de l'OCDE donnent lien à des "fuites de carbonne", i.e., qu'elles conduisent à une augmentation des émissions dans les régions non-OCDE. Dans la section IV, la couverture des accords internationaux est élargie aux pays non-OCDE. Les gains d'un accord efficient du point de vue des coûts sont également quantifiés de même que sont analysées les implications d'une taxe commune à tous les pays et des échanges de droits à polluer sur la distribution regionale des gains et pertes. La section finale traite de l'élimination des distortions existantes des prix de l'énergie.

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and Joaquim Oliveira Martins (1)

I. Summary and Conclusions

In recent years there has been growing concern that human activities may be affecting the global climate through growing atmospheric concentrations of "greenhouse gases" (GHGs): carbon dioxide (CO_2), methane, chlorofluorocarbons (CFCs) and nitrous oxide. The Intergovernmental Panel on Climate Change (IPCC) estimates that the average rate of increase of global mean temperature over the next century could 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 (2). 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.

CO_2 has contributed over half of the global warming in the past and is expected to contribute the same share in the future. Furthermore, around 75 per cent of man-made CO_2 emissions arise from the burning of fossil fuels, with the remainder coming from deforestation and cement production. Given the phasing out of CFCs under the Montreal and London Protocols and the great uncertainty about the sources of methane, much of the policy discussion on global warming has focused on the need to curb CO_2 emissions.

The OECD Secretariat has developed a multi-region, multi-sector, dynamic applied general equilibrium (AGE) model -- GREEN (the GeneRal Equilibrium ENvironmental model) -- to quantify the economy-wide and global costs of policies to curb CO_2 emissions. The purpose of this paper is to present simulation results with GREEN, using alternative policy instruments (e.g. carbon taxes, energy taxes and tradeable permits) to achieve emission reduction targets, in the context of agreements in which only the OECD countries act to cut their emissions (Section III) and agreements in which all countries participate (Section IV). The effects of removing existing distortions in energy prices across regions are also examined (Section V). All of these alternatives are presently under consideration in the context of a possible global convention on climate change.

The new version of the GREEN model differs from the version published in Burniaux *et al*. (1991) (complete details are provided in the Technical Manual -- see Burniaux *et al*. (1992):

- The time horizon has been extended to the year 2050 (previously 2020) (3).

-- Back-stop technologies, i.e. new energy sources coming on stream in the future when relative energy prices are sufficiently high, have been introduced both for fossil fuels and electricity.

-- A putty/semi-putty production structure has been introduced, to model adjustment costs.

-- The world oil price has been endogenised.

-- The regional breakdown of the world economy has been extended to cover 12 regions.

The main dimensions of the GREEN model (sectors, regions and factors) are listed in Table 1.

The current version of GREEN has the following limitations:

-- The potential benefits of curbing CO_2 emissions, in terms of slowing climate change and reducing airborne pollutants such as nitrogen oxides, sulphur oxides, carbon monoxide and suspended particulates, are not taken into account (4).

-- Other greenhouse gases -- CFCs, methane and nitrous oxide -- are not included.

-- Energy taxes and subsidies are the only distortions incorporated explicitly.

-- The set of policy instruments to curb emissions is limited to carbon taxes, energy taxes and tradeable permits. Command-and-control instruments, e.g. emission standards, cannot be simulated for the moment.

-- The oil market is treated as being perfectly competitive (5).

-- Expectations about future events do not affect current saving and investment (6).

The contribution of GREEN to the growing literature on the CO_2 issue is to combine a large regional coverage with a consistent treatment of world trade flows and energy price distortions (7). This makes it well suited to analysing the effects of international agreements upon output, economic welfare, international competitiveness and trade.

In GREEN, if no actions are taken to curb CO_2 emissions (i.e. the so-called Business-as-Usual (BaU) scenario), global emissions are projected to grow at 2 per cent per annum from 1990 on, to reach 19 billion tons of carbon in 2050. By the year 2050, China would account for almost 30 per cent of world emissions, a larger share than the OECD countries, because of the growing importance of coal as an energy source. The evolution of emissions over the next half century, though, is linked very strongly to assumptions about economic growth, the growth of world population and key model parameters such as the magnitude of inter-fuel substitution and the rate of energy efficiency improvement.

The threat of global warming is a result of increasing CO_2 concentrations in the atmosphere, among many other factors. As an example of the orders of magnitude involved, the IPCC has noted that to stabilise CO_2 concentrations by the middle of the next century at about 450 parts per million compared with 350 currently, might require cutting back man-made global CO_2 emissions to about 4 billion tons of carbon per year by 2050. Relative to the GREEN BaU scenario, this represents a cut of 80 per cent in the year 2050. How does this compare with emission cuts now discussed in the context of a climate convention? How to achieve these, or any other, cuts at minimum cost? How to ensure the participation of all major CO_2-emitting countries in international agreements to reduce global emissions?

The GREEN simulations presented in this paper have been designed to answer these questions. An overview of the simulations is presented in Table 2. The first two simulations consider agreements under which emission curbs are only applied by the OECD countries or the EC, and no actions are taken by the non-OECD regions. Particular attention is paid to the possibility that unilateral action by the OECD countries might give rise to carbon leakages, i.e. the possibility of higher emissions in the non-OECD regions. Scenario 3 extends the coverage of the international agreements to both OECD and non-OECD countries. Scenarios 4 and 5 analyse cost-effective international agreements, exploring how a common equilibrium carbon tax or tradeable permits affects the distribution of gains and losses across regions. The final three scenarios deal with eliminating energy price distortions.

Actions by the OECD countries alone to stabilise emissions in 2000 at 1990 levels -- a target which corresponds roughly to their announced commitments to combat global climate change -- would result in an average cut-back of OECD emissions of 43 per cent below BaU levels by 2050. This, however, leads to a fall of only 11 per cent in <u>global</u> emissions in 2050; this highlights the key message that action to tackle the climate change issue must include the major non-OECD countries if it is to have any hope of success. Carbon leakages are negligible when <u>all</u> OECD countries act together to curb emissions but they become larger when only the EC takes action. The cost to the OECD countries of achieving this stabilisation target is very small: their real income is 0.6 per cent lower in present values (8).

A Toronto-type agreement (Scenario 3) would cut world emissions in 2050 by two-thirds below BaU levels, implying continuing growth in atmospheric concentrations. Given the wide differences in marginal costs of abating emissions across regions, this is not a cost-effective agreement, suggesting it would be impossible to commit countries to implement it. A cost-effective agreement (Scenario 4) could potentially be achieved by imposing the <u>same</u> carbon tax on all participating countries ($140 per ton of carbon in 2050), leaving each country free to achieve the optimal reduction of its emissions. As a result of this cost-effective reallocation of emissions cuts, the global welfare loss is only 1 per cent (in present values), 1 percentage point lower than under a Toronto-type agreement in which each region has to achieve specific reductions. Emission reductions are shifted from countries in which the marginal cost of cutting emissions is higher -- mainly the OECD countries and some semi-industrialised LDCs -- to coal-based economies where emission curbs can be achieved at a lower marginal cost. The Energy-exporting LDCs benefit from this reallocation as carbon reductions are achieved by cutting back more on coal instead of oil use. The OECD countries contribute less to the global emissions reduction than in the previous scenario and the coal-based economies (China, India, the former Soviet Union and the CEECs) bear more of the burden of stabilising world emissions.

Although a Toronto-type agreement which imposes a common carbon tax across all regions is less costly for the world as a whole, it still implies significant welfare costs for some non-OECD regions. These regions are unlikely to be willing to implement such an agreement unless they are offered some compensation. This could potentially be achieved by extending the scope of the agreement to allow participating countries to trade emission rights (Scenario 5). A central consideration, of course, is the allocation of emission rights which has a major impact on the distribution of gains and losses associated with a cost-effective allocation of carbon cuts across regions.

Energy markets are characterised by large cross-country differentials in prices of fossil fuels. A major explanation for these differentials is the existence of domestic distortions represented by taxes and subsidies; this factor is particularly important in some non-OECD regions, such as the former Soviet Union, the CEECs, India and China, which subsidise primary energy use heavily. In GREEN, these distortions are proxied by aggregate wedges between domestic and "world" prices of fossil fuels: averaged over all 12 regions, fossil fuels appear to be subsidised by between 15 to 33 per cent.

An international agreement was simulated which commits all regions to eliminate these distortions gradually over the period 1990-2000 (Scenario 6). Removing these energy taxes/subsidies has a major impact on global emissions: by 2050, these are 20 per cent below their BaU level with all of the reduction coming in the non-OECD regions. Not only does elimination of these distortions serve to lower world emissions significantly, it also produces welfare gains for some regions. Real income, averaged across all regions, is 1/2 per cent (in present values) above its BaU level, with particularly large gains in the former Soviet Union and the CEECs. Some of the countries in these latter regions are currently implementing policies designed to lower their subsidies to energy use and this step could produce large gains for them. It could also form part of the basis for an international agreement to curb CO_2 emissions provided that some provision is made for compensating the losers.

To illustrate this, a Toronto-type agreement, allowing for tradeable permits, was combined with the removal of existing distortions (Scenario 8). This stabilised emissions at zero cost for the non-OECD regions as a whole. But large inequalities still remain in the way gains and losses are distributed among them. This suggests that alternative endowments of tradeable permits should be investigated in order to improve the distribution of gains and losses across non-OECD regions (9). However, this scenario illustrates that a substantial reduction of world emissions can be achieved at <u>no cost for the non-OECD countries</u> taken as a whole, whereas OECD countries lose less than in the Toronto-type scenario with no permits trading and no removal of existing distortions.

II. Business-as-Usual (BaU) Path of CO_2 Emissions

The business-as-usual (BaU) path is the path that CO_2 emissions would be expected to take in the absence of policy actions to restrain their growth. It determines the required magnitudes of the cuts in emissions needed to achieve any given target. The assumptions about GDP and population growth rates underlying the BaU scenario are taken from the guidelines laid down for EMF12 and the model comparisons project (see Table 3).

The world oil price is endogenous in GREEN from 1990 on; its time path is related to the depletion of oil reserves in the Energy-exporting LDCs (10). The potential oil supply constraint becomes binding around 2030, thereafter oil output declines by over 2 per cent per annum until 2050. From 1985 to 1990, the world oil price is set exogenously at its historical level. It then rises steadily in real terms to 2030, at an average annual rate of 1.7 per cent. From 2030 to 2050, the rate of price increase slows (to 1.1 per cent per year) as oil competes with the carbon-based synthetic fuel.

Two important assumptions about policies underlie the BaU path in GREEN. First, no allowance is made for the commitments to reduce CO_2 emissions which have been announced by OECD countries. Second, the distortions in energy prices across regions in the benchmark (1985) year do not change over time. This latter assumption about energy pricing policies has a major impact on the results, as shown in Section V.

A. Composition of energy demand

18. Figure 1 shows the shares of primary energy demands in the OECD and the non-OECD regions accounted for by the fossil fuels and the three back-stop options (carbon-based synthetic fuels, carbon-free liquid fuel and a carbon-free electric option). The most striking trend is the steep rise in the share of coal: up from 29 per cent in the OECD area in 1985 to 43 per cent in 2050 and from 37 to 63 per cent in the non-OECD regions. The rising importance of coal comes at the expense of oil, especially in the OECD area.

All three back-stop energy sources are assumed to be available in virtually infinite supply from 2010 on. From 2030 on, oil use in the OECD area is rapidly replaced by the carbon-based synthetic fuel which accounts for almost 20 per cent of total energy demand by 2050. Beginning in 2010, the carbon-free electric option acts as the marginal energy source in the OECD countries. However, it only makes important inroads as an energy source in Japan, where it replaces all conventional electricity by 2030.

In sharp contrast to the OECD regions, the non-OECD regions make no use of the back-stop options: by 2050, the carbon-based synthetic fuel only accounts for 2 per cent of their total energy demands. Total energy demand also increases much faster in the non-OECD regions than in the OECD area: the annual growth rate is 2.3 per cent over the period 1985-2050 compared with 0.8 per cent in the latter.

The main explanation of why back-stop technologies are not used by the non-OECD regions lies in the existence of price distortions on primary fossil fuels in some major countries/regions such as China, India, the former Soviet Union and the CEECs. Table 4 shows that fossil-fuel prices, particularly for coal, were heavily subsidised in these regions in 1985 (the benchmark year in GREEN) (11). Since it is assumed in the BaU scenario that these subsidies are not eliminated, fossil-fuel prices in most non-OECD regions do not reach the break-even levels at which back-stop options become profitable.

B. CO_2 emissions

Emissions growth over the period to 2050 depends on several factors. First, it reflects the projections of GDP growth; on the basis of this factor alone emissions growth would be expected to slow down in the next century and such deceleration does indeed occur after 2010 in the non-OECD regions (see Table 5). Second, as noted above, the rise in the real oil price encourages substitution towards coal, thereby tending to raise emissions growth. Third, the phasing-in of back-stop options also affects emissions growth, depending upon whether the back-stop is "clean" or "dirty". For example, the phasing-in of the carbon-free electricity option in Japan contributes to a sharp fall in emissions growth in the OECD area in the first decade of the next century. But after 2010 this downward pressure on OECD emissions growth is more than offset by the growing penetration of the "dirty" synthetic fuel option in the OECD countries. Because of the high cost differential *vis-à-vis* conventional electricity sources, the carbon-free electric back-stop only makes a small inroad in the OECD countries -- it accounts for under 11 per cent of energy demand in 2050.

The net outcome of these opposing trends is a stable 2 per cent per annum growth rate of global emissions (Table 5), yielding almost 19 billion tons of carbon by 2050 (Figure 2). The regional distribution of emissions changes sharply over this period. The OECD countries, which accounted for 49 per cent of global emissions in 1985, only account for 26 per cent in 2050. This is offset by the growing importance of China: its share rises from 9.5 per cent in 1985 to 29 per cent in 2050. Rapid growth of emissions in China reflects its above-average growth rate and a switch towards coal. This is exacerbated by the low domestic prices of coal relative to world prices in China, India, the former Soviet Union and the CEECs. Together, these four regions account for 55 per cent of global emissions in 2050 compared with 36 per cent in 1985. So long as these regions maintain their large coal subsidies, neither of the carbon-free back-stops becomes competitive with coal.

C. Sensitivity analysis around the BaU emissions path

Since the BaU emissions path is a crucial element in quantifying the costs of measures to restrict emissions, it is important to assess its sensitivity to key exogenous variables (GDP and population growth) and parameters [the autonomous energy efficiency improvement (AEEI), the inter-energy elasticity of substitution and the coal supply elasticity]. In each case, the reference scenario was re-run for the following variants:

GDP:	the projected annual growth rates were lowered by 1 percentage point in all regions;
Population:	the U.N. "high"- and "low-fertility" variants were run, assuming that the region-specific growth rates of GDP per capita implicit in the EMF12 GDP projections were maintained;
AEEI:	its annual growth rate was halved to 0.5 per cent in all regions;
Inter-energy elasticity of substitution:	its long-run value was cut in half from 2 to 1 and the corresponding short-term elasticity was also halved from 0.25 to 0.12;
Supply elasticity for coal:	the upward supply elasticity was cut over time from 4-5 to 2 in all regions.

Under the lower GDP growth scenario, global emissions in 2050 would be 10.2 billion tons. The range of variation in the other five scenarios is between 17 and 22 billion tons. It is worth noting that the updated IPCC scenarios range from 7.5 to over 20 billion tons in 2050.

Emission levels in GREEN are very sensitive to the assumptions made about GDP and population growth. Among the three model parameters, both AEEI and the inter-energy elasticity of substitution are more important determinants of emissions than the coal supply elasticity. Halving the AEEI parameter produced 11 per cent more global emissions in 2050; halving the inter-energy substitution elasticity lowered global emissions by 13 per cent in 2050, with virtually all of the reduction occurring in the non-OECD regions. In contrast, lowering the coal supply elasticity only cut global emissions by 3 per cent. Thus, substitution between fossil fuels in the non-OECD regions, in particular from oil and gas towards coal, is a major factor behind emissions growth in GREEN.

III. Agreements by OECD Countries to Curb CO$_2$ Emissions

This section considers international agreements which involve action by the OECD countries alone or a sub-set of them, e.g. the EC, sticking closely to announced commitments. Particular attention is paid to the issue of so-called "carbon leakages", i.e. the possibility that unilateral action to restrict emissions by a group of countries could be partly negated by an increase in emissions from countries that do not participate in the agreement. A range of policy instruments -- carbon taxes, energy taxes and tradeable permits -- are used to achieve the chosen emissions curbs, always under the assumption of revenue neutrality.

A. OECD countries stabilise their emissions in 2000 at 1990 levels

This stabilisation target is not far from the announced commitments by OECD Member countries for dealing with global climate change (12). All countries except Japan are assumed to stabilise their emissions in 2000 at their 1990 levels; Japan, in line with its announced commitment, is assumed to stabilise on a per capita basis (13). The emissions restrictions are imposed gradually starting from 1990 and the targets are maintained until 2050. The chosen instrument to achieve the targets is a carbon tax.

Stabilising OECD emissions at their 1990 levels implies a significant cut, relative to the BaU path of 43 per cent by 2050. This, however, has a marginal impact on global emissions which are only 11 per cent lower in 2050.

1. Carbon leakages

It has been argued that emissions in countries which do not participate in international agreements may increase in response to a cut in emissions by countries which implement the agreement (14). There are two possible sources of such carbon leakages in GREEN. First, energy-intensive industries (pulp and paper, chemicals, iron and steel, non-ferrous metals) may gain in competitiveness in the non-participating countries as relative energy prices in the participating countries are driven up. Second, if the restriction imposed by the agreement is sufficiently binding, world prices of fossil fuels may fall, thereby raising emissions in the non-participating countries.

The fall in OECD output of energy-intensive industries is quite small in response to the stabilisation target: on average over the period 1990-2050, OECD output of these industries is only 1.4 per cent below its BaU level. The largest decline is recorded in Japan (-2.6 per cent) and the smallest (-0.4 per cent) in the United States. The corresponding expansion of these industries in the non-OECD regions is even smaller: output, averaged over all eight regions, is only 0.5 per cent above BaU levels. Most of the gains in competitiveness are captured by the CEECs (+1.2 per cent), the DAEs (+1.1 per cent) and the former Soviet Union (+0.6 per cent).

Carbon leakages in the non-OECD countries are calculated relative to the total cut in emissions achieved by the OECD countries. The results show differing patterns of leakages across regions and over time as emissions increase in some regions, notably in the former Soviet Union, in response to the cut in OECD countries while they decline in others, notably in the Energy-exporting LDCs and China. Emissions decrease slightly in the Energy-exporting LDCs as a result of the fall in output induced by lower oil exports to the OECD regions. In China, emissions also fall slightly as a result of substitution from coal to oil in response to the small fall in the oil price. Averaged over all non-OECD regions, some leakages do occur. But they are insignificant: they peak at 2.5 per cent of the cut in OECD emissions in 2000, become slightly negative in 2010 and then turn positive again, rising slowly to 1 1/2 per cent in 2050 (Figure 4).

Sensitivity analysis was undertaken to see if this result of negligible leakages was robust to large changes in the values of the foreign trade elasticities (they were tripled in agriculture, energy-intensive industries and other industries to values ranging from 9-12). A much more severe emission constraint was also imposed on the OECD countries, requiring them to cut their emissions in 2050 by over 80 per cent compared with the BaU level. In both cases, the net leakages in the non-OECD regions remained small, never exceeding more than 6 per cent of the cut in emissions in the OECD countries, with the largest impact occurring in the period up to 2010 before back-stops come on-stream. This suggests that concerns expressed about significant carbon leakages in the non-OECD countries as a result of OECD actions to curb emissions are not well founded.

2. Carbon taxes

Back-stop technologies play a crucial role in determining the level of carbon taxes in the long run in GREEN -- see the Appendix for a detailed discussion of the determinants of the carbon tax (15). Before it reaches the level at which a back-stop substitute becomes competitive, the carbon tax is determined by four main factors: average energy prices, the carbon content of primary energy demand, the emission reduction target and the overall ease of substitution between inputs. But, as soon as one conventional energy source competes with its back-stop alternative, its price (inclusive of the carbon tax) stops rising and the carbon tax stabilises at a level determined by the arbitrage condition between the two energy sources.

When the conventional energy source has been completely replaced by its back-stop alternative, the overall level of inter-energy substitution is reduced given the assumption in GREEN that all energy sources are imperfect substitutes. Thus, the expectation is that the carbon tax will start rising again until it reaches the level at which a more expensive back-stop source becomes competitive.

With the exception of Japan, the carbon taxes required to achieve the stabilisation target are very similar across OECD regions. The carbon restrictions can be met by cutting back on the use of the carbon-based synthetic fuel. Therefore, as long as some synthetic fuel is being used, the demand for carbon is very elastic and the taxes in the United States, EC and Other OECD regions stabilise from 2010 on in a narrow range of $50-75 per ton of carbon (in 1985 prices and exchange rates). The highest tax, at almost $200 per ton in 2050, is recorded in Japan. The high tax in Japan reflects the fact that it has the most severe emissions restriction (-60 per cent compared with baseline) as well as the highest relative fossil-fuel prices in the benchmark year.

3. Effects on welfare and output

Achieving this stabilisation target imposes a small welfare cost on the OECD countries from 2005 on (Figure 5). Before then, they record small welfare gains as the improvement in their terms of trade arising from the cut-back in oil imports more than offsets the efficiency losses due to the carbon tax. The OECD regions' terms of trade deteriorate from 2030 on as they substitute towards crude oil, adding to their welfare loss which reaches 1.3 per cent by 2050. The largest welfare loss in 2050 (-2 per cent) is in Japan, followed by the EC (-1.4 per cent). Cutting back emissions in the OECD countries alone has only marginal effects on welfare in the non-OECD countries, with the sole exception of the Energy-exporting LDCs. This latter region experiences welfare losses over most of the simulation period: the maximum real income loss is almost 3 per cent below BaU levels in 2005, with the loss declining steadily after 2010 and even turning into a small gain in 2050 as the substitution away from the carbon-based synthetic fuel in the OECD regions raises the demand for crude oil.

Real GDP in the OECD area is almost 1 per cent below baseline in 2050, with the largest fall (-1.4 per cent) in Japan. Output effects in the non-OECD countries are marginal, with the sole exception of the Energy-exporting LDCs. Their GDP is 0.5 per cent below its BaU level in 2050 in response to the decline in oil output after 2030.

4. Tradeable permits

The dispersion in taxes, notably between Japan and the other OECD regions, suggests that some gains could be achieved by allowing trade in emission rights between OECD countries. The stabilisation scenario was re-run under the assumption that OECD regions could trade freely their fixed endowments of emission rights. This produced a reallocation of the emission cuts, with Japan being required to cut emissions by a lesser amount (-40 per cent in 2050) and the United States to increase its emissions cut (from -42 to -47 per cent in 2050) compared with the no-trade version of the agreement.

The bulk of the resulting trade in permits occurs between Japan and the United States. The volume of this trade is small: only 5 per cent of total OECD emissions are traded by 2050. The welfare gains from trading permits are also very small and are mainly reaped by Japan and the Energy-exporting LDCs. The latter region gains because more of the burden of the cut in OECD emissions is switched from crude oil to the carbon-based synthetic fuel. Hence, OECD imports of crude oil are higher than under the no-trade scenario. At the same time, the United States records almost no benefits from selling permits, the real income gains from permit sales to Japan being offset by the terms-of-trade loss from increasing oil imports.

B. EC stabilises emissions in 2000 at 1990 levels using a mixed energy/carbon tax

The joint Energy/Environment Council of EC Ministers decided in October 1990 on a commitment to stabilise emissions in the Community in 2000 at 1990 levels. The EC Commission has recently proposed a comprehensive strategy to the Council to achieve this commitment -- for details, see Commission of the European Communities (1991). A novel element in this strategy is a proposal for a mixed energy cum carbon tax. The Commission proposed that a tax equivalent to $3 per barrel of oil would be introduced at the beginning of 1993 and the tax would rise by an additional $1 per barrel in subsequent years to reach $10 per barrel in 2000. The tax would be split 50/50 between an energy component and a carbon-content component, equivalent in 2000 to a tax of $42 per ton of carbon and $874 per terajoule (16).

A simulation was run with GREEN to assess the effects of this tax. The Commission's proposal envisages exempting certain energy-intensive sectors and sectors heavily exposed to international competition from the tax until the Community's main trading partners take similar measures. However, no decision has yet been taken as to which sectors should be exempt and whether the exemption should be partial or total. For that reason, the tax was applied to all sectors in the simulation.

In keeping with the Commission's proposal, the tax was phased in gradually by the Community over the period from 1990 to 2000 and stabilised thereafter at $10 per barrel. As a result of imposing this tax, EC emissions in 2000 are simulated to be 13 per cent lower than in the BaU case (Table 7); this is slightly more than would be required to achieve stabilisation at 1990 levels -- emissions in 2000 are 5 per cent lower than in 1990. Maintaining the energy cum carbon tax after 2000 continues to exercise a restraining effect on EC emissions: by 2050, they are almost 40 per cent below the BaU level. This might seem surprising but it reflects the fact that the imposition of the tax encourages a switch away from coal and the "dirty" synthetic fuel back-stop towards the carbon-free electric back-stop after 2010 and oil after 2030. However, this action by the EC has a negligible impact on global emissions: at 18.5 billion tons of carbon in 2050, they are only 2.5 per cent lower.

1. Carbon leakages

The magnitude of the net leakage effect is measured in GREEN in terms of the ratio between the change in emissions outside the EC and the size of the emissions cut in the EC. In GREEN, the carbon leakages induced by the EC proposal are moderate: they peak around 11 per cent by 2000, and then decline thereafter to zero by 2050 (Figure 1). The leakages are larger than in the case when all OECD countries take action to stabilise emissions, reflecting the fact that the vast bulk of OECD trade is intra-area trade.

Positive leakages result from a shift in the comparative advantage of producing energy-intensive goods away from the EC towards the other OECD regions and certain non-OECD regions, notably the former Soviet Union, the CEECs and RoW. The negative leakages are due, in part, to income effects related to the contraction of oil exports from the Energy-exporting LDCs; they also occur in some other regions via inter-fuel substitution. Imposing the carbon/energy tax puts downward pressure on the world oil price and this creates less incentive to substitute away from oil in coal-intensive regions, like China.

2. Economic costs

The economic costs to the Community, in terms of lower output and welfare, of achieving this commitment to stabilise emissions in 2000 are very small. Read GDP is almost 1/2 of a percentage point below its BaU level in 2010 and the output loss rises slowly to 0.6 per cent by 2050 (Table 7). These output losses are slightly lower than those reported by a simulation undertaken for the Commission by DRI using its econometric models for eight Member States: this estimated that GDP would be 0.8 per cent lower than baseline after 15 years; they are, however, very close to those reported in Manne and Richels (1992) using the Global 2100 model. The estimated welfare effects are very similar to the GDP losses until 2030. After 2030, the EC suffers a terms-of-trade loss which aggravates its welfare loss. By 2050, EC real income is almost 1 1/2 per cent lower than its BaU level. However, over the whole period, the welfare loss to the EC is only -0.5 per cent (in present values computed assuming a fixed discount rate of 1 1/2 per cent).

The only other region which is affected by the EC tax is the Energy-exporting LDCs. Not surprisingly, this region records lower output and welfare as the imposition of the tax cuts back on EC oil imports. Real output and welfare in the Energy-exporting LDCs is 1/4-1/2 of a percentage point below its BaU level over the period 2000-2050. Its welfare loss reaches a maximum of 1 per cent in 2010 before fading away post-2030 as its terms of trade recover. Its welfare loss over the whole period (in present values) is -0.6 per cent.

IV. International Agreements including the Non-OECD Regions

A. A Toronto-type agreement

As part of a Toronto-type agreement, it is assumed that the OECD and the non-OECD regions bear different burdens in terms of carbon restrictions. Specifically, it is assumed that i) the OECD countries would cut back their emissions in 2010 to 80 per cent of their 1990 levels and stabilise them thereafter; and ii) emissions in the non-OECD regions would be restricted to be 50 per cent higher than their 1990 levels by 2010, and stabilised thereafter (17).

The net result of this agreement is that world emissions stabilise by 2010 at 6 billion tons of carbon per year, less than one-third of the BaU level in 2050 (see Figure 7). This scenario implies a relatively larger proportional cut in emissions relative to BaU levels in the non-OECD countries (-68 per cent) by 2050 compared with a cut of 54 per cent in the OECD countries, reflecting the fact that BaU emissions growth is much faster in the non-OECD regions, with the notable exceptions of the former Soviet Union and the CEECs. Hence, stabilising emissions post-2010 imposes greater stringency on the non-OECD regions. By 2050, the OECD area only accounts for 20 per cent of the global emissions cut whereas India and China together bear almost half of the global burden.

1. Carbon taxes

Levying carbon taxes puts downward pressure on the real oil price. By the year 2030, the world oil price is almost 15 per cent below its BaU level. After 2030, the oil price rises faster than in the BaU scenario as carbon taxes make the carbon-based synthetic fuel unprofitable and the oil supply constraint in the Energy-exporting LDCs becomes binding.

On average, the OECD carbon tax rises to a peak of $250 per ton of carbon in 2005, before falling back slowly to $116 in 2050 compared with a global average tax of $160 (Figure 8). The dispersion of taxes across OECD regions is particularly wide before 2010 when no back-stop options are available. As back-stops come on stream, OECD countries tend to rely heavily in the BaU case on the carbon-based synthetic fuel, the "dirtiest" energy source. Thus, carbon taxes tend to converge on the levels at which the carbon-based synthetic fuel option is no longer profitable as an energy source. This level is higher in Japan than in the other OECD regions because it taxes oil more heavily. The higher is the price of oil (including taxes), the higher must be the carbon tax which makes the carbon-based synthetic fuel unprofitable -- see the Appendix for further discussion.

Before 2010, when back-stops are not available, taxes reflect rates of emissions growth and relative energy prices across countries. As Japan has the fastest growth of emissions among the OECD regions over this period as well as the highest relative energy prices (see Table 4), it requires very high taxes to meet the emission constraint. The inverted V-shaped profile of the carbon tax over the period 1995-2010 reflects the interaction of the putty/semi-putty specification of technology -- the short-run elasticity of inter-energy substitution is very low relative to the long-run value -- with the phasing-in of the emission restriction. In these circumstances, much higher taxes are required in the short run to meet the emissions constraint (18). In Japan, the tax reaches almost $500 per ton in 2005 before falling back sharply to $50 in 2010 when the carbon-free electric back-stop becomes available. After 2010, the tax rises steadily to around $200 per ton in 2050, a level at which the carbon-based synthetic fuel only accounts for a minor part of total demand for oil.

Compared with the OECD countries, carbon taxes are much lower in the former Soviet Union and the CEECs. Carbon constraints do not become binding before 2005 in the former Soviet Union and 2010 in the CEECs. With low rates of emissions growth in the BaU scenario and heavily subsidised fossil-fuel prices, these regions do not require high taxes to meet their constraint: by 2050, taxes are still below $50, a level at which no back-stop options are profitable.

The other non-OECD regions fall into two distinct groups: i) low-cost countries which either rely massively on cheap, subsidised coal (China and India) or on the carbon-based synthetic fuel (RoW); and ii) high-cost countries which combine above-average GDP growth with energy demand relying mainly on oil (Brazil, DAEs and the Energy-exporting LDCs). Taxes in the low-cost countries are negligible until 2010, but they rise steadily thereafter as the constraints become more binding: by 2050, both China and India have a tax of over $260 per ton of carbon. In both China and India, the marginal cost of replacing coal as an energy source rises sharply over time as coal continues to be heavily subsidised; as a result it never gets eliminated as an energy source by a back-stop. In RoW, the required carbon reduction can be achieved at a lower cost than in China and India by eliminating the carbon-based synthetic fuel.

In Brazil, the DAEs and the Energy-exporting LDCs, on the other hand, stabilising emissions post-2010 requires taxes sufficiently high to permit the carbon-free synthetic fuel to replace oil. Indeed, Brazil has the highest marginal abatement cost of all the non-OECD regions for most of the period because i) its electricity sector relies mainly on hydro-power, a "clean" energy source; and ii) it is very dependent on imports of oil. The tax increase in the DAEs is somewhat slower since they can achieve part of their required curb in emissions by using the carbon-free electric back-stop. The Energy-exporting LDCs rely mainly on oil and, since they subsidise its use domestically, their marginal abatement cost is likely to rise rapidly over the long run.

Thus, Figure 8 shows that marginal abatement costs under a Toronto-type agreement are higher in the OECD regions than in the non-OECD regions until the back-stops come on stream. By 2050, the situation is completely reversed: emission reductions are much more costly in some non-OECD regions.

2. Use of back-stop options

Total primary energy demand in the OECD regions recovers to its 1990 level in 2050 thanks to the growing penetration of the carbon-free electric option (Figure 9a). The major changes in the composition of OECD energy demands are: i) the decline in the share of the carbon-based synthetic fuel (down from 17 per cent in the BaU scenario to only 10 per cent by 2050); ii) the rise in the share of oil (up from 9 per cent in the BaU to 28 per cent); and iii) the increase in the share of the carbon-free electric option (up from 10 per cent in the BaU to 24 per cent).

The significant inroads of the back-stops in the OECD countries contrast with their virtual absence in the non-OECD regions (Figure 9b). Cutting back on the demand for coal accounts for 85 per cent of the required emissions reduction in these regions.

3. Terms of trade

The OECD countries experience terms-of-trade gains over most of the period as the carbon constraints force them to cut back sharply on oil imports. These terms-of-trade gains peak around 2010 and begin to ebb away slowly thereafter as the restrictions can be met by using back-stop options instead of cutting down on oil imports. By 2050, all the OECD regions record terms-of-trade losses as carbon taxes induce them to substitute oil imports for the carbon-based synthetic fuel.

Most non-OECD regions experience very small terms-of-trade losses or gains. But there are three exceptions. Brazil, which is very reliant on imported oil, experiences very large terms-of-trade gains up to 2030. The Energy-exporting LDCs experience a sharp terms-of-trade loss until 2030, in line with the decrease of the world oil price relative to the BaU scenario; their terms of trade, however, recover sharply after 2030 as a result of the switch away by the OECD countries from the carbon-based synthetic fuel towards imported oil. Finally, China experiences a growing terms-of-trade loss from 2030 on as it responds to the carbon restriction by substituting oil imports for coal and the carbon-free synthetic fuel. These substitutions reflect the initial pattern of energy price distortions in China: coal is heavily subsidised whereas the domestic oil price is very close to the world price.

4. Welfare and GDP effects

Figure 10a shows that the welfare loss of the OECD countries fluctuates over the period. It reaches 2 per cent in 2010 but, as the back-stops lower the costs of cutting emissions between 2010 and 2030, the loss falls to only 1 per cent in 2030. It increases again after 2030 to reach 2.1 per cent in 2050 as a result of growing terms-of-trade losses in line with the increase of the world oil price. Thus, OPEC oil supply in the middle of the next century is a significant factor in determining the magnitude of the welfare loss suffered by the OECD countries under a Toronto-type agreement.

The CEECs enjoy welfare gains for most of the period while the former Soviet Union records very small losses (Figure 10b). Their carbon constraints are not binding before 2010 and are moderate thereafter; at the same time, they benefit from the falling oil price until 2030 -- the former Soviet Union becomes a net oil importer after 2020. Both regions experience small welfare losses in 2050 as the world oil price hardens.

Figure 10c reveals a very diverse set of welfare impacts among the other non-OECD regions. Before 2030, the largest losses are recorded by the Energy-exporting LDCs -- their real income is almost 10 per cent below baseline in 2030. Brazil and the DAEs record welfare gains in line with the falling world oil price. Post-2030, there is a significant shift in the patterns of welfare gains and losses. The recovery of oil demand in the OECD countries and domestic supply shortages combine to produce an income shift in favour of the Energy-exporting LDCs. As a result, their welfare loss narrows sharply to 3 1/4 per cent in 2050. China and India become the main losers among the non-OECD regions as a result of their high carbon taxes: by 2050, their welfare losses reach 8 and 4 per cent, respectively.

By 2050, world GDP is 2 per cent below its BaU level; the output loss in the OECD area is only 1 per cent (Table 8). Losses of 4 per cent or more are recorded in China, Brazil and the Energy-exporting LDCs. Not surprisingly, the coal industry bears the brunt of this output loss: its output world-wide is almost 80 per cent below its BaU level by 2050. World oil output is 12 per cent above BaU in 2050. This reflects an intertemporal reallocation of oil reserves by the Energy-exporting LDCs: falling demand for their oil before 2030 allows them to conserve reserves which are used to meet the additional OECD import demand after 2030. Very little reallocation occurs among energy-intensive industries within the OECD regions, reflecting the similarity of their industrial structures and the small dispersion of their carbon taxes. The largest shifts occur between Japan, on the one hand, where output of these industries is 1.7 per cent lower than baseline in 2050 and the United States where output in this sector is 0.7 per cent higher in 2050.

Sectoral reallocation is much larger among the non-OECD regions in line with the greater diversity of marginal abatement costs across countries/regions. In particular, countries/regions with the highest taxes (Brazil, DAEs, Energy-exporting LDCs and India) lose competitiveness in energy-intensive industries to the benefit of RoW and the CEECs.

5. Comparison of alternative policy instruments

Two further simulations were run to assess the costs of achieving a Toronto-type agreement using either a pure energy tax or a mixed energy cum carbon tax along the lines of the recent EC Commission proposal. Since the ultimate target is to curb emissions, a tax on the energy content of primary energy demands cannot equalise the marginal costs of reducing emissions across sectors since each fossil fuel has a specific carbon content. Thus, the output and welfare losses would be expected to be larger under these two alternative taxes as compared with a carbon tax.

This expectation is borne out by the simulation results. Averaged over all 12 regions, the output and welfare effects are as follows:

(Percentage changes relative to BaU levels)

	Energy tax			Energy _cum_ carbon tax			Carbon tax		
	2010	2030	2050	2010	2030	2050	2010	2030	2050
Real GDP	-1.1	-1.9	-2.8	-1.0	-1.8	-2.4	-1.1	-1.5	-2.0
Real income	-2.0	-2.7	-3.8	-1.9	-2.5	-3.4	-2.0	-2.2	-2.9

A comparison of the cost estimates across the three scenarios reveals that regions which are either significant oil and gas producers such as the Energy-exporting LDCs or are dependent on imports of such fuels (the DAEs, Brazil) suffer larger welfare losses when the emissions reduction target is achieved by an energy tax as opposed to a carbon tax. For example, the Energy-exporting LDCs record a welfare loss of over 10 per cent in 2050 with an energy tax compared with a 3 per cent loss under a carbon tax. In contrast, large coal-consuming countries such as China and India record smaller welfare losses under an energy tax.

B. Cost-effective Toronto-type agreements

A Toronto-type agreement is _not_ a cost-effective agreement given the very wide dispersion in marginal abatement costs across regions revealed in Figure 8. We now attempt to quantify the potential magnitude of the gains that could be reaped if the agreement were extended to allow marginal costs of cutting emissions to be equalised across regions.

1. Gains and losses from a cost-effective allocation of carbon restrictions

A first scenario is simulated in which every region applies _a common equilibrium tax_ which achieves the same cut in global emissions as in the Toronto-type agreement. However, each region is allowed to choose the level of emissions cut which corresponds to equalising its specific marginal cost to the common world tax.

The global carbon tax falls to $140 per ton of carbon in 2050 instead of $161 in the no-trade case. This produces a welfare gain of 1 per cent (in present values) to the world as a whole compared with the scenario in which constraints are imposed on each region. Figure 11 compares the average real income changes under the previous Toronto-type agreement with those yielded by the cost-effective allocation of emission cuts. It shows that the Energy-exporting LDCs gain substantially from this latter agreement. Cutting back on oil demand is an expensive way of curbing emissions and any alternative distribution of emissions curbs which cuts back more on coal demand will be more cost-effective at the world level. It also has a significant impact on the oil price profile. Oil demand decreases less than under the previous scenario and the oil price increase post-2030 is larger: by 2050, the world oil price is 17 per cent higher than its BaU level. On the other hand, such a cost-effective agreement shifts the burden of stabilising emissions from the OECD and semi-industrialised LDCs to coal-based economies whose real incomes fall more than in the previous Toronto-type agreement. Therefore, the Toronto-type scenario with either fixed region-specific constraints or a cost-effective allocation of emission cuts yields an uneven distribution of income losses. In the former scenario, the Energy-exporting LDCs bear high real income losses whereas in the latter scenario, the main losses are borne by the low-income LDCs, like China and India and by the former Soviet Union and the CEECs.

2. Toronto-type agreement with tradeable permits

Permits trading provides a way of modifying the distribution of real income losses which is associated with cost-effective allocation of emission cuts in order to make it more compatible with equity goals. Specific restrictions on CO_2 emissions are regarded as initial endowments of emission rights which can be traded between regions. These endowments are fixed over the simulation period. This initial allocation rule is arbitrary and it can be varied in GREEN to reflect a variety of international distributional considerations. The same global constraint on CO_2 emissions is imposed as under the no-trade version of the Toronto-type agreement. When trade in emission rights is allowed and all regions are assumed to be "small" in the permits market, i.e. no region has market power, emission cuts will be optimally allocated across regions when a common equilibrium tax is established in <u>all</u> regions.

Figure 12 shows the resulting patterns of trade in permits over the period. Traded emissions rise to 12 per cent of global emissions in 2010 and this share remains rather stable thereafter. A major factor driving this large trade in permits is the generosity of the initial endowment of permits to the former Soviet Union relative to its low marginal abatement cost by treating it like the other non-OECD regions. As its emissions growth in the BaU is much lower than in the other non-OECD regions, it benefits from this allocation rule.

The former Soviet Union is the major seller of permits: by 2050, it accounts for almost 80 per cent of all permits traded, with the remainder being sold by the CEECs. Before 2030, the main buyers of permits are the OECD regions, principally the United States and the EC. But as the OECD regions increase their reliance on back-stop options, their demands for permits correspondingly shrink. From 2030 on, China, Brazil, the DAEs and especially the Energy-exporting LDCs become the main buyers of permits. Because they subsidise their domestic energy prices so heavily, these regions make no use of back-stop options and, hence, have a strong incentive to buy permits instead. Thus, tradeable permits provide them with a substitute for the use of back-stops.

3. Gains and losses from tradeable permits

Figure 11 shows how tradeable permits modify the distribution of losses in the cost-effective scenario. The former Soviet Union and the CEECs gain from permits trading to such an extent that they would record net real income gains (3 and 2 per cent, respectively) from such an allocation of emission rights. On the other hand, regions which have to buy permits lose relative to the cost-effective scenario although some of them still gain compared with the initial Toronto-type scenario with no permits trading. Relative to the initial no-trade case, OECD countries and RoW are slightly better off whereas some semi-industrialised LDCs which rely more on crude oil -- such as the DAES and Brazil -- report higher welfare losses. In these latter countries, the additional burden from the international oil price increase and from buying permits is not outweighed by the benefit from applying lower carbon restrictions. For instance, in Brazil, the real income loss amounts to 4.4 per cent in 2050 compared with 2.2 per cent in the no-trade scenario, with most of this additional loss due to the increase of the oil price. Figure 10 also shows that tradeable permits make the distribution of losses between OECD and non-OECD countries more equitable than in the other two scenarios.

4. Alternative endowments of tradeable permits

In order to highlight the sensitivity of welfare gains and losses to the initial allocation rule for permits, a variant of the above scenario was run in which the former Soviet Union and the CEECs were subject to the same carbon restriction as the OECD regions. This gave them a smaller endowment of permits compared with the previous case. The simulation was run first, without tradeable permits and then with tradeable permits.

For the world as a whole, this version of the Toronto-type agreement produced a slightly larger cut in emissions relative to BaU (-69 per cent) in 2050 than in the previous version of the agreement (-64 per cent). This cut is achieved at higher marginal cost since the average global carbon tax in 2050 increases from $160 per ton of carbon in the previous version of the agreement to $200 per ton in this version. Higher taxes are required in the former Soviet Union ($126 instead of $35) and in the CEECs ($163 instead of $42) to meet their more stringent constraints. These higher taxes are still, however, below the levels at which back-stop options are profitable. They also yield higher welfare losses for both regions compared with the previous version of the agreement: the average discounted welfare loss for the former Soviet Union is -1.0 per cent (compared with a loss of only -0.2 per cent) and -1.1 per cent for the CEECs (compared with a gain of 1 per cent).

Figure 13 shows the resulting pattern of trade in permits. The proportion of total emissions traded in any period varies between 7 and 9 per cent from 2010 on. The fact that the proportion of global emissions traded is less than in the previous version of the agreement suggests that endowing the former Soviet Union and the CEECs with the same amount of permits as the OECD regions is closer to the optimal allocation of emission constraints which would emerge from equalising marginal abatement costs across regions. During the period when the former Soviet Union and the CEECs have to achieve their larger emission cuts, China is the major seller of emission rights. This situation is reversed after 2030, when it becomes increasingly costly to stabilise emissions in China, and the former Soviet Union, as before, takes over as the major seller.

Figure 14 compares the welfare gains from permits trading under the two alternative allocations of permits. As expected from the lower volume of permits traded, the gains are smaller when the former Soviet Union and the CEECs are treated like the OECD regions: the average discounted OECD welfare gain is 0.2 per cent compared with 0.4 per cent under the alternative allocation rule and the average discounted gain for the non-OECD regions is 1.4 per cent compared with 2.1 per cent under the previous allocation rule. The distribution of these gains across the non-OECD regions is also different: China is now a major beneficiary from trade in permits and the gains to the former Soviet Union are much smaller. The Energy-exporting LDCs also benefit much less than in the previous scenario since less trade in permits means less of the global burden of emissions cuts being borne by the coal-based economies and, therefore, a lower oil price.

V. Eliminating Distortions in Energy Prices

A constant theme in this paper has been the significance of the large differentials in energy prices across regions which are present in the 1985 benchmark data. These differentials play an important role in substitution between the fossil fuels and the choice between conventional energies and back-stop options. Therefore, they are a major determinant of emissions. One major element in explaining these price differentials is differential energy taxes/subsidies across regions. This suggests that a possible alternative strategy to an international agreement calling for the imposition of carbon or energy taxes, while preserving the existing structure of energy price distortions, would be an agreement to eliminate these distortions. This section presents the results of such a simulation. It also compares the outcomes of a Toronto-type agreement (with and without permits trading) which includes the removal of distortions with one which does not.

A. Quantifying energy price distortions in 1985

The ideal approach would carefully identify and quantify the separate tax *cum* subsidy rates applied to each energy source in all 12 regions. Some work along these lines has been undertaken for the OECD countries by Hoeller and Coppel (1992) using IEA data, and their approach has been used for the purposes of this exercise. It would, however, be a mammoth research task to extend this to cover the non-OECD regions (19). Instead, a much more rudimentary approach has been followed which consists of computing wedges between the domestic prices of primary fuels (computed from the national I-O tables) and average "world" prices (20). For coal, a further adjustment was made to the estimated wedges to allow for inland transportation costs (21). No adjustment for transport costs was made for oil or natural gas.

The resulting nominal wedges on primary fuel prices by region are reported in Figure 15. This shows that, on average across all twelve regions, fossil fuels are subsidised: the average subsidy rate ranges from 15 per cent for coal to 33 per cent for gas. Most energy subsidies are concentrated in China, India, the Energy-exporting LDCs, the former Soviet Union and the CEECs; the latter two regions have the largest subsidy rates. The DAEs and Brazil have much lower subsidy rates. Coal use appears to be heavily taxed in Brazil and RoW, but the price data for the latter region are particularly poor, so not too much reliance should be put on them. Among OECD regions, only Japan and the EC appear to tax primary energies, principally coal: the estimated tax rate in both regions is around 40 per cent. Given the crude method of calculating these wedges, these estimates are only illustrative. Nevertheless, it is an undeniable fact that large differences in energy prices do exist across regions, especially in some non-OECD regions, and they must be considered seriously in any assessment of measures to curb CO_2 emissions (22).

B. Elimination of these wedges

The simulation assumes that these initial wedges between domestic and "world" prices are removed gradually over the period 1990-2000. Removing these wedges has a significant impact on the world oil price compared with its profile under the BaU scenario. By 2000, the oil price has fallen by 8 per cent in real terms below its level in the BaU scenario and this gap widens over the rest of the period, especially after 2030 when oil competes with the carbon-based synthetic fuel option. Thus, by 2050, the world oil price is 24 per cent below its BaU level (23). The natural gas price is 27 per cent below its BaU level in 2050, reflecting the removal of the large subsidies in the former Soviet Union. Unlike oil and gas prices, the world average coal price is little changed from its BaU level. This reflects two factors specific to coal: i) its lower average subsidy rate (after adjusting for transport costs); and ii) its higher supply elasticity. As the price of coal rises relative to oil and gas, emissions should grow at a slower rate than in the BaU scenario.

Removing distortions has a significant impact on the use of back-stop technologies. In response to the downward pressure on the world oil price, OECD countries rely much less on the carbon-based synthetic fuel: it accounts for only 7 per cent of primary energy demand in 2050 compared with 18 per cent in the BaU scenario (compare Figure 16 with Figure 1). The reliance on oil increases correspondingly: it accounts for 23 per cent instead of 9.5 per cent. The composition of energy demand in the non-OECD regions is not very different to the BaU scenario, but its level (in terajoules) is 32 per cent below the BaU level in 2050.

1. Carbon emissions

A comparison of Tables 5 and 9 shows that emission growth rates in most non-OECD regions fall significantly when energy price distortions are eliminated. Brazil and RoW stand out as the only non-OECD regions with faster emissions growth. In Brazil, this reflects the removal of oil subsidies which accelerates the phasing-in of the carbon-based synthetic fuel. In RoW, the removal of oil subsidies combined with the removal of very large coal taxes shifts its energy demand towards greater use of coal and synthetic oil. Emissions growth is slightly faster in the OECD regions, reflecting the removal of coal taxes in Japan and the EC.

Figure 17 illustrates an important feature of this scenario: the removal of existing distortions has a greater long-term effect on lowering emissions than it has in the short-term: world emissions are only 7 per cent below their BaU level in 2000, but they are 20 per cent lower, at 14.8 billion tons, in 2050. This long-term effect on emissions reflects the stabilisation of the world oil price at a lower level than in the BaU case, thereby mitigating the degree of substitution towards coal. Figure 18 shows that the contribution of the OECD countries to world emissions is higher when distortions are removed than it is in the BaU scenario -- 35 per cent compared with 26 per cent (see Figure 2). The most significant changes are the halving in the shares of China (from 29 to 14 per cent) and the sharp rise in the share of RoW (from 6 to 17 per cent). These shifts reflect not only the direct effects of removing large energy subsidies (China) and large energy taxes (RoW), but also the replacement of oil by the synthetic fuel from 2030 on.

2. Terms-of-trade effects

Removal of the energy price distortions induces large terms-of-trade swings relative to the BaU case, swings which are mainly related to shifts in the net trade of oil. In the OECD countries, the fall in the world oil price at first leads to terms-of-trade gains. These turn to losses from 2010 on in Japan and the EC, the main oil-importing regions. All OECD regions record terms-of-trade losses after 2030 as there is less pressure to use the carbon-based synthetic fuel than in the BaU case. Whereas OECD oil imports almost disappear in the BaU, they continue to import large volumes of crude oil in this scenario in response to the lower world oil price.

As most non-OECD regions subsidise energy, their terms of trade improve when they eliminate these subsidies. But these gains tend to vanish by 2050 for some regions (DAEs, RoW) which are heavily dependent on oil imports. India and Brazil, on the other hand, experience large gains over the entire period. The former Soviet Union also experiences a large terms-of-trade gain; as its large oil subsidies are eliminated, it exports large volumes of oil and these exports persist until 2050. The Energy-exporting LDCs experience a significant terms-of-trade loss until 2030, but they reallocate their oil reserves over time which permits them to maintain their oil exports over the period 2030 to 2050. By 2050, their terms-of-trade loss has turned into a gain. China experiences a large terms-of-trade loss since the removal of its large coal subsidy shifts demand towards imported oil.

3. Real income

Welfare effects come from both the efficiency gains associated with the removal of the distortions and the terms-of-trade changes. The OECD regions experience small average welfare gains until around 2030 when this turns into a small welfare loss (Figure 19). The latter outcome is dominated by the terms-of-trade changes: the lower world oil price reduces the profitability of the carbon-based synthetic oil and increases the reliance of the OECD regions after 2030 on imported oil. Over the period as a whole, the real income gain for the OECD area is negligible (0.1 per cent in present-value terms).

The main gainers from removing distortions are the former Soviet Union and the CEECs: their real incomes are almost 19 and 14 per cent, respectively, above BaU levels in 2050. These gains reflect not only the large improvement in the terms of trade noted above but also large efficiency gains arising from the suppression of energy subsidies. Most other non-OECD regions record welfare gains too, but on a much smaller scale. The main beneficiaries are Brazil and India, with gains of 4.8 and 3.8 per cent in 2050. China experiences a small welfare loss of 1.2 per cent in 2050 due to its terms-of-trade loss. The Energy-exporting LDCs record large welfare losses over the period to 2010, but they decline thereafter; indeed, by 2050 they even have a small welfare gain. The present value of the welfare gain for the non-OECD regions over the entire period is 1 per cent higher real income.

C. A Toronto-type agreement combined with removal of energy price distortions

The required cut in global emissions below BaU levels in 2050 is slightly smaller (-58 per cent) under this expanded agreement compared with a Toronto-type agreement which does not include removal of distortions (Figure 20). The required curbs on emissions are less stringent in some regions which subsidise energy (former Soviet Union, China, India). However, the constraint is more stringent in some regions which tax energy such as Japan, the EC, the DAEs and Brazil. In RoW, a larger emissions cut is needed to meet the Toronto-type target due to the elimination of its large tax on coal.

As the overall emissions reduction is slightly smaller at the global level, the expectation might be that it would require smaller carbon taxes to achieve it as compared with a Toronto-type agreement without removal of distortions. On the other hand, the "average carbon price" -- a good indicator of the carbon tax (see the Appendix) -- has increased relative to the BaU case in regions where energy was subsidised, reflecting not only the elimination of these subsidies but also the decline in average carbon content of primary energy demand in regions (such as China) where coal was more heavily subsidised than oil or gas. These two opposing effects offset each other and the global average carbon tax of around $160 per ton in 2050 is identical under both scenarios. The OECD average tax of around $150 in 2050 is higher than under the agreement maintaining the distortions, mainly as a result of a higher tax in Japan. The latter outcome reflects the greater effort required to stabilise Japanese emissions when the large coal tax is removed.

Figure 21 shows that Toronto-type targets can be achieved at a lower welfare cost (in present values) for the world as a whole if energy price distortions are removed at the same time: a loss of 1.5 per cent compared with 2 per cent when distortions are maintained. The main beneficiaries from this would be the non-OECD regions: their aggregate welfare loss would fall from 3.1 per cent to 1.9 per cent. Some of these regions, notably the former Soviet Union, the CEECs, India and Brazil, would even record welfare gains from a Toronto-type agreement which was also combined with the elimination of existing distortions. In contrast, the Energy-exporting LDCs would record larger losses (11 instead of 7 per cent) in line with the fall in the world oil price. The welfare loss to the OECD regions would be slightly larger (-1.3 per cent instead of -1.1 per cent).

D. A Toronto-type agreement combining removal of energy price distortions with trade in permits

Under this scenario, the volume of traded emissions as well as the pattern of permits trading across regions are quite similar to the scenario in which distortions are not removed (see Figure 12). Figure 22 compares the average real income changes (in present values) for three versions of a Toronto-type agreement. In two of them, existing distortions are maintained and the sole difference is whether the agreement allows for permits trading or not; the third scenario combines permits trading with elimination of distortions. In all three scenarios, the former Soviet Union and the CEECs are grouped with the other non-OECD regions.

The most striking result from Figure 22 is that the average welfare loss for the non-OECD regions falls to zero when permits trading is combined with the elimination of distortions. The global welfare loss is only 0.5 per cent compared with 2 per cent in the Toronto-type agreement with no trade in permits. But the distribution of winners and losers is very uneven among the non-OECD regions. The former Soviet Union and the CEECs, which were already net gainers from permits trading, record even larger real income gains when they remove their large energy subsidies. Oil-dependent economies such as the DAEs and Brazil also benefit. China's welfare loss is lower when permits trading is combined with elimination of distortions. The energy-exporting LDCs are the only region to record large real income losses (-7 per cent) when distortions are eliminated and permits are traded. The OECD regions' average loss is 0.8 per cent, slightly less than under the scenario with no trade in permits.

Notes

1. Helpful comments on previous drafts of the paper were received from Paul Atkinson, Jonathan Coppel, Andrew Dean, Jorgen Elmeskov, Robert Ford, Peter Hoeller, and Constantino Lluch. We are very grateful to Laurent Moussiegt and Isabelle Wanner for statistical assistance, and to Lyn Louichaoui and Brenda Livsey-Coates for technical assistance.

2. See IPCC (1990) for a detailed review of the evidence. However, the latest assessment of the scientific evidence by IPCC (1992) suggests a lower net rate of increase in global mean temperature, at least over the period when sulphur emissions continue to increase.

3. With the extended time horizon, the model computes equilibria at the following dates: 1990, 1995, 2000, 2005, 2010, 2030 and 2050. Results in the rest of this paper are, however, reported for all five-year intervals, with figures for intermediate years post-2010 being linear interpolations of the model outcomes for 2010, 2030 and 2050.

4. Glomsrød *et al.* (1990) point out that a side-benefit from curbing CO_2 emissions would be an associated reduction in emissions of such airborne pollutants. Their calculations for Norway indicate that the ancillary benefits would offset 70 per cent of the GDP loss due to the CO_2 restriction.

5. Berger *et al.* (1991) argue that a more reasonable description of the oil market is one in which there is a dominant producer (OPEC) with a fringe of price-taking producers. They show that under imperfect competition the type of international agreement can have a significant impact on the markets for fossil fuels.

6. Several models which have been used to quantify the costs of curbing CO_2 emissions assume that agents have perfect foresight. This is the case, for example, in the Global 2100 model of Manne and Richels (1992*a*) and in the DGEM model of the U.S. economy developed by Jorgenson and Wilcoxen (1990).

7. See Hoeller *et al.* (1991); Boero *et al.* (1991); and Cline (1992) for comprehensive surveys of the literature quantifying the economic costs of reducing CO_2 emissions.

8. Real income gains and losses in GREEN are expressed in terms of Hicksian "equivalent variation", i.e. the amount of income that 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. For full details on how this welfare measure is computed, see Burniaux *et al.* (1992).

9. It would be possible to simulate with GREEN the effects of varying the endowments of permits over time with the objective of minimising real income changes across regions. It is hoped to investigate this possibility in future work.

10. The endogenous oil price profile in GREEN is very close to the exogenous profile laid down for EMF12. This is not surprising because the latter is consistent with the EMF12 assumptions on back-stop prices which are also used in GREEN.

11. Shah and Larsen (1991) review energy pricing regimes in developing countries and highlight the fact that substantial subsidies for fossil-fuel use exist in a small number of large CO_2 emitters.

12. See IEA (1991*a*) for an up-to-date overview of the status of OECD countries' formal commitments to actions to deal with climate change.

13. With the Japanese population projected to decline by 0.2 per cent per annum from 2010 on, the emission restriction imposed in Japan is relatively more stringent than in the other OECD regions by the end of the period since the projected population in 2050 is below its 1990 level.

14. See Perroni and Rutherford (1991) and Rutherford (1992) for discussions of this issue.

15. One important aspect of the treatment of back-stop technologies is the assumption that they are not traded between regions. Instead, following the approach adopted by Manne and Richels in their Global 2100 model, it is assumed that back-stop technologies become available at given dates in the future at the same cost in all regions. This rules out any incentive to trade in "new" energy sources between regions.

16. A tax of $874 per terajoule is equivalent to a tax of $36 1/2 per ton of oil equivalent.

17. There is one change in the specification of the Toronto-type agreement from that presented in Burniaux *et al.* (1991). The former Soviet Union is no longer grouped with the OECD countries but is now treated as one of the non-OECD regions with a less binding emission restriction.

18. Other models which have been used to address the climate change issue and which include putty-clay technology and back-stop technologies also show an inverted V-shaped profile of the carbon tax across regions up to 2010. This is the case with the Global 2100 model of Manne and Richels (1992*a*) and the CRTM model of Rutherford (1992). Obviously, allowing for perfect foresight would smooth out this profile but, as the results with the Manne-Richels model show, not eliminate it entirely.

19. Shah and Larsen (1991) present some evidence showing very large energy subsidies in some non-OECD regions, notably the former Soviet Union, China and India.

20. "World" prices for coal and natural gas in 1985 are calculated on the basis of f.o.b. export prices from major exporting countries by using UN Trade Statistics and Energy Statistics. These yielded a world price for coal of \$47.4 per ton, equivalent to \$1777.8 per terajoule, and a world gas price of \$3627 per terajoule. The world oil price in 1985 was \$27.6 per barrel, equivalent to \$4826 per terajoule.

21. Estimates of transport cost margins were obtained from IEA (1991*b*, Table 5.1) by assuming that the average inland transportation distance is half of the reported distance from coal mines to ports. This produced the following estimates: United States (27 per cent); Other OECD countries (Australia, 17 per cent); Energy-exporting LDCs (South Africa, 13 per cent). In the absence of such data for the former Soviet Union, China and India, an arbitrary 25 per cent margin for transport costs was applied.

22. Part of the tax on refined oil products, especially in OECD regions, is best regarded as a method of taxing road users for congestion and/or user charges for the provision and maintenance of roads, rather than as a distortion giving rise to deadweight costs. In a full discussion of end-use energy pricing, it would be desirable to take account of the two externalities, i.e. congestion costs and emissions. See Newbery (1992) for a discussion of this complication. But the estimated tax wedges in GREEN are levied on primary fuel use not on refined oil.

23. The world oil price falls in proportion to its global average rate of subsidy. The explanation for this is related to the arbitrage condition between the crude oil price (P^o) and the carbon-based synthetic fuel (P^c):

$$P^o.(1 - s) = P^c$$

or $$P^o = P^c/(1 - s)$$

with s = the subsidy rate on oil. Assuming that the reserve constraint on crude oil is binding in the Energy-exporting LDCs, eliminating the subsidy rate should lower the oil price by s per cent.

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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
9) Carbon-based back-stop
10) Carbon-free back-stop
11) Carbon-free electric back-stop

Consumer Sectors

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

Regions

1) United States
2) Japan
3) EC
4) Other OECD (b)
5) Central and Eastern Europe (c)
6) The former Soviet Union
7) Energy-exporting LDCs (d)
8) China
9) India
10) Dynamic Asian Economies (e)
11) Brazil
12) 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]

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

b) Australia, Canada, New Zealand, EFTA (excluding Switzerland and Iceland) and Turkey.

c) Bulgaria, Czechoslovakia, Hungary, Poland, Romania and Yugoslavia.

d) 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.* (1992).

e) Hong Kong, Philippines, Singapore, South Korea, Taiwan and Thailand.

Table 2. **Summary of simulation results**

Description of scenario	Emissions cut in 2050 (per cent change relative to BaU)			Carbon taxes in 2050 (1985$ and exchange rate per ton of carbon)			Present value of real income changes (1) over the period 1995-2050 (per cent relative to BaU)		
	OECD	Non-OECD (2)	World	OECD	Non-OECD (2)	World	OECD	Non-OECD (2)	World
1. Stabilisation of OECD emissions in 2000	-43	0	-11	76	0	12	-0.6	-0.3	-0.4
2. EC imposes a mixed for energy/carbon tax	-10	0	-3	8	0	2	-0.2	-0.2	-0.2
3. Toronto-type agreement	-54	-68	-64	116	183	161	-1.2	-3.2	-2.1
4. Toronto-type agreement with common carbon tax (3)	-50	-69	-64	109	158	140	-0.5	-1.6	-1.0
5. Toronto-type agreement including tradeable permits (4)	-50	-69	-64	111	156	140	-0.8	-1.1	-1.0
6. Eliminating distortions in energy prices	10	-31	-20	0	0	0	0.1	1.1	0.5
7. Toronto-type agreement plus elimination of distortions in energy prices	-54	-70	-66	149	173	165	-1.2	-1.7	-1.4
8. Toronto-type agreement plus elimination of distortions in energy prices and tradeable permits (4)	-46	-73	-66	109	153	136	-0.8	0.2	-0.3

1. The present value is computed as the discounted sum of the annual gains and losses relative to the sum of annual real income. A fixed discount rate of 1.5 per cent per annum was applied in all regions.
2. Brazil, China, DAEs, Energy-exporting LDCs, India, former Soviet Union, CEECs, RoW.
3. This scenario implies one common carbon tax in nominal values for all regions. Expressed in 1985$ and exchange rates, real tax levels differ across regions in line with region-specific real exchange rates.
4. These scenarios imply a common world price for emissions permits (a "shadow price" of carbon) in all regions. Expressed in 1985$ and exchange rates, real prices of emissions permits differ across regions in line with region-specific real exchange rates.

Table 3. GDP and population projections underlying the BaU scenario in GREEN

Annual average growth rate

	1990-2000		2000-2020		2020-2050	
	Real GDP	Population	Real GDP	Population	Real GDP	Population
United States	2.6	0.7	2.2	0.4	1.6	0.0
Japan	3.7	0.3	2.7	-0.1	2.2	-0.3
EC	2.2	0.1	1.7	-0.1	1.3	-0.3
Other OECD	2.2	1.2	1.7	0.7	1.3	0.3
Central and Eastern Europe	2.7	0.4	2.2	0.3	1.7	0.1
Former Soviet Union	2.6	0.6	2.1	0.4	1.6	0.2
Energy-exporting LDCs	3.6	2.3	3.5	1.8	2.7	1.1
China	4.6	1.3	4.4	0.8	3.4	0.3
India	4.6	1.8	4.5	1.2	3.4	0.7
Dynamic Asian Economies	4.4	1.4	4.2	0.9	3.2	0.5
Brazil	4.4	1.7	4.2	1.1	3.2	0.6
RoW	3.5	2.6	3.2	2.2	2.4	1.4
Total OECD	2.6	0.5	2.1	0.2	1.6	-0.1
Total non-OECD	3.6	1.8	3.4	1.4	2.7	0.9
World	2.9	1.6	2.6	1.3	2.1	0.8

Source: Study design for EMF12. Since the number of regions in GREEN is significantly larger than the five-region breakdown adopted for EMF12, the GDP and population growth projections had to be adapted to the needs of GREEN. It was assumed that relative growth differentials between groups of regions, projected by the World Bank for the period 1986-95, will persist until 2050, while remaining consistent with the aggregate projections made over the long term by EMF12.

Table 4. Fossil-fuel emission shares and prices in the benchmark data sets by country/region, 1985

(a) Share of fossil fuels in total CO_2 emissions (%)

	United States	Japan	EC	Other OECD	Energy-exporting LDCs	China	Former Soviet Union	India	CEECs	DAEs	Brazil	RoW	WORLD
Coal	34.7	30.5	32.9	32.8	20.0	86.2	38.1	74.1	66.9	37.5	21.0	45.3	42.0
Crude oil	46.7	61.4	51.8	51.1	61.6	12.5	33.4	24.4	20.1	60.2	76.1	46.7	42.2
Gas	18.6	8.1	15.3	16.1	18.4	1.4	28.6	1.6	13.0	2.3	2.9	8.0	15.8

(b) Relative fossil-fuel prices (1)

1985 prices and exchange rates: average U.S. price = 100

	United States	Japan	EC	Other OECD	Energy-exporting LDCs	China	Former Soviet Union	India	CEECs	DAEs	Brazil	RoW	WORLD
Coal	35.4	126.4	63.9	27.0	30.8	20.5	24.8	25.6	26.2	68.5	110.6	25.7	35.8
Crude oil	152.2	178.3	166.7	136.8	99.4	155.0	24.1	95.4	100.1	135.2	123.8	142.5	119.9
Gas	92.5	167.1	140.6	81.9	84.4	106.7	17.0	61.3	44.9	166.1	71.9	198.6	76.4
Average	100.0	162.6	131.2	92.4	87.8	46.9	21.8	47.8	48.4	118.5	120.1	106.7	81.6

1. Defined as the unit value of one terajoule relative to the average unit value of fossil fuels in the United States. Fossil fuel demands are converted into a common energy unit (1 terajoule = 10 E 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 carbon. 1 terajoule of oil = 19.2 tons of carbon. 1 terajoule of gas = 13.7 tons of carbon.

Table 5. Carbon emissions by region in the BaU scenario

Annual average growth rates

	1990-2000	2000-2010	2010-2030	2030-2050	1990-2050
United States	1.1	1.2	0.9	0.6	0.9
Japan	2.8	-0.4	1.2	1.9	1.4
EC	0.8	0.7	0.7	0.8	0.8
Other OECD	1.1	1.1	1.0	0.9	1.0
Energy-exporting LDCs	2.7	2.6	2.6	2.2	2.5
China	3.7	4.5	3.9	3.2	3.7
Former Soviet Union	1.9	2.3	1.3	1.0	1.4
India	3.7	4.3	4.0	3.7	3.9
CEECs	1.6	2.2	1.6	1.3	1.6
DAEs	3.3	2.7	2.4	2.4	2.6
Brazil	3.0	2.1	2.2	2.2	2.3
RoW	2.5	2.5	2.3	1.8	2.2
Total OECD	1.2	0.8	0.9	0.9	0.9
Total non-OECD	2.6	3.0	2.6	2.4	2.6
World	2.0	2.1	2.0	2.0	2.0

Table 6. **Summary results from scenario in which OECD countries stabilise emissions in 2000 at 1990 levels**

	Cut in CO_2 emissions in 2050 (% relative to BaU)	Carbon tax in 2050 (1985$/ton of carbon)	GDP changes over the period 1990-2050 (% relative to BaU)	Present value of real income changes over the period 1990-2050 (% relative to BaU)
United States	-42	53	-0.3	-0.4
Japan (1)	-60	198	-0.9	-1.0
EC	-36	74	-0.3	-0.5
Other OECD	-45	60	-0.2	-0.3
Energy-exporting LDCs	0	0	-0.7	-1.0
China	0	0	-0.1	-0.1
Former Soviet Union	0	0	0.0	-0.1
India	0	0	0.0	-0.1
CEECs	0	0	0.2	0.1
DAEs	0	0	-0.1	0.0
Brazil	0	0	0.1	0.4
RoW	0	0	0.0	0.0
OECD	-43	76	-0.4	-0.5
World	-11	12	-0.3	-0.4

1. Stabilisation is in terms of the per capita level in 1990.

Table 7. **Effects on the EC of a mixed energy/carbon tax**

Percentage changes relative to the BaU case

	Carbon emissions	Real GDP	Real income
2000	-13	-0.2	-0.2
2010	-20	-0.4	-0.6
2030	-30	-0.6	-0.8
2050	-38	-0.6	-1.4

Table 8. **Summary of main results from a Toronto-type agreement**

	Cut in CO_2 emissions in 2050 (% relative to BaU)	Carbon tax in 2050 (1985$/ton of carbon)	GDP changes over the period 1990-2050 (% relative to BaU)	Present value of real income changes over the period 1990-2050 (% relative to BaU)
United States	-53	105	-0.8	-0.7
Japan	-66	204	-1.3	-1.2
EC	-49	102	-0.8	-0.7
Other OECD	-56	111	-0.7	-0.7
Energy-exporting LDCs	-65	414	-4.3	-4.0
China	-84	266	-2.3	-2.0
Former Soviet Union	-37	35	-0.2	-0.2
India	-85	266	-1.9	-1.6
CEECs	-42	42	0.5	0.4
DAEs	-68	441	-1.8	-1.6
Brazil	-63	409	-2.4	-2.0
RoW	-59	152	-0.6	-0.5
OECD	-54	116	-0.9	-0.8
World	-64	161	-1.4	-1.3

Table 9. Carbon emissions by region when energy price distortions are eliminated

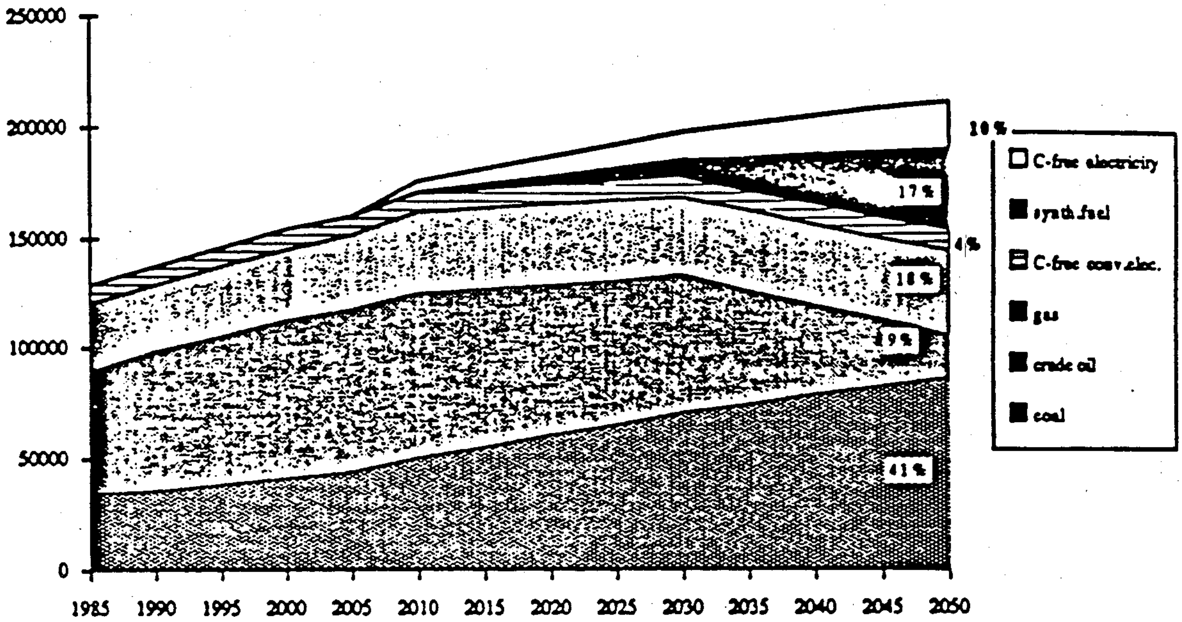
Annual average growth rates

	1990-2000	2000-2010	2010-2030	2030-2050	1990-2050
United States	1.1	1.2	0.9	0.7	0.9
Japan	4.0	0.5	1.5	1.7	1.8
EC	1.6	1.2	1.0	0.8	1.1
Other OECD	1.2	1.1	1.0	0.9	1.0
Energy-exporting LDCs	1.5	1.5	2.1	2.2	1.9
China	0.9	2.4	2.6	2.7	2.3
Former Soviet Union	0.4	1.3	1.3	1.3	1.1
India	1.8	2.9	3.2	3.2	2.9
CEECs	-0.2	0.9	0.8	0.8	0.6
DAEs	3.3	2.8	2.6	2.5	2.7
Brazil	2.8	2.2	2.7	2.9	2.7
RoW	5.6	4.8	3.4	2.1	3.6
Total OECD	1.7	1.1	1.0	0.9	1.1
Total non-OECD	1.6	2.3	2.3	2.1	2.1
World	1.6	1.7	1.8	1.6	1.7

Figure 1. The composition of total primary energy demands in the BaU scenario

Thousands of terajoules

a) OECD area



b) Non-OECD area

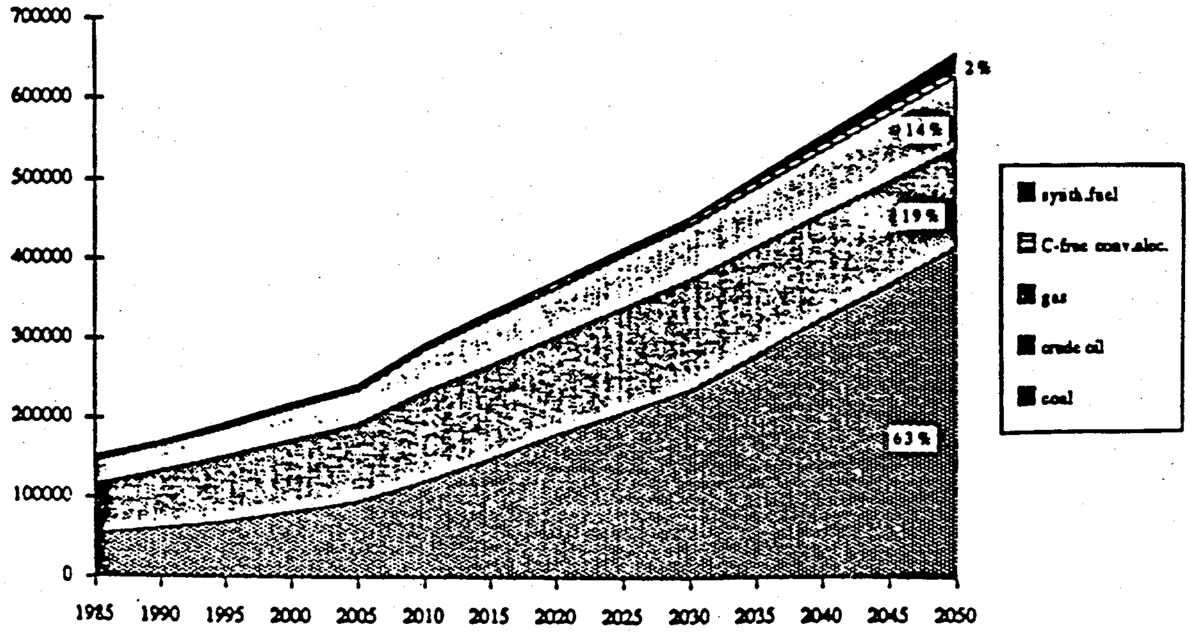


Figure 2. **Carbon emissions in the reference scenario**

(millions of tons of carbon)

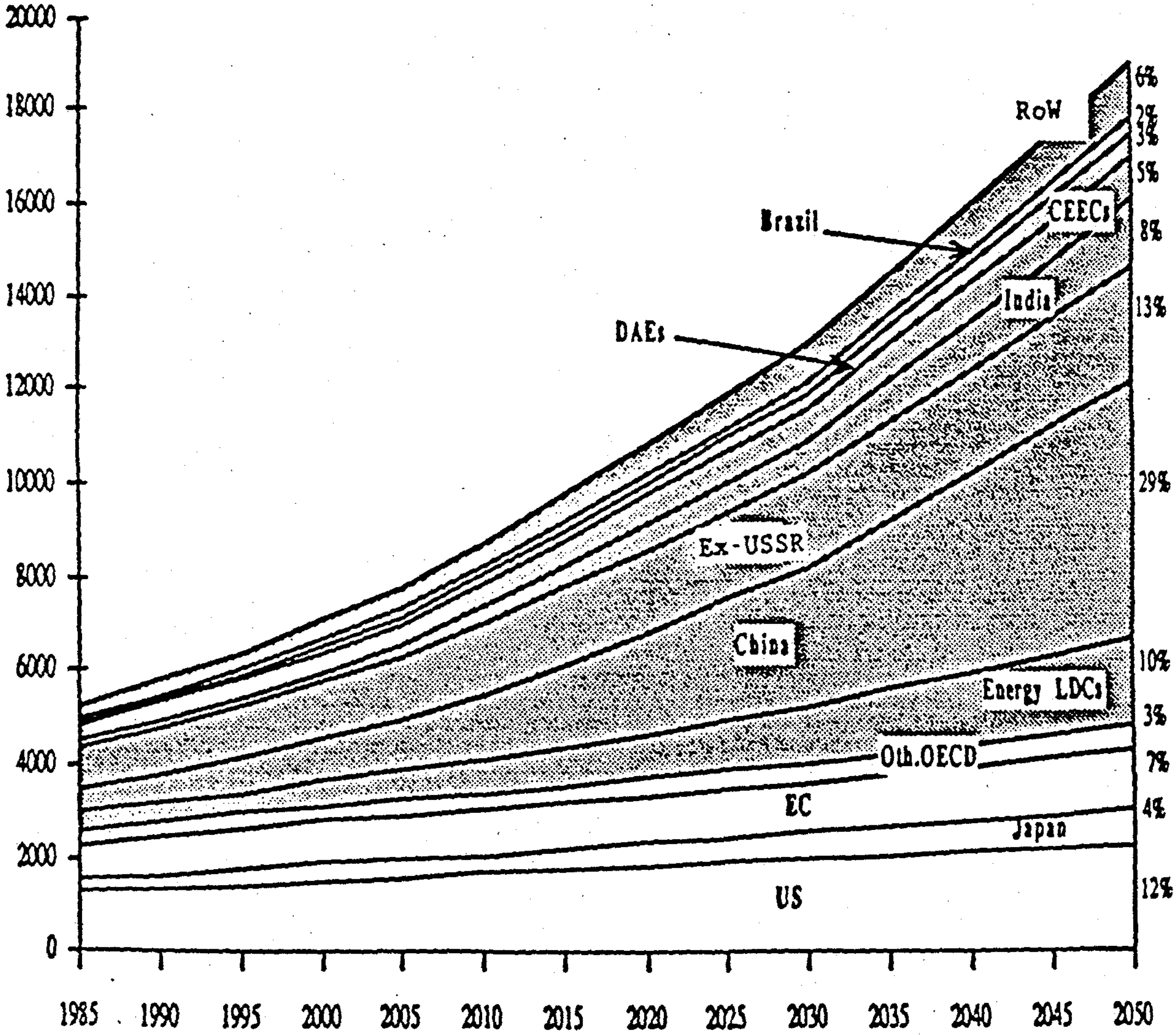
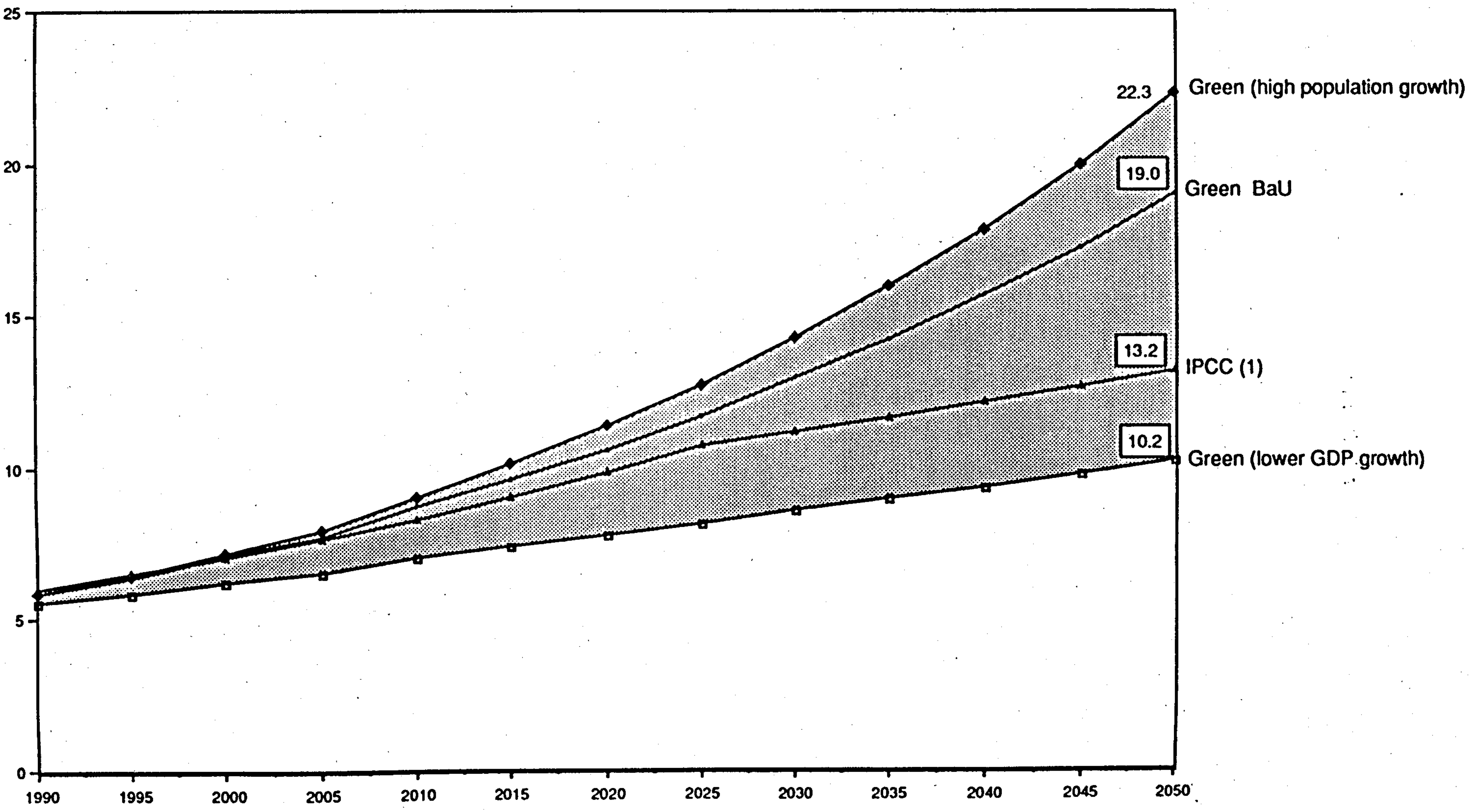


Figure 3. **Global CO2 emissions : a comparison of three GREEN scenarios and the IPCC BaU**

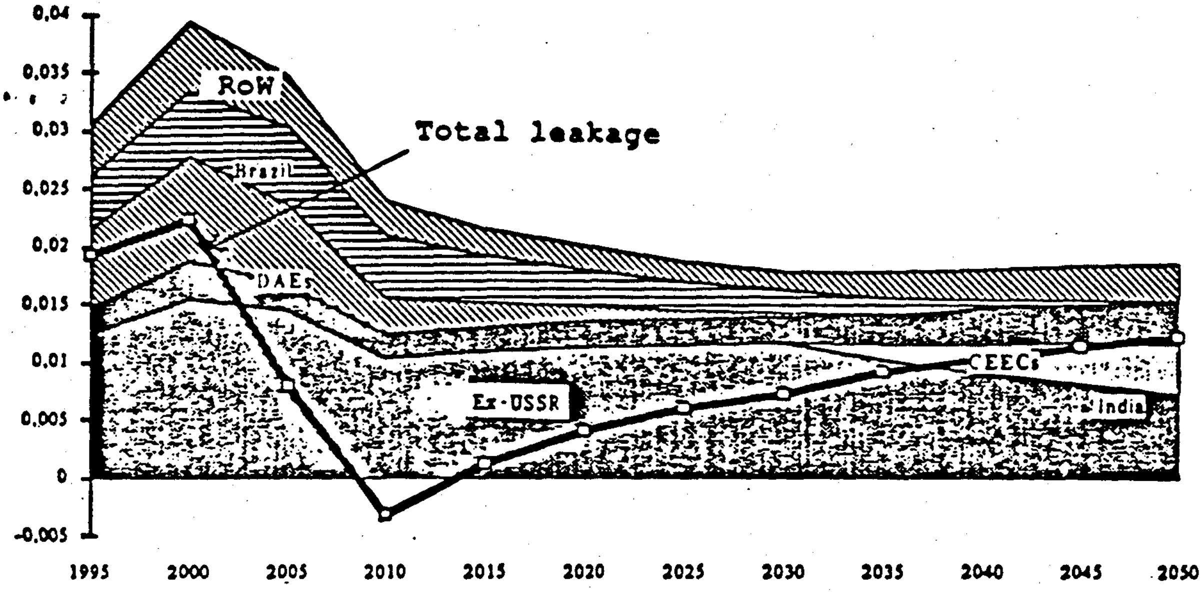
(billions of tons of carbon)



1. This is the IPCC Reference scenario labelled IRS91a from Swart et al. (1991). The projection relates to CO2 emissions from energy use only.

Figure 4. **Carbon leakages in the non-OECD countries**
Percentage of total emissions cut in the OECD countries

a) Positive leakages



b) Negative leakages

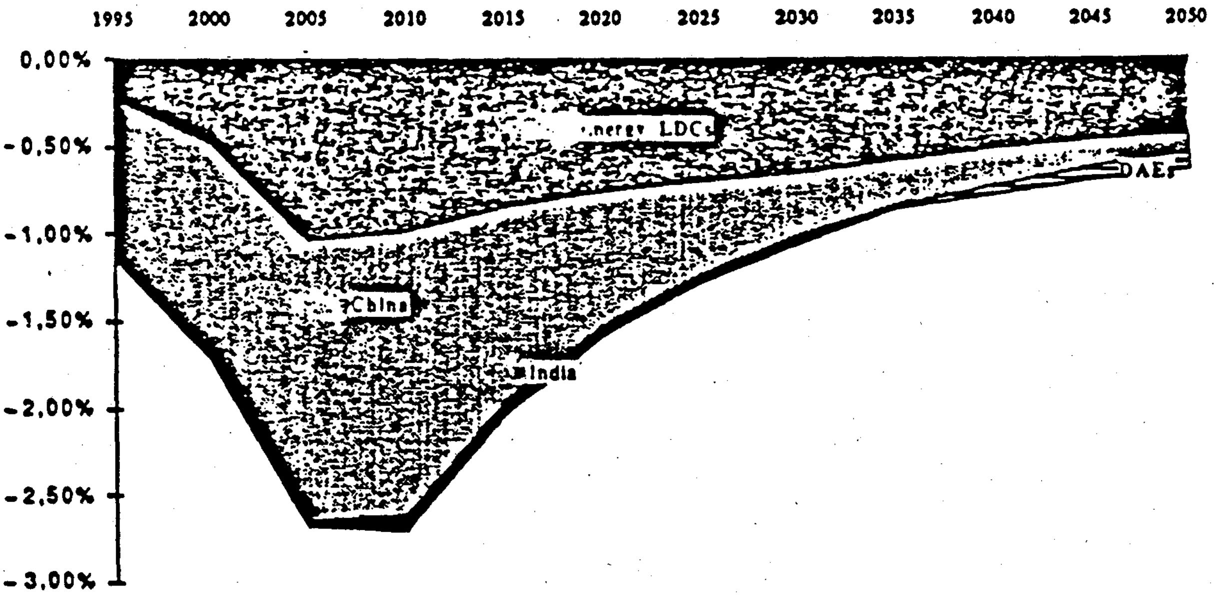


Figure 5. Real income losses in the OECD regions under the stabilisation scenario

Percentage deviations relative to BaU)

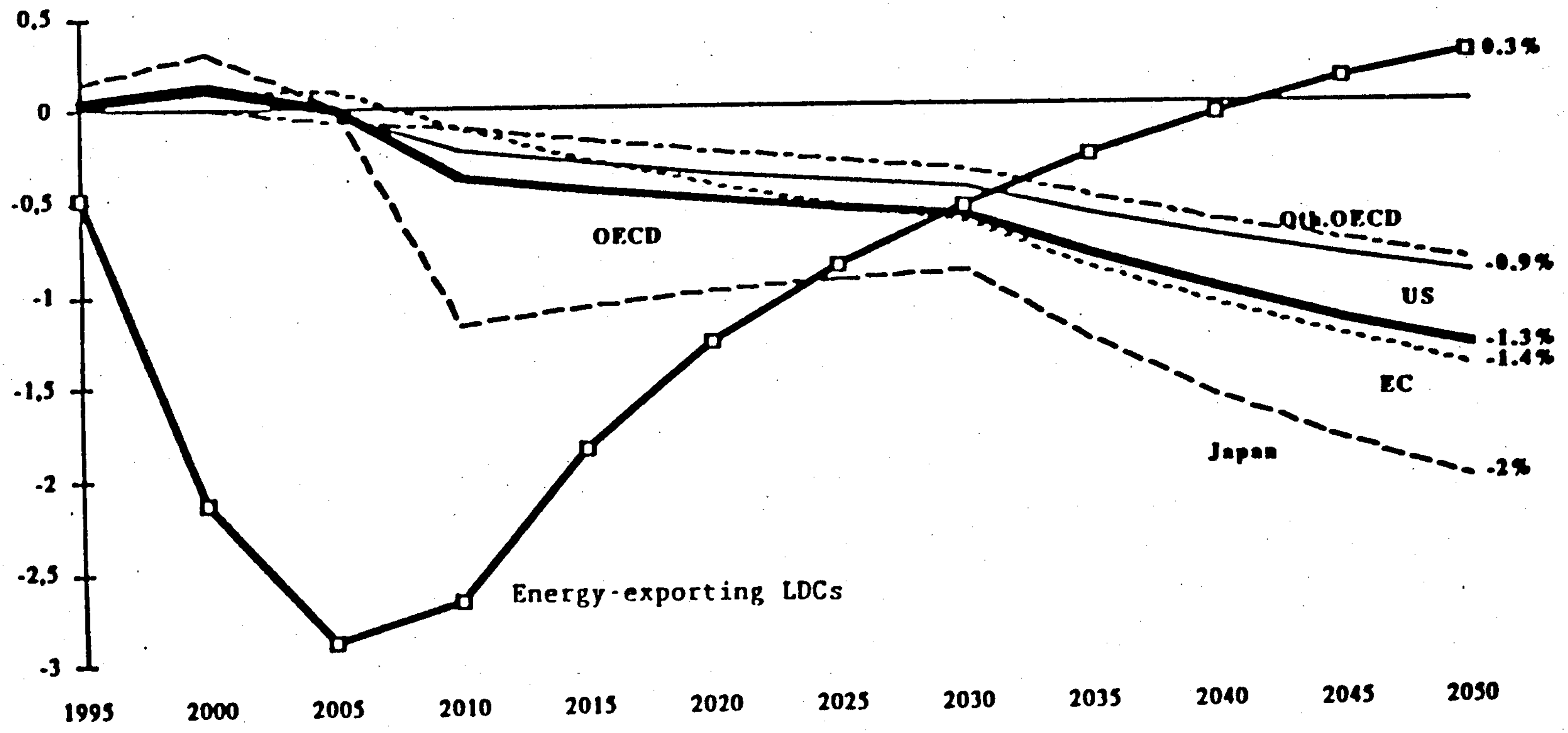


Figure 6. Carbon Leakages

Percentage of total emissions cut in the EC region.

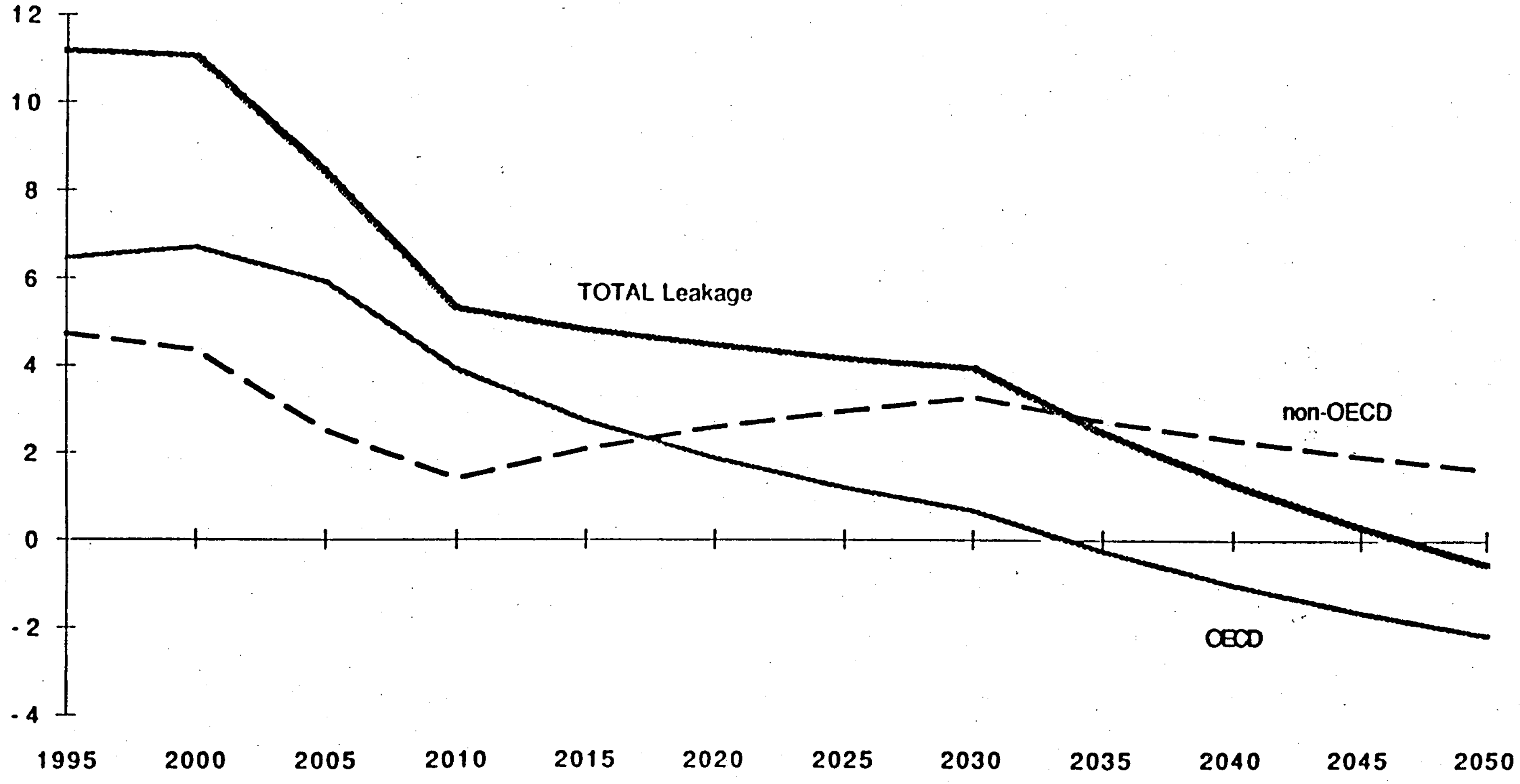
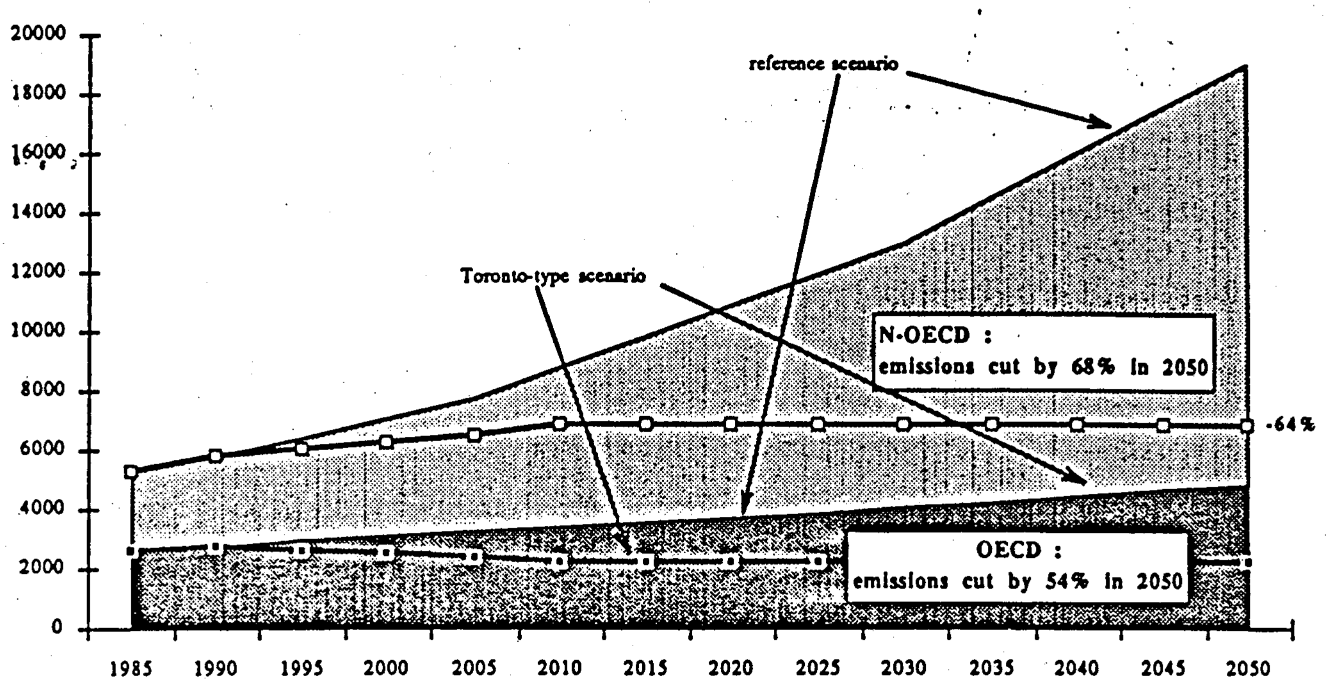


Figure 7. Impact of a Toronto-type agreement on emissions

a) Levels of emissions (million tons of carbon)



b) Distribution of emission cuts in 2050 by region

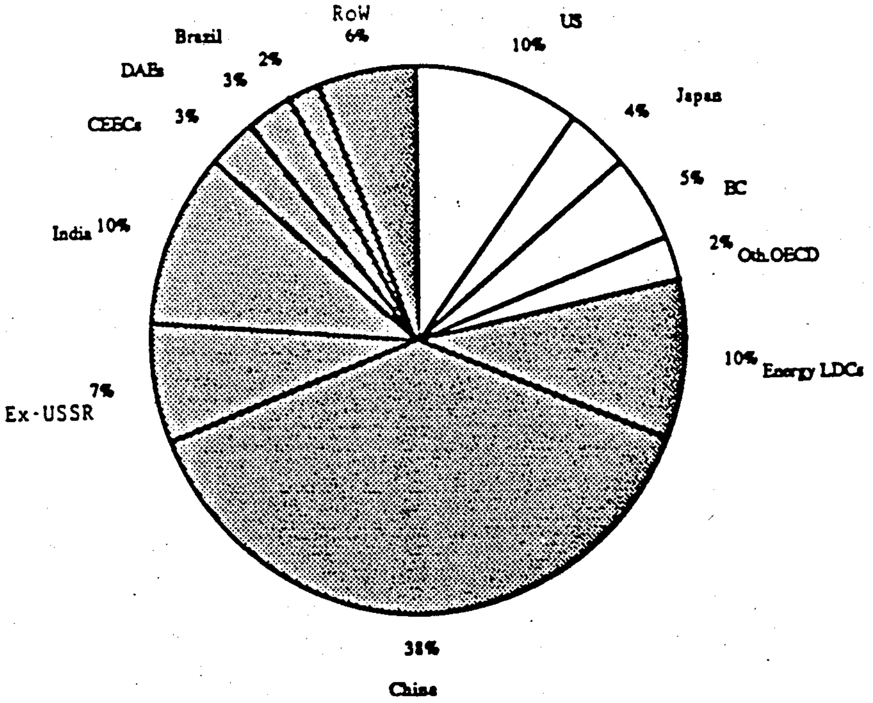
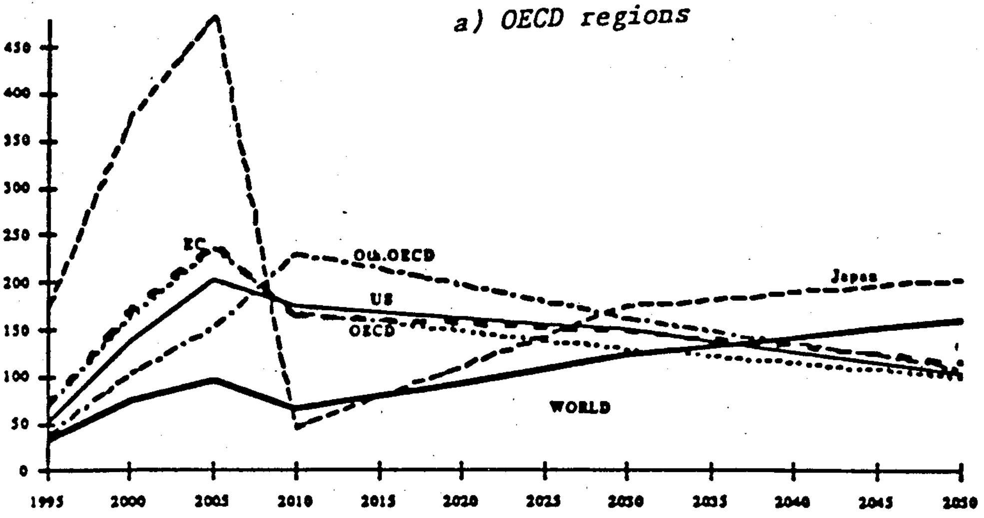


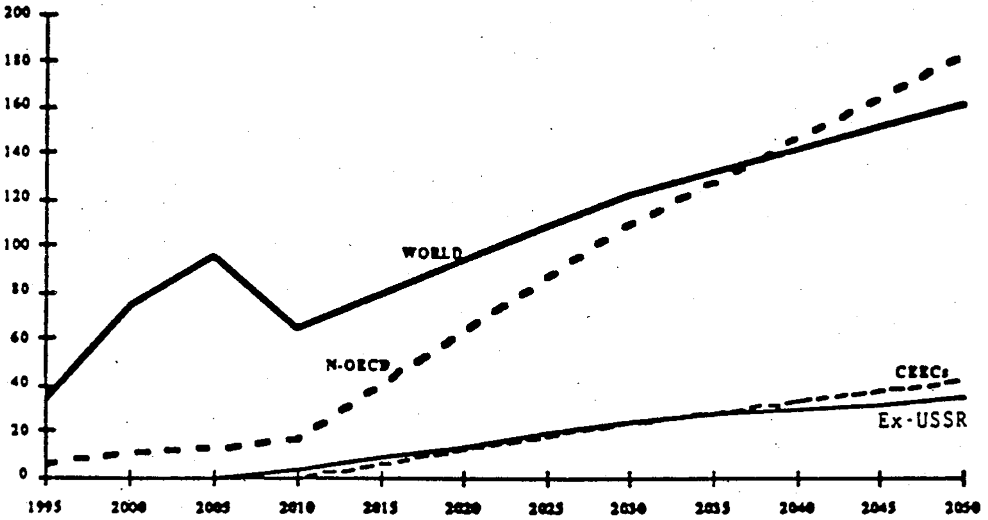
Figure 6. Carbon taxes under the Toronto-type agreement

1985$ and exchange rates per ton of carbon

a) OECD regions



b) The former Soviet Union and the CEECs



c) Other non-OECD regions

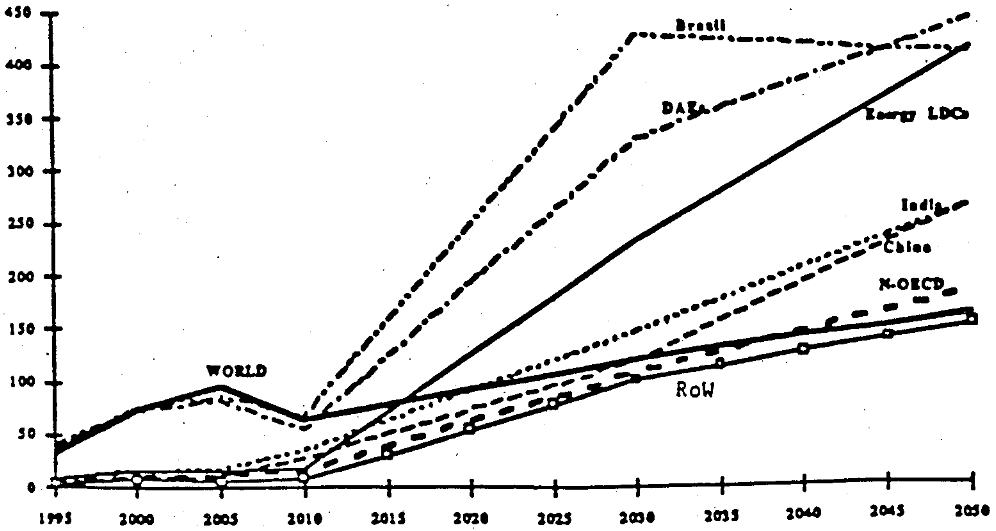
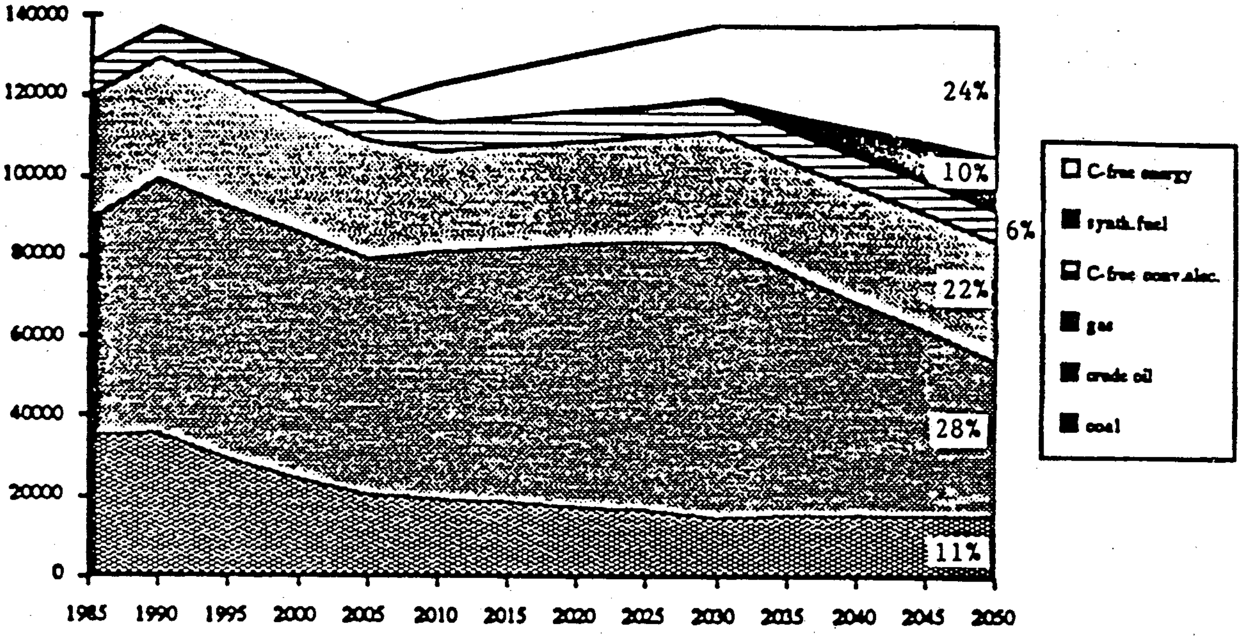


Figure 9. Composition of primary energy demands under a Toronto-type agreement

(Thousands of terajoules)

a) OECD regions



b) Non-OECD regions

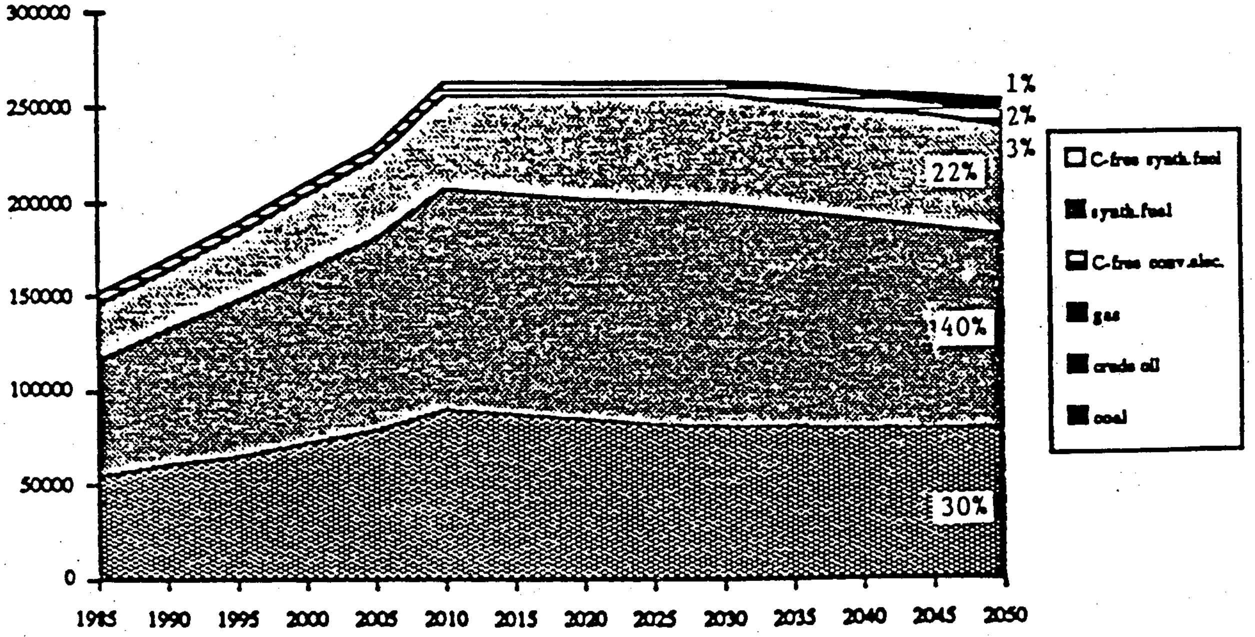
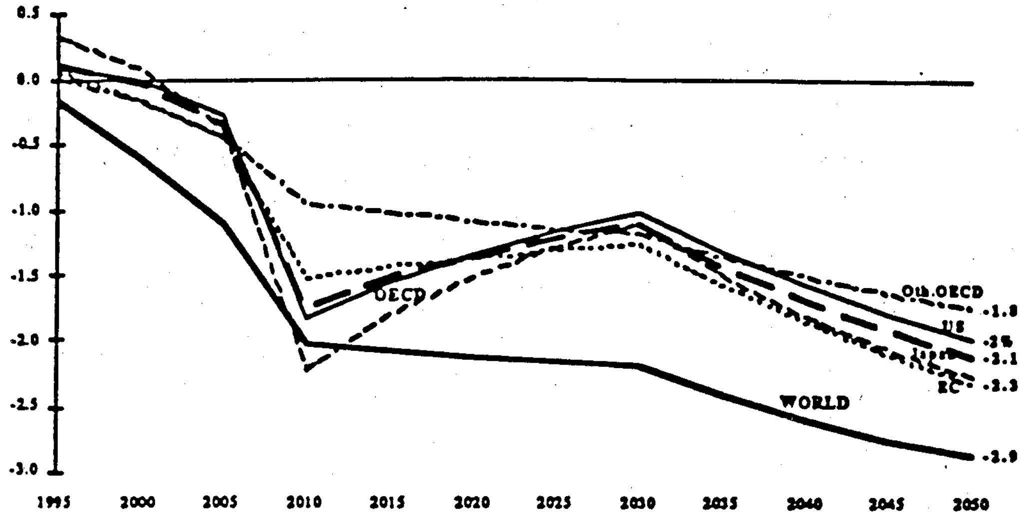


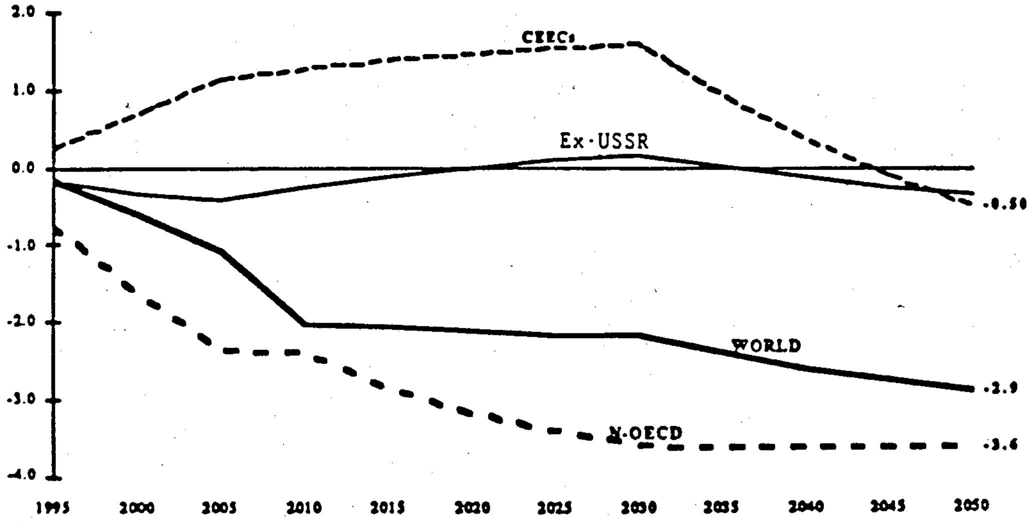
Figure 10. Real income effects under a Toronto-type agreement

(Percentage deviations relative to baseline)

a) OECD regions



b) The former Soviet Union and the CEECs



c) Other non-OECD regions

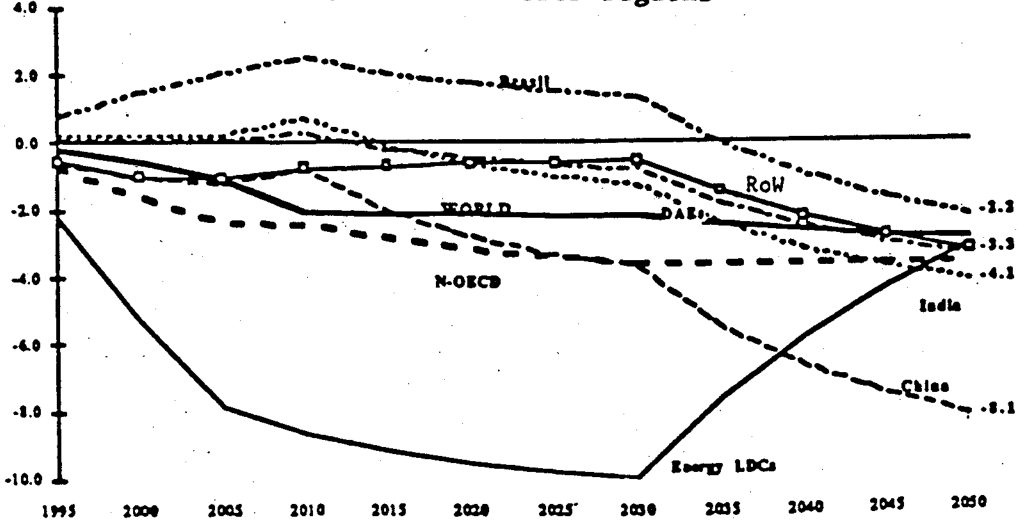


Figure 11. Average real income changes under three alternative Toronto-type agreements

Average percentage deviations over the period 1995-2050

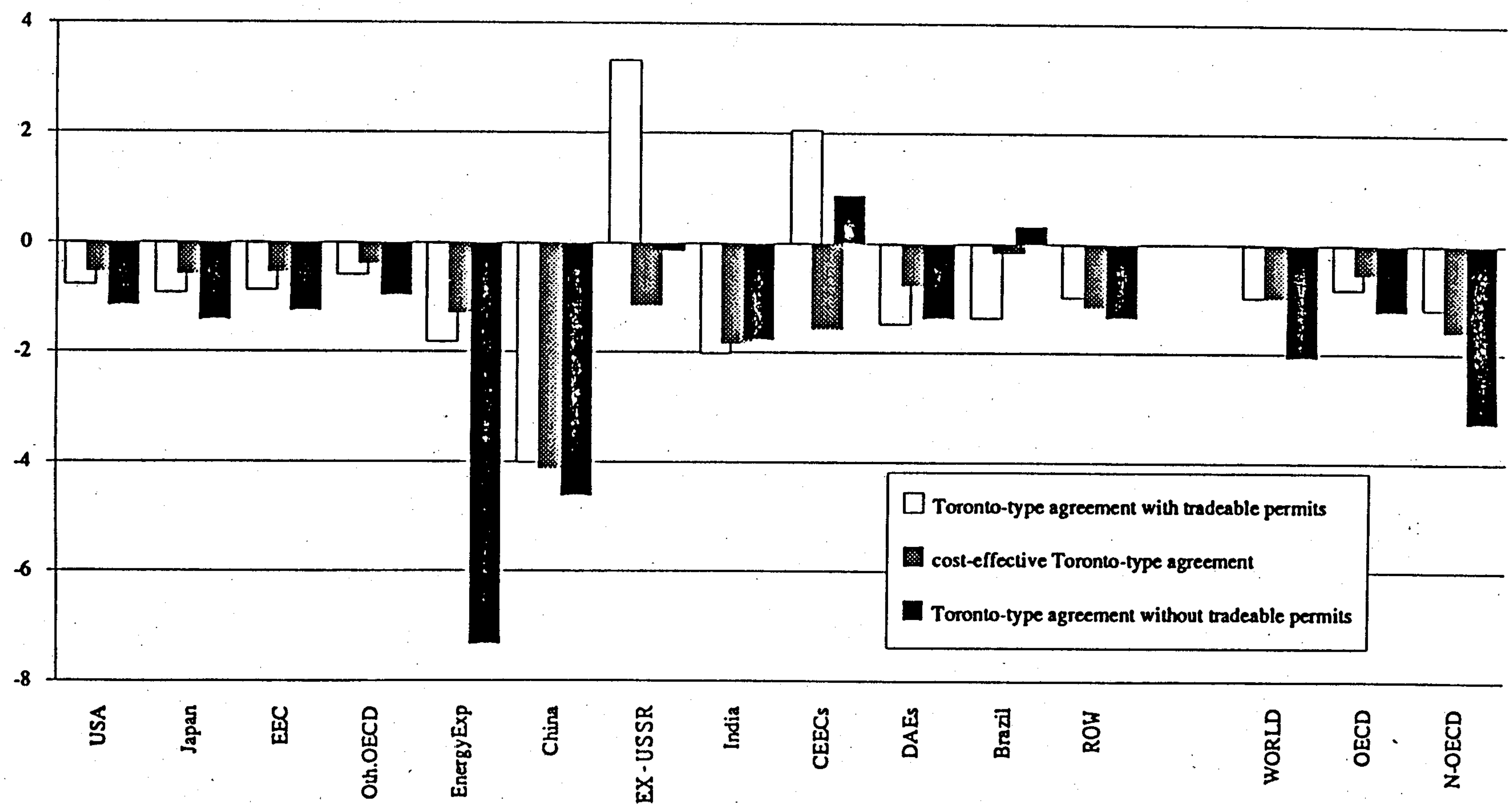
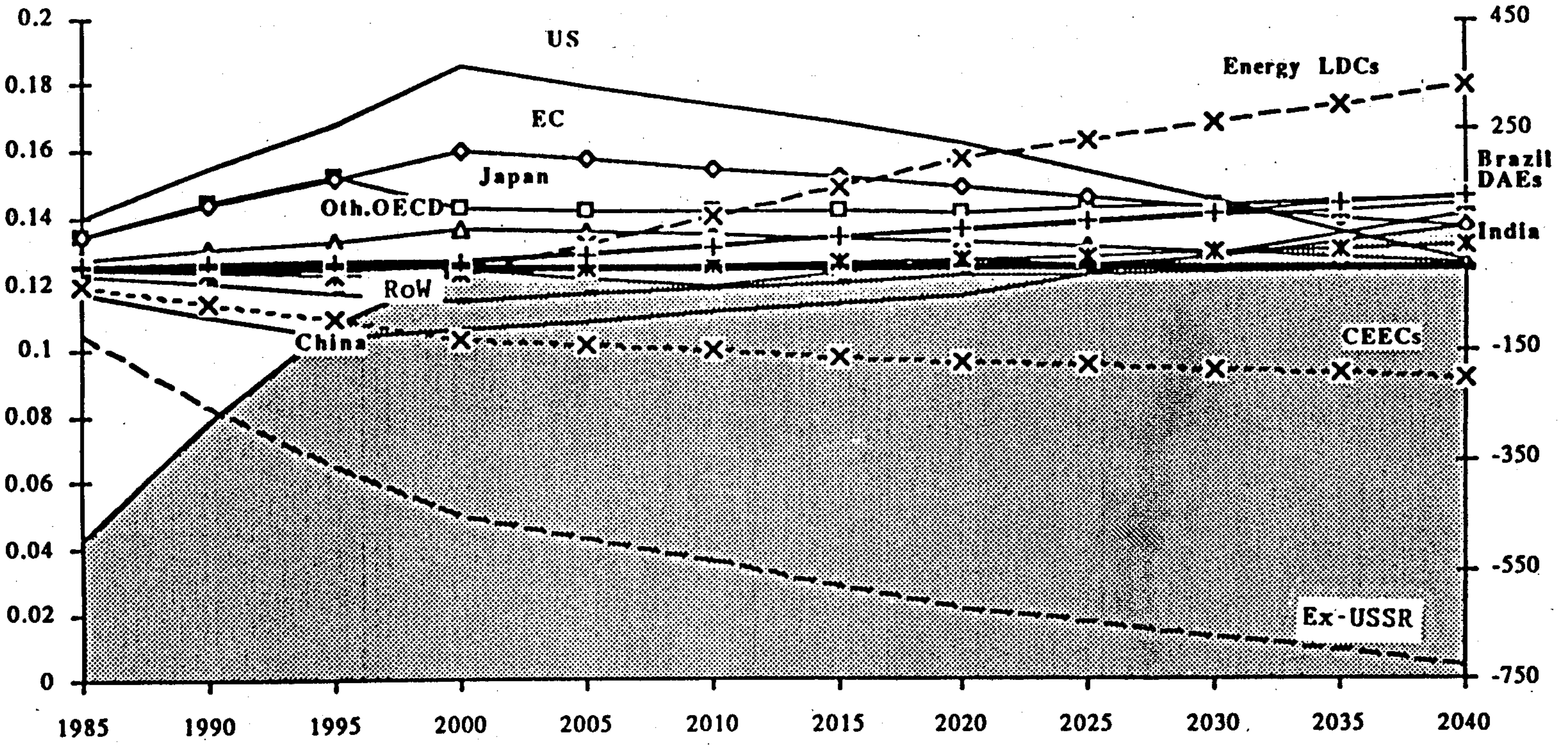


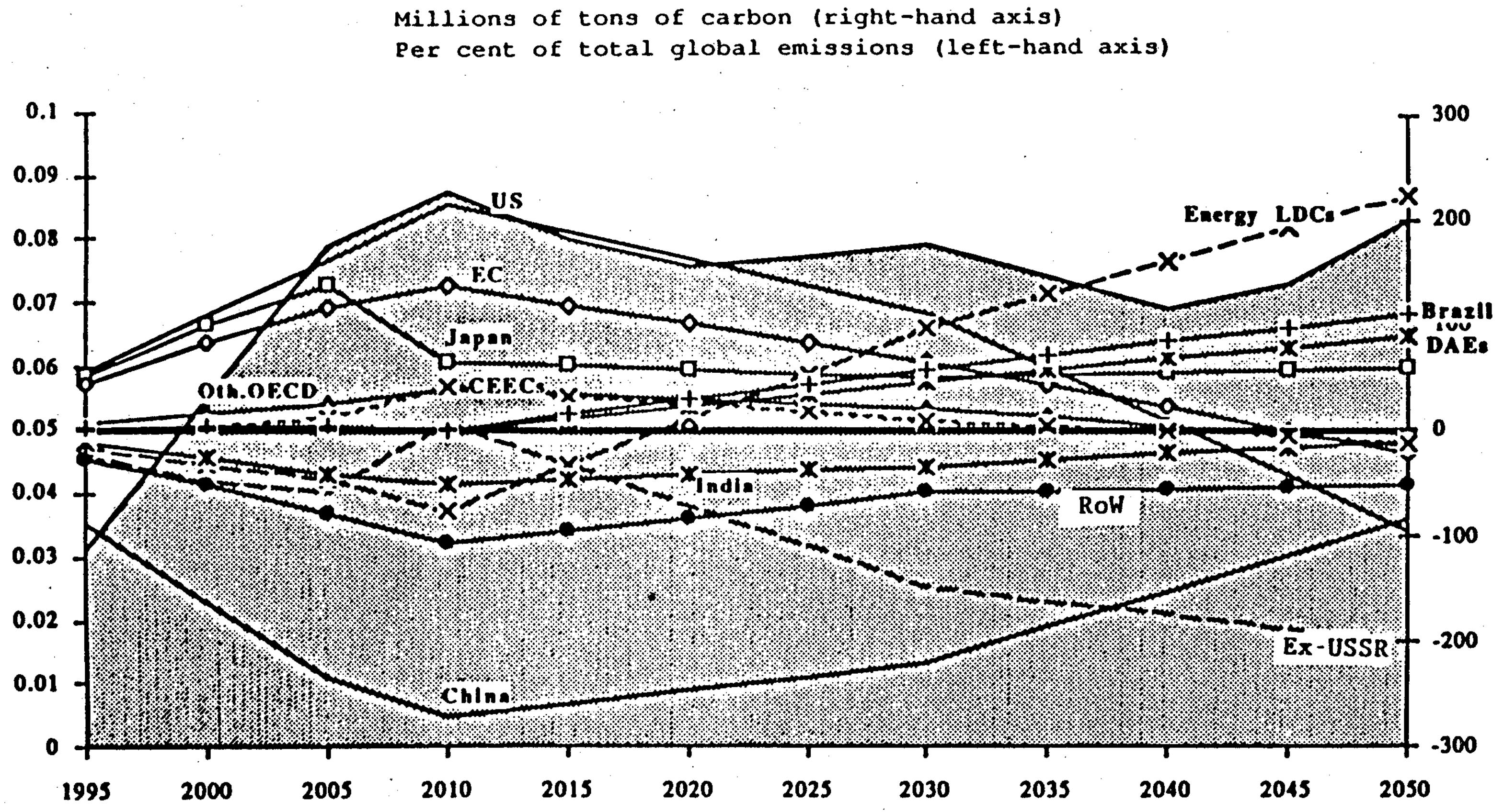
Figure 12. Trade in emission rights under a Toronto-type agreement (1)

Millions of tons of carbon (right-hand axis)
Per cent of total global emissions (left-hand axis)



1. In this version of the agreement, the former Soviet Union and the CEECs face the same emission constraint as the other non-OECD regions. The shaded area shows the percentage of global emissions that are traded in each period.

Figure 13. Trade in emission rights under an alternative version of the Toronto-type agreement (1)



1. In this alternative version of the agreement, the former Soviet Union and the CEECs face the same emissions constraint as the OECD regions. The shaded area shows the percentage of global emissions that are traded in each period.

Figure 14. Gains from tradeable permits under two alternative initial endowments of permits

(Average percentage changes relative to baseline over the period 1995-2050)

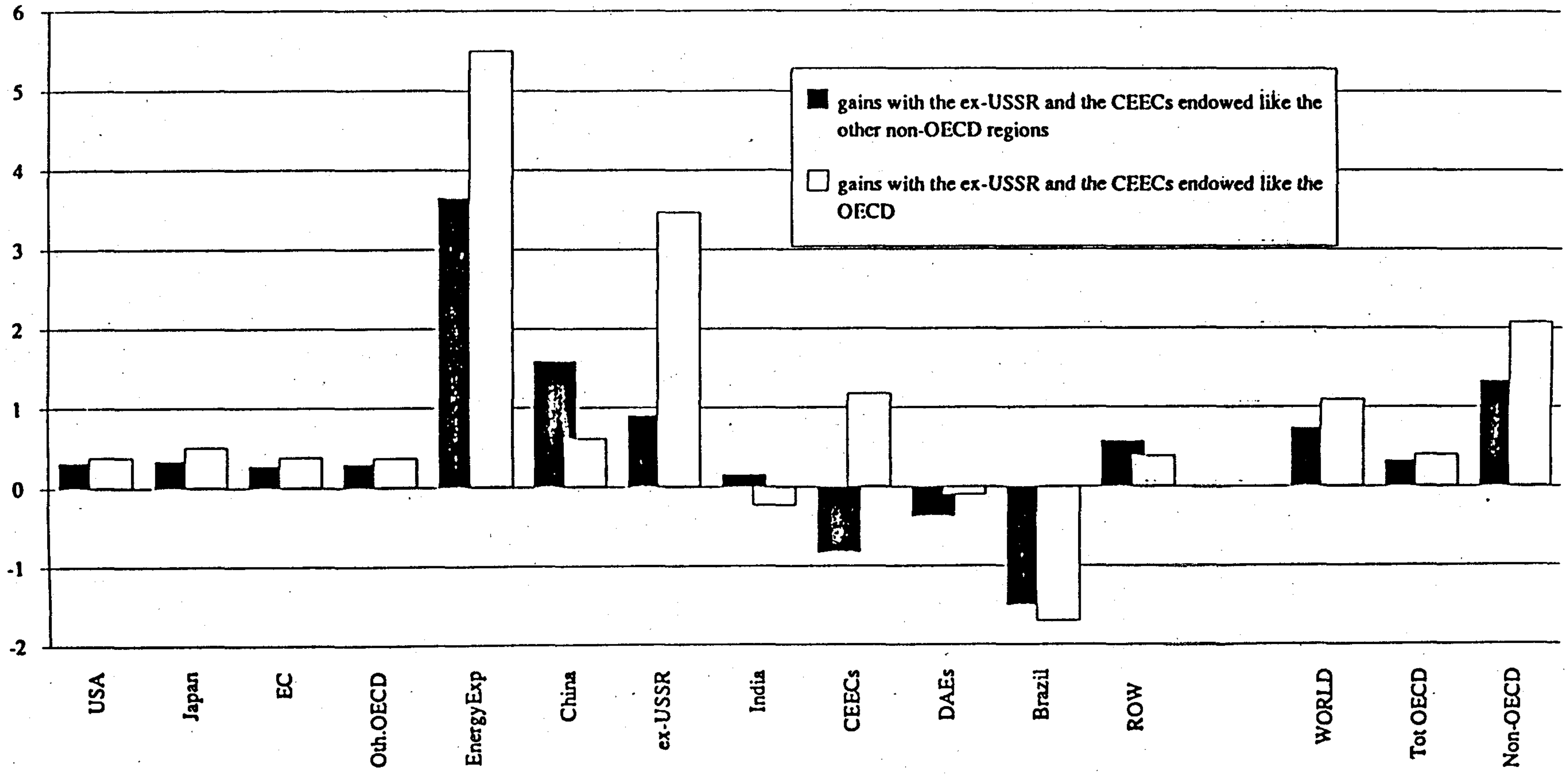
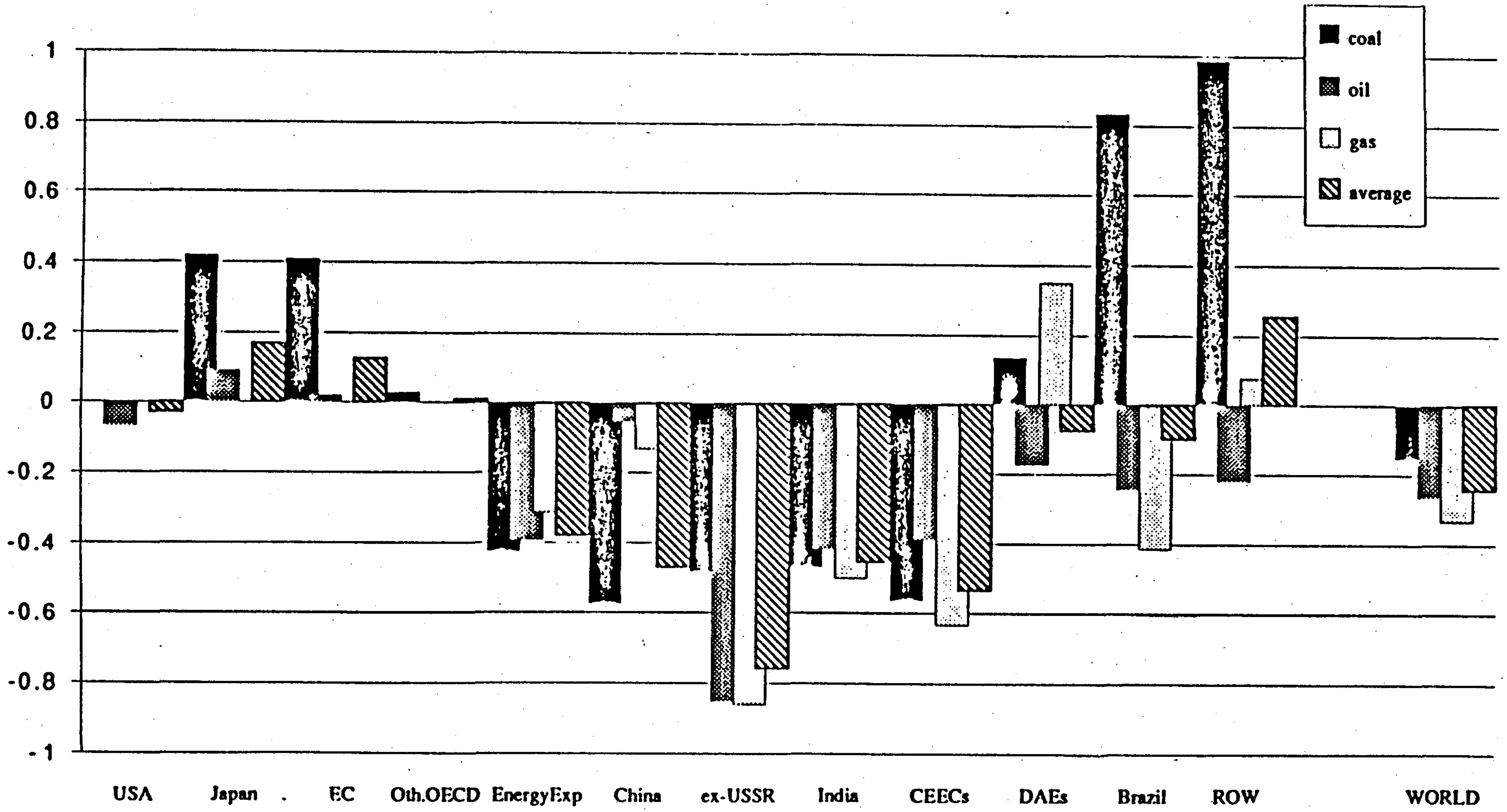


Figure 15. Estimated wedges on primary fossil fuels by region, 1985 (1)



1. A positive value indicates that domestic prices are greater than the world price. i.e. primary energy use is taxed: a negative value indicates a subsidy to energy use.

Figure 16a. The composition of primary energy demands when energy price distortions are eliminated: OECD regions

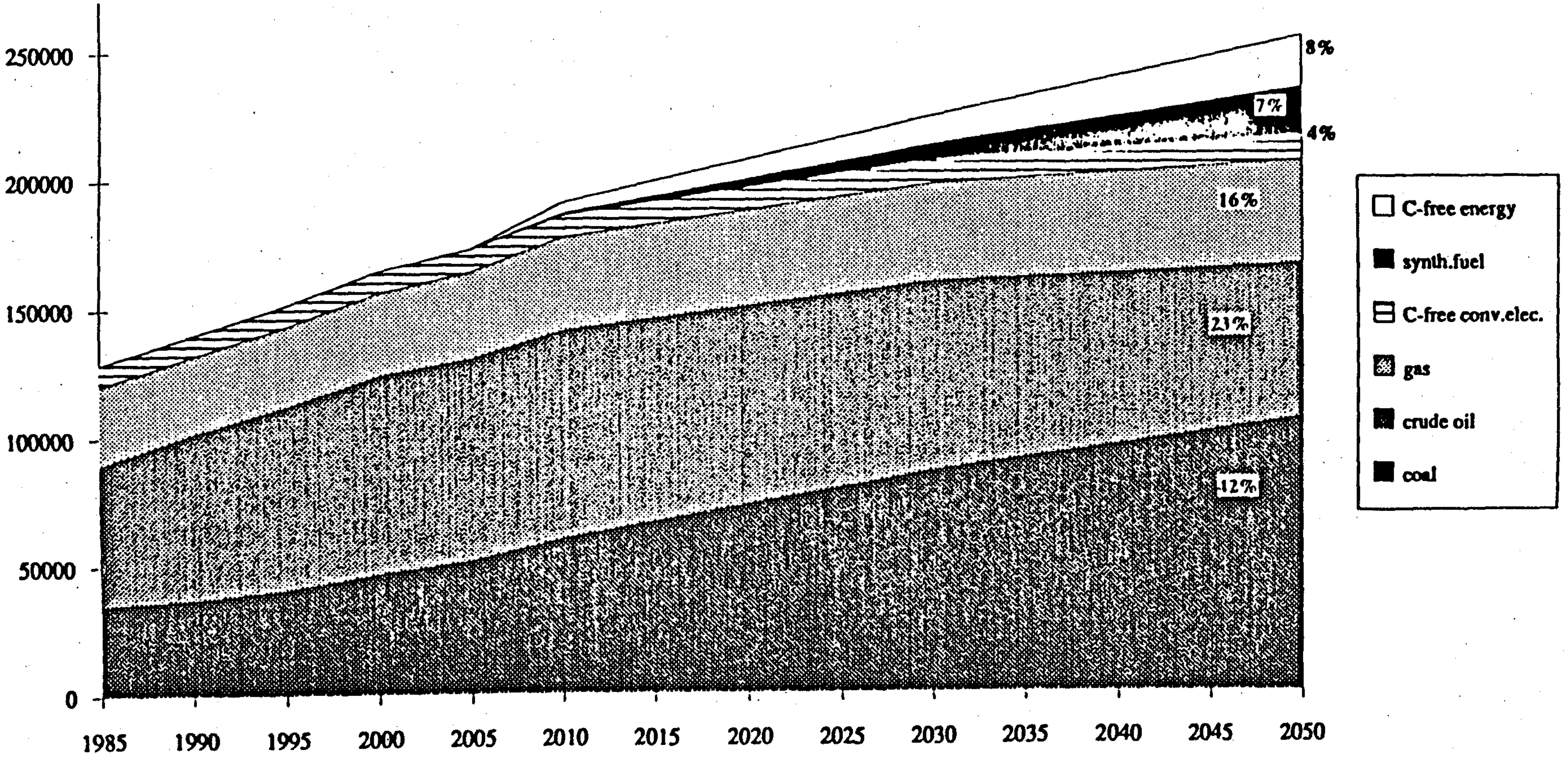


Figure 16 b. The composition of primary energy demands when energy price distortions are eliminated: Non-OECD regions

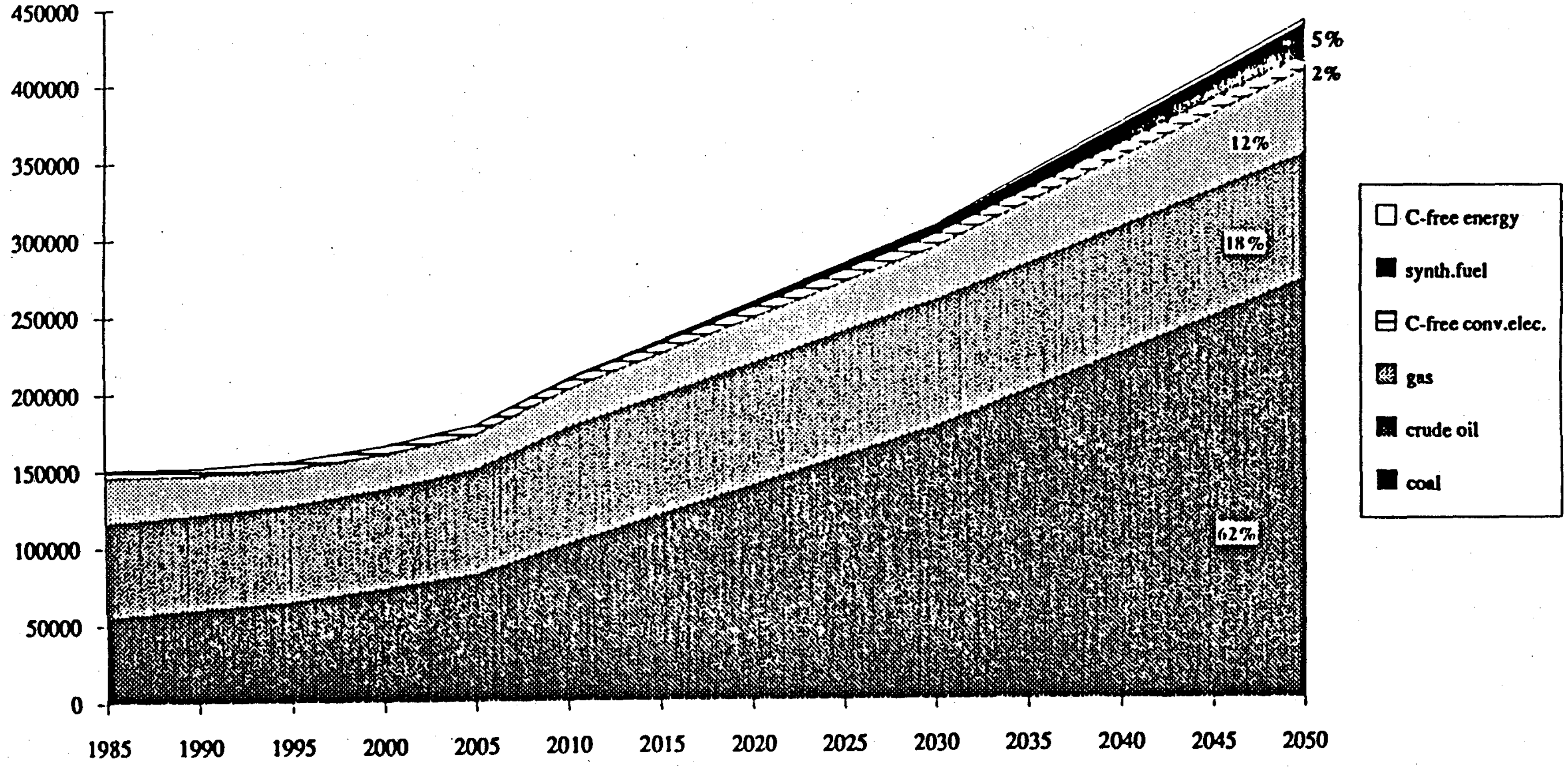


Figure 17. Changes in carbon emissions in 2000 and 2050 following the removal of existing distortions

(Percentage changes relative to world emissions in the BaU Scenario)

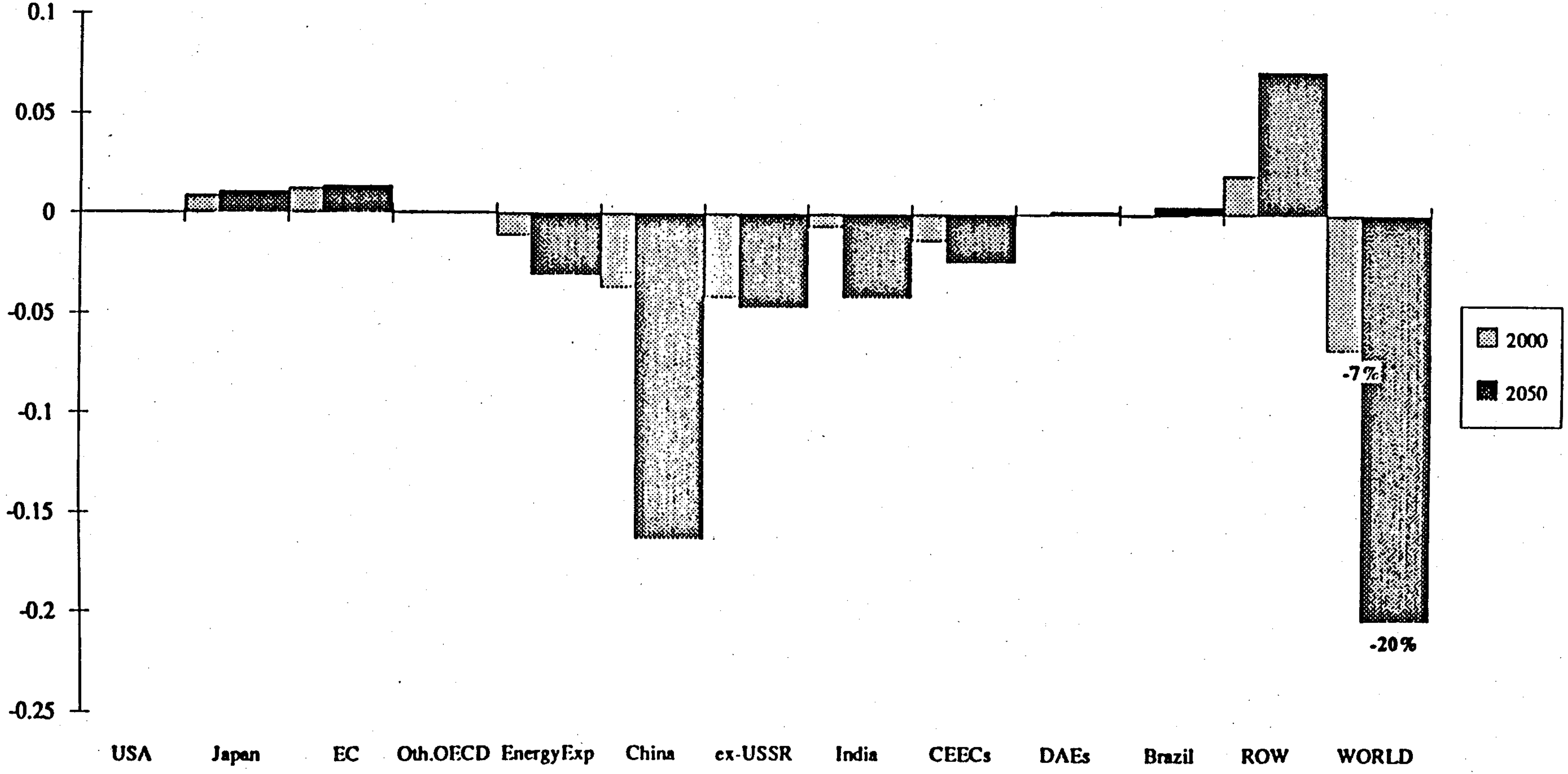


Figure 18. Carbon emissions following the removal of existing distortions

(Millions of tons of carbon)

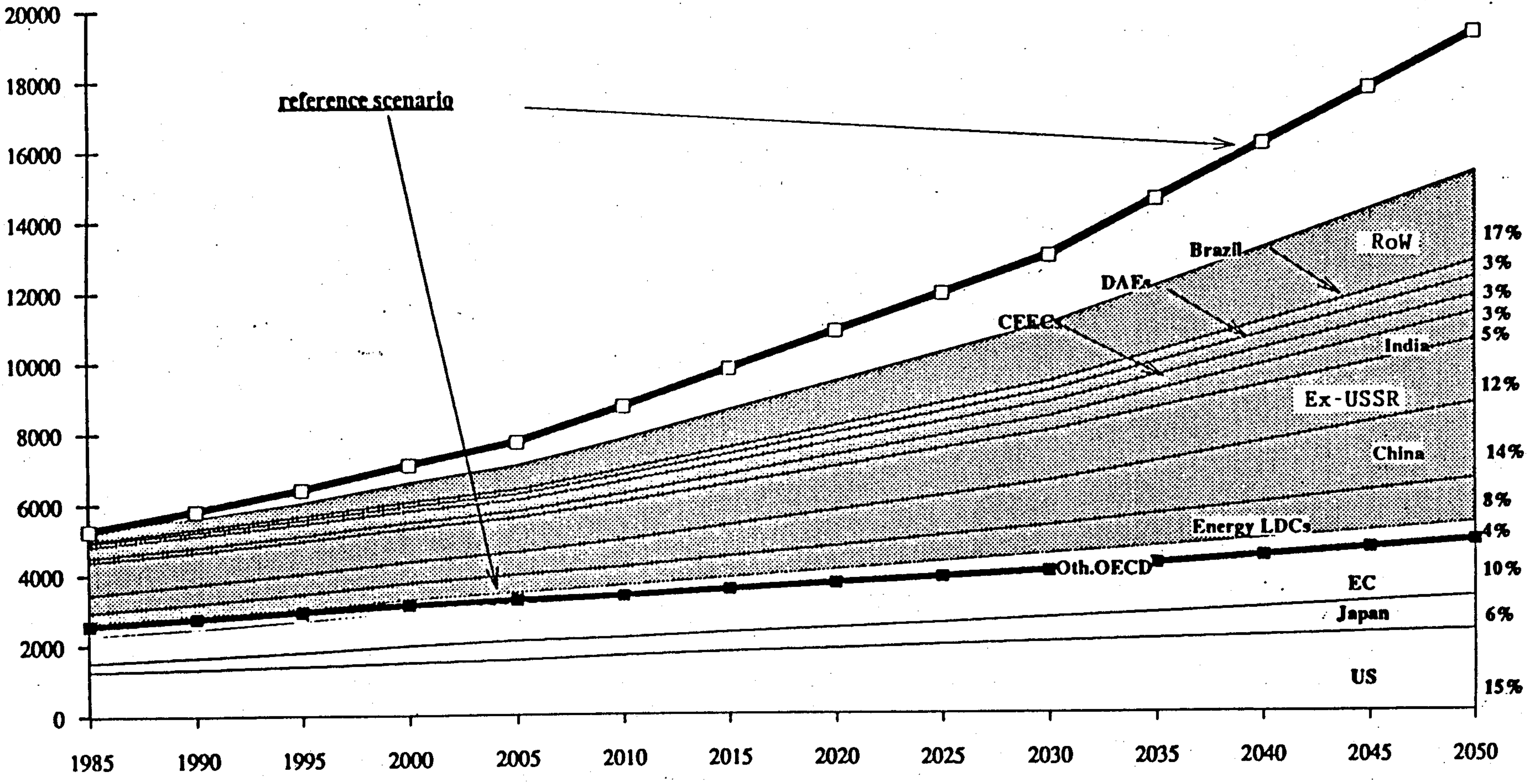


Figure 19a. Real income changes following the removal of existing distortions: OECD regions

(Percentage changes relative to the BaU level)

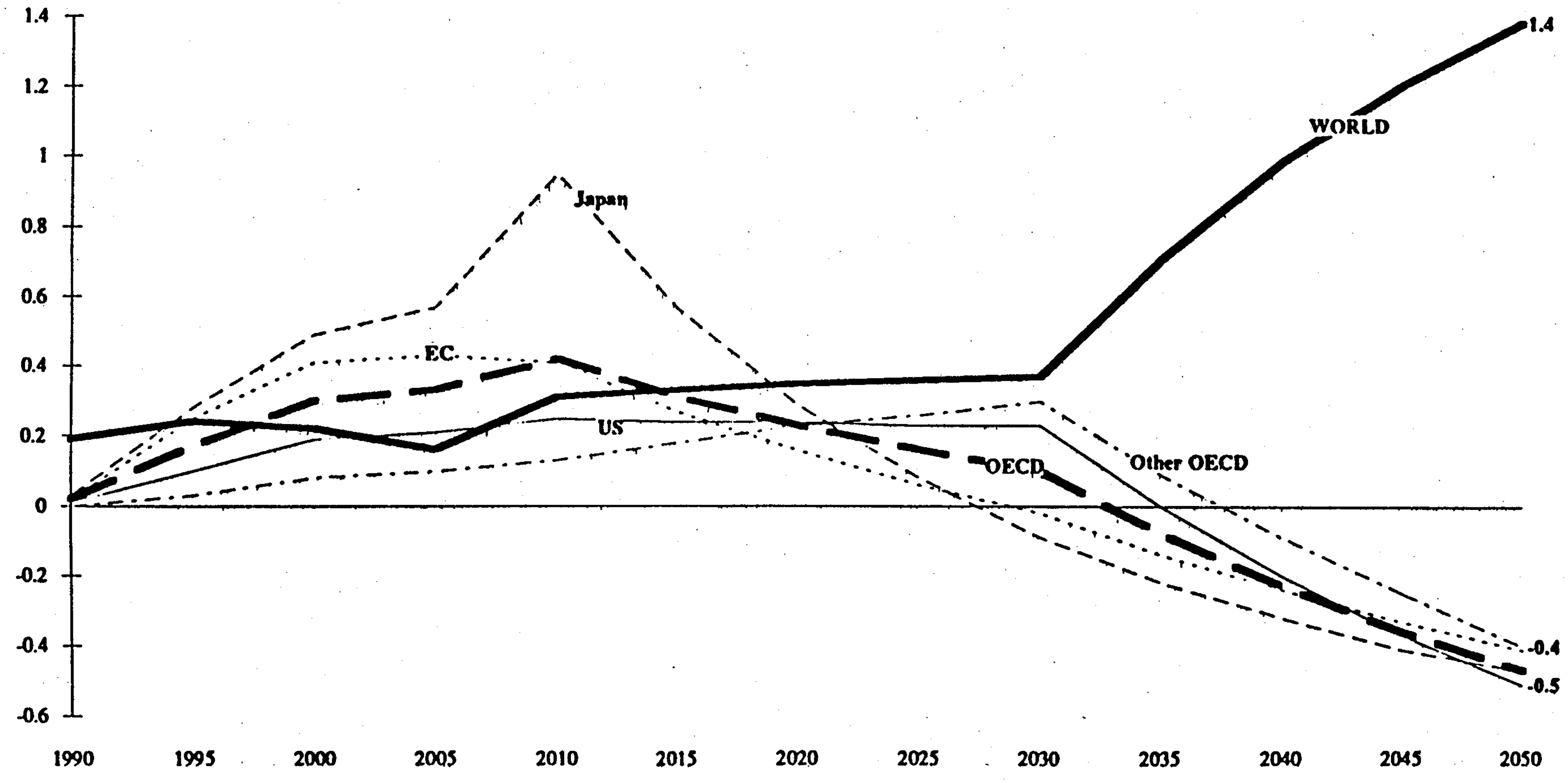


Figure 19b. Real income changes following the removal of existing distortions: The former Soviet Union and the CEECs

(Percentage changes relative to the BaU level)

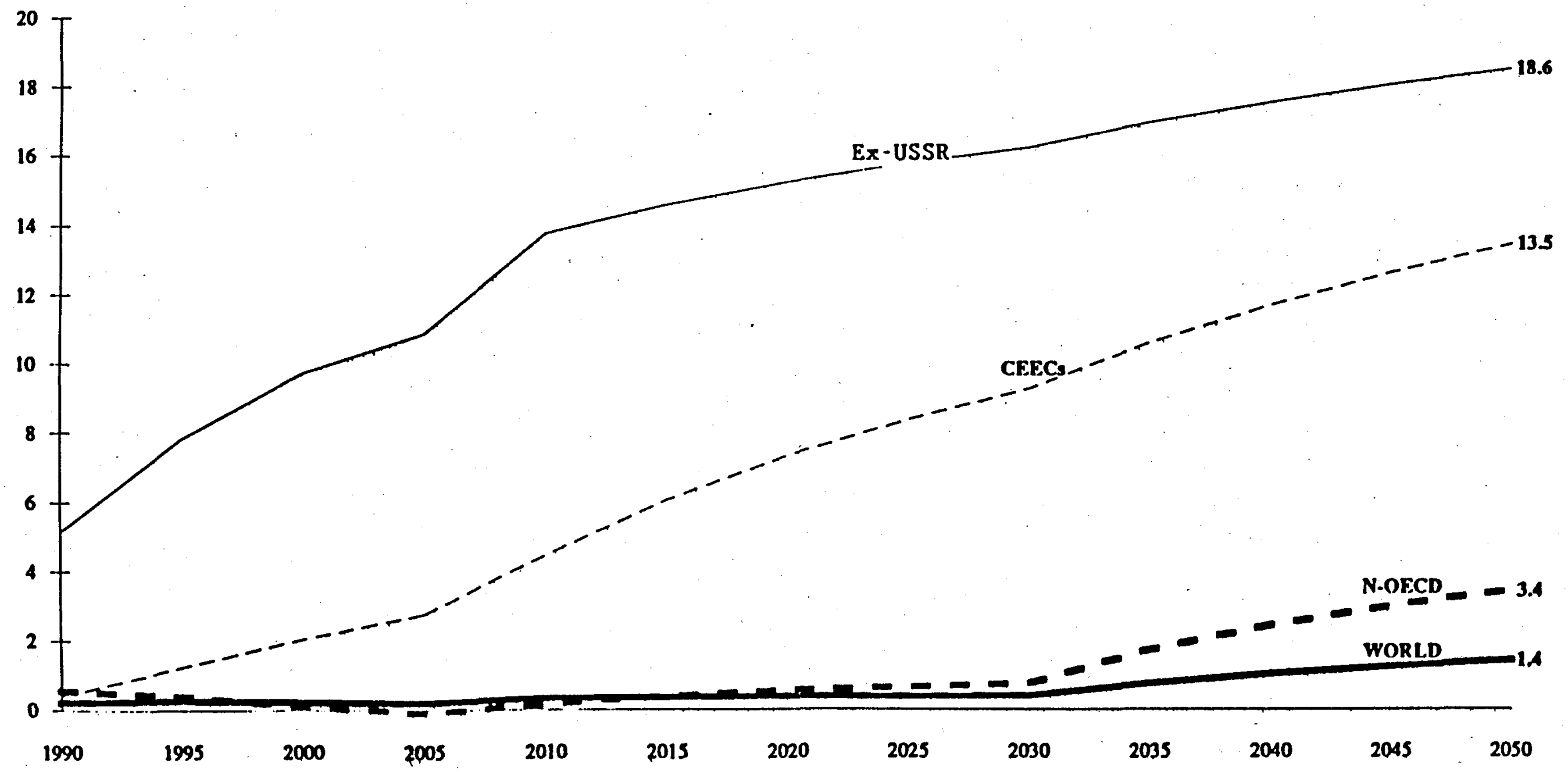


Figure 19c. Real income changes following the removal of existing distortions: Other non-OECD regions

(Percentage changes relative to the BaU level)

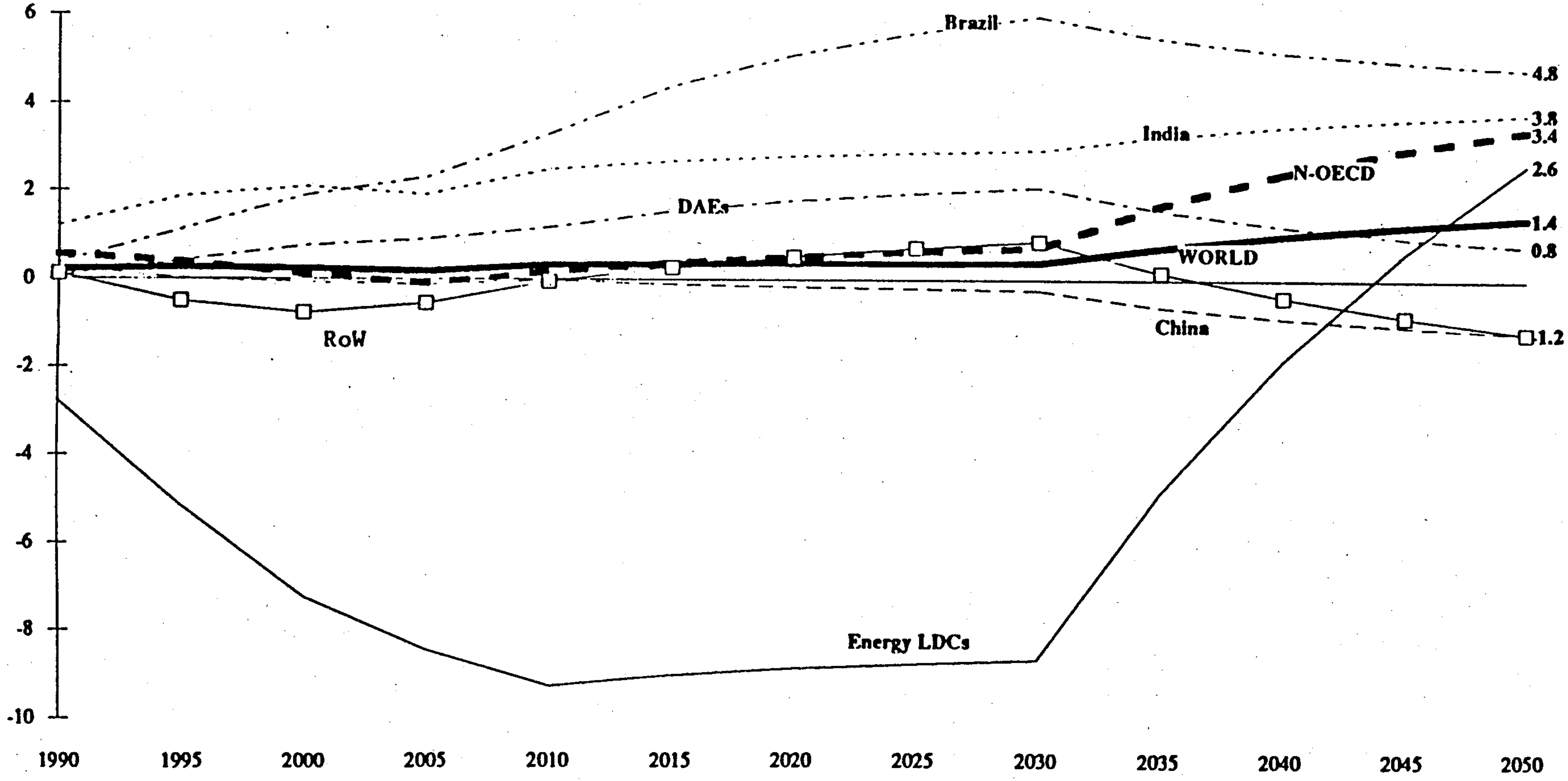


Figure 20. Emissions reductions in 2050 under a Toronto-type agreement with and without removal of existing distortions

Percentage deviation relative to BaU levels in 2050

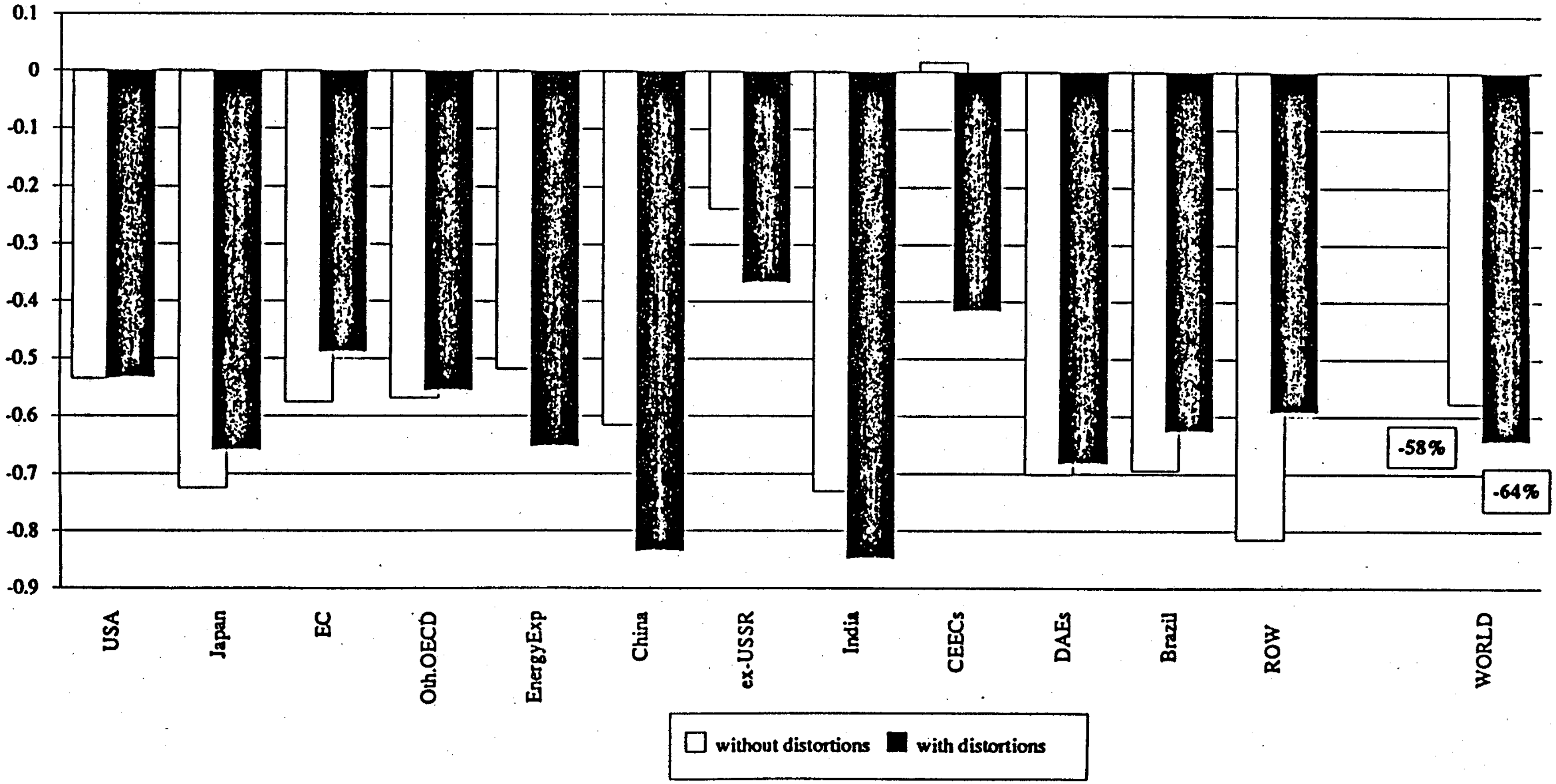


Figure 21. Average real income changes over the period 1995-2050 under a Toronto-type agreement with and without the removal of existing distortions

Percentage changes relative to BaU

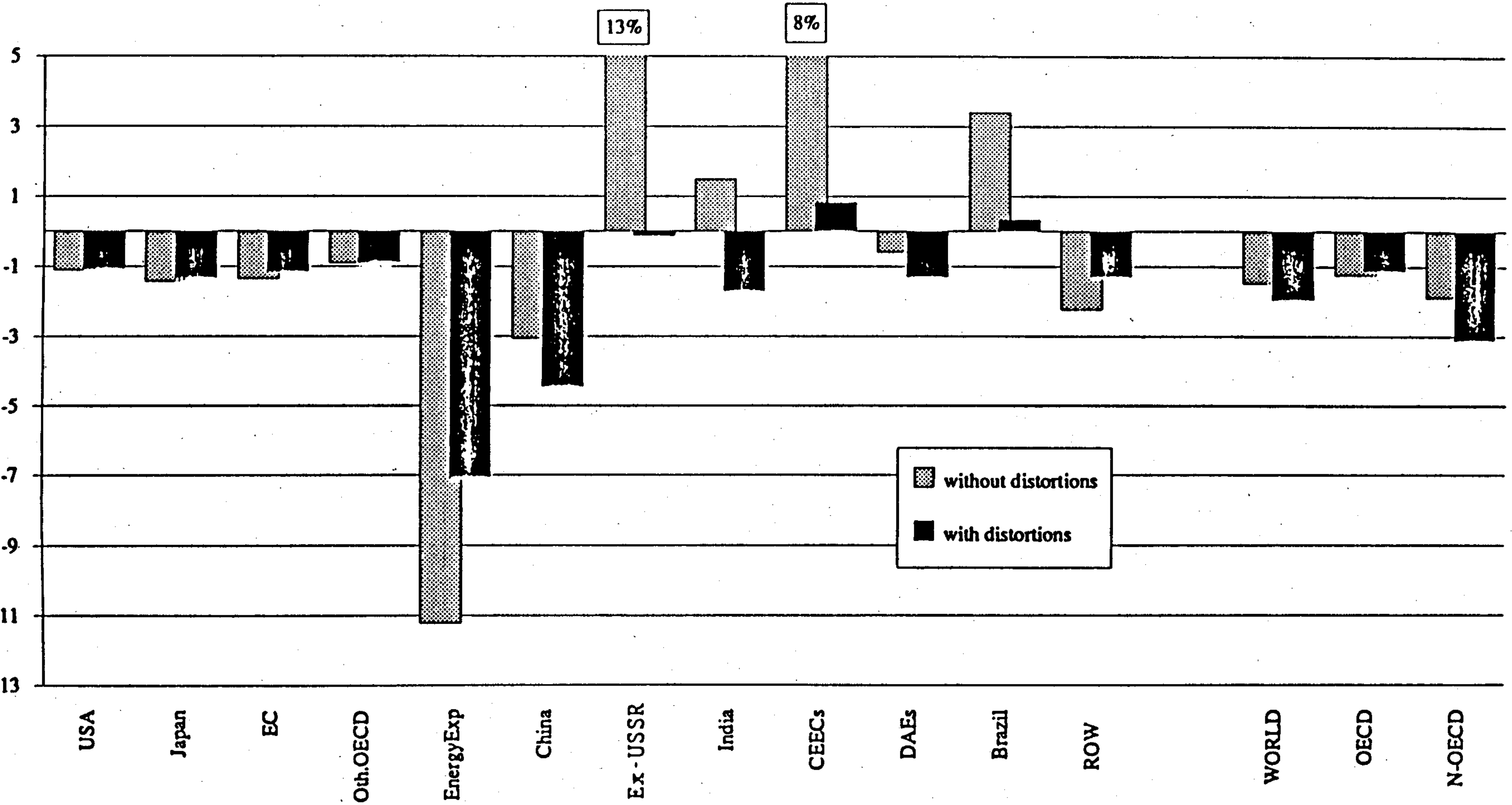
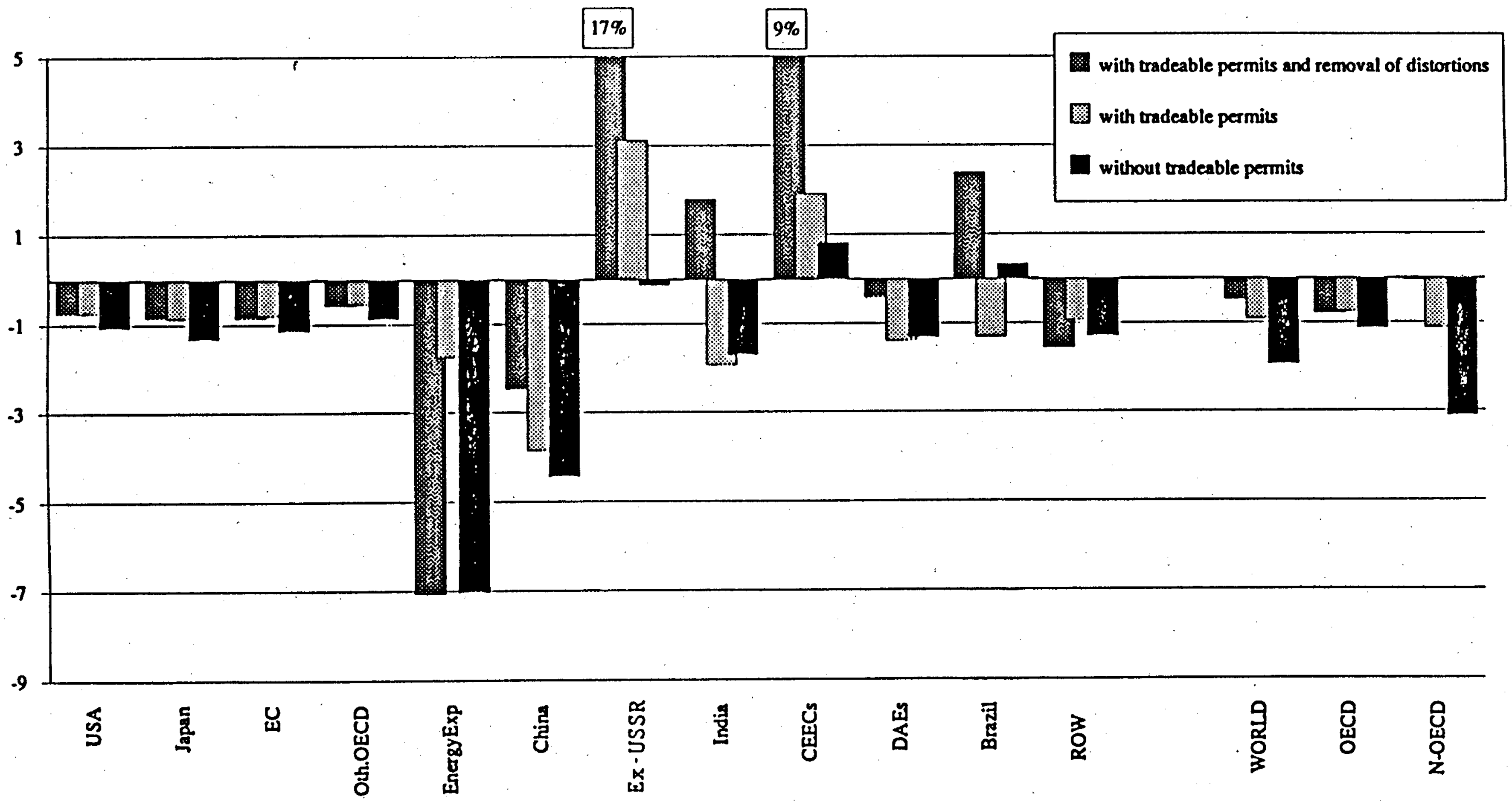


Figure 22. A comparison of average real income changes over the period 1995-2050 under three alternative versions of a Toronto-type agreement

Average percentage changes relative to BaU



Appendix

Determinants of the Carbon Tax in GREEN

Fuels are characterised by specific emission rates. A given carbon tax, expressed in 1985$ per ton of carbon, causes a higher relative price increase, the higher is the carbon content of the fuel. On the other hand, since the carbon tax is an excise tax, a higher tax is required to achieve a given increase of the relative fuel price, the higher is the price of the fuel net of tax. Therefore, the marginal cost of cutting emissions -- which corresponds to the carbon tax -- is related in each country to the so-called "average carbon price", which is calculated by dividing the average price of primary energy demand (expressed in 1985$ per terajoule) by the average carbon content of carbon-based energies. This average carbon price is an indicator of the level of the carbon tax required in each region to meet a given carbon constraint in the absence of back-stop technologies.

When the carbon tax rises to such a level that it becomes more profitable to use a back-stop option, the demand elasticity for the corresponding conventional energy increases sharply and further emissions cuts can be achieved at virtually constant marginal cost. Therefore, the arbitrage value of the carbon tax (see below) is a key determinant of the level of the carbon tax in the long run.

1. Average carbon prices

Figure A1 shows the average carbon prices in the OECD regions in the BaU. The OECD average price is higher than the world average, although the difference tends to diminish after 2030. Carbon prices fall from 1985 to 1990, in line with the fall in the world oil price; they increase from 1990 to 2010 before stabilising, as the carbon-based synthetic fuel begins to phase-in. Carbon prices tend to fall in all OECD countries after 2030 as increasing reliance on the carbon-based synthetic fuel raises the average carbon content. Japan is an outlier among OECD countries: its carbon price is much higher than the OECD average, reflecting its greater reliance on crude oil which is taxed. As long as back-stop options are not available, the expectation is therefore that higher taxes will be needed in Japan in order to satisfy a given emissions constraint -- see Figure 7 for an illustration that this is indeed the case.

There is a wide divergence in average carbon prices in the non-OECD regions. Figure A2 shows that carbon prices in more coal-based economies (China, India and the CEECs) remain stable, far below the world average. This is also the case in the former Soviet Union, where large gas reserves together with energy subsidies keep the average carbon price low. In contrast, the carbon prices in the other regions rise well above the world average. This is due to the fact that these economies rely more on crude oil whereas, at the same time, their energy subsidies delay the introduction of the carbon-based synthetic fuel. As a result, average carbon prices in Brazil, the DAEs and the Energy-exporting LDCs exceed the OECD average by 2050. Thus, the expectation is that these three regions will need higher carbon taxes than the other non-OECD regions.

2. Arbitrage carbon taxes

The availability of back-stops after 2010 has a major influence on the levels at which carbon taxes stabilise. Three back-stop fuels are distinguished in GREEN: the first two are substitutes for fossil fuels (a liquid synthetic fuel derived from coal or shale and a carbon-free liquid fuel) and the third is a carbon-free electric option. Data on the costs, carbon-emission coefficients and earliest possible dates of introduction of these back-stop fuels are taken from the Stanford-based Energy Modelling Forum Study No. 12 (EMF12) exercise (Table A1). It is important to note that, while synthetic fuel has by far the lowest estimated costs of the three back-stops, it is extremely "dirty" in terms of CO_2 emissions; indeed, it is much dirtier than coal.

In GREEN, back-stops are assumed to be CES substitutes for conventional energies. The demand arbitrage between them can be approximated by calculating relative price levels at which the demand for the back-stop energy represents a given proportion of the demand for the conventional energy source in country r. The price of the back-stop (P^n) is equal to a constant price expressed in 1985$ (see Table A1) times the world deflator (D) (1). The arbitrage condition is derived from the CES demand functions as follows:

$$P^o_r + (r^o.T) = [(\alpha_o/s.\alpha_n)]^{-1/\epsilon} . [(P^n.D) + (r^n.T)] \qquad [1]$$

where T is the carbon tax; P^o_r is the price of the "old" energy option in country r; and r^o and r^n are the emission rates of "old" and "new" energies, respectively. The coefficients α_o and α_n are the distribution parameters for "old" and "new" energy sources and ϵ is the substitution elasticity; s is the proportion of the demand for the conventional energy source relative to the demand for the corresponding back-stop option.

From [1], we derive the level of the arbitrage carbon tax, expressed in 1985$:

$$T^{85} = (P^n.D - k.P^o)/[R_r.(k.r^o - r^n)] \qquad [2]$$

with $k = [(\alpha_o/s.\alpha_n)]^{-1/\epsilon}$ and R_r being the real exchange rate of country r.

Since they are based on the prices from the BaU scenario, the taxes reported in Table A2 are "*ex-ante*" approximations of the arbitrage taxes at which substitutions between various energy sources take place. However, they have been corrected for the endogenous change of the international oil price which is induced by the imposition of the carbon limitations. Table A2 reports lower and upper bounds for the arbitrage taxes: the lower bounds correspond to taxes at which the conventional fuel still accounts for 70 per cent of total energy demand, whereas at the upper bound taxes, it only accounts for 30 per cent. These bounds give the ranges of carbon taxes over which back-stop options are gradually phased-in in GREEN.

The first two columns in Table A2 show the ranges of the carbon tax needed to make conventional electricity unprofitable *vis-à-vis* the carbon-free electricity. The extraordinarily high taxes in Brazil reflect the importance of the hydroelectric sector in that country. In China and India, a high tax is also needed to trigger the phasing-in of the back-stop option since electricity is based almost entirely on cheap, subsidised coal. Zero taxes indicate that the conventional electric option is already being replaced in the BaU scenario. There are large differences between lower- and upper-bound taxes, mainly in the OECD countries: they indicate that the back-stop electric option phases-in very progressively since the carbon content of conventional electricity (which appears in the denominator of the arbitrage equation) is rather low, due to the shift towards the carbon-free conventional electricity (nuclear, hydroelectric).

The second pair of taxes are those needed to eliminate the carbon-based synthetic fuel in countries/regions where this option is used (if not the case, the arbitrage tax is equal to zero). Since its rate of emission is 60 per cent higher than for coal, this synthetic fuel is eliminated first as soon as carbon taxes are imposed. Hence, it provides a way of cutting emissions at lower cost. This arbitrage is also affected by existing distortions: the carbon tax required to eliminate the carbon-based synthetic fuel will be higher in countries where crude oil is more heavily taxed. This explains why the corresponding arbitrage tax level is higher in Japan than in the other OECD countries.

The third group of columns gives the tax levels at which crude oil is replaced by the carbon-free synthetic oil. The fourth group of columns shows the taxes which are needed to rule out the carbon-based synthetic fuel <u>when no more crude oil is available</u>. These latter taxes correspond to the long-term equilibrium tax level in the Manne and Richels model; in GREEN, however, they vary from one country to another in line with real exchange rate differentials. The two final pairs of columns show the arbitrage taxes for coal and gas; they illustrate that these two fossil fuels are likely to be replaced by back-stop energies only at taxes exceeding $500 per ton of carbon.

Unlike the Manne and Richels model, GREEN does not yield a unique equilibrium carbon tax in the long run (2). Within the time horizon to 2050, taxes differ across regions even when back-stop energy sources are available. There are several reasons for this. <u>First</u>, existing distortions on domestic energy prices affect the rate of phasing-in of back-stop options. In particular, back-stop energies will compete earlier in countries where energy is heavily taxed whereas energy subsidies will delay the use of back-stop technologies. Thus, it will be more costly to wipe out the carbon-based synthetic fuel in countries, like Japan, where crude oil is heavily taxed. <u>Second</u>, differences in economic growth rates in the BaU scenario yield different real exchange rates across regions. As back-stop options have the same costs in all regions, their relative prices differ in line with real exchange rates differentials. In particular, back-stop options are relatively more expensive in some non-OECD regions with faster population and/or economic growth than in OECD countries. <u>Third</u>, over the period to 2050, the carbon-based synthetic fuel can always be replaced by crude oil whereas, in the Manne and Richels model, the long-term equilibrium tax level relies on the assumption that it is impossible to substitute crude oil for the carbon-based synthetic fuel due to reserve depletion. In GREEN, OECD regions can import additional crude oil, even if the supply constraint in the Energy-exporting LDCs is binding, since energy subsidies prevent the non-OECD regions from using large amounts of synthetic fuel in the BaU scenario. In other words, carbon taxes will shift crude oil demand from non-OECD to OECD regions instead of forcing the oil price up to the level of the synthetic oil price (which corresponds to the long-term equilibrium tax in Manne and Richels). Fourth, unlike in the Manne and Richels model, non-electric energy sources are not assumed to be perfect substitutes in GREEN. This implies, for instance, that a given tax level will induce an oil-based electric plant to use synthetic oil but it will require a higher tax to induce a coal-based plant to shift towards the synthetic fuel since it is assumed that there are adjustment costs in moving from an oil-based to a coal-based plant.

Notes

1. The world average of factor prices in each region.

2. In a fully intertemporal model, like the Manne and Richels one, it is necessary to impose restrictive conditions in order to have a steady state.

Table A1. Estimated costs and CO_2 emission coefficients for the three back-stop options

Back-stop options	Unit costs	Unit costs in 1985$ per terajoule	CO_2 emission coefficient (tons of carbon per terajoule)
Synthetic fuel	50 (1985$/barrel)	8 743	39
Carbon-free liquid fuel	100 (1985$/barrel)	18 950	0
Carbon-free electric option	75 (1985 mills/KwH)	28 126 (1)	0

1. A fixed distribution margin of 35 per cent is added to the EMF12 estimated unit costs to allow for the fact that the latter refers to producer costs. In addition, a second, region-specific adjustment is made to correct for aggregation bias arising from the fact that the electricity sector in GREEN also includes the distribution of gas and wager. The region-specific margins are calculated by comparing the average unit costs for the electricity, gas and water sector calculated from the 1985 I-O tables with electricity prices from the IEA publication *Energy Prices and Taxes*. The resulting margins for the OECD regions are: 33.3 mills/KwH in the United States; 14.5 mills/KwH in Japan: 35.9 mills/KwH in the EC: and 20.6 mills/KwH in the Other OECD. In the absence of any reliable data, an average margin of 30 mills/KwH was assumed for all the non-OECD regions.

Source: Study design for EMF12.

Table A2. Arbitrage tax levels in 2050 in the reference scenario

(1985$ and exchange rates per ton of carbon)

	Electricity vs. carbon-free fuel		Oil vs. synthetic fuel		Oil vs. carbon-free fuel		Carbon-free fuel vs. synthetic fuel		Coal vs. carbon-free fuel		Gas vs. carbon-free fuel	
	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
United States	122	480	9	88	341	485	222	299	610	730	887	1 107
Japan	0	0	81	199	805	470	255	343	584	722	1 096	1 349
EC	47	301	40	125	277	410	206	276	533	644	852	1 056
Other OECD	489	912	0	40	411	564	237	318	663	791	1 049	1 283
Energy-exporting LDCs	336	570	0	0	750	968	338	454	950	1 133	1 635	1 971
China	1 221	1 521	23	144	494	707	330	443	940	1 119	1 428	1 755
Former Soviet Union	640	806	0	0	1 078	1 297	338	454	958	1 141	1 734	2 069
India	1 984	2 759	0	0	814	1 046	359	482	1 020	1 214	1 792	2 147
CEECs	412	536	0	0	634	820	288	386	810	965	1 401	1 685
DAEs	0	282	0	44	526	719	300	403	789	951	1 244	1 541
Brazil	42 413	59 281	0	0	476	638	251	336	595	731	1 188	1 437
Row	363	654	0	68	445	618	268	360	755	900	986	1 251

Figure A1. Average carbon prices in the OECD countries in the reference scenario (1985$ per ton of carbon)

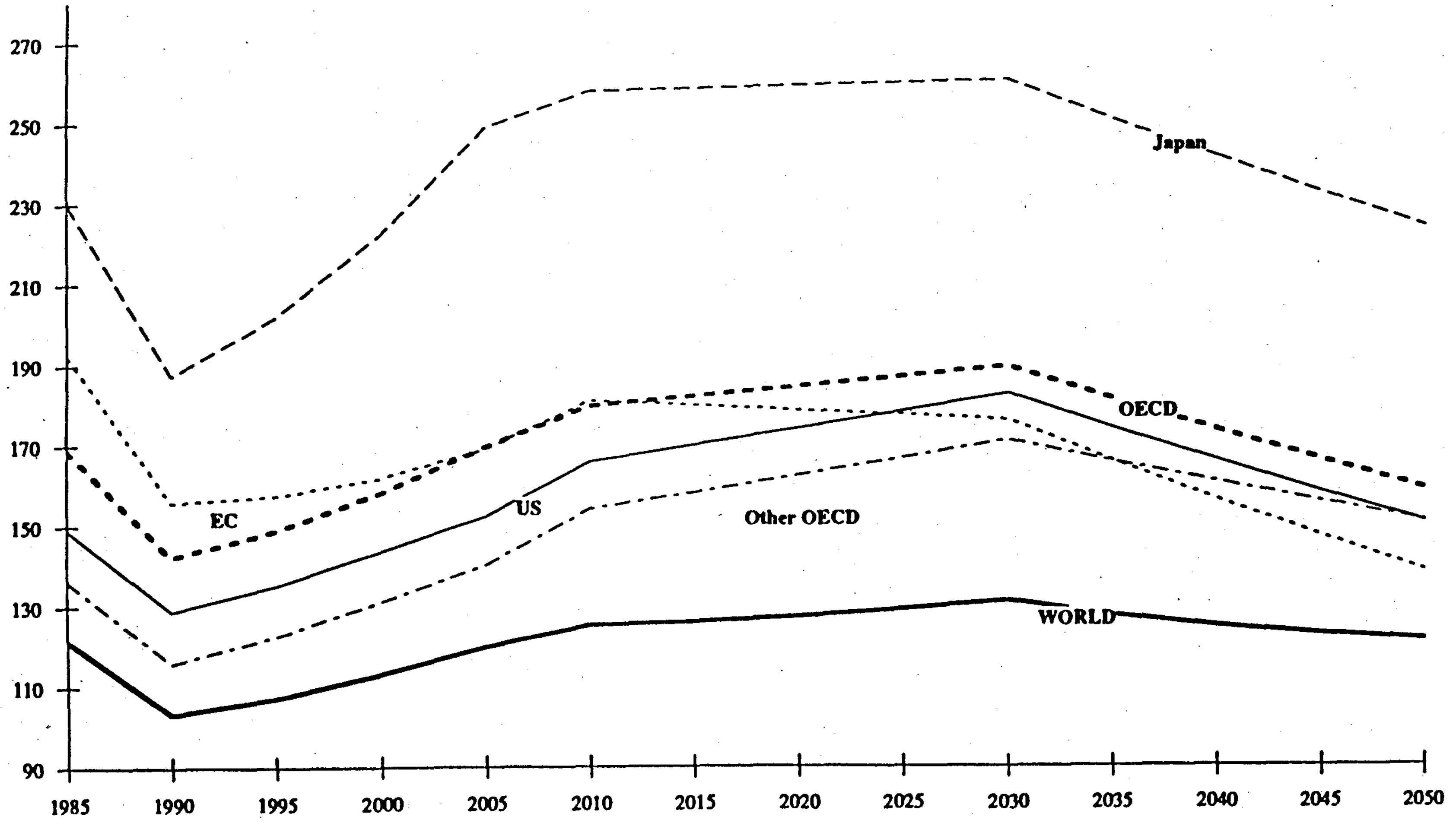
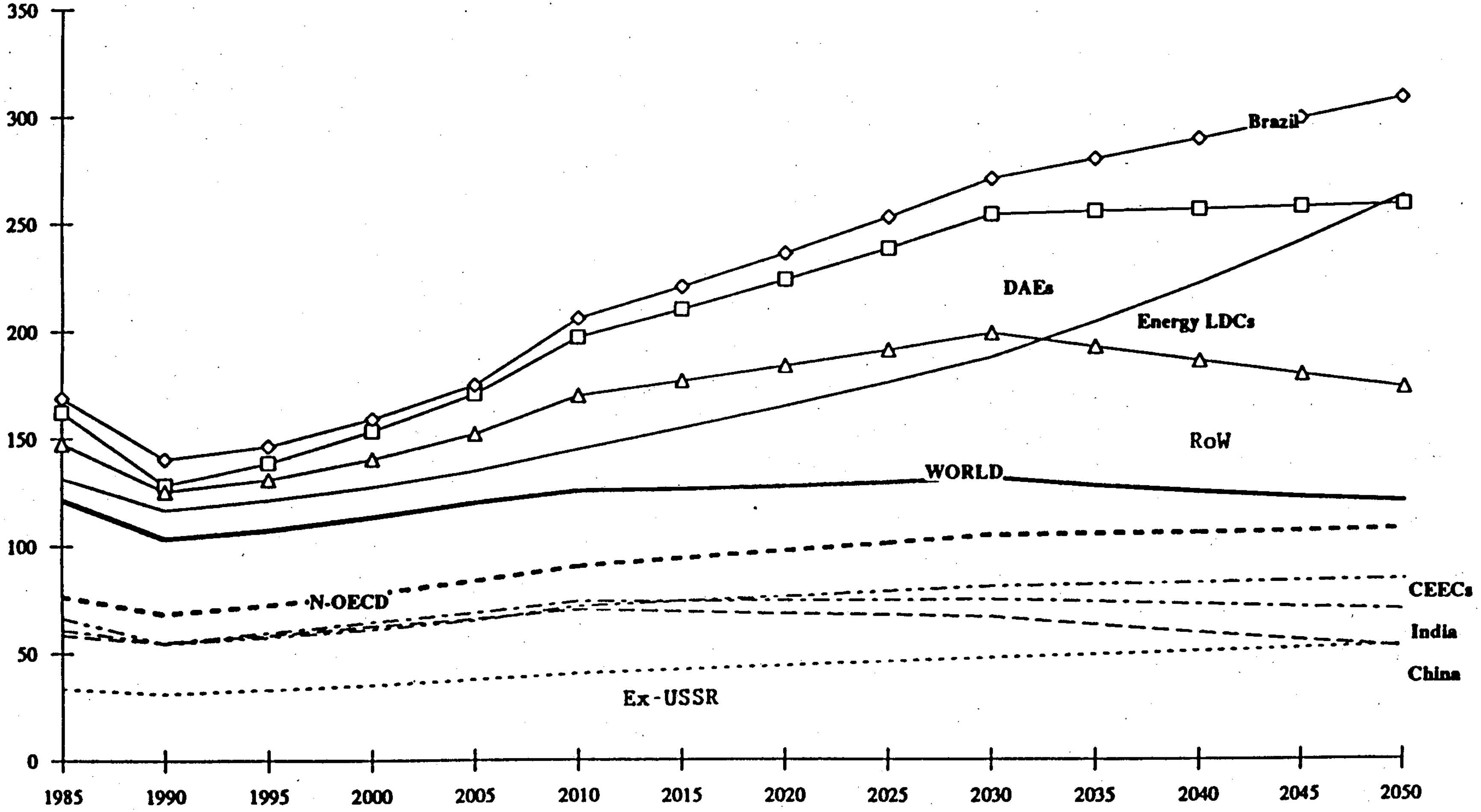


Figure A2. Average carbon prices in the non-OECD countries in the reference scenario (1985$ per ton of carbon)



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