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OECD Model Comparison Project (II) on the Costs of Cutting Carbon Emissions: Comparison of Model Structure and Policy Scenarios: GREEN and 12RT

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OECD MODEL COMPARISON PROJECT (II) ON THE COSTS OF CUTTING CARBON EMISSIONS

COMPARISON OF MODEL STRUCTURE AND POLICY SCENARIOS: GREEN AND 12RT

by
Alan Manne and Joaquim O. Martins

ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

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This paper forms part of the second round of the OECD Model Comparison Project on "The costs of cutting carbon emissions". It provides an overview of two global general equilibrium models GREEN and 12RT. The comparison exercise was carried out by means of five policy scenarios and a set of additional controlled experiments. The scenarios focus on alternative forms of joint implementation of international agreements to stabilise CO_2 emissions.

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Ce document fait partie du second projet OCDE sur "Les coûts de la réduction des émissions de carbone". Il fournit une vue d'ensemble de deux modèles d'équilibre général mondiaux, GREEN et 12RT. La comparaison a été effectuée à travers cinq scénarios de politique économique et des simulations de contrôle. Les scénarios sont centrés sur des formes alternatives d'accords internationaux visant à stabiliser les émissions de CO_2.

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COMPARISON OF MODEL STRUCTURE AND POLICY SCENARIOS: GREEN AND 12RT

by

Alan Manne and Joaquim O. Martins[1]

I. Introduction

This paper presents a comparison of two models participating in the second OECD Model Comparisons (MC-II) Project. Like the earlier comparison, this one is designed to assess the costs but not the benefits of greenhouse gas abatement. The focus of the earlier project was the size and key determinants of the costs of cutting CO_2 emissions[2]. Its main objective was to provide a diagnosis of the differences in baseline emissions and abatement costs (both marginal and average) between six global models. The simulations were designed accordingly and did not aim to represent policy-relevant scenarios.

The design of this comparison exercise is more policy-oriented. It covers only two models[3], but provides a better harmonisation of assumptions and a deeper understanding of the underlying structures.

One of these models is 12RT (see Manne, 1993). It has a rather detailed treatment of the energy supply sector through an activity analysis of physical process flows. The other is GREEN (see Burniaux,

1. Stanford University and OECD, Economics Department. For helpful comments, the authors are indebted to Michael Feiner, Leo Schrattenholzer and Peter Sturm. We also benefited from useful discussions and input from Jae Edmonds, Pete Wilcoxen and other participants of a workshop in Washington. The authors are also grateful to Christophe Complainville for efficient research assistance, and to Lyn Louichaoui for technical assistance. The opinions expressed in this paper are those of the authors and cannot be held to represent the views of the OECD or its Member countries.

2. See Dean and Hoeller (1992) and OECD (1993).

3. Originally, it was intended to include several global models in the comparison. However, in the course of the exercise it turned out that a close harmonisation of assumptions could only be obtained for GREEN and 12RT, which are reviewed here.

Nicoletti and Martins, 1992)[4]. It models energy demands and supplies through a nested-CES input-output structure. The models share the same regional disaggregation and have comparable sectors with respect to the production of fossil fuels and energy-intensive goods. They diverge, however, rather radically in their treatment of expectations and of international trade flows. 12RT provides a fully intertemporal equilibrium with perfect foresight whereas GREEN employs recursive dynamics. GREEN is an Armington-type trade model, assuming that goods from different origins are imperfect substitutes. 12RT is close to the Heckscher-Ohlin framework and assumes homogeneity.

This report begins with a short overview of the two models with respect to the specification, parameterisation and exogenous assumptions. The results for a Baseline scenario are then compared. It turns out that the two models yield similar projections of total primary energy demands, and that the difference in global carbon projections can be explained largely by differences in assumptions with respect to the availability of carbon-free fuel supplies. Finally, the outcomes of the two models are analysed for a set of policy-oriented scenarios. These scenarios focus on alternative forms of joint implementation of international agreements to stabilise CO_2 emissions.

II. Overview of 12RT and GREEN

By the design of the MC-II project, both GREEN and 12RT share the same regional disaggregation and have comparable sectors with respect to the production of fossil fuels and energy-intensive goods. There was close communication on technical details between the two modelling groups. Because of differences in their underlying data sources, the models are benchmarked on two different base years (1985 for GREEN and 1990 for 12RT). Both solutions were converted into US$ at 1990 exchange rates.

In GREEN there are eleven producing sectors. Eight sectors cover the supply and distribution of energy: coal mining, crude oil, natural gas, refined oil, electricity[5] and three backstop technologies. The model allows for the depletion of exhaustible resources of oil and gas. Three alternative backstops come on stream in all regions by the year 2010. One is carbon-based, and the other two are carbon-free electric and non-electric backstops. The remaining sectors are broad aggregates: agriculture, energy-intensive industries and other industries and services.

12RT has a much more detailed focus on the energy sector than GREEN. As in Manne and Richels (1992), the energy sector is modelled through an activity analysis of physical flows. There are nine electricity technologies and ten non-electric technologies. Each electric and non-electric technology is characterised by its cost (Tables 1a and 1b) and efficiency coefficients and possible expansion and decline limits. Oil and gas are viewed as exhaustible resources. Outside the energy sectors, there is no sectoral disaggregation except for trade in the energy-intensive sectors (EIS).

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4. For a full description and an up-date of the implementation of GREEN, see also van der Mensbrugghe (1994).

5. Because of data constraints, it was impossible to isolate the electricity sector from the gas and water distribution sector.

In GREEN, production technologies (including energy) are modelled mainly by nested constant-elasticity-of-substitution (CES) functions. There are a few exceptions to CES nesting. All inputs are used in fixed proportions in the production of fossil fuels (coal, crude oil, natural gas), petroleum products and the backstop technologies. Figure 1 gives a schematic comparison of the production functions employed in the two models.

In both, the supply of labour (in "efficiency units") is predetermined in each period. In GREEN, the supply of capital is exogenous, and rates of return on capital are endogenous. For 12RT, these assumptions are reversed. The rates of return are exogenous, and capital supplies are endogenous. There are no restrictions on capital flows between regions, but there is an intertemporal constraint that the net present value of these flows be zero.

In GREEN, the supplies of the sector-specific "fixed-factors" -- agricultural land, the carbon-free electric resource (nuclear, hydro and geothermal), coal and the remaining reserves of oil and natural gas -- depend upon their contemporaneous prices with a constant supply elasticity. In 12RT, the supplies of exhaustible resources are determined both by short-term extraction costs and by long-run price expectations of their value in future periods.

Both in GREEN and in 12RT, the international oil market is viewed as competitive, and the price of crude oil is determined endogenously. In GREEN, this is implemented by introducing a supply equation for oil in the Energy-exporting developing countries. In both models, the costs of backstop technologies are exogenous and identical in all regions; they are derived mainly from the Stanford-based Energy Modelling Forum Study no. 12 (see Weyant, 1993). By definition, backstop technologies, once they are no longer subject to expansion constraints, are available in all regions in unlimited quantities at constant marginal costs. Since backstop costs are identical in all regions, this rules out incentives for trade in energy supplies or emission permits during the backstop phase of development.

Table 2 gives a schematic comparison of the key features of each model with respect to their specification and main exogenous variables. Apart from their dynamic structure, perhaps their most important distinguishing feature is the treatment of trade flows. In GREEN, the basic assumption with regard to trade is that imports originating in different regions are imperfect substitutes. This Armington specification implies that each region faces downward-sloping demand curves for its exports. The framework is implemented for all goods except crude oil. Oil is viewed as a homogeneous commodity, and the world price is identical across all regions. In 12RT, all traded goods are homogenous. There are no distinctions drawn between their region of origin. However, in the trade of energy-intensive products (hereafter, EIS), it is assumed that there is a cost associated with deviations from base-year trade patterns. This penalty is quadratic in the magnitude of these deviations. With this specification, it is theoretically possible for a region's entire EIS supplies to be provided by imports rather than domestic production.

III. Five Policy Scenarios

A. Design

The following set of policy simulations is related to the FCCC (Framework Convention for Climate Change). These scenarios illustrate the impacts (in terms of costs and income distribution) of pursuing alternative international carbon abatement strategies. By comparing alternative cases, we can estimate the efficiency gains achievable through international co-operation.

Scenario #1: Baseline scenario. Differs from "business-as-usual" in that it includes the removal of existing subsidies. See Annex.

Scenario #2: Stabilisation of CO_2 emissions at 1990 levels through 2050 in each individual country/region for the FCCC Annex-1 countries. This group includes the OECD, the former USSR and Eastern Europe.

Scenario #3: Achieving the stabilisation of CO_2 emissions at 1990 levels jointly for the group of FCCC Annex-1 countries. Tradeable permits within the Annex-1 group, with allocations based on 1990 emissions (a grandfathering scheme).

Scenario #4: Same as #3 through 2010. From 2010 onward, all regions join an agreement to stabilise global emissions at 1990 levels. Permit allocations are based on a two-tiered system with gradual transition from shares based on 1990 emissions to shares based on 1990 population. The following sequence of weights is employed for the emission vs. population criteria:

	2000	2010	2020	2030	2050
1990 emissions	100%	75%	50%	25%	0%
1990 population	0%	25%	50%	75%	100%

Scenario #5: Global carbon tax. In Annex I countries: $50 tax in 2000, rising at 5% per year (in terms of constant 1990 dollars) up to 2030 and constant thereafter. In other regions: $25 tax in 2010, rising at 5% per year through 2050. With this sequence, the tax is always higher in the Annex-1 countries than elsewhere in the world but the differences diminish over time.

Scenarios #2 and #3 permit us to analyse the "carbon leakage" phenomenon. That is, unilateral restrictions in the Annex I countries could lead to indirect emission increases in those countries not covered by the agreement[6]. For an agreement restricted to a limited set of countries to be effective in terms of global emission abatement, a necessary condition is that it should not lead to a large amount of carbon emission leakages outside the coalition[7].

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6. For an analysis of the leakage effect in the GREEN model, see Martins, Burniaux and Martin (1992). For this in 12RT, see Manne (1993).

7. Note that outside the coalition, the leakage rate is not necessarily positive in all regions.

B. Baseline scenario

Both models followed the identical set of key assumptions described in the Annex. The "baseline" (scenario #1) is one in which there are no constraints on the level of CO_2 emissions. Figure 2 gives the carbon emission path in GREEN for the period 1990-2050. Emissions in Annex-1 group are projected to grow from around 4.2 in 1990 to 8.8 billion tons in 2050. These are, respectively, 71 and 51 per cent of world emissions. By 2050, both Annex-1 countries and the rest of the world have equal shares in the world's emissions. Despite the removal of energy subsidies in China and India, the fastest emissions growth occurs there. Their GDP is growing rapidly. Their coal resources are large and could cover a high share of domestic energy demands.

According to GREEN, global emissions are likely to be higher than those projected by 12RT. For the world as a whole in 2050, they are 17 billion tons for the one model and 13.4 for the other (Figure 3a). There is a similar pattern when we compare the Annex-1 countries only (see Figure 3b). Given that both models employ uniform assumptions with respect to the determinants of demand (GDP growth rates, subsidy removal and autonomous energy efficiency improvements), the reasons for this divergence seem to be related to the carbon intensity of energy sector supplies.

Composition of Primary Energy Demands and Supplies

Figures 4a-b show world energy consumption -- by source of supply -- in the two models. The overall primary energy requirements are comparable in the two models. Both lead to projections of about 20 billion toe (tons of oil equivalent) in 2050. For 2010, the projections are roughly consistent with the latest IEA World Energy Outlook (IEA, 1994). This projects a 50 per cent increase of world energy consumption between 1990 and 2010. Nevertheless, the carbon intensity is higher in GREEN than in 12RT. In 12RT, the aggregate of carbon-free energy supplies (nuclear, hydroelectric, the carbon-free electric backstop and other carbon-free fuels) cover 31 per cent of world energy demands by 2050. In GREEN, these same energy sources account for only 17 per cent. There is greater optimism in 12RT than in GREEN on the availability of low-cost carbon-free sources. The share of coal-based fuels (conventional and back-stop) is 54 per cent in GREEN and 48 per cent in 12RT. The balance is provided by oil and gas. Their 2050 market shares are 30 per cent in GREEN and 22 per cent in 12RT.

These differences are important because they determine the size of the emissions cut needed to achieve any emission target specified in levels relative to a certain date (e.g. stabilisation relative to 1990 emissions). The lower the Baseline carbon emissions, the lower the costs of achieving a stabilisation target. The carbon intensity is a key variable in determining the marginal costs of emission reduction. At the margin, the higher the carbon content of energy demand, the lower will be the carbon tax required to achieve the same proportional emission cut.

World Energy Market

One factor that could explain differences in model behaviour is the specification of expectations. According to GREEN, all agents are myopic. According to 12RT, they are all endowed with perfect foresight, and they optimise simultaneously over the entire time horizon. These two extreme assumptions could affect the determination of oil prices, the production of exhaustible oil and gas resources and the rate of market penetration of backstop sources of energy supplies. Figure 5 shows the Baseline oil price path in the two models. Both display a steady increase, with the price converging towards $50/per barrel, the break-even point between conventional crude oil and carbon-based synthetic fuels[8]. The convergence is somewhat faster in 12RT. It reaches the backstop price by 2050, but occasionally remains constant because the model is based upon discrete categories of oil extraction costs (see Table 1b).

Figure 6a compares the world production of oil in both models. 12RT projects lower oil output over the simulation period than GREEN. Is this related to the differences in treatment of foresight? Probably not. Figure 6b provides a controlled comparison in which oil and gas depletion are parameterised in GREEN in much the same way as in 12RT[9]. In this case the two models behave similarly with respect to oil production. With 12RT, we conducted a different type of controlled comparison. The time horizon was shortened from 2050 to 2010. This rules out the possibility that long-term price expectations could affect behaviour prior to 2010. It turns out that there are some differences in oil and gas prices and production levels, but virtually no difference in global carbon emissions through 2010. As a result of these two experiments, we believe that the treatment of expectations has little or no power in explaining the differences between Baseline carbon emissions in GREEN and in 12RT. The explanations lie elsewhere. For example, the two models differ in terms of global electricity production. By 2050, according to 12RT, electricity generation will be 25 per cent higher than in GREEN (Figure 7) and part of it is produced with carbon-free energy sources.

Figures 8a and 8b compare detailed results for two broad regions: the OECD and the non-OECD group of nations. In the OECD, Figure 8a shows that the penetration of carbon-free energy sources is higher in GREEN than in 12RT, and the levels of electricity generation are rather similar. Nevertheless, the OECD's emissions are higher in GREEN because the overall energy consumption requirements are also higher. The most striking differences are in the non-OECD countries. By 2050, the penetration of carbon-free supplies is roughly three times larger in 12RT than in GREEN. There is also a larger gas consumption. Recall that the carbon intensity of this fuel is about half that of coal.

To summarise, despite the harmonisation of key assumptions concerning growth and energy efficiency, the two models lead to rather different patterns for the composition of energy supplies and for carbon emissions in the Baseline scenario. 12RT embodies much more optimistic assumptions with respect to the penetration of carbon-free technologies such as the electric backstop option and natural gas trade. In GREEN, much of the rapid growth of emissions in the non-OECD countries can be explained by the penetration of coal both in electricity generation and in direct use. According to 12RT, the long-term role of coal is likely to be limited to the production of synthetic fuels. Existing coal-fired electricity plants are progressively phased out between 1990 and 2010. New coal-fired plants have higher costs than the low-cost electric backstop that becomes available in 2030 (cf. Table 1a).

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8. Recall that in 12RT all energy sources are assumed to be perfect substitutes. In GREEN oil and synthetic fuels are viewed as imperfect substitutes but with a very high elasticity (10).

9. The potential supply of depletion of oil and gas depends on two key coefficients: the extraction rate and the conversion rate. The former represent the maximum amount of production that can be extracted from proven reserves. The second gives the proportion of undiscovered resources that can be converted into proven reserves. Because each oil and gas cost category in 12RT may have different extraction and conversation rates, it is possible to make only an approximate correspondence with the specification of GREEN.

These differences are deeply linked to model design. 12RT, an activity analysis physical process model, enables one to formulate specific technological options, and to introduce explicitly many of the modellers' *a priori* beliefs about the future development of the energy sector. In GREEN, technology choices are anchored to observed economic structures. Thus, energy projections are more dependent upon historical input/output and trade data.

C. Emission reduction scenarios

The next scenarios simulate a progressive extension of the Climate Convention. They also test the relative costs of carbon taxes vs. tradeable permits to achieve alternative emission targets. Figure 9 shows GREEN's results for the effect on world emissions of each emission reduction scenario. If Annex-1 emissions are stabilised at their 1990 levels (scenarios #2 and #3), world emissions are brought down from 17 to 12.6 billion tons by 2050. This would represent a reduction of approximately 26 per cent at a global level, and a halving of emissions in the Annex-1 countries. Scenarios #4 and #5 cover all regions of the world. They employ different instruments (respectively, tradeable permits and carbon taxes), but have much the same effect. Both scenarios achieve stabilisation of world emissions at their 1990 levels.

In order to translate these emission paths into CO_2 concentrations, climate change and ecological-economic impacts, we need a new generation of models, the "integrated assessments"[10]. However, uncertainties are very large, and will probably remain for several decades. Accordingly, the results presented in Figure 10 must be interpreted with considerable caution. They show the evolution in CO_2 concentrations and the implied global average temperature change derived from scenarios #1, #3 and #4 and calculated with a climate sub-model[11].

According to the Baseline scenario, CO_2 concentrations in 2050 could reach 550 ppmv[12]. This would represent a doubling of CO_2 concentrations in the atmosphere relative to its pre-industrial level. The mean global temperature increase would be 1.8°C relative to 1990. If stabilisation is restricted to Annex-1 countries (scenario #3), there would be only a small impact on concentrations and hardly any effect on temperature.

The *global* stabilisation scenario (#4) would have a significant impact on concentrations. Given the momentum of the climate system, concentrations would still increase after 2050, but there would be a clear deceleration by comparison with the paths followed in scenario #1 and #3. Even with this far-reaching global agreement, the mean temperature change would be only 0.2°C below the Baseline scenario in 2050. These calculations suggest that we will have to look well beyond 2050 in order to evaluate jointly the costs and benefits of carbon abatement.

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10. See, for example, Edmonds *et al.* (1991).

11. We want to thank R. Richels and S. Swinehart for letting us use the climate module of the MERGE model. For further information on this model, see Manne, Mendelsohn and Richels (1993).

12. ppmv = Parts per million volume.

Carbon taxes and emission quota prices

In scenario #2, each of the Annex-1 countries employs unilateral measures for stabilisation. Since there are no provisions for joint implementation, there can be significant departures from economic efficiency. Figure 11a displays the carbon taxes (marginal abatement costs) required to achieve the stabilisation of emissions in each individual region of the Annex-1 group. In GREEN (Figure 11a), the taxes lie within a fairly narrow range in 2010 ($50 to $100 per ton of carbon) for the United States, the EC and Other OECD. Japan has a very high tax in 2000, but it is reduced dramatically in 2010 with the large-scale penetration of the carbon-free electric backstop[13]. By 2050, except for Japan, the taxes range between $100 and $160. The former Soviet Union (FSU) and Eastern Europe (EET) countries have zero taxes before 2010. With price reforms and the removal of energy subsidies, their emissions decline relative to 1990 levels.

In the earlier years, carbon taxes tend to be slightly higher in 12RT (Figure 11b) than in GREEN, but this pattern is reversed latter on. In 2010, the taxes range from $70 for the USA to $200 for the Other OECD region. Thereafter, these taxes tend to change only slowly. By 2050, all Annex-1 regions have taxes below $100. The former Soviet-Union and Eastern Europe are not constrained by the stabilisation target until after 2040[14]. Accordingly, the level of the carbon tax is quite low in these regions.

According to Figures 11a and 11b, there are significant differences between GREEN and 12RT. Several factors can explain them. First, the Baseline emission paths are not the same. This translates into different abatement efforts. For example, in order to achieve stabilisation of Japanese emissions by 2000, GREEN requires an emission cut of 30 per cent whereas in 12RT the emission cut is only 9 per cent relative to Baseline. The reverse applies for the Other OECD region. The impact of these differences is illustrated with a controlled experiment conducted with GREEN and shown in Figure 11c. This displays the carbon tax levels corresponding to the same emission reduction target in GREEN as in 12RT. For Japan and Other OECD -- the two extreme cases in Figures 10a and 10b -- the taxes in early periods are now much closer in the two models.

The nature of expectations may also play a role here. GREEN optimises at each point in time without any valuation of future costs. 12RT assumes perfect foresight over the entire period. To disentangle these effects, another experiment was conducted with 12RT. This consisted of shortening the planning horizon from 2050 to 2010. The results are shown in Figure 12. The top chart reproduces the carbon taxes in 12RT for scenario #2 with the full horizon whereas the bottom chart refers to the truncated horizon. Consistently, in all regions, the bottom chart displays higher taxes in 2000 and lower taxes in 2010. With more myopic behaviour, there is a tendency to neglect future costs. Thus taxes can be lower in the short-run, but higher later on. With a longer planning horizon early costs may be higher, but are more stable through time[15].

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13. For a comprehensive analysis of the carbon tax determinants in GREEN, see Martins, Burniaux, Martin and Nicoletti (1992).

14. These regions have lower emissions in 12RT than in GREEN. In the former, a larger portion of energy demands is supplied by carbon-free sources and by natural gas.

15. Note that this result holds only if the carbon constraint is exogenous to the system.

Under scenario #3, there is joint implementation. With a uniform marginal cost of abatement there would be economic efficiency within the Annex-1 group. The resulting price for tradeable emission quotas is indicated in Figure 13a. According to GREEN, the quota price increases steadily, and it reaches more than $200 by 2050. In 12RT it stays below $100. A similar pattern occurs in scenario #4 where all regions join in an agreement to stabilise world emissions (bottom Figure 13b).

Baseline emissions and expectations do not explain all of the differences in emission quota price between the two models. Much also depends on the optimistic assumptions concerning the speed of penetration of carbon-free technologies. 12RT assumes that a low-cost carbon-free electric backstop is available after 2020 (see Table 1a and Annex). With this assumption the tax can be stabilised at a lower level. Figure 14 illustrates the effect of introducing this alternative assumption into GREEN. For scenarios #3 and #4, the prices of emission quotas are now more comparable in the two models.

Aggregate Costs

As a rough-and-ready indicator, it is convenient to measure aggregate economic costs as the difference in GDP between the Baseline and the emission abatement scenarios. Primarily because of terms-of-trade effects, this is not the most appropriate way to measure welfare costs[16]. However, it has the advantage of being the most nearly comparable between the two models. Figure 15 shows the GDP losses for scenarios #2 and #3. As a per cent of GDP, overall losses are small in both models. GREEN estimates the cost of stabilising emissions in each Annex-1 country/region to be 0.8 per cent of GDP by 2030. The gains from joint implementation can be estimated by comparing scenarios #2 and #3 across models (Figure 15c). With joint implementation, Annex-1 costs are roughly halved. 12RT produces a somewhat lower GDP loss and a lower gain from a joint agreement (0.2 instead of 0.4).

At the aggregate level the results are consistent with the patterns of marginal abatement costs. Across regions, the patterns of GDP costs differ between GREEN and 12RT. According to GREEN, Japan incurs the highest GDP cost, but in 12RT the highest per cent cost occurs in the Other OECD region. This determines the pattern of gains from joint implementation. The gaps are also striking in the cases of the Former Soviet Union (FSU) and Eastern Europe (EET). In GREEN, the former Soviet Union gains 1.1 per cent (i.e. 0.8+0.3) of GDP from a tradeable quota scheme whereas in 12RT the GDP loss is increased. Figure 16 suggests the reason for this difference. It shows the volume of trade in emission quotas by 2030. The sales of emission quotas are much larger in GREEN, and the FSU's share of this market is above 80 per cent. This more than fully compensates the FSU for the direct effects of the carbon constraint. Figure 16 also indicates that there could be sizeable financial transfers associated with this system of tradeable emission quotas within the Annex-1 group. For 2030, these could range between 22 and 37 billion US$ of 1990 purchasing power.

16. GDP is calculated as the sum of Consumption, Investment and the Trade balance, all variables measured at constant prices. In GREEN, welfare losses are usually computed from Household real income, or the Hicksian equivalent measure. In 12RT, one could compute a discounted stream of consumption flows.

The case of Eastern Europe is less straightforward. In GREEN, GDP gains relative to the Baseline are due to the implicit removal of energy subsidies after the imposition of a carbon tax[17]. The gains are amplified by the participation of EET in the joint agreement. This region is a net seller of emission quotas.

It is worth noting the impact of these two Annex-1 agreements on the Energy exporting LDCs (EEX). Even though they do not participate in the emission reduction protocol, Energy-exporting LDCs gain from the implementation of a cost-efficient agreement among the Annex-1 group. This occurs especially in GREEN because, on average, taxes are higher over the long run. Emissions are reduced more efficiently, and there is a less marked decline of energy imports of Annex-1 countries from the EEX region.

Figures 17a and 17b show the GDP losses corresponding to the global emission reduction scenarios #4 and #5, respectively. For the tradeable permit scheme (#4) both models estimate similar overall costs: 1.4 to 1.3 per cent of world GDP by 2030. The regional breakdown is different. 12RT estimates higher costs in the Annex-1 group and GREEN estimates higher costs for the non-Annex-1 regions, especially for the Energy-exporting LDCs.

In GREEN, the global carbon tax induces a lower world GDP loss than tradeable emission quotas (Figure 17c). The reverse applies to 12RT. From a global point of view, these differences are small. Either policy scenario would be a cost-effective way to stabilise global emissions. Nonetheless, among Annex-1 regions, the former Soviet-Union and Eastern Europe would show a strong preference for the tradeable quota scheme. As they are net sellers of emission quotas, their GDP losses would be much higher for the carbon tax policy option followed in scenario #5. When comparing the two systems, it would also be necessary to take into consideration the equity questions between Annex-1 and non-Annex 1 groups.

Trade in emission quotas represents large and increasing financial transfers in GREEN (Figure 18). The amount of trade reaches more than 160 billion of 1990 US$ for the year 2050. In 12RT, the volume of quota trade is significantly lower except for the end of the period. The difference between the two models can be explained by the lower permit price projected by 12RT (cf. Figure 13). The high penetration of carbon-free back-stop fuels in 12RT also makes trade in quotas a less attractive option to achieve a given emission abatement at least cost.

Carbon Leakages

Carbon leakages have been a controversial issue. The term "carbon leakages" refers to the possibility that unilateral reductions in CO_2 emissions in one country or region may be partially offset by increased emissions elsewhere[18]. Leakage does not necessarily need to be positive, it may also be negative.

Two basic channels determine the size and the extent of leakages. The *first channel* relates to the use of energy as an intermediate input, especially in energy-intensive industries (EIS). Imposing a carbon tax will raise the production costs of some goods more than others, and will entail a change in comparative

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17. The two models assume removal of subsidies to energy consumers (see Annex). This make domestic prices comparable with international prices. However, in GREEN there are still energy producer subsidies in the base input/output data, and these are assumed to remain constant.

18. See, for example, Perroni and Rutherford (1991), Rutherford (1992), Manne (1992) and Martins *et al.* (1992). Winters (1992) provides a survey on this topic.

advantage toward less carbon-intensive goods. In countries where no carbon tax is imposed, comparative advantage will move in the opposite direction, and may lead to an increase in emissions. The *second leakage channel* is directly related to world energy markets. If energy demands are reduced in a large region, this could induce a significant drop in world energy prices --particularly if there is a low supply elasticity of fossil-fuels. The impact on global emissions is ambiguous. It will depend on the overall substitution between energy and non-energy goods and also on inter-fuel substitution possibilities.

Figure 19 illustrates the leakage effects in the case of Annex-1 unilateral stabilisation of emissions. Leakages are large in 12RT. In some years, they can be as high as 35 per cent of the Annex-1 emission cut. In GREEN, they are small and sometimes negative. How might one reconcile these two contrasting views? The next chart provides some hints on this question (Figure 20).

The small leakages in GREEN are partly due to the compensation between positive and negative effects. Indeed, in the Energy-exporting LDCs and China emissions decrease after stabilising emissions in the Annex-1 group only. That is leakages are negative. In the case of Energy-exporters, this outcome is related to the decline of their energy exports; this reduces factor income, investment and lowers economic growth in future periods. For China, the decrease in emissions is due to the substitution from coal towards crude oil, an effect that reduces the carbon intensity of energy demand. This rather unexpected result is caused by a lower crude oil price in the early periods. Elsewhere, emissions tend to increase (positive leakage), but their magnitude is small. In 12RT, the largest leakage occurs in China. By 2050, this region accounts for 20 per cent of total leakages. As in GREEN, some negative leakages appear in the Energy exporters (EEX) and also in the DAEs, in 2000 however both become positive thereafter.

Previous experiments with GREEN[19] have shown that the EIS leakage channel is likely to be small. For example, even in the group of energy-intensive sectors energy inputs account for a small fraction of total cost. Only for very specific industries -- e.g. aluminium ingots -- could there be a large impact of increased energy prices. In 12RT, EIS trade is much more sensitive to this channel.

12RT does not have sectoral production functions. EIS trade is represented through a net export activity with internationally uniform coefficients for electric and non-electric energy. When EIS products are imported rather than produced domestically, there is a cost of deviating from the base year EIS trade balance. This cost is a quadratic function of the deviation. EIS products are viewed as homogenous, and are more vulnerable to international competition than with the Armington specification used in GREEN. In 12RT, EIS consumption is projected exogenously, but net trade is endogenous. In effect, EIS trade provides a mean of buying/selling the energy embodied in this category of goods. In GREEN, instead, it is determined through a full general equilibrium interaction between consumption and production[20].

Figure 21 assesses the magnitude of EIS trade as a channel for leakages in 12RT. In this experiment, the net exports of EIS remain fixed at their base levels. Without the EIS channel total leakages are much smaller. They peak at 20 per cent by 2040, but on average are below 10 per cent. Namely, leakages in China would now peak at only 8 per cent. Nonetheless, they are still higher than in GREEN.

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19. See Martins *et al.* (1992).

20. In other words the change of EIS output in one country requires the reallocation of production factors both in the domestic and in foreign economies.

These results show that EIS trade provides the major source of leakage in 12RT, but that there can also be small amounts of leakages related to oil and gas trade. In GREEN, natural gas is an Armington good, and this may be viewed as a proxy for high transportation costs. For the distant future, this may have the disadvantage of imposing overly pessimistic constraints on the development of international gas trade via tankers or pipelines.

IV. Summary and policy conclusions

This paper reports the results of a comparison between two global general equilibrium models, GREEN and 12RT. This comparison provided for harmonisation of the assumptions and a better understanding of the differences between the model structures. During the comparison process, there was close communication between the two modelling groups.

The comparison was carried out by means of five policy-oriented scenarios and a set of additional controlled experiments with the two models. The policy simulations are related to the FCCC (Framework Convention for Climate Change). These scenarios focus on alternative forms of joint implementation of international agreements to stabilise CO_2 emissions.

The following are the main conclusions that can be drawn from this exercise:

1. The global Baseline primary energy demands are comparable in the two models. Both lead to projections of about 20 billion toe (tons of oil equivalent) in 2050. For 2010, the projections are roughly consistent with the latest IEA World Energy Outlook (IEA,1994) which projects a 50 per cent increase of world energy demand between 1990 and 2010.

2. Despite comparable energy demands, baseline carbon emissions are higher in GREEN than in 12RT. As a result of several experiments, we believe that the treatment of expectations has little or no power in explaining these differences. The differences can be explained largely by the assumptions with respect to the availability of carbon-free fuel supplies. In GREEN, much of the rapid growth of emissions in the non-OECD countries can be explained by the consumption of coal both in electricity generation and in other uses.

3. If Annex-1 emissions are stabilised at their 1990 levels, this would represent a reduction of approximately 25 per cent at a global level, and a halving of emissions in the Annex-1 countries in 2050. Global scenarios #4 and #5 employ different instruments (respectively, tradeable permits and carbon taxes), but they both achieve stabilisation of world emissions at their 1990 levels.

4. The unilateral stabilisation of Annex-1 emissions (scenarios #2 and #3) has only a small impact on concentrations and virtually no impact on temperature change. Global stabilisation (scenarios #4 and #5) has a significant impact on concentrations. Given the momentum of the climate system, however the mean temperature change relative to the Baseline would still be small in 2050. In order to see the long-term effects of carbon emissions, one must look well beyond that horizon date.

5. According to GREEN, stabilisation of Annex-1 emissions at their 1990 levels by 2010 requires carbon taxes that lie in a fairly narrow range of $50 to $100. By 2050, except for a very high tax in Japan ($350), the taxes range between $100 and $160. With a tradeable permit scheme the quota price increases steadily, and it reaches more than $200 by 2050. In 12RT, taxes are higher by 2010 but are stabilised below $100 by 2050. These differences can be reconciled largely by taking account of different baseline emissions, expectations and different assumptions about the availability of carbon-free energy sources.

6. As a percentage of GDP, the losses are typically small in both models. GREEN estimates the cost of stabilising emissions in each Annex-1 country/region to be 0.8 per cent of global GDP loss by 2030; the loss is the same for the Annex-1 group only. However, the gains from joint implementation are larger in GREEN than in 12RT. Accordingly, the sales of emission quotas are also much larger in GREEN. The former Soviet Union has a large share in the emission quota market (above 80 per cent). Sizeable financial transfers are implied by this quota trade. In the case of global stabilisation of emissions, GREEN projects over 160 billion of 1990 US$ of overall quota trade in 2050.

7. Even when they are not participating in an emission reduction protocol, Energy exporters are a big gainer from the implementation of a cost-efficient agreement. Indeed, by reducing world emissions more efficiently, the decline of their energy exports and terms of trade is less marked.

8. Global agreements with either tradeable emission quotas or a rising carbon tax generate close global GDP costs and therefore are equally cost-effective ways of stabilising global emissions. However, the former Soviet Union and eastern European countries could show a strong preference for a tradeable quota scheme because of the large financial transfers generated by the quota system. When comparing the two systems, it would be necessary to consider the equity as well as the efficiency questions.

9. In 12RT, the possibility of expansion of trade in energy-intensive products is larger than in GREEN. The leakage channel associated with world energy markets is also more active. Namely, in 12RT, carbon abatement can give an artificial stimulus to gas trade. The specification and parameterisation of GREEN is more in line with historical data. Accordingly, emission leakages are large in 12RT and may occasionally reach 35 per cent. They are small and sometimes negative in GREEN.

Annex: Key Baseline Assumptions

Timing of distortion removal

In the first model comparison project (MC-I), *ad valorem* energy subsidy and tax rates were held constant throughout the period 1990-2050 in GREEN. The subsidy rates calibrated in 1985 are summarised in Table below[1]:

Energy subsidy rates in GREEN: all years (% of producer price)

Region	*Coal*	*Oil*	*Gas*
United States	--	4	--
Japan	--	--	--
EC	--	--	--
Other OECD	--	--	--
Former Soviet Union	56	88	88
CEECs	52	39	17
Energy-exporting LDCs	3	36	21
China	55	2	11
India	42	42	50
DAEs	--	17	--
Brazil	--	24	42
RoW	--	18	--

Because energy price reforms have been taking place in China and the former Soviet Union (FSU), the following phase-out rules are employed:

a) Phase out subsidies on sale prices for coal and gas by 2010 in all regions.
b) Phase out subsidies on sale prices for oil by 2000 in all regions.

1. These are net subsidy rates derived from the comparison between world and domestic energy prices, adjusted for inland transportation costs. For more details on the computation of the distortions in GREEN, see Burniaux, Nicoletti and Martins (1992).

Price and timing of backstop technologies

a) Backstop technologies are introduced in 2010.
b) The prices of coal, oil and gas backstops remain the same as in the earlier Model Comparisons Project (MC-I). The prices of the backstop fuels are as follows: $ 50 per barrel for the carbon-based backstop, $100 per barrel for the carbon-free backstop.
c) In GREEN, the price of the electric backstop remains unchanged at $75 mills/KWh. In 12RT, a high-cost electric carbon-free backstop becomes available in 2010 at a cost of 75 mills/kWh, and by 2020 a low-cost backstop becomes available at 50 mills/kWh.

GDP growth rates

The EMF-12 assumptions for GDP growth rates were adjusted according to recent trends. In particular, upward adjustments for China and DAEs in all years, and downward adjustments were applied for FSU and EET for the 1990-2000 decade.

Potential GDP growth rates -- annual per cent

	United States	Japan	EC	OOECD	ENX	China	FUSSR	India	CEEUR	DAE	Brazil	RoW
1990	2.56	3.70	2.18	2.19	3.63	6.0	0.0	4.64	0.0	4.37	4.38	3.50
2000	2.13	2.73	1.66	1.67	3.42	5.0	2.3	4.44	2.3	4.16	4.17	3.12
2010	2.13	2.73	1.66	1.67	3.42	4.5	3.0	4.44	3.0	4.16	4.17	3.12
2020	1.63	2.22	1.28	1.29	2.69	4.0	3.0	3.40	3.0	3.23	3.24	2.36
2030	1.63	2.22	1.28	1.29	2.69	3.5	2.5	3.40	2.5	3.23	3.24	2.36
2040	1.63	2.22	1.28	1.29	2.69	3.5	2.0	3.40	2.0	3.23	3.24	2.36

Non-renewable resource base

Same assumptions as EMF-12.

Other variables/parameters

The value of the AEEI (autonomous energy efficiency improvement) coefficient was taken to be 1 per cent per year in all regions and all periods.

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Table 1a. **Electricity cost coefficients in 12RT**
(in mills per kWh)

	HYDRO	OIL-R	GAS-R	COAL-R	NUC-R	GAS-N	COAL-N	ADV-HC	ADV-LC
United States	2.6	4.3	3.2	20.1	20.6	13.7	51.0	75.0	50.0
Japan	2.6	4.3	3.2	23.2	20.6	13.7	61.0	75.0	50.0
EC	2.6	4.3	3.2	23.2	20.6	13.7	61.0	75.0	50.0
Other OECD	2.6	4.3	3.2	23.2	20.6	13.7	61.0	75.0	50.0
Energy-exporting LDCs	3.6	6.0	4.5	27.9	25.4	15.0	51.0	75.0	50.0
China	50.0	3.4	2.6	26.1	18.2	13.1	51.0	75.0	50.0
Former USSR	2.6	4.3	3.2	20.1	20.6	13.7	51.0	75.0	50.0
India	50.0	6.0	4.5	27.9	25.4	15.0	51.0	75.0	50.0
CEECs	2.6	4.3	3.2	20.1	20.6	13.7	51.0	75.0	50.0
DAEs	3.6	6.0	4.5	27.9	25.4	15.0	51.0	75.0	50.0
Brazil	50.0	6.0	4.5	27.9	25.4	15.0	51.0	75.0	50.0
ROW	50.0	6.0	4.5	27.9	25.4	15.0	51.0	75.0	50.0

Note: Many of these coefficients do not include amortisation and depreciation of capital costs for existing plants.

Legend: HYDRO: hydroelectric, geothermal and other existing low-cost renewables.
GAS-R and OIL-R refer, respectively, to existing oil and gas-fired plants.
GAS-N: advanced combined cycle.
COAL-R: coal -- remaining.
COAL-N: coal -- new.
NUC-R: nuclear -- remaining.
ADV-LC: backstop advanced -- low cost.
ADV-HC: backstop advanced -- high cost.

Table 1b. **Non-electric energy cost coefficients in 12RT**
(in 1990 $ per barrel)

	CLDU	SYNF	RNEW	NE-BAK	GAS-LC	GAS-HC	OIL-1	OIL-2	OIL-3	OIL-4	OIL-5
United States	12	50	36	100	9	18	9	15	21	27	33
Japan	18	50	36	100	9	18	9	15	21	27	33
EC	18	50	36	100	9	18	9	15	21	27	33
Other OECD	12	50	36	100	9	18	9	15	21	27	33
Energy-exporting LDCs	12	50	36	100	3	15	6	9	12	15	18
China	12	50	36	100	9	18	9	15	21	27	33
Former USSR	12	50	36	100	9	18	9	15	21	27	33
India	12	50	36	100	9	18	9	15	21	27	33
CEECs	12	50	36	100	9	18	9	15	21	27	33
DAEs	12	50	36	100	9	18	9	15	21	27	33
Brazil	12	50	36	100	9	18	9	15	21	27	33
ROW	12	50	36	100	9	18	9	15	21	27	33

Legend: CLDU: coal direct uses.
SYNF: synthetic fuels (includes unconventional oils such as tar sands and heavy oils).
RNEW: renewables (e.g. ethanol from biomass, etc.).
NE-BAK: non-electric backstop fuel.
GAS-LC: gas low-cost.
GAS-HC: gas high-cost.
OIL-1, ... 5: oil in different cost categories.

Table 2. **Comparison of the key features of GREEN and 12RT**

	GREEN	12RT
Regions	United States, Japan, EC and Other OECD -- and eight non-OECD regions -- the former USSR (FSU), Central and Eastern Europe in transition (EET), China, India, the Energy-exporting LDCs (EEX), the Dynamic Asian economies (DAEs), Brazil and the Rest of the World (ROW)	
Time periods	1985, 1990, ..., 2010, 2030, 2050	1990, 2000, ..., 2050
Dynamics	Recursive (myopic)	Intertemporal (clairvoyant)
Real exchange rates	Endogenous	Fixed through international numéraire
Capital flows	Exogenous	Endogenous -- s.t. intertemporal foreign exchange constraint
Savings	Constant marginal propensity	Determined through maximisation of discounted utility of consumption
Rates of return	Endogenous	Virtually exogenous, held close to 5% through benchmarking, utility discount rate and numéraire
Labour supply	Exogenous	Exogenous
Labour productivity	Exogenous	Exogenous
Adjustment rigidities	Putty/semi-putty production function and imperfect capital mobility in declining sectors	Putty-clay production function
Trade: homogenous goods	Oil, carbon emission quotas	Oil, gas, carbon emission quotas and international numéraire
Trade: Armington goods	Gas, coal, agriculture, energy-intensive goods, other industries and services	None
Trade: Quadratic penalty	None	Energy-intensive sectors
Specification of energy sector	CES nesting	Activity analysis description -- limits on rate of introduction
Non-renewables resources	Oil and gas	Oil and gas
Energy efficiency	Demand decoupling factor of 1% per year (AEEI)	Demand decoupling factor of 1% per year (AEEI)

Figure 1. Production nesting and elasticities in GREEN and 12RT

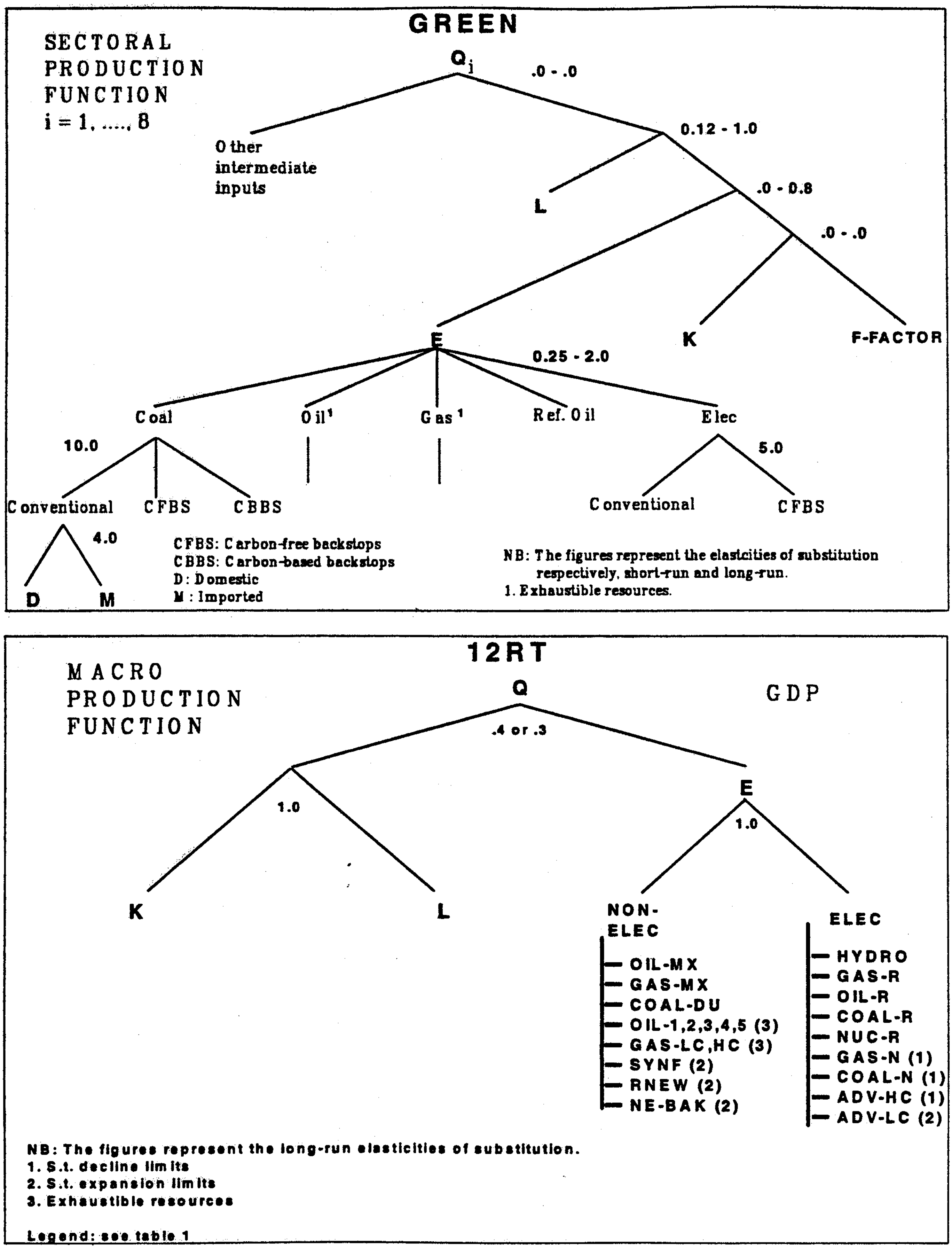


Figure 2. Carbon emissions in the Baseline scenario (#1) in GREEN

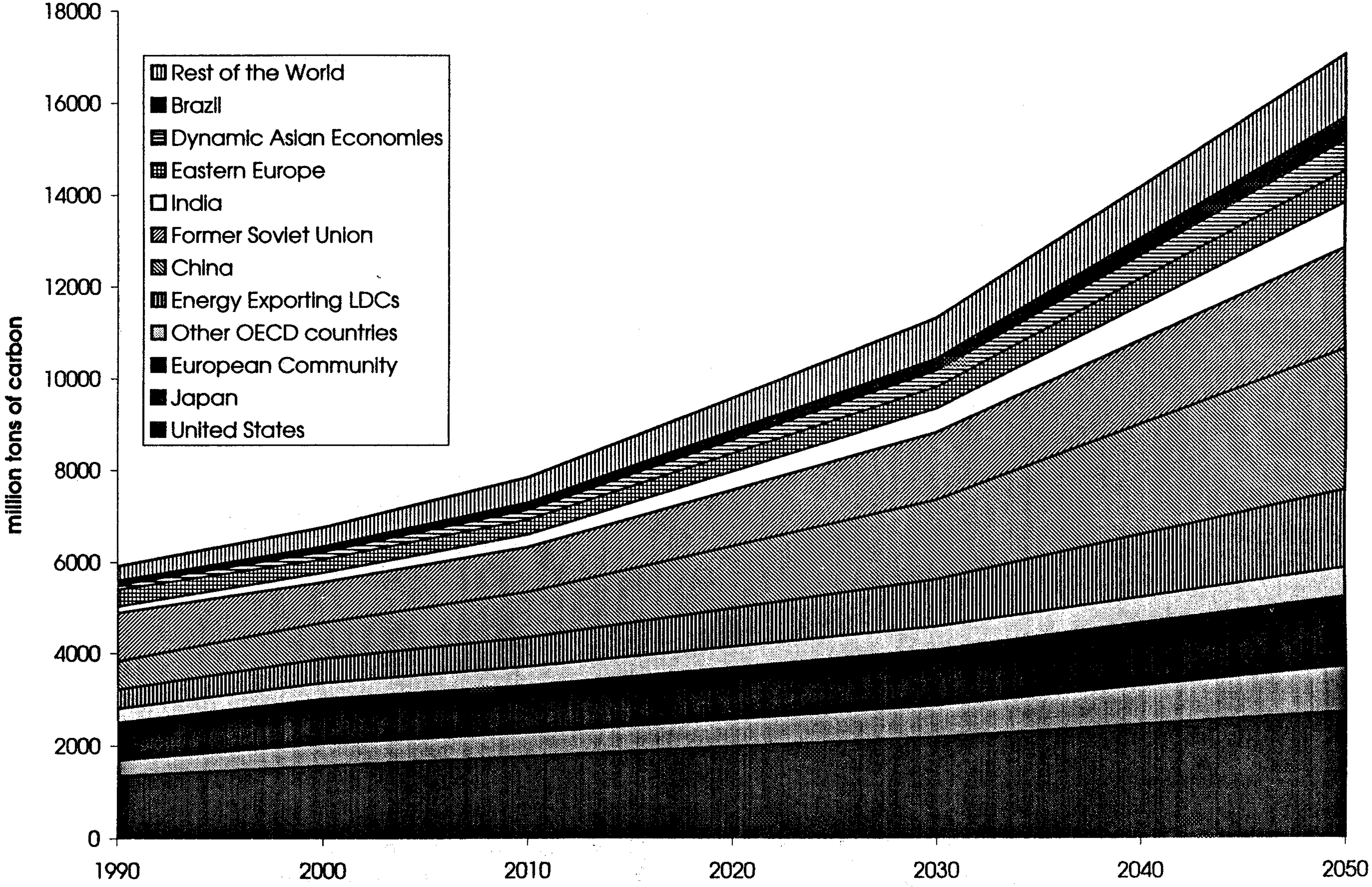
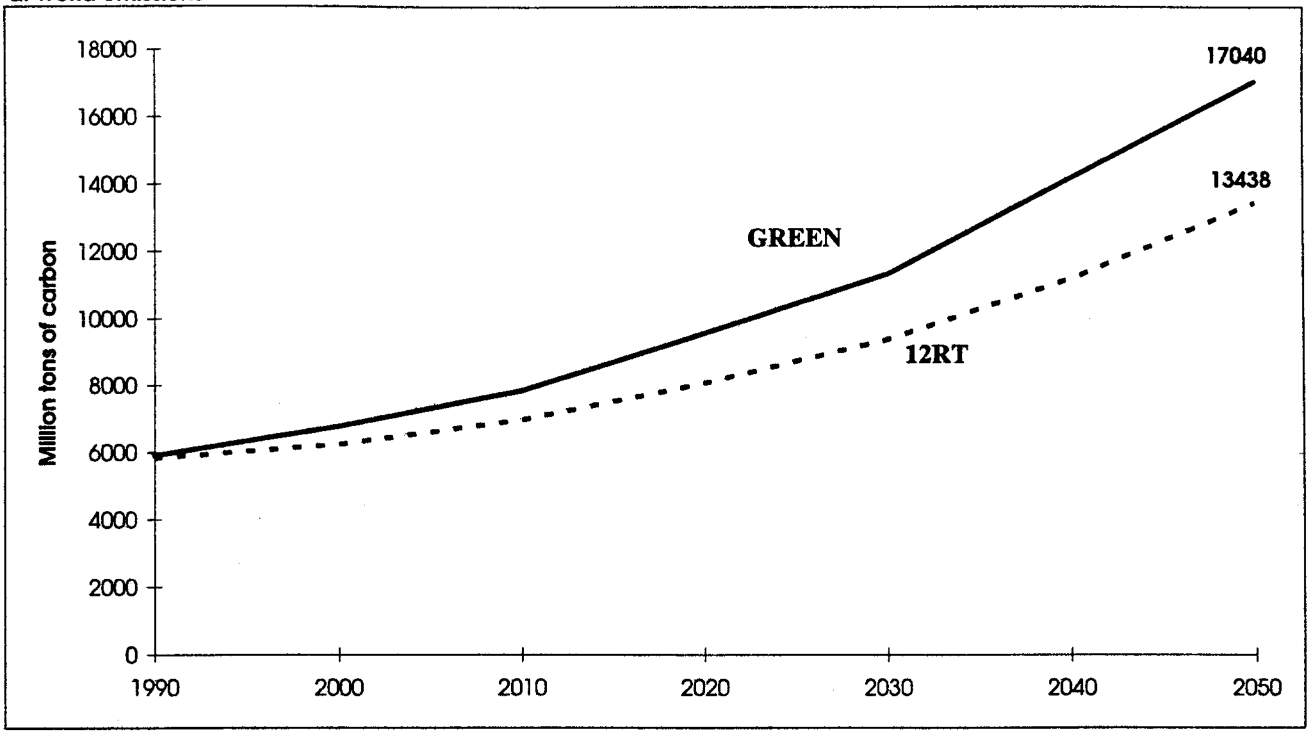


Figure 3. Baseline (#1) emissions in GREEN and 12RT

a. World emissions



b. Annex-1 emissions

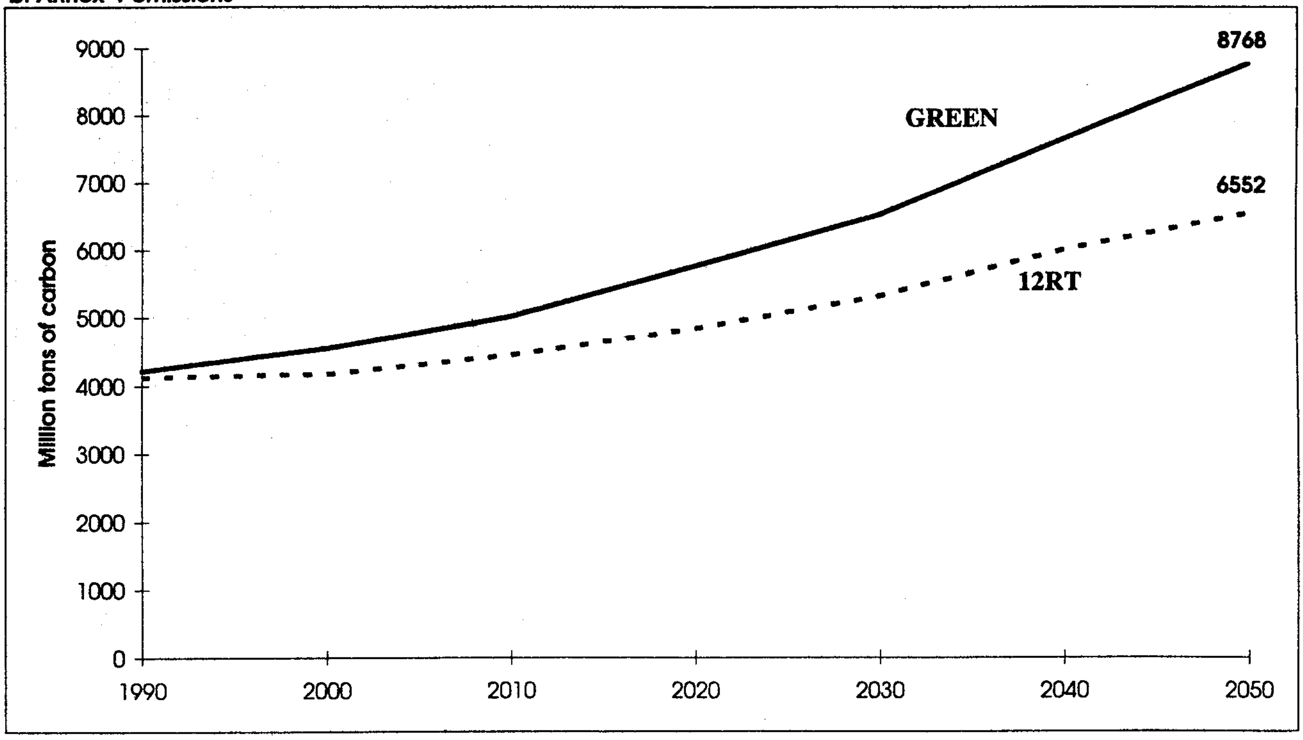
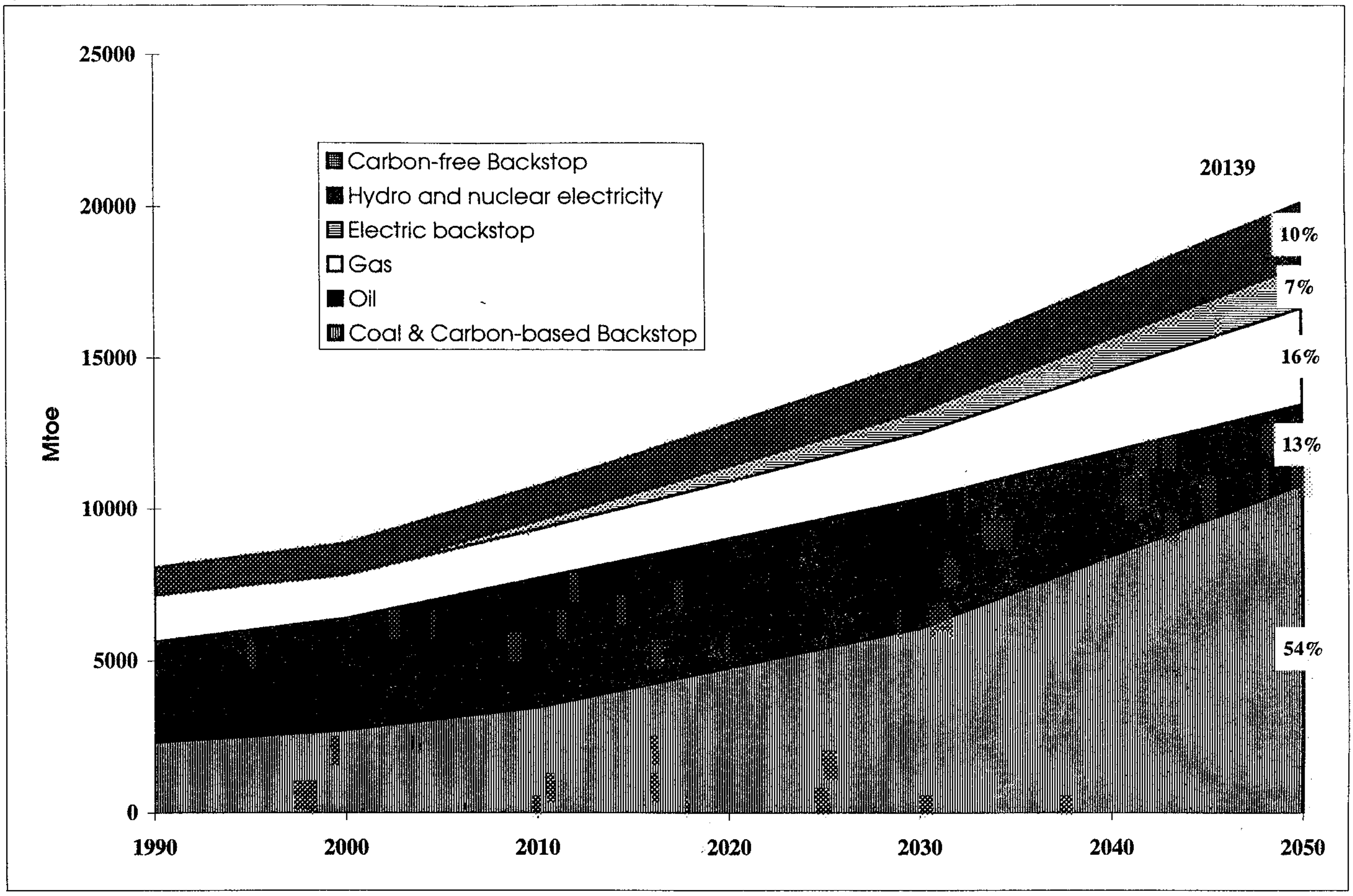


Figure 4. World Baseline (#1) primary energy consumption

a. GREEN



b. 12RT

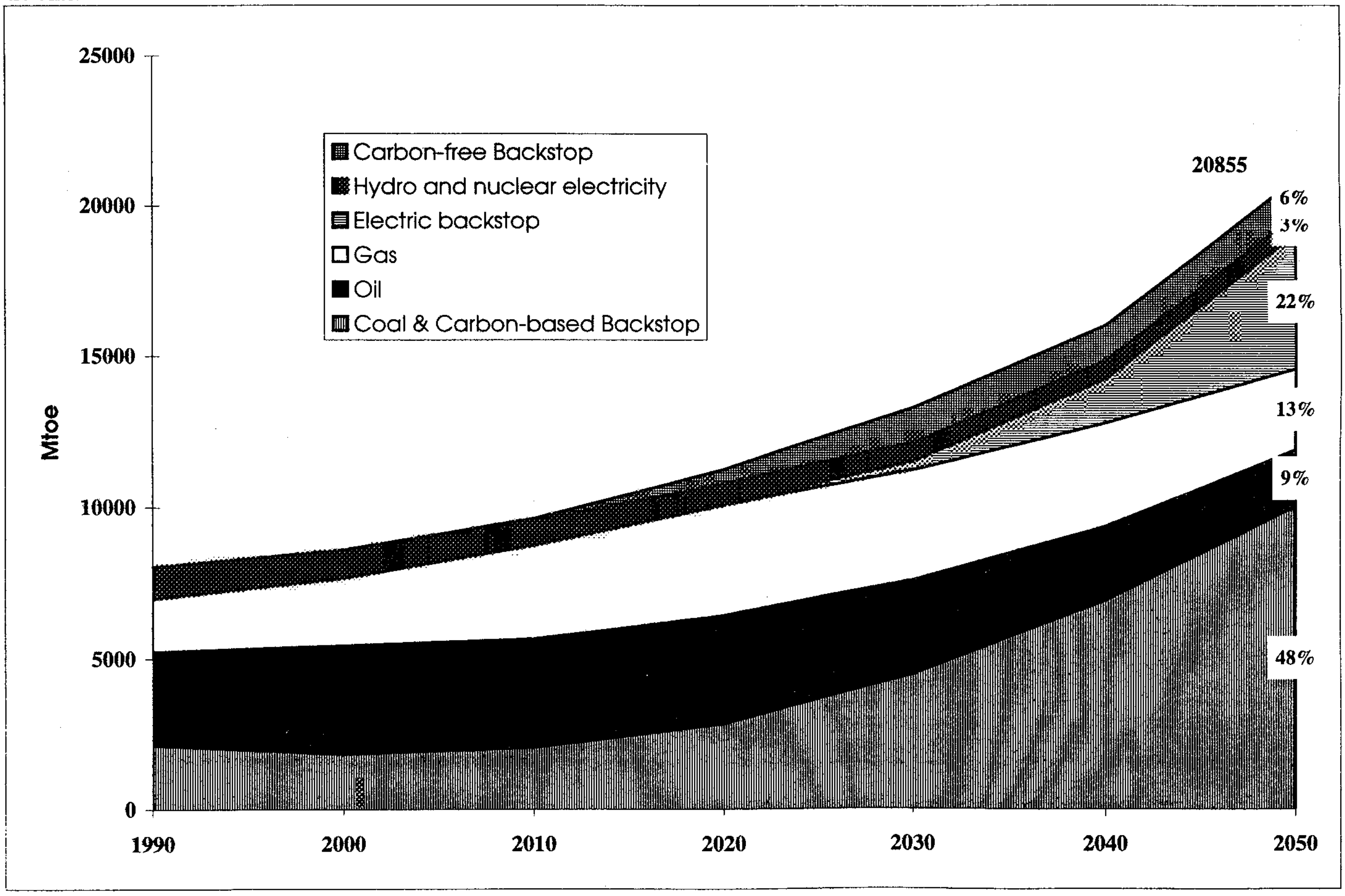


Figure 5. World oil price in the Baseline scenario (#1)

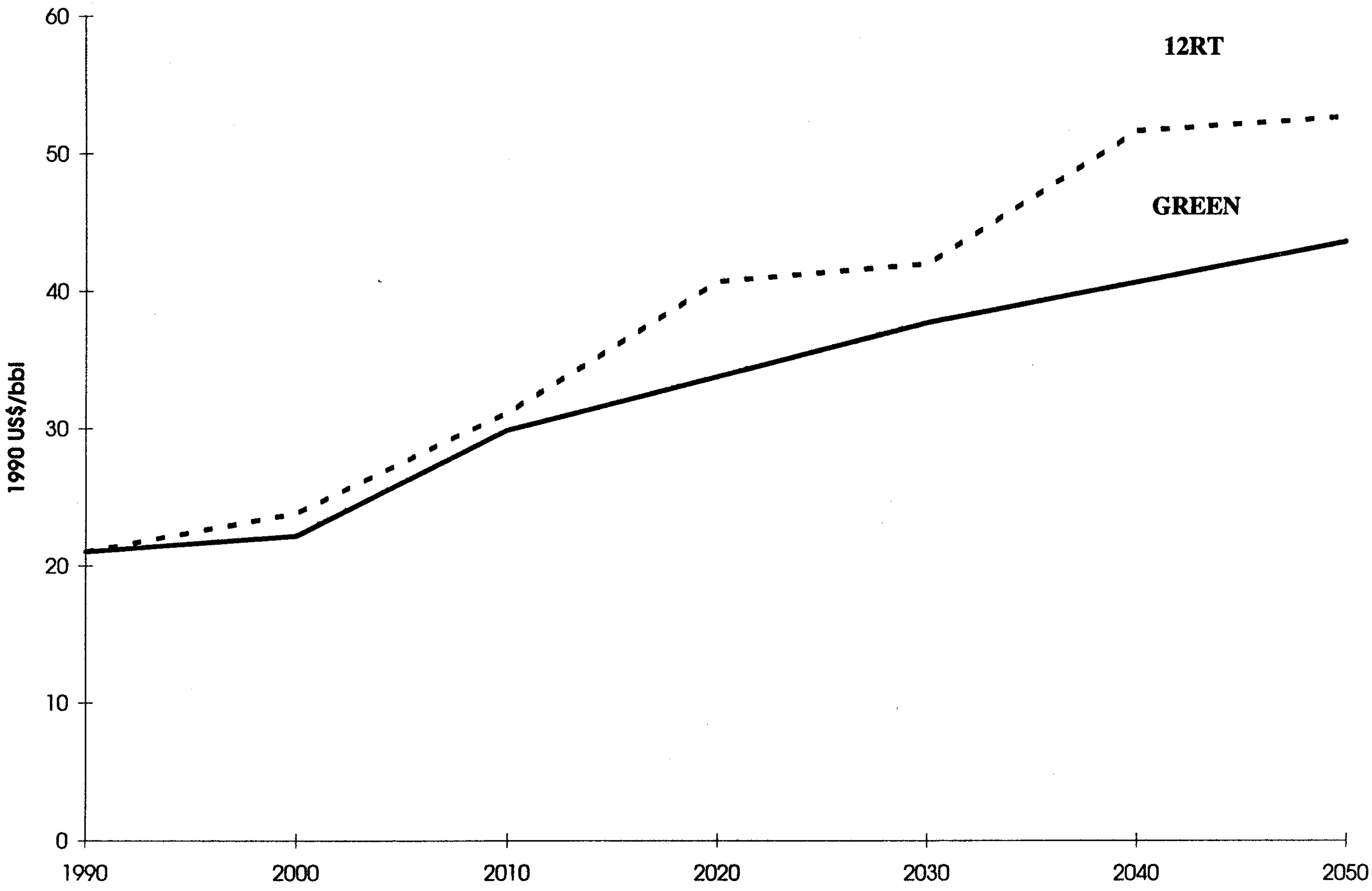
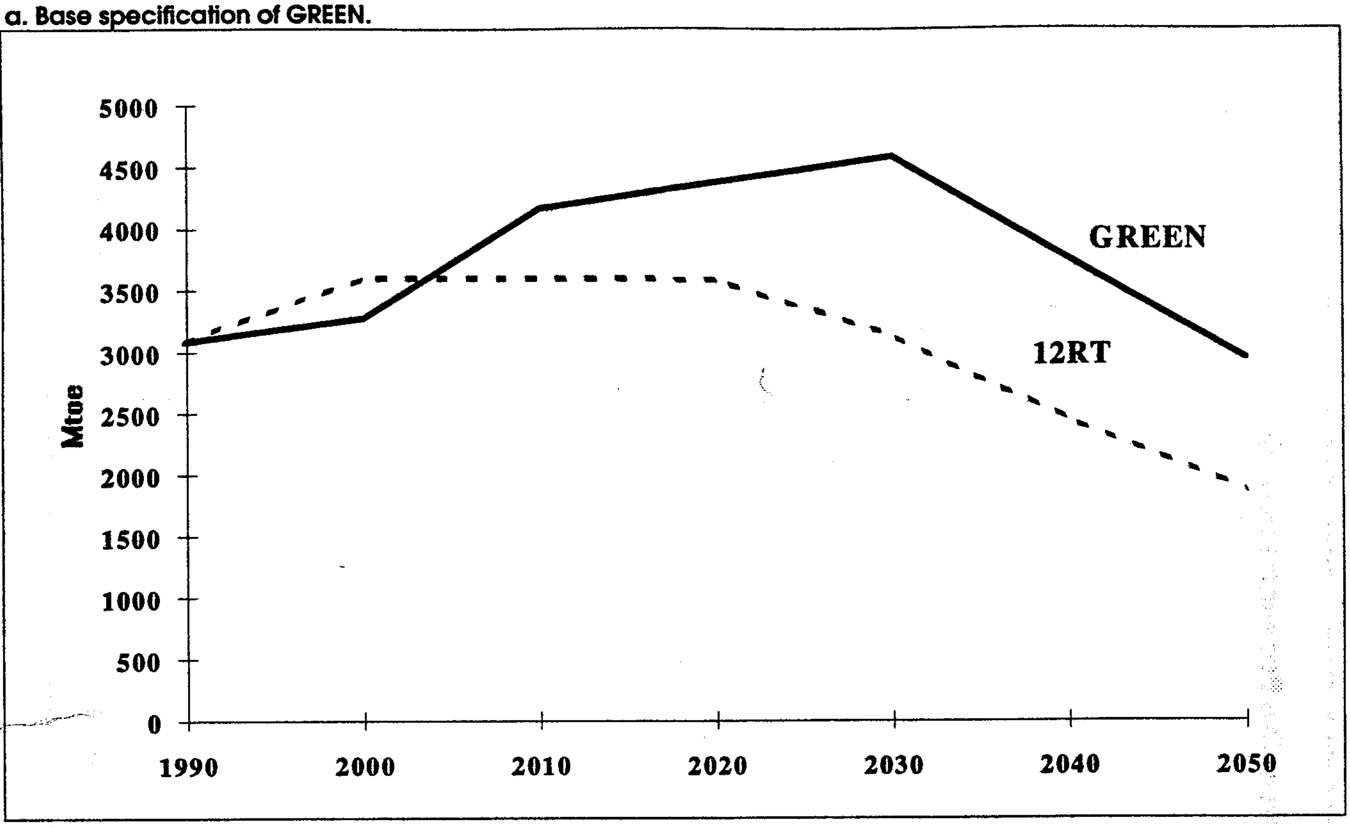
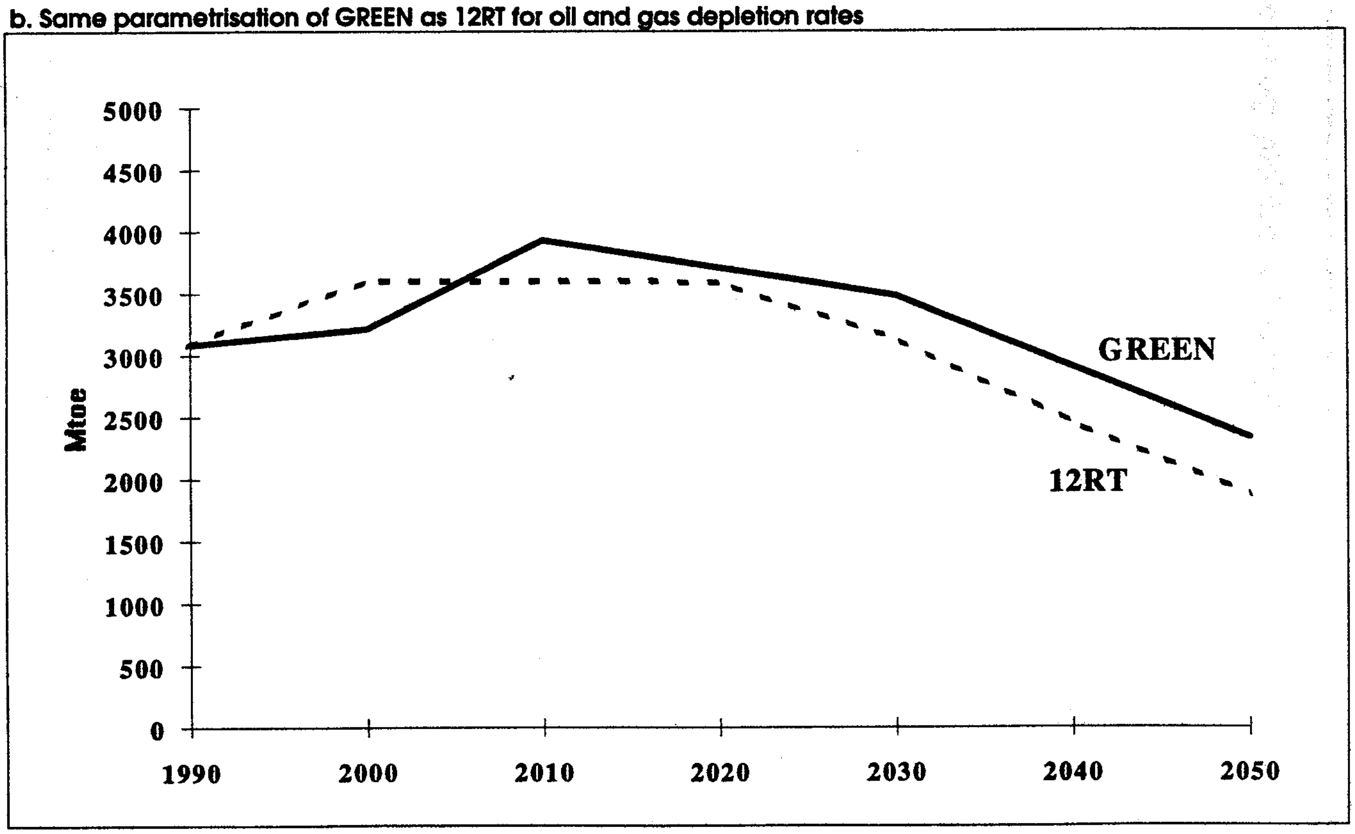


Figure 6. World oil production in the Baseline scenario (#1)

a. Base specification of GREEN.



b. Same parametrisation of GREEN as 12RT for oil and gas depletion rates



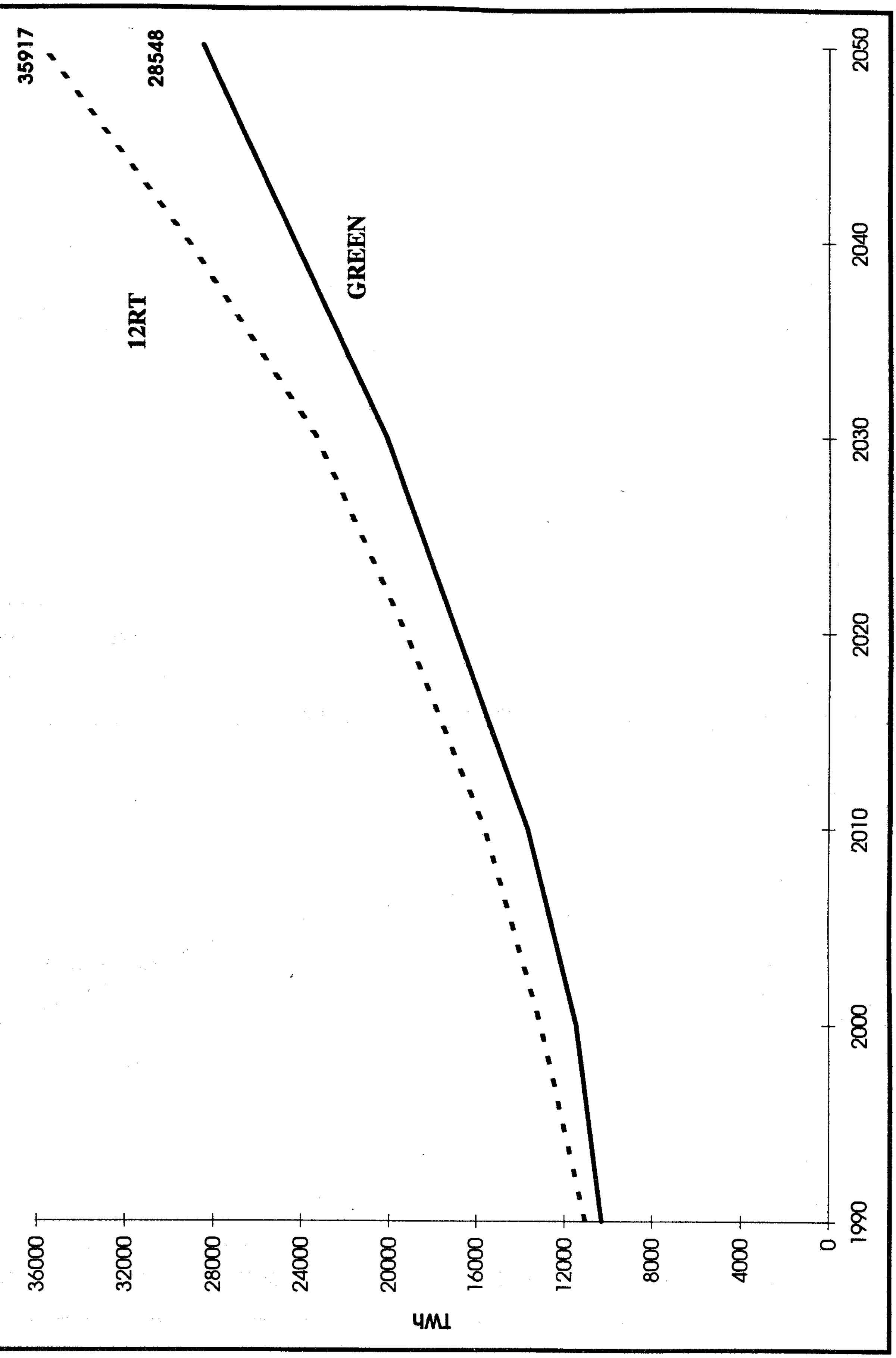


Figure 7. Electricity generation in the Baseline scenario (#1)

Figure 8a. Comparison of the Baseline scenarios (#1) for the OECD regions

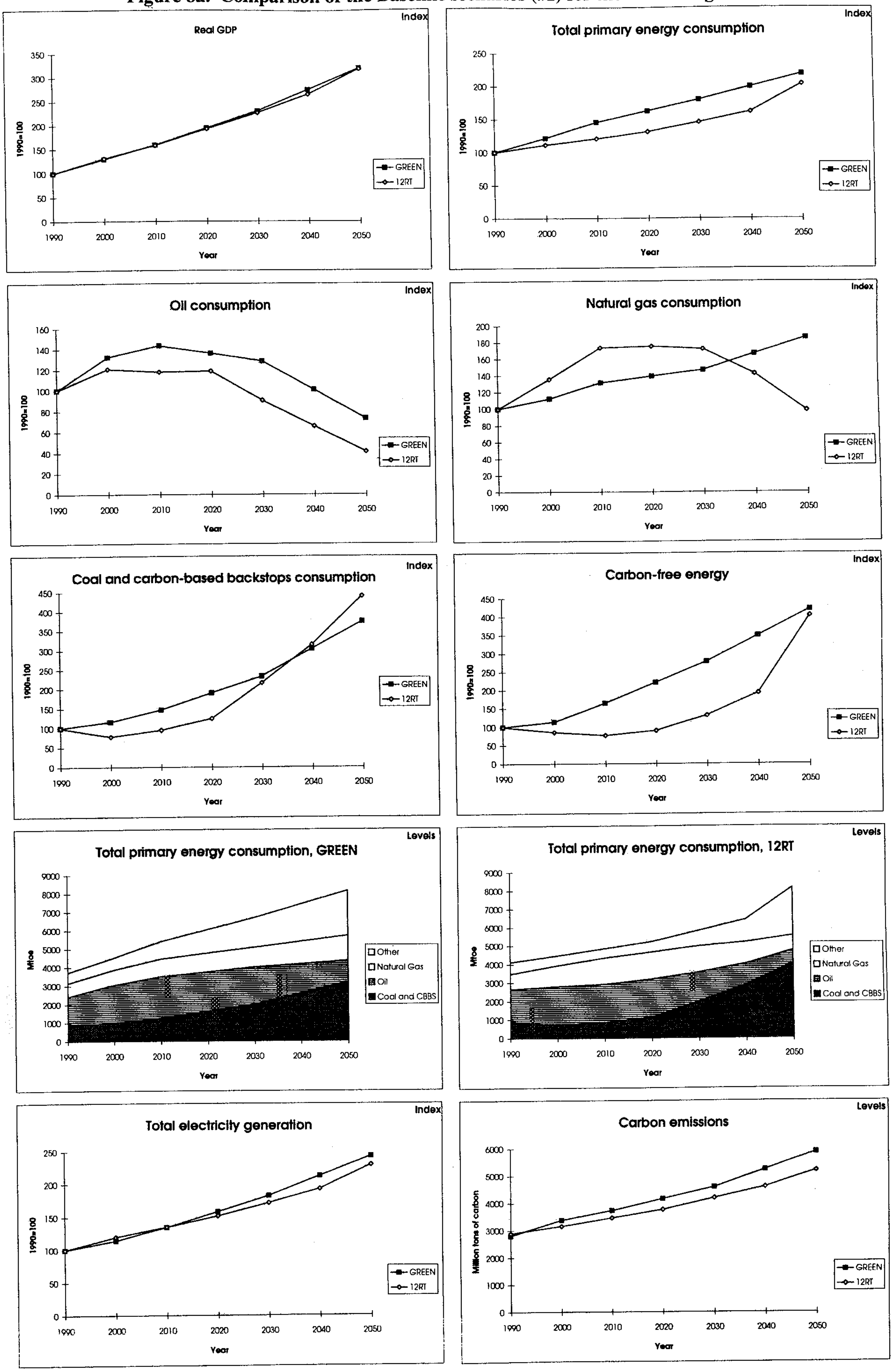
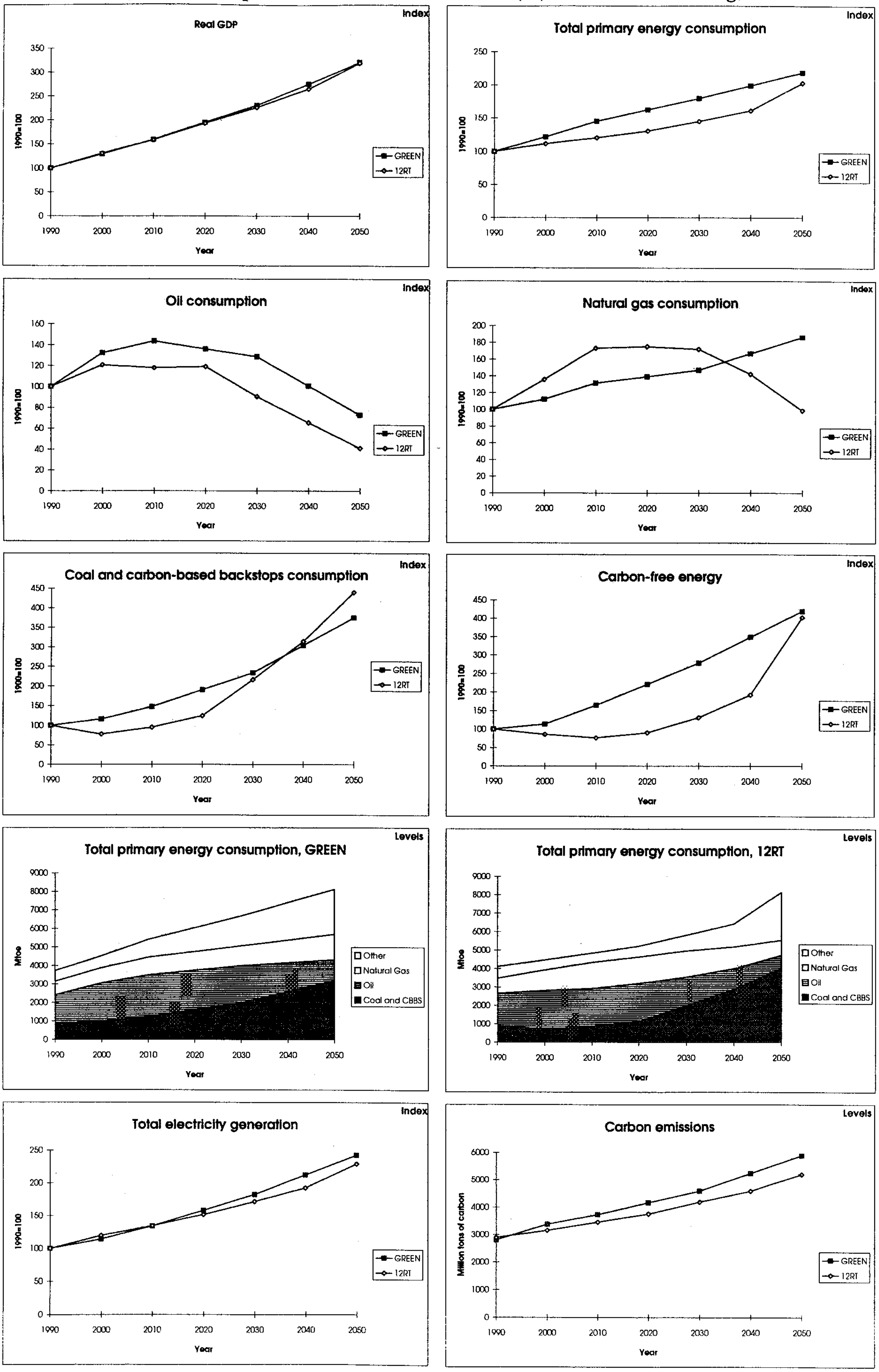


Figure 8b. Comparison of the Baseline scenarios (#1) for the non-OECD regions



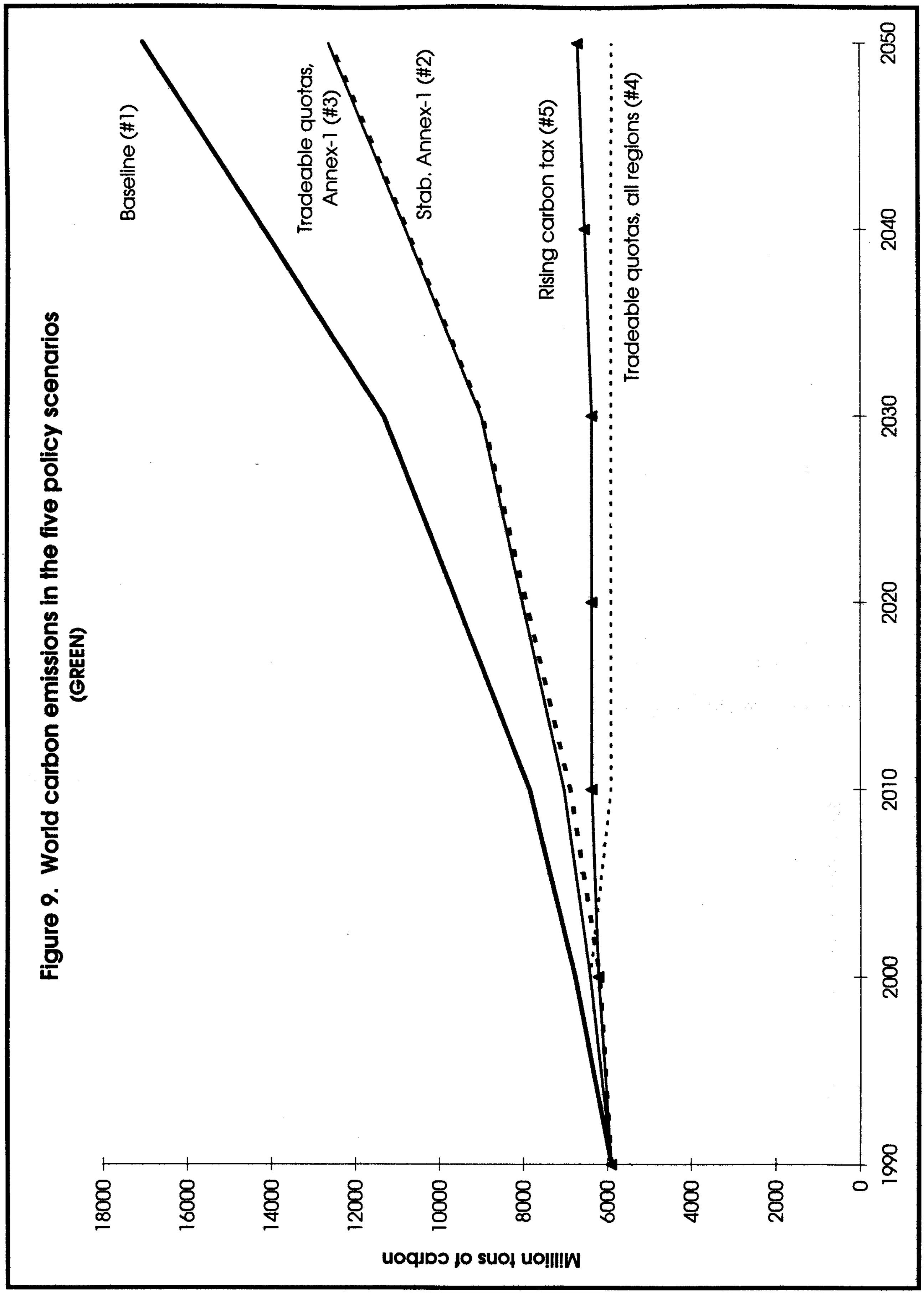
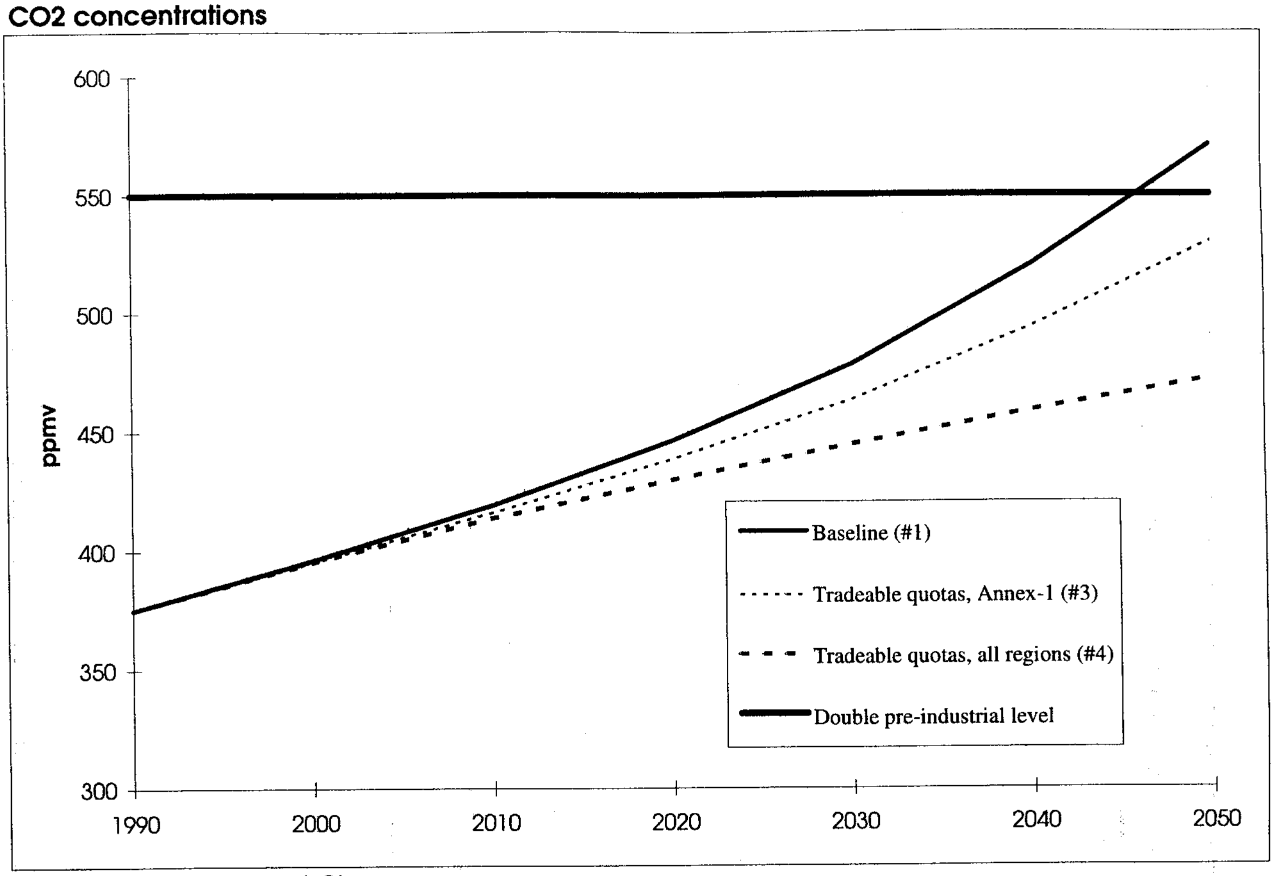


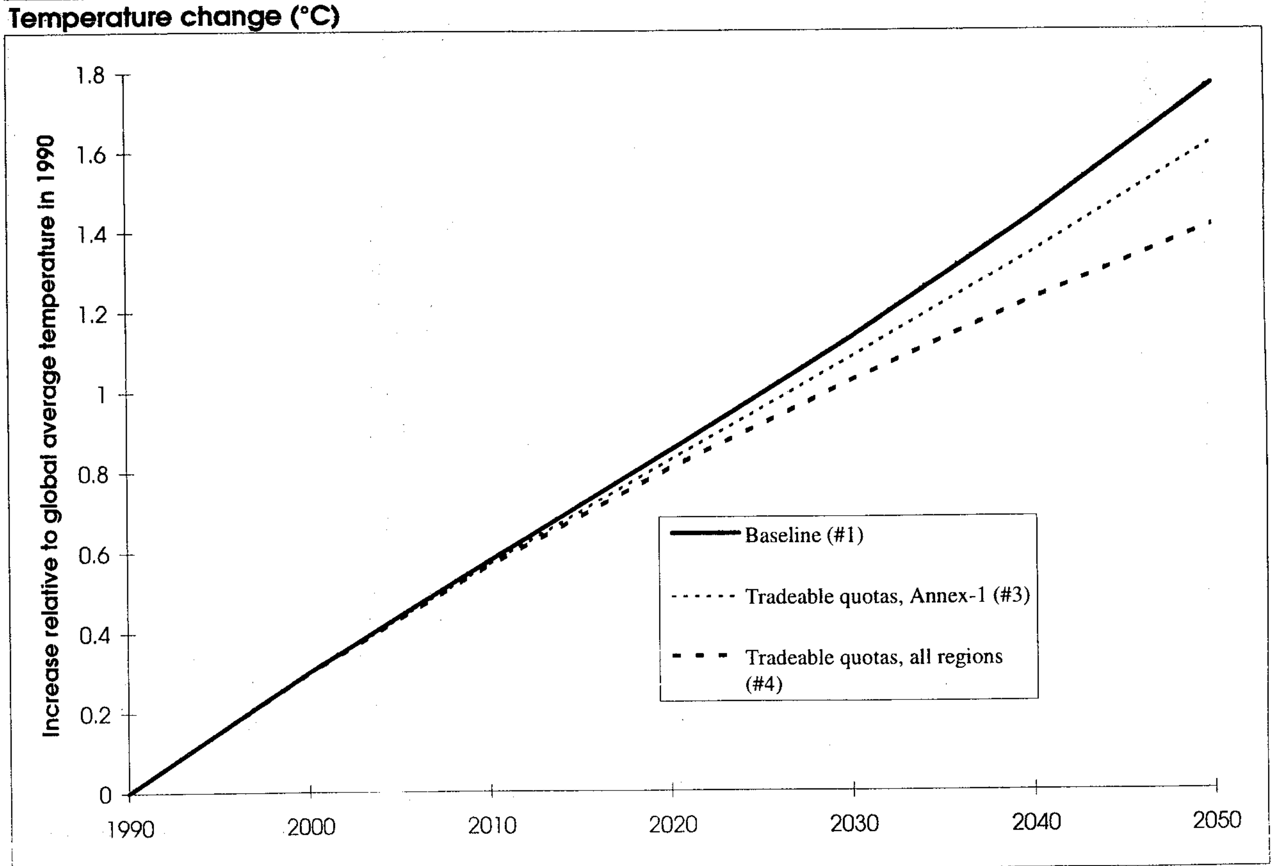
Figure 9. World carbon emissions in the five policy scenarios (GREEN)

Figure 10. CO_2 concentrations and global average temperature change resulting from policy scenarios (#3) and (#4), GREEN

CO_2 concentrations



Temperature change (°C)



Source: MERGE model (Manne, Mendelsohn and Richels, 1993)

Figure 11. Comparison of carbon taxes in the Annex-1 stabilisation scenario (#2)

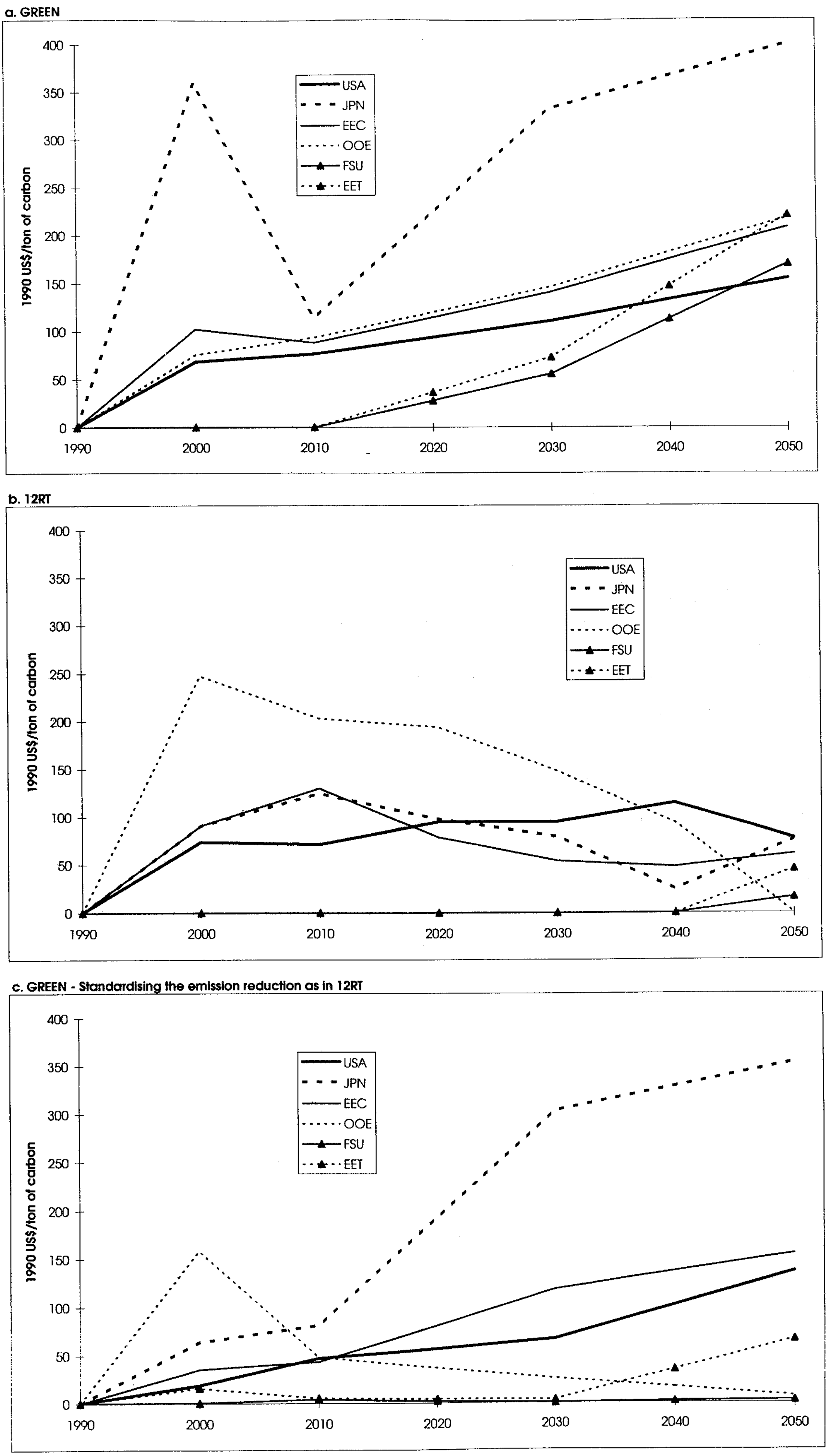
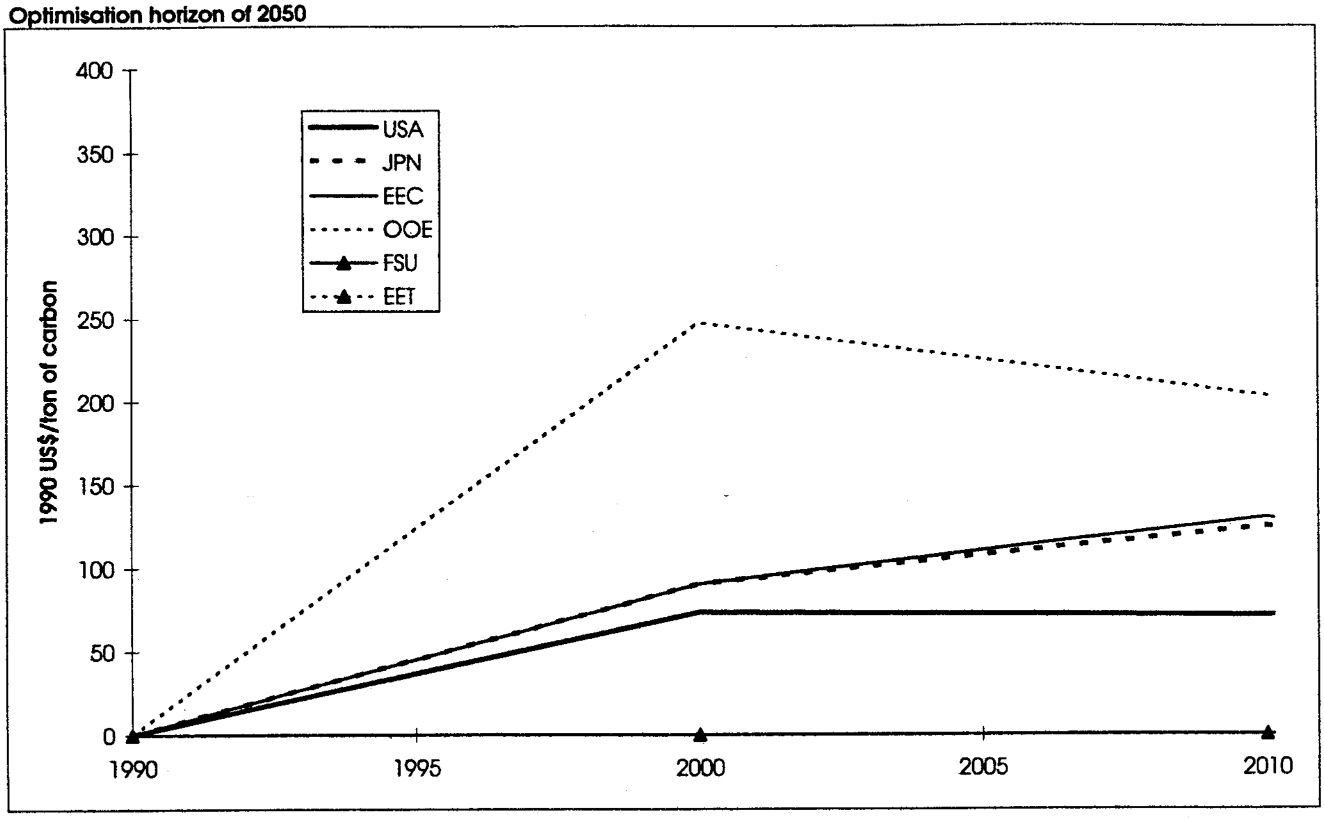


Figure 12. Carbon taxes in 12RT with different optimisation horizons. Annex-1 stabilisation scenario (#2)

Optimisation horizon of 2050



Optimisation horizon of 2010

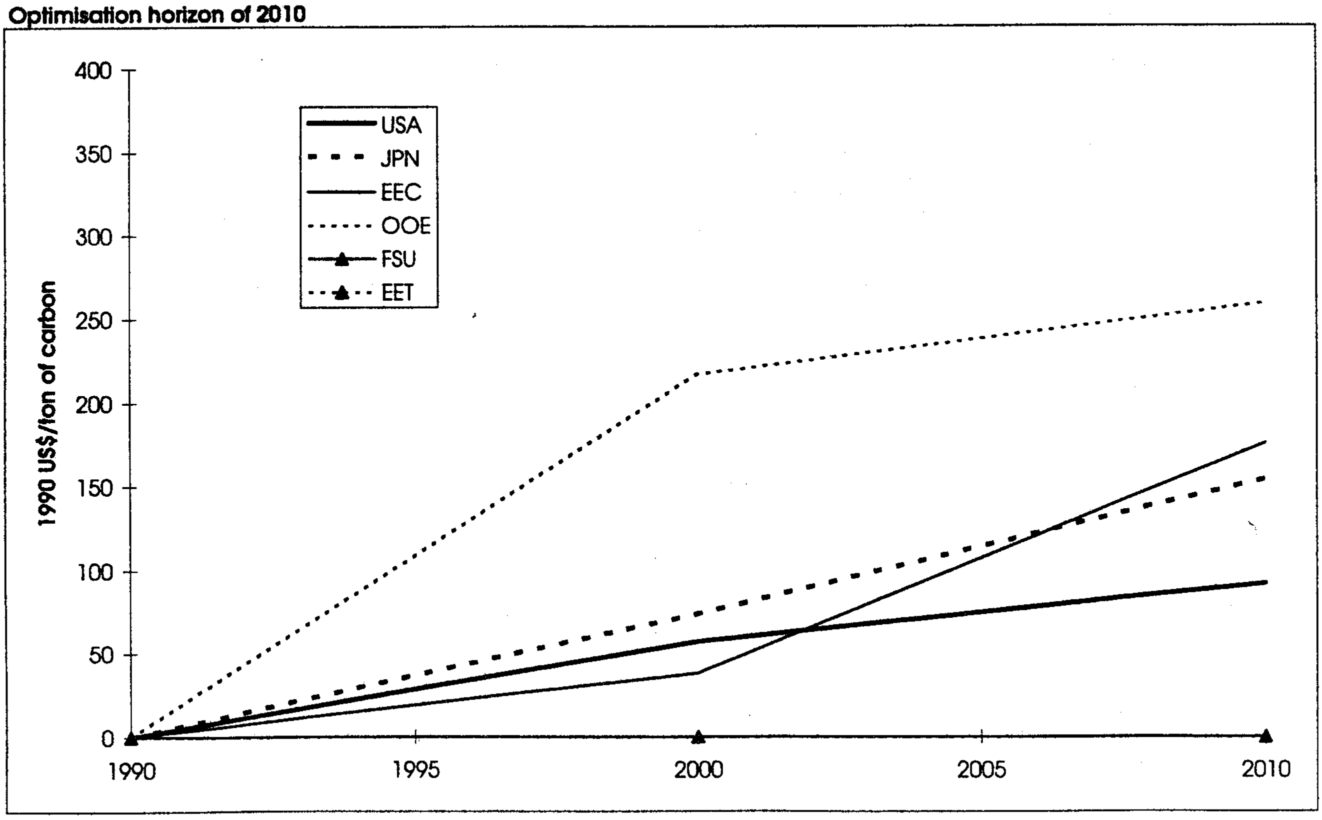
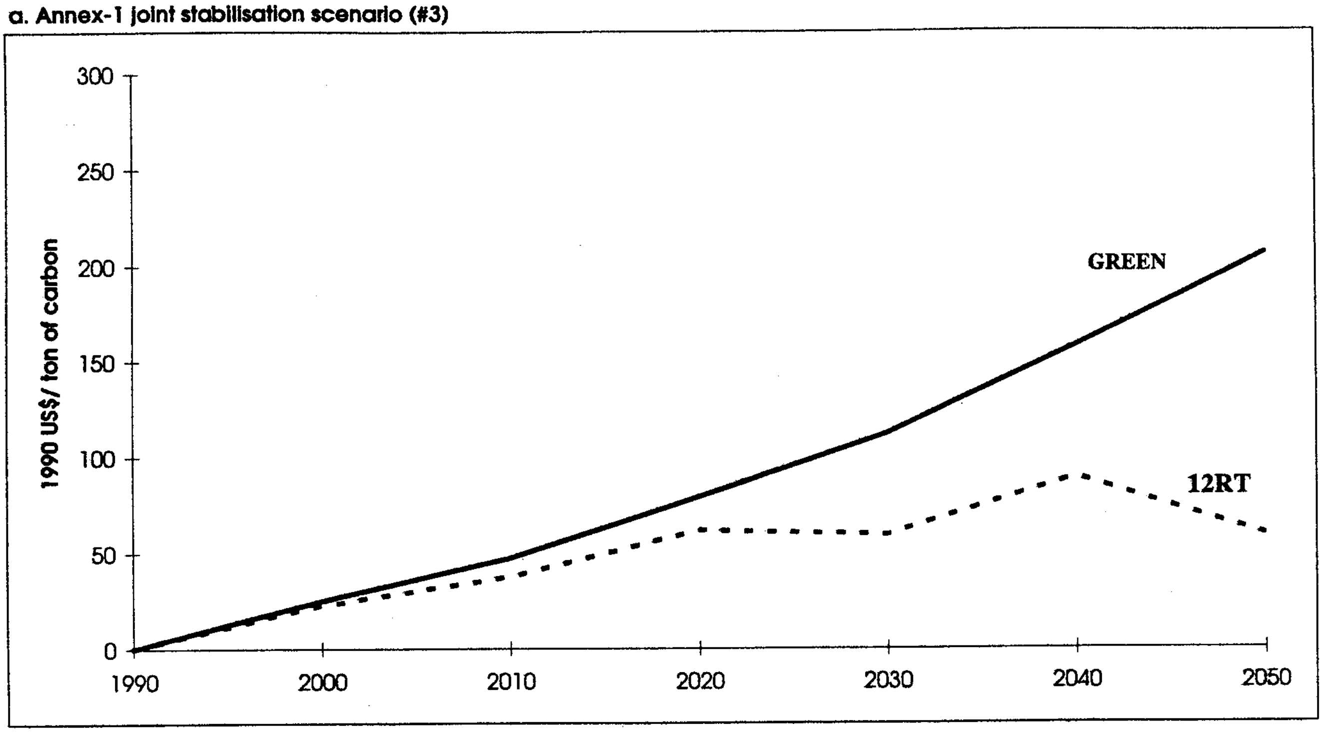


Figure 13. Emission quota price

a. Annex-1 joint stabilisation scenario (#3)



b. Global joint stabilisation scenario (#4)

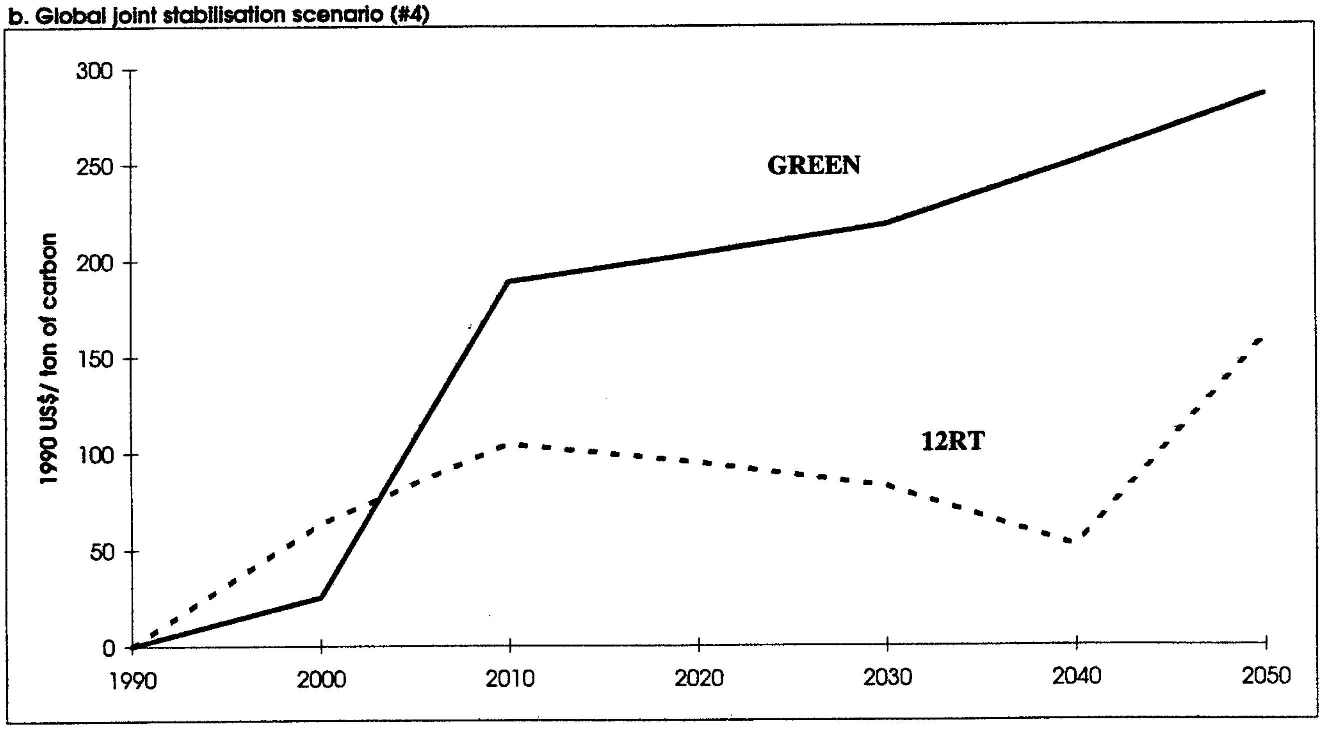
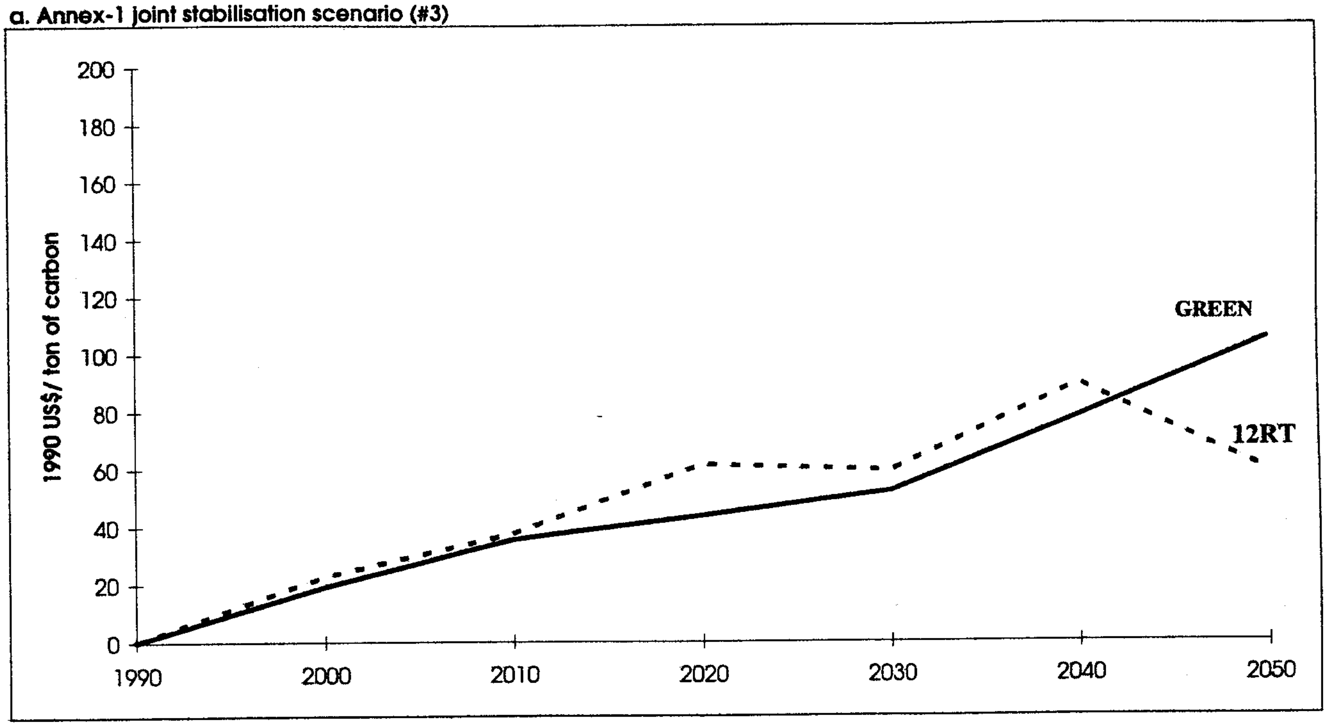


Figure 14. Comparison of emission quota price with alternative specification of the electric backstop cost in GREEN

a. Annex-1 joint stabilisation scenario (#3)



b. Global joint stabilisation scenario (#4)

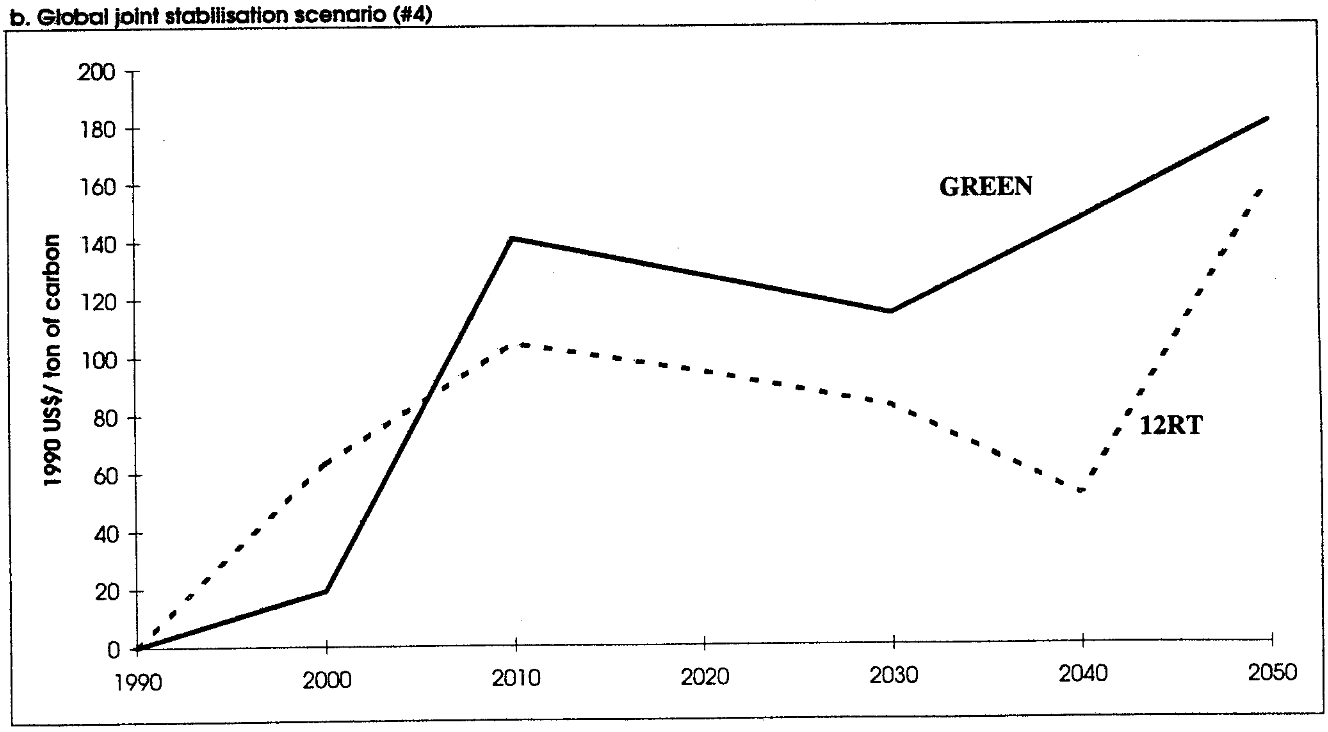


Figure 15. GDP changes in the Annex-1 stabilisation scenarios (#2 and #3), 2030 (% deviations relative to Baseline)

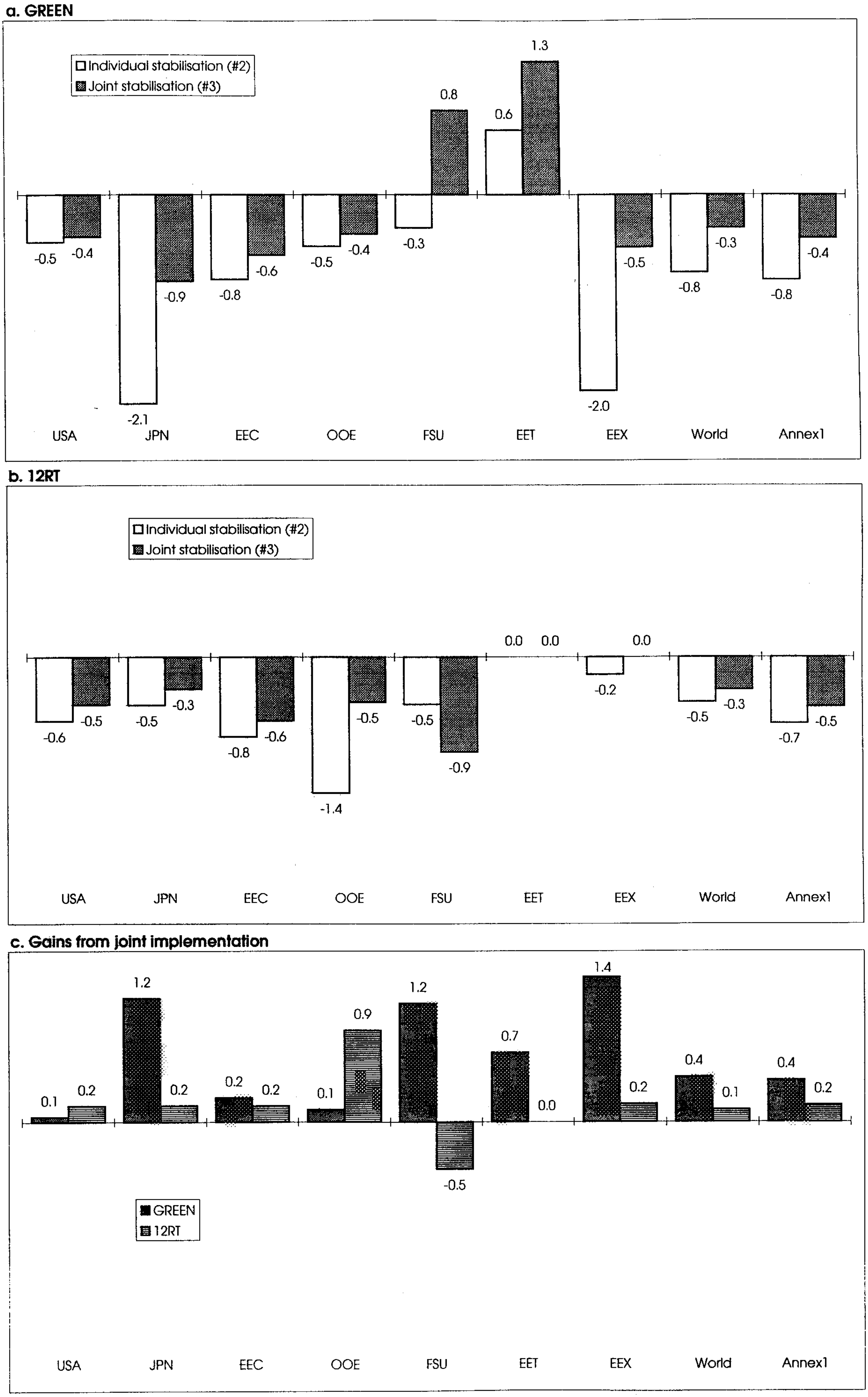


Figure 16. Trade in emission quotas in the Annex-1 joint stabilisation scenario (#3), 2030
(In million 1990 US$)

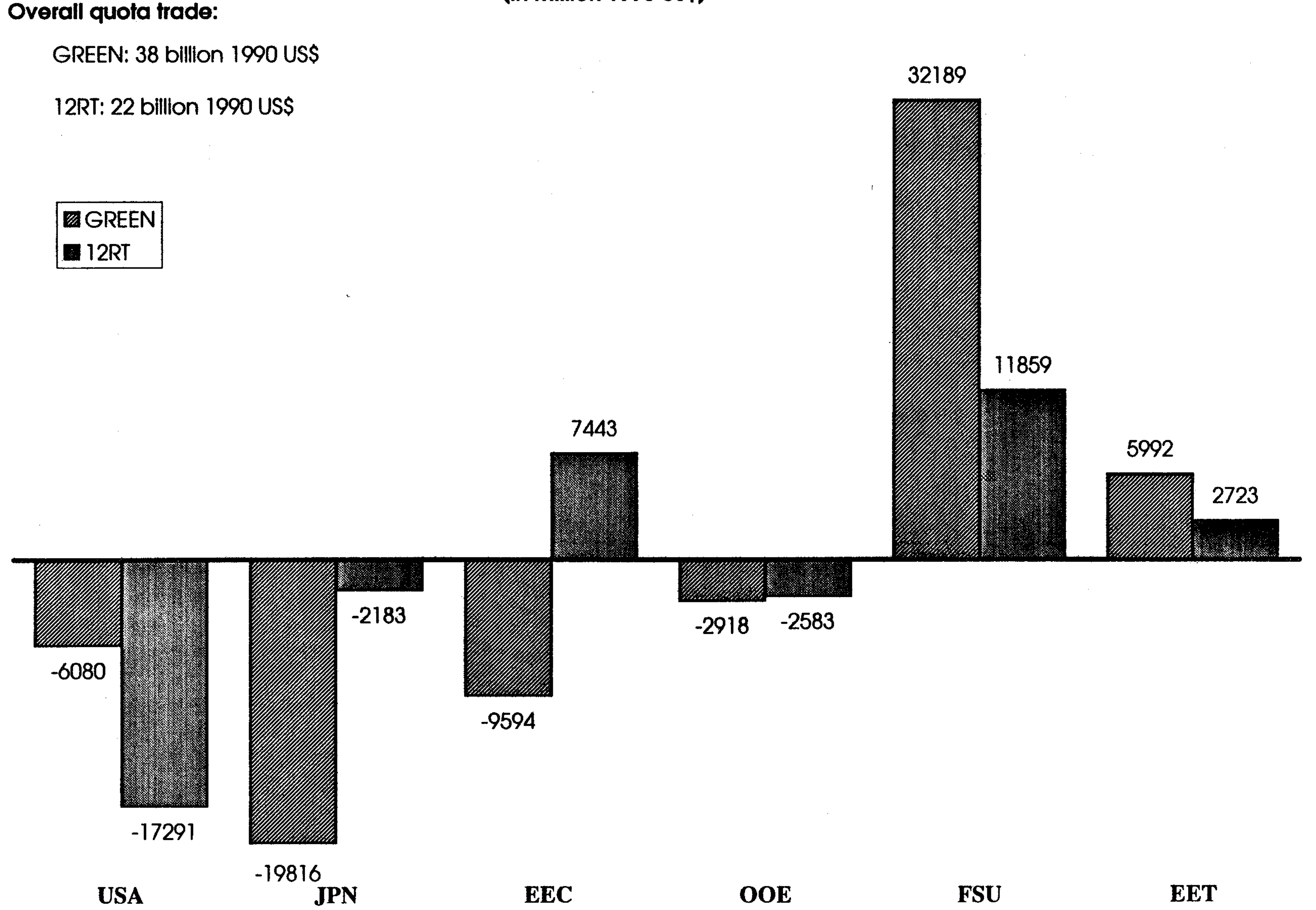
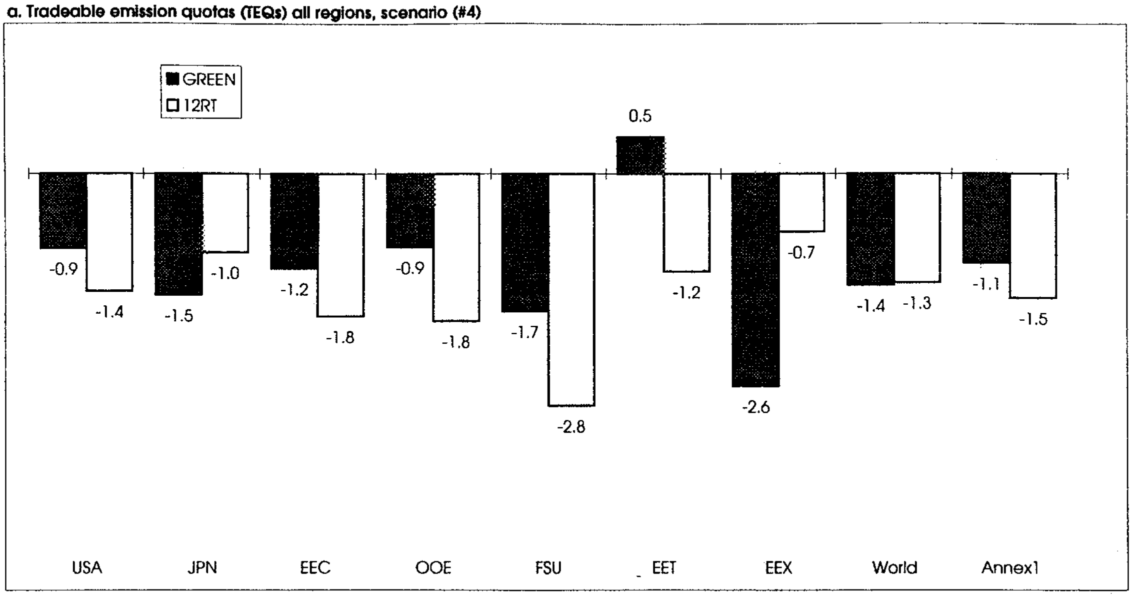
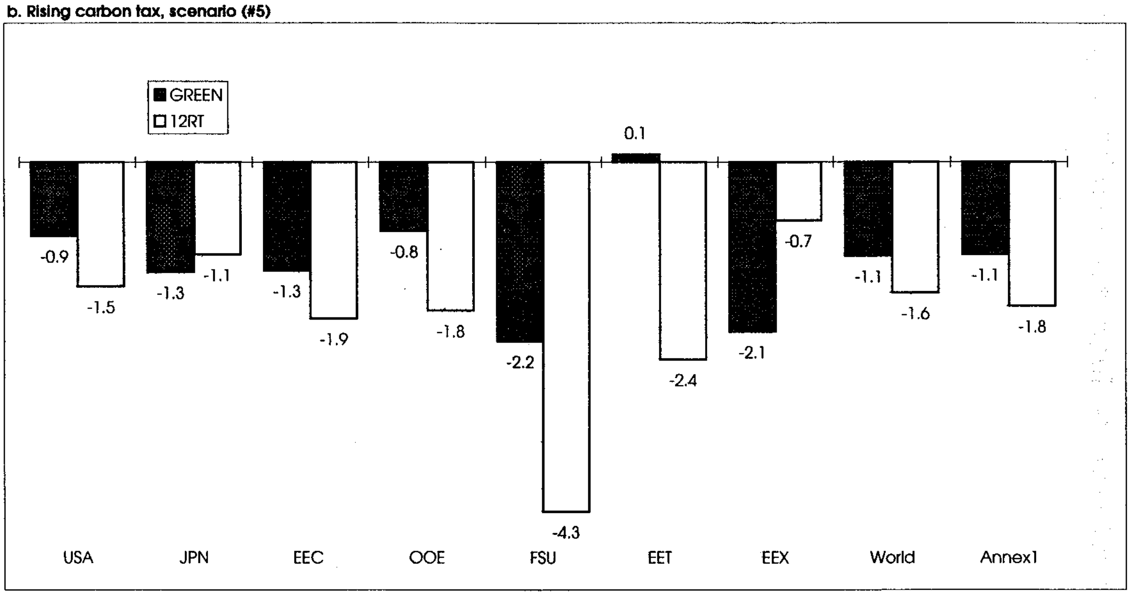


Figure 17. GDP changes, % deviation relative to Baseline, 2030

a. Tradeable emission quotas (TEQs) all regions, scenario (#4)



b. Rising carbon tax, scenario (#5)



c. Gains/losses from a TEQs system (#4) compared to a raising carbon tax (#5)

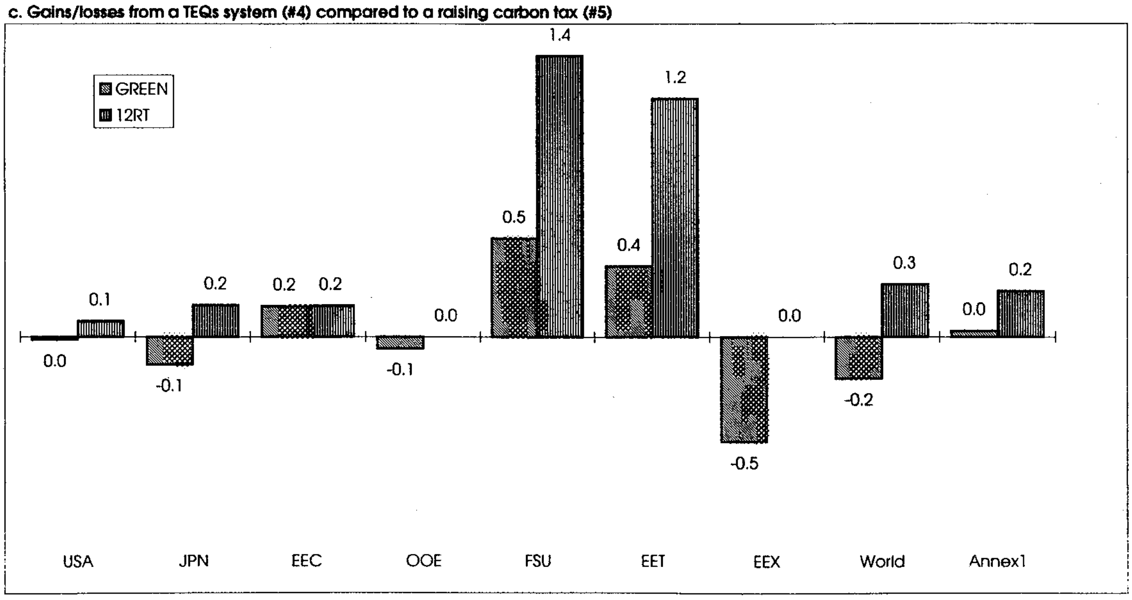


Figure 18. Interregional exports (imports) of emission quotas, global joint stabilisation scenario (#4)

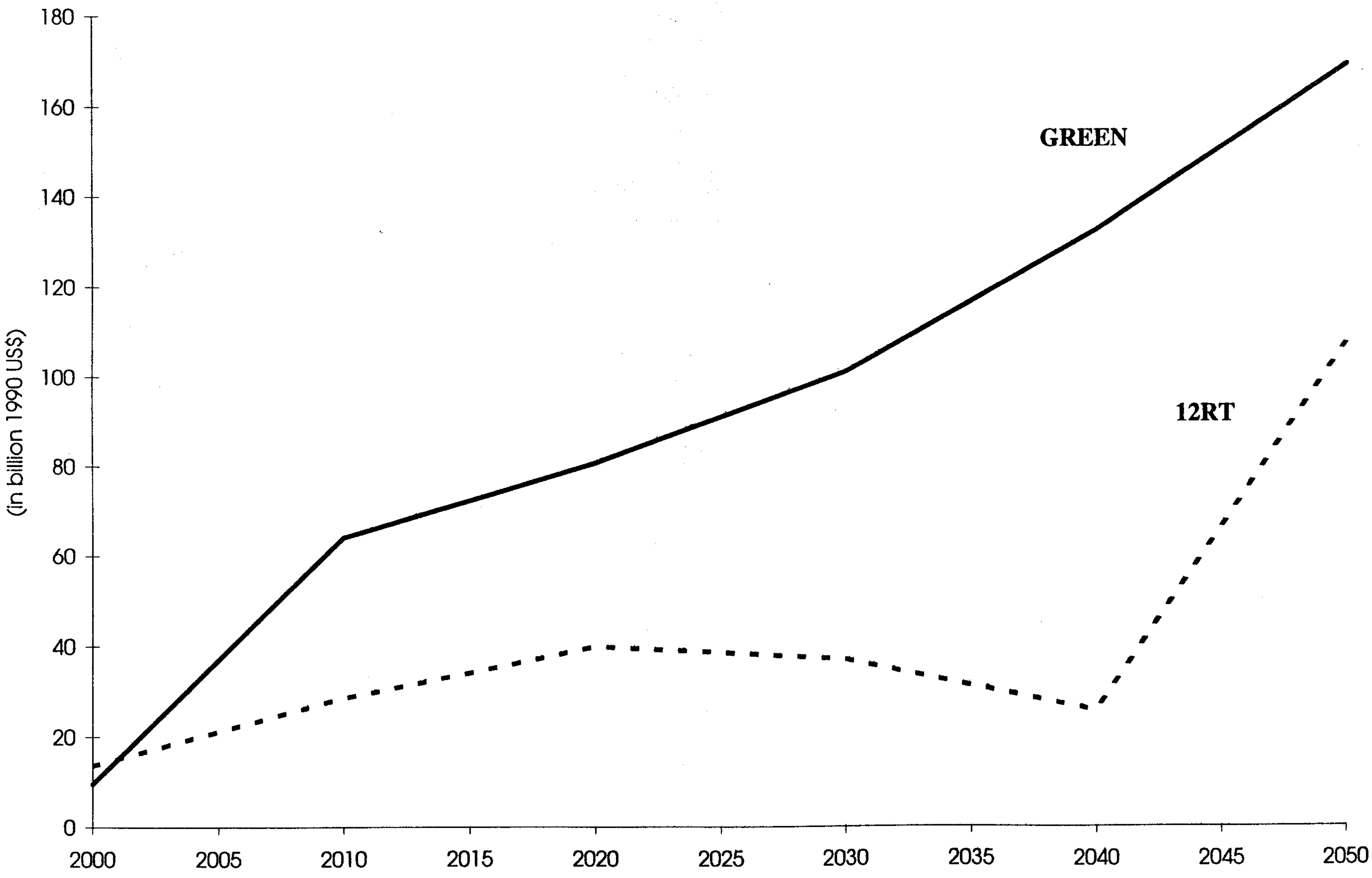
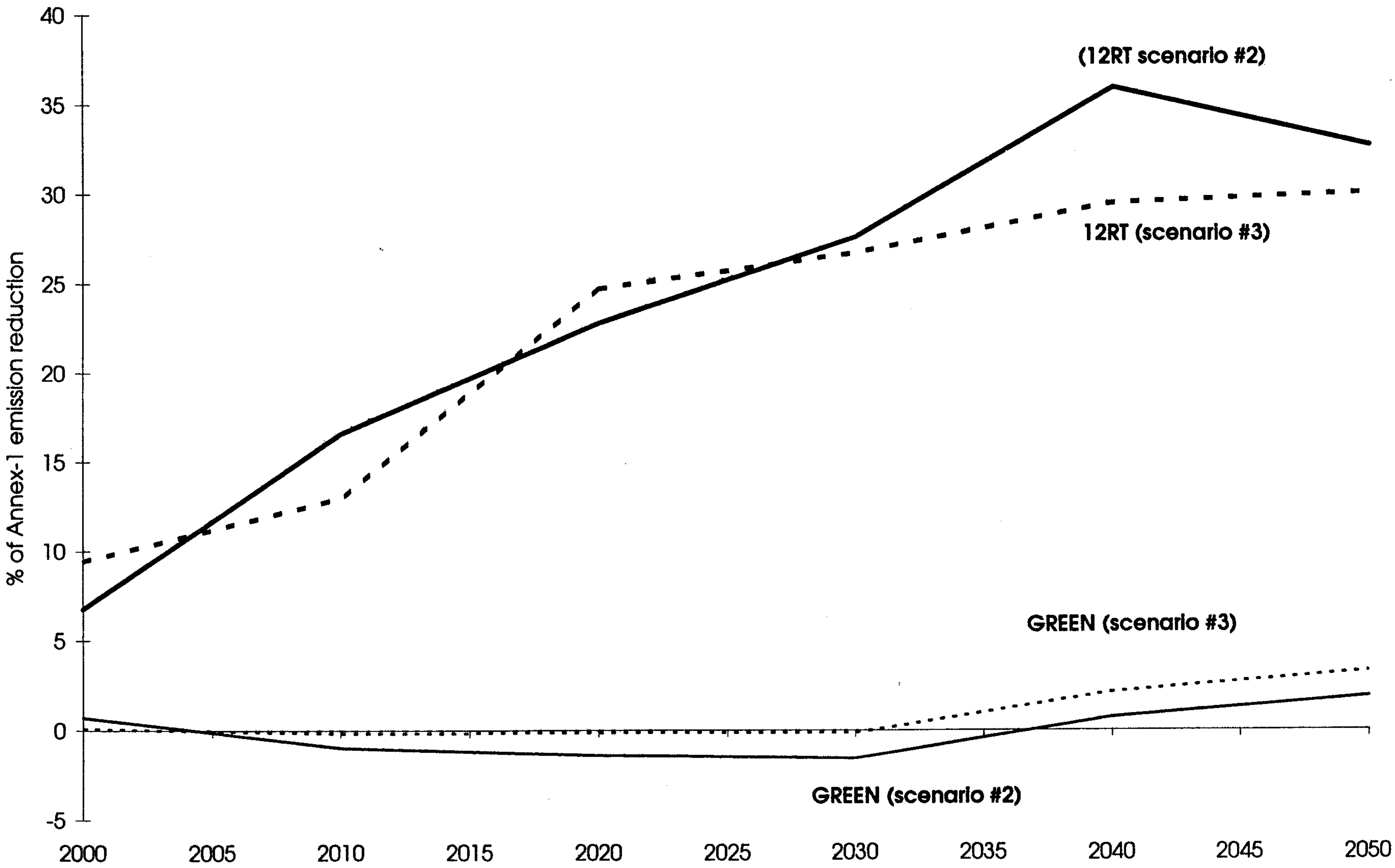


Figure 19. Carbon leakage rate, Annex-1 stabilisation scenarios (#2 and #3)



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