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Stabilisation of CO_2 concentrations: Mitigation scenarios using the Petro model

Abstract:
How to stabilise the CO_2 concentration in the atmosphere depends crucially on baseline assumptions of future economic growth, energy demand and supply technologies etc. In this paper we investigate how different assumptions about the future affects the necessary global policy measures to reach specific concentration targets for CO_2. This is done by constructing two contrasting baseline scenarios within an intertemporal model of fossil fuels markets. We find that the appropriate CO_2 emission and concentration paths for a given concentration target is very dependent on the baseline. Moreover, the impact on oil wealth for OPEC and other oil producers of stabilising CO_2 concentrations depends significantly on both the baseline and on whether the target is reached through carbon taxes or autonomous technological change in carbon-free energy sources. Carbon leakage through changes in international fossil fuel prices is found to be negligible and possibly negative.

Keywords: CO_2 concentration, Carbon taxes, Exhaustible resources, Petroleum wealth

JEL classification: H23, Q25, Q30, Q42

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1. Introduction

The ultimate goal of the UN Framework Convention on Climate Change is to achieve "stabilisation of greenhouse-gas concentrations… at a level that would prevent dangerous anthropogenic interference with the climate system" (United Nations, 1992).[1] However, the required level is still unclear for two main reasons, see Azar and Rohde (1997). First, the climatological, ecological, and social impacts associated with any given level of atmospheric greenhouse gas concentration are still uncertain. Second, even if the scientific impacts were known for certainty, the concepts of dangerous interference is a question of value judgements. As a result, the Intergovernmental Panel of Climate Change (IPCC) developed a set of illustrative pathways stabilising the atmospheric CO_2 concentrations at 350, 450, 550, 650 and 750 ppmv over the next few hundred years (see IPCC, 1995). These pathways were criticised by Wigley *et al.* (1996), in a paper that provoked much debate (see, e.g. Azar, 1998, for an overview). They pointed out that there is a large degree of freedom as regards to the emission path we can choose in order to stabilise the atmospheric concentration of CO_2. Actually, certain long run stabilisation paths can be reached without reducing emissions for the next couple of decades. On the other hand, this also implies that the emission constraint in the Kyoto protocol may be consistent with a variety of stabilisation goals.

Both IPCC (1995) and Wigley *et al.* (1996) used the single baseline scenario IS92a (IPCC, 1992). Consequently, the emission path towards a specific concentration target could differ even more if the baseline scenarios were different. Indeed, a review of mitigation scenarios in general shows that these scenarios and policies are strongly related to their baselines, and that there has been no systematic comparison of the relationship between baselines and mitigation scenarios. On this ground IPCC encouraged modellers around the world to prepare different baseline scenarios for the coming century. Based on these numerous scenarios four so-called marker scenarios were constructed that are supposed to represent different future worlds without greenhouse gas mitigation. These are presented in the forthcoming Special Report on Emissions Scenarios (SRES) (Nakicenovic *et al*, forthcoming).[2] The four marker scenarios are intended to replace the former central baseline scenario IS92a.

In this paper we want to investigate how the mitigation scenario, for a given CO_2 concentration target, depends on the chosen baseline. This is done by using the Petro model, tuning and calibrating the model to fit in with key characteristics of two of the four marker scenarios in SRES (see below). We

[1] Nevertheless, at the Kyoto conference in 1997, policy-makers decided to adopt near-term targets.

[2] During the time of the exercise the SRES scenarios had not been approved in the IPCC process, and the results presented in this draft paper will be finalized in May 2000.

also want to study the impact of changing the concentration target for a given baseline (i.e., 450, 550, 650 or 750 ppmv). There are several questions we want to examine.

First, we explore to what degree the *emission and concentration paths* change when we change the baseline, keeping the concentration goal fixed. For instance, different expectations about the availability of carbon-free energy technologies in the second half of this century may have significant implications for how much emissions should be reduced in the near term (i.e., allocation of the 'carbon budget'). We are also interested in what *policy measures* are needed in order to reach a specific concentration target under various baseline assumptions. Moreover, how does the necessary policy measure change when the concentration goal is tightened?

Another interesting question is how the *fuel mix* over the coming century is affected by mitigating carbon emissions, that is, are there general findings across the two baselines? Furthermore, do policy measures implemented in the Annex B area lead to *carbon leakage*, i.e., increased emissions, in Non-Annex B through changes in international prices on fossil fuels? We are also concerned with how the leakage rate changes when the concentration target is tightened.

Finally, based on the resistance against ambitious targets from OPEC and other oil producers, we investigate how their *oil wealth* depends on the concentration goal and how the goal is reached. That is, oil revenues will typically depend on a combination of the baseline assumptions and the necessary policy measures to reach a specific concentration target.

Petro is a numerical, intertemporal global equilibrium model for the fossil fuels markets, and has earlier been applied to related issues (see Berg *et al.*, 1997a, 1999, and Lindholt, 1999), and on specific studies of the oil market (see Berg *et al.,* 1997b). We use the model version presented by Lindholt (1999). In order to construct baseline scenarios in accordance with key characteristics of the two marker scenarios in SRES, we have used similar GDP growth rates as in SRES for each region. We have also calibrated income elasticities and technological growth rates so that energy demand intensities (i.e., energy use per GDP) and CO_2 emissions at the end of the century are in line with the marker scenarios. This is described more fully below. The Petro model does not include calculations of CO_2 concentrations. However, a specific generator based on the Bern Carbon Cycle Model (Joos *et al.*, 1996) was used to extrapolate CO_2 emissions trajectories and CO_2 concentrations between 2100 and 2300 based on the data for CO_2 emissions up to 2100.

The analysis presented in this paper has been encouraged by the IPCC, who wants to compare mitigation scenarios from different models for a given baseline, and further learn what different baseline scenarios and different concentration targets imply for the mitigation of CO_2 emissions. One earlier attempt to use different models for comparison of mitigation scenarios is presented by Dean and Hoeller (1992), where six models with harmonised baseline are used to study the effects of carbon taxes on CO_2 emissions. Another attempt is presented by Weyant (1999), where several models with different baselines have been used to study the economic impacts of the Kyoto protocol.

The paper is structured in the following way. Section 2 gives a short description of the storylines of the different marker scenarios in SRES. Then, in section 3 a brief overview of the Petro model is given. The two baseline scenarios are presented in section 4, while section 5 describes the mitigation scenarios. In the two following sections we investigate the effects on the oil market and oil wealth, and on carbon leakage. Section 8 concludes.

2. SRES marker scenarios

Nakicenovic et al. (forthcoming) present four alternative baseline scenarios of greenhouse gas emissions for the coming century. These replace the IS92a scenario that IPCC has earlier used as a baseline scenario for future emissions (IPCC, 1992). The four new so-called marker scenarios are intended to represent the wide range of possible future development in all the main driving forces behind emissions of greenhouse gases, except policies with the primary intent of mitigating such gases. The main driving forces are growth in economy and population, changes in energy intensities and technologies, and measures against local air pollution. Behind each of the four marker scenarios, there is a storyline that supports the choices of assumptions of the driving forces.

The scenarios are named A1, A2, B1 and B2, and may be described along two key dimensions. The first dimension distinguishes between material values (A1 and A2) and 'green' values (B1 and B2). This dimension has impact on environmental protection in general (except climate change), such as local pollution and sustainable development in poor regions. The other dimension distinguishes between international co-operation (A1 and B1) and regionalisation (A2 and B2). This dimension affects the development and diffusion of new technologies, e.g., related to the energy system. In this study we concentrate on the two marker scenarios A1 and A2, as it is somewhat difficult to implement material vs. green values within the Petro model.

In A1 the emphasis on material values and international co-operation transfer into rapid technological progress and diffusion of new technologies, and high economic growth combined with low population growth. Overall, this leads to significant increases in demand for energy. On the other hand, improvements in technology also affect the energy markets directly through reductions in energy intensities and significant decreases in the costs of supplying fossil fuels and in particular carbon-free energy sources. Over the next century, combining all these factors leads to high growth in energy demand, but only moderate growth in carbon emissions in the long run due to large availability of carbon-free energy sources.

In A2 the combination of material values and a heterogeneous world with an emphasis on local identities, is associated with more divergent development of technology and economic prosperity, with lower economic growth on a global level than in A1. Population growth is higher. Here, too, the disparities in technological improvement affect the energy markets directly, with somewhat less reductions in energy intensities and energy supply costs on a global level than in A1. In particular, the availability of carbon-free energy sources is more limited, and so the dependency on fossil fuel continues. Over the next hundred years, global energy demand grows moderately and somewhat slower than in A1, whereas carbon emissions rise over the whole century with no sign of levelling off. Hence, with respect to climate change, A2 is the worst case of the four marker scenarios in SRES.

3. The Petro model - a short description

A brief description of the Petro model is given here, emphasising the important characteristics of the model. A formal description is given in Appendix A. Further details are presented in Berg *et al.* (1997a,b) and Lindholt (1999). First we describe the model structure, which has not been changed in constructing the new baselines (except for a slight change in substitution possibilities between backstop and coal, see below). Next we present some important data or parameters in the model, and explain how they have been changed in the construction of the two new baselines.

3.1. The model structure

The model describes the international markets for the three fossil fuels oil, natural gas and coal. The model is intertemporal, taking into account that the fuels are non-renewable resources. All prices and quantities at each point of time are determined simultaneously in the model. Consumers determine their demand according to current income and prices of the fuels, whereas producers determine their supply according to the market conditions in all periods assuming perfect foresight. The strength of the model is the explicit modelling of the resource scarcity and the market power in the oil market, while the weakness is the strong aggregation on the demand side and the lack of a macro module.

Consumers are situated in four regions, OECD-Europe, Rest-OECD, Economies in Transition (EIT)[3] and Rest of the World (ROW). The first three regions constitute the Annex B area defined by the Kyoto Protocol. Demand for each fuel is represented by log-linear demand functions, which are decreasing in the consumer price of the specific fuel, and increasing in the consumer price of the two other fossil fuels. Moreover, income elasticities are used to shift the demand functions over time due to economic growth (taking into account changes in energy intensities). All price- and income elasticities are fixed over time. In addition we assume that there exists a single carbon-free backstop technology which serves as a perfect substitute for all fossil fuels.[4] This technology is available in copious supply at a given consumer price at each point of time in all regions. Technological progress occurs over time to reduce the costs of this technology (as for the extraction costs for fossil fuels).

The supply of fossil fuels is determined in an intertemporal way, since the resources are non-renewable. However, instead of considering the resources as strictly exhaustible, we assume that the unit extraction costs are increasing functions of cumulative production, which approach infinity as cumulative production approaches infinity.[5] Thus, with a finite backstop price the economic reserves are finite (see, e.g. Heal, 1976). Simultaneously, the technological progress has a decreasing effect on the cost of extraction, and so we cannot *a priori* tell whether the unit costs will increase or decrease over time.

The oil market is modelled in most detail. We define two groups of producers in the world oil market, namely OPEC that acts as a cartel and a competitive fringe with numerous identical producers. While the fringe always considers the oil price path as given, the cartel regards the price as a function of its supply, i.e., it utilises its market power. Thus, whereas marginal revenue for the fringe is equal to the producer price, marginal revenue for the cartel is in general lower than the price. Another important difference between the two groups of producers is that OPEC has low initial unit costs compared to the fringe and large resources available at costs below current oil prices. We choose the Nash-Cournot model of a dominant firm to calculate the open loop solution of the game, where each fringe producer and the cartel take the supply of all other producers as given when deciding their own production profile (see Salant, 1976).

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[3] EIT includes Russia, Ukraine and Eastern European countries. This group is included in the Annex B area, but the countries have until recently not been members of the OECD.

[4] In marker scenario A1, it is assumed a slightly imperfect substitution between coal and backstop (see below).

[5] In Berg *et al.* (1999), exploration activity in Non-OPEC has also been included in the Petro model.

There are three separate natural gas markets with perfect competition. The first two markets correspond to the first two demand regions, i.e., OECD-Europe and Rest-OECD, whereas the last gas market includes the remaining two demand regions, i.e., Non-OECD.

The coal market is assumed to be a competitive world market. Moreover, as vast coal resources exist around the world at low costs, there is no connection between accumulated production and unit costs for coal in the model. For this reason, the coal supply is actually not intertemporal, but demand-driven.

Since the backstop technology is assumed to be a perfect substitute for each fossil fuel, there is a maximum producer price for each fuel at each point of time in each region (note however the exception below). This is determined by the consumer price of the backstop technology, delivery costs for the fossil fuels and existing taxes. The CO_2 tax on the fuels comes in addition to delivery costs and existing taxes. When the price of a fossil fuel reaches this maximum level, we let the fossil fuel supply (if available) be exploited completely before any backstop supply is utilised.

This modelling of a backstop technology implies an immediate shift between the fossil fuel and the alternative energy source. Of course, this must not be taken literally - in reality there will be a transition period where both the fossil fuel and the backstop are demanded even though consumer prices are not identical. The future supply and characteristics of carbon-free energy sources are probably the most uncertain factor in long-term projections of carbon emissions. Therefore, our choice of a backstop technology must be seen as one out of many possible future restrictions on fossil fuels demand.

In marker scenario A1 our modelling of the backstop technology would lead to a sudden drop to zero emissions before 2100 in several of the mitigation scenarios (i.e., all the three fossil fuels become more costly than the backstop technology). This makes it impossible to achieve a good stabilisation performance for the atmospheric concentration of CO_2. For this reason we have chosen to introduce a slightly imperfect substitution between coal and the backstop technology.[6] There are several reasons for choosing coal rather than oil and gas. From a stabilisation point of view, coal is the last fossil fuel to be replaced by the backstop, and therefore the stabilisation performance is only improved if there is imperfect substitution between coal and the backstop. From a modelling point of view, since coal supply is not modelled in an intertemporal way, there is no need to make drastic changes in the model to avoid inconsistency problems with this approach (as it would with oil and gas). Finally, these technical arguments may be supported by the fact that coal resources are more widespread and

[6] For instance, when the backstop consumer price is 20 per cent below the consumer price of coal, two third of coal demand is replaced by backstop demand. When the backstop price is 50 per cent below, the replacement rate is 89 per cent.

available for use by consumers, without as much treatment and distribution as for oil and gas resources. Hence, coal may still be used in, e.g., rural areas even though the alternative energy source should be cheaper in the spot market. We stress that the effect on appropriate carbon taxes of introducing this imperfect substitution is quite small.

3.2. Data - important parameters

Parameters in the model are either taken directly from other literature, or calibrated. In Table 1 we display which key characteristics that have been adopted from the marker scenarios in SRES (Nakicenovic *et al.*, forthcoming), and which parameters in the model that have been directly replaced or calibrated. This is explained in more detail below.

Table 1. Implementation of SRES marker scenarios in the Petro model

Key characteristics in marker scenarios in SRES	Parameters in the Petro model
GDP growth rates	GDP growth rates
Energy intensity changes	Income elasticities
Technological progress (qualitative feature)	Technological rate of change in fossil fuel production and backstop supply
Degree of globalisation (qualitative feature)	Harmonisation of taxes and delivery costs for fossil fuels Introduction of carbon taxes in Non-Annex B
CO_2 emissions in 2100	Cross price elasticities between fossil fuels (only A2 scenario) Substitution possibilities between coal and backstop (only A1 scenario) Technological rate of change in backstop supply

The most important parameters on the demand side are the price elasticities. In the A1 scenarios the direct price elasticities for fossil fuels are -0.9 for the OECD regions, and -0.75 for the others. The cross price elasticities between fossil fuels are 0.1. Consequently, the substitution possibilities are quite low. In the A2 scenarios the cross price elasticities are increased to 0.45, which makes it possible to study the effect of higher fuel substitution. This is in line with the marker scenario A2 in SRES, where coal replaces oil demand in the last part of the next century, leading to huge emissions of CO_2. The size of the cross price elasticity is calibrated so that global emissions in 2100 are similar to the results of the marker scenario. The direct price elasticities are reduced to -1.6 and -1.45 for OECD and Non-OECD, respectively, so that the total price elasticity for fossil fuel is the same in A2 as in A1.

The income elasticities are determined so that the energy intensities are in accordance with the SRES marker scenarios. They are presented in Appendix B.[7] GDP growth rates are also based on the marker scenarios, see Appendix B. Existing taxes and delivery costs for the fossil fuels are equalised across regions from either 2025 (A1 scenarios) or 2035 (A2 scenarios), following the storylines of A1 and A2.

Unit costs of oil in OPEC start at $3.3 per barrel and for Non-OPEC at $10.9. The price of the backstop technology starts at $108 per barrel of oil equivalent (boe). At current technology (i.e., without technological progress), OPEC can produce 770 billion barrels before the unit costs reach $20; Non-OPEC can produce 239 billion barrels. These figures correspond to estimates of remaining proven reserves taken from BP (1995).

Future rates of technological change are of course very difficult to conjecture, and are perhaps the most important parameters for future CO_2 emissions. Consequently, it is instructive to investigate different pace of technological progress, as in the two marker scenarios in SRES. The technological progress for the backstop technology is calibrated in both baselines in order to obtain emission levels in 2100 in line with the marker scenarios A1 and A2 in SRES. For fossil fuels we simply add or subtract 0.5 to/from the technological rate of change in the original baseline in Petro for A1 and A2, respectively (see Appendix B for details).

The model has a time horizon of 110 years, starting in 1995. We use ten years time intervals so that, e.g., results for the year 2000 represent the average for the period 1995-2005.

4. Description of baseline - two reference cases in Petro

In this chapter we will describe the baseline for the two reference cases A1 and A2 in Petro. Note that these are not completely identical to the original marker scenarios A1 and A2 in SRES (Nakicenovic *et al.*, forthcoming). Rather, as indicated above, important characteristics are in accordance with the SRES scenarios. For instance, global CO_2 emissions at the end of the century are in line with the marker scenarios.

Global carbon emissions up to 2100 are shown in Figure 1, as it is projected within the Petro model. In Figures 2 and 3 we display the development in fuel use for the three fossil fuels and the carbon-free

[7] Note that this calibration was done using existing prices of fossil fuels. Therefore, the derived energy intensities in the baseline scenarios may differ somewhat from the ones in the marker scenarios if, e.g., higher prices lead to lower energy demand, whereas GDP is exogenous.

backstop technology over the same time horizon. Note that the emission profiles and fuel mix are very different for the two baseline scenarios, and that there is a marked shift in the figures around 2040-50 with respect to the comparison of the two scenarios. As this is caused by important circumstances taking place around the middle of the century, we will start by examining the two baselines in the first half of the century, and subsequently discuss the effects in the second half. Detailed growth rates for emissions and energy use are displayed in Appendix B.

Figure 1. Global carbon emissions - A1 and A2 baseline

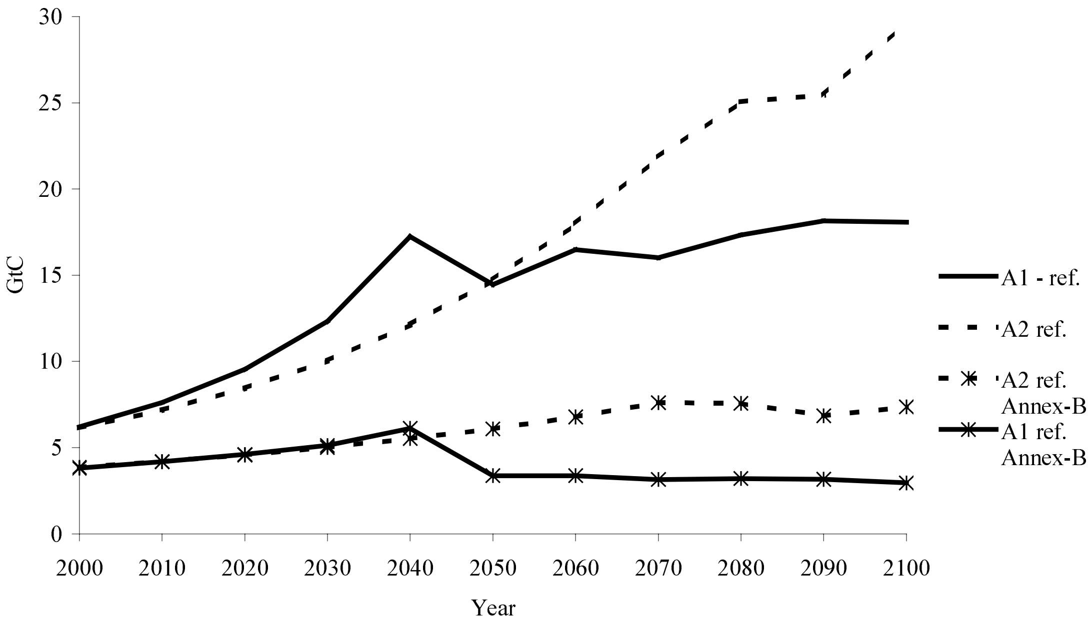


Figure 2. Global fossil fuel consumption - A1 and A2 baseline

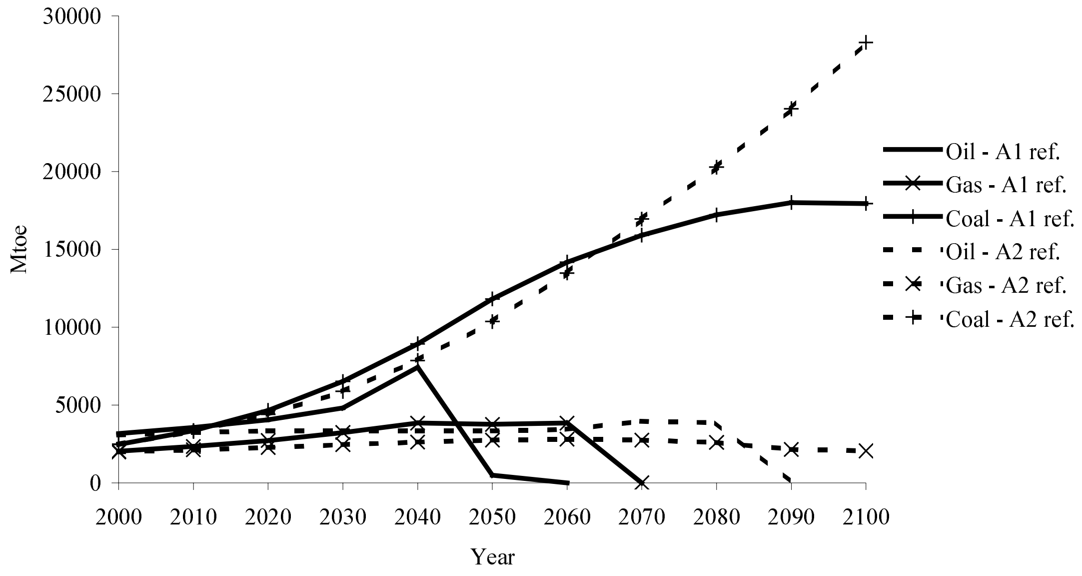
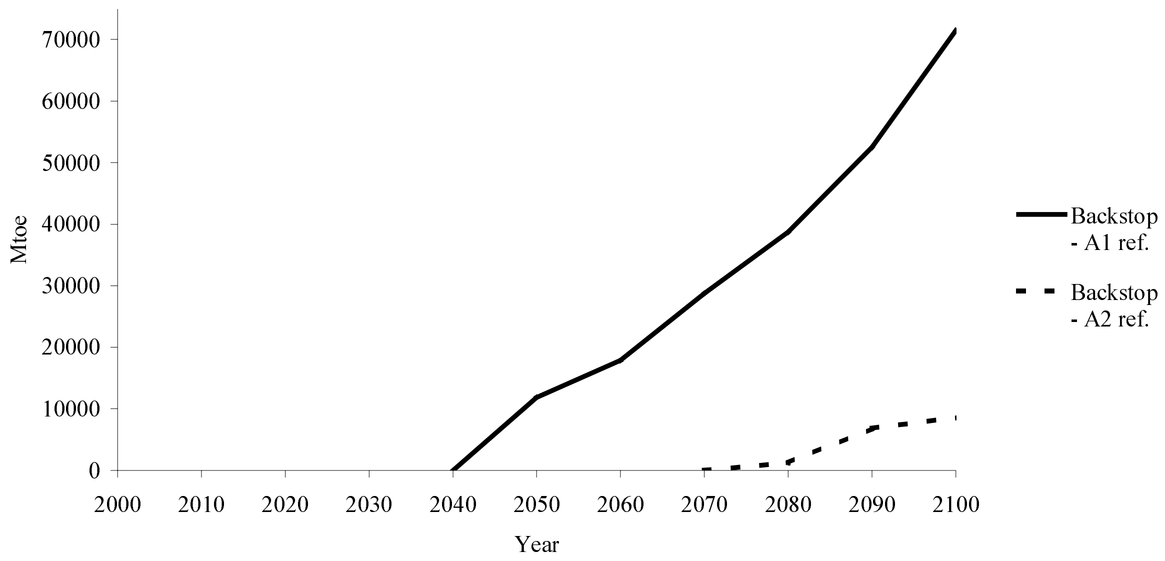


Figure 3. Global backstop consumption - A1 and A2 baseline



In the first decades emissions are highest in the A1 scenario, see Figure 1. This is due to the optimistic assumptions of economic development in this scenario, which override the effects of reduced energy intensities (this reduction is slightly more than one per cent p.a. on a world basis). In the period 2000-2040 global emissions increase at a rate of 2.6 per cent p.a. Carbon emissions increase far more rapidly outside the Annex B area than inside due to much higher economic growth. Thus, before 2020 more than half of the global CO_2 emissions are emitted in areas not comprised by the Kyoto protocol. In the A2 scenario economic growth is somewhat slower, and even though improvements in energy intensities are also somewhat slower, emissions increase at a lower rate in the first half of the century. That is, global emissions increase by 1.7 per cent per year in 2000-2040. In particular, emissions in Non-Annex B grow much slower than in A1, whereas emissions in Annex B grow almost at the same rate. Emissions inside and outside Annex B are not equal until 2030 in the A2 baseline.

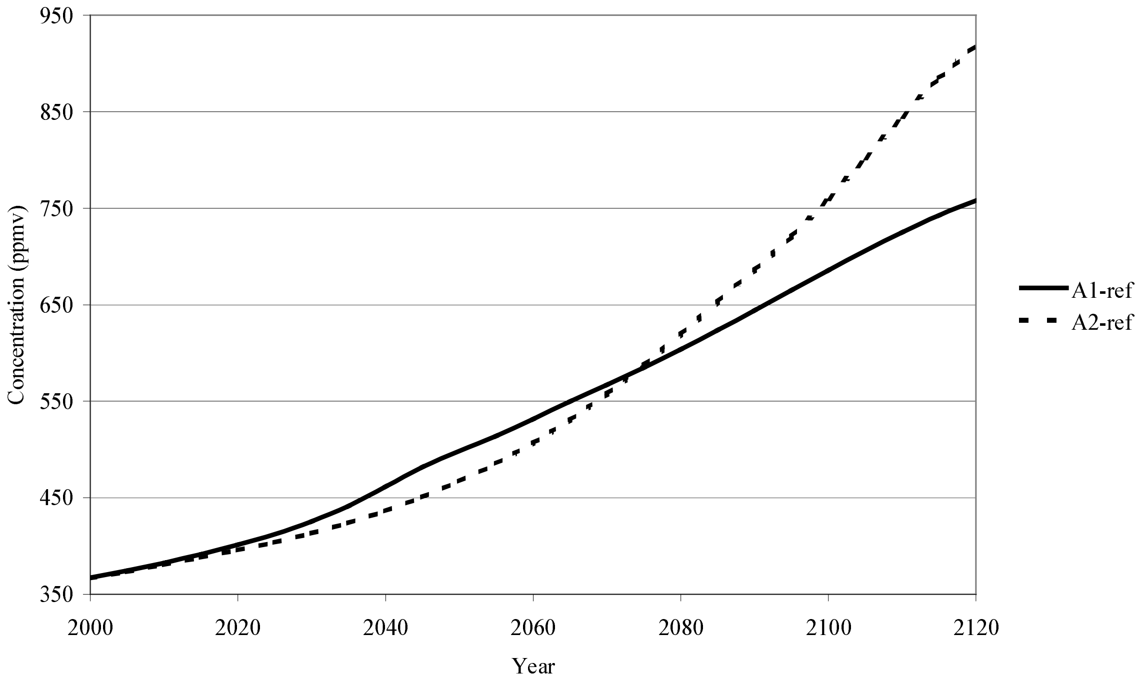
Figure 2 shows that in the first half of the century consumption of oil and gas increases significantly over time in A1, but is fairly constant in A2. Coal consumption increases rapidly in both baselines. The backstop technology is so far too expensive to be competitive. As a result, we see that in both scenarios there is a substitution towards the most carbon intensive fuel over time. This is related to the fact that oil and gas resources are becoming scarcer, i.e., the technological progress is not strong enough to counter the depletion effect on the resources, and so oil and gas prices are rising. The substitution effect is somewhat bigger in the A2 baseline, which is due to higher substitution possibilities between the fossil fuels in this scenario (see above). This, together with slower economic growth, explains the little increase in oil and gas demand in A2. All in all, we conclude that the difference in carbon emissions between A1 and A2 in this period is not related to dissimilar changes in the fuel mix, but rather to different scale effects in energy use caused by different economic growth rates.

From around 2040 emissions in the A1 baseline stabilise around 14-18 GtC per year for the rest of the century. Annex B emissions fall somewhat whereas emissions in the rest of the world increase slowly until 2100. In the A2 baseline, however, emissions continue to grow at about the same rate as before (at least until 2080) and so the two global emission paths in Figure 1 cross in 2050. Global emissions reach 30 GtC in 2100 without showing any signs of turning down. Most of the emission increase comes outside the Annex B area, but emissions also increase somewhat inside Annex B.

This divergence between A1 and A2 is also related to the scarcity effect on oil and gas supply described above. In A1 higher oil and gas prices are met by the introduction of the carbon-free backstop technology, which by assumption has become much cheaper. This technology replaces oil and gas before 2070 (see Figure 2 and 3). In 2100 the backstop technology has a market share of 80 per cent. On the other hand, in A2 the technological progress for the backstop technology is assumed to be much slower. Moreover, as illustrated above, oil and gas demand (and supply) are increasing less rapidly in A2 than in A1, which means that unit costs in oil and gas supply are rising more modestly. In combination, this implies that the time when unit costs reach the maximum producer price is delayed in A2 compared to A1. Consequently, oil resources are not exhausted until 2090 in the A2 baseline, whereas gas resources are not exhausted at all during the century. In the last decades before 2100 the backstop technology comes into market in A2, too, and reaches a market share of 22 per cent in 2100. Nevertheless, the main difference between A1 and A2 in the second half of the century is therefore that oil and gas are replaced by a carbon-free technology in A1, and by a more carbon intensive fuel in A2.

As we have seen above, the scarcity effects on oil and gas supply are one of the important determinants of the projected carbon emissions in the future. An interesting point is that even though technological progress in fossil fuel extraction is assumed to be higher in A1 than in A2, oil and gas resources are exhausted earlier in A1 than in A2. The reason is that we are concerned with economic exhaustion rather than physical exhaustion. In A1 the backstop technology becomes cheap and available much earlier than in A2, and so makes the remaining oil and gas resources unprofitable. Therefore, more oil and gas are consumed over the next century in A2 than in A1. Another important factor in the oil market is the behaviour of OPEC. In a later chapter we will discuss more thoroughly the future oil markets in the two baselines, and the impacts of the mitigation scenarios on oil prices and production, and on OPEC's and other oil exporters revenues.

Figure 4. CO_2 concentration level - A1 and A2 baseline



In Figure 4 we show the paths of CO_2 concentration in the atmosphere up to around 2120 that correspond with the emission paths in Figure 1. The concentration paths are derived by using the AIM Stabilization Scenario Generator (AIM-SSG), based on the Bern Carbon Cycle Model (Joos *et al.*, 1996), on the emission profiles up to the year 2100.[8] We see that initially the concentration level rise at a constantly higher rate in the A1 baseline due to high emission growth, but rises more linearly when emissions stabilise around the middle of the next century. In 2100 the concentration level has reached about 685 ppmv, and is still growing moderately. A stabilisation check shows that the A1 baseline is not able to stabilise concentration of CO_2 in the atmosphere at levels of 800 ppmv or below. The concentration path for the A2 baseline shows a slower increase initially than under A1 due to less emission, but after 2030 the curve rises more rapidly. Around 2075 the two curves intersect, but at this time global emissions are 40 per cent higher in A2 than in A1 and the slope of the concentration path is almost 70 per cent higher. Hence, around 2100 the concentration level in A2 reaches around 760 ppmv, and is still rapidly increasing. The A2 baseline is not able to stabilise concentration of CO_2 in the atmosphere at levels of at least 950 ppmv or below, according to the stabilisation generator.

[8] Emissions from land use change are included in the stabilisation generator, but not in the rest of our discussion. The concentration path shown beyond 2100 is partly based on extrapolated emissions after 2100, which again are based on the emissions in 2090-2100 within the model.

5. Mitigation scenarios to stabilise CO_2 concentration

5.1. Stabilisation targets

Neither of the baseline scenarios described above were able to stabilise concentration of CO_2 in the atmosphere at 750 ppmv or below. In the stabilisation check we require that the concentration level is within a range of 5 per cent from the target in 2150 and beyond. For this reason, we would like to derive mitigation scenarios that stabilise CO_2 concentrations at the specific levels 450, 550, 650 and 750 ppmv (see the introduction), based on both the A1 and the A2 baseline. Then we can compare the policy measure needed to stabilise concentration at a specific level for the two baselines, and investigate how the necessary policy measure changes when the stabilisation target changes for a given baseline. The scenarios are named according to their baseline and their concentration target (e.g., A1-550).

5.2. Policy

Since the only goal of the mitigation scenarios is to reach a specific stabilisation level in the future, there are numerous emission profiles that are able to reach the goal. Both the time profile and the spatial profile (e.g., Annex B vs. Non-Annex B) may vary. As the Petro model only describes the energy markets, there is no way to impose a least-cost strategy in order to choose among these profiles. Thus, we have rather searched for a carbon tax that is fixed over time and just high enough to attain the target. Moreover, we have chosen to let the carbon tax be initially introduced in the Annex B area only. After a certain time period the same tax is also introduced in the rest of the world, as it is unreasonable to assume that only Annex B countries will reduce CO_2 emissions for the rest of the planning horizon. For the A1 scenarios this happens from 2025, whereas for the A2 scenarios the tax becomes global ten years later. This discrepancy follows the storylines of the A1 and A2 worlds.

Although the spatial profile is in accordance with the Kyoto protocol, the time profile may not be. That is, we have not put particular restrictions on emissions in the Annex B area around 2010. Since the protocol is not yet ratified, such restrictions should not be taken as inevitable. Moreover, the Petro model is not very suitable for medium-term analyses. However, we will come back to how the mitigation scenarios look like compared to the Kyoto agreements.

5.3. Discussion of mitigation scenarios

The tax rates that stabilise the respective concentration levels are shown in Table 2. For instance, to stabilise at the concentration level of 550 ppmv, which corresponds closely to a doubling of the pre-industrial concentration level of CO_2, a carbon tax of \$45 and \$181 is necessary in A1 and A2, respectively (\$10 per ton carbon corresponds to \$1.1 per barrel of oil). Note that each time the concentration target is tightened (increased) by 100 ppmv in both A1 and A2, the carbon tax needed to attain the target roughly doubles (halves). Furthermore, for each concentration target, the carbon tax is 4-6 times higher in the A2 mitigation scenario than in the corresponding A1 scenario. This is partly due to the fact that accumulated emissions over the century are higher in A2 than in A1 (1,787 GtC and 1,535 GtC), and that the tax is introduced later outside Annex B in A2. However, the main reason is that the backstop technology is more expensive in A2. Consequently, it is more difficult to reduce emissions from a given level in A2 than in A1, and a higher tax is necessary in order to make the alternative energy source competitive.

Table 2. CO_2 tax rates in mitigation scenarios

Mitigation scenario	Constant CO_2 tax rate (1994-$/ton C)	Year for global CO_2 tax
A1-750	9	2025
A1-650	24	
A1-550	45	
A1-450	99	
A2-750	59	2035
A2-650	99	
A2-550	181	
A2-450	361	

Figures 5-8 show the impacts of different mitigation scenarios on global carbon emissions and CO_2 concentration level. We will mainly concentrate the discussion on the 550 ppmv target, and leave the other scenarios to the figures. In Appendix B we display the percentage reduction in the 550 ppmv scenarios compared to baseline for CO_2 emissions and energy use.

In the A1 mitigation scenarios the carbon tax gives a moderate initial drop in CO_2 emissions from the baseline. In 2025 the carbon tax is levied outside Annex B and this leads to a further drop in emissions compared to baseline. Still, the growth rate in global emissions up to 2040 is only slightly reduced from the baseline to A1-550 (2.6 vs. 2.3 per cent p.a.). Note that in A1-450 the emission path diverges far more from the baseline in these periods than in the other mitigation scenarios (see Figure 5). Towards the end of the century we see that the emissions in the different mitigation scenarios are at very different levels - in A1-550 global emissions are around 6 GtC, i.e. one third of the baseline level. A major feature in all A1 mitigation scenarios is that the emissions clearly show signs of turning down around the turn of the century. This is not the case for the A1 baseline.

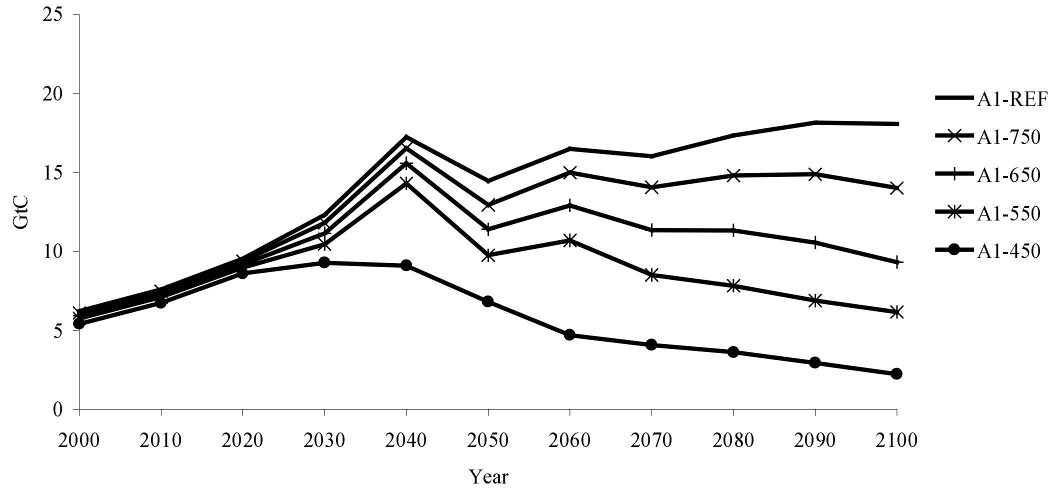
In the A2 mitigation scenarios the carbon tax is levied outside Annex B in 2035, one period later than in A1. In these scenarios the initial drop in CO_2 emissions compared to baseline is higher than in the corresponding A1 scenarios (see Figure 6 and 7). This is obviously caused by the much higher tax rates in A2 than in A1. The more underlying reason is, however, that overall emissions over the century in the A2 baseline are higher than in the A1 baseline. Thus, with constant carbon taxes over time emissions are initially reduced more drastically in A2 than in A1, even though baseline emissions are somewhat lower in A2 in the first periods. When the tax is levied outside Annex B, the deviation from the baseline increases sharply. Here, too, the A2-450 scenario differs from the other mitigation scenarios in the middle of the century. At 2100 global emissions are at very different levels in the various mitigation scenarios. In A2-550 annual emissions are 8 GtC, i.e., one fourth of the baseline level. Except in the A2-450 scenario, all A2 mitigation scenarios seem to have rising emissions at the turn of the century.

When we compare the A1 and A2 mitigation scenarios, we observe that for a given concentration target, the emission paths in A1 are above the corresponding paths in A2 for most of the century (see Figure 7). For instance, with 550 ppmv as the target, emissions in A1-550 are higher than in A2-550 until 2090. However, in 2100 global emissions are significantly higher in A2-550 than in A1-550. Still, global CO_2 emissions over the century are 23 per cent higher in A1-550 than in A2-550 even though the long-term target of CO_2 concentration is the same. This is a striking result in light of the fact that global emissions in the A1 baseline are 14 per cent *lower* than in the A2 baseline. One explanation for this is found by looking at the slope of emissions at the end of the century. Global emissions in all the A1 mitigation scenarios show signs of turning down, whereas in all the A2 mitigation scenarios except one, emissions are still rising as carbon-free energy sources are still somewhat expensive. Hence, in order to have a consistent trend in global emissions after 2100, the A2 mitigation scenarios require more reductions during this century in order to stabilise concentration at the target level. This implies that the necessary policy measure in the A2 world is much tougher than in the A1 world.

Looking at the concentration paths in Figure 8 supports this explanation. We see that the concentration level of CO_2 in 2100 is significantly higher in A1-550 than in A2-550. However, the level increases three times higher in the A2 mitigation scenario than in the A1 scenario at this time. Actually, the concentration path of A1-550 lies above the A2-750 path until around 2075. That is, for more than half a century more emissions are allowed with the target 550 ppmv in the A1 world than with the much higher target 750 ppmv in the A2 world. These results show how important the baseline is for the appropriate emission and concentration paths for a given target.[9]

The Petro model is not very suitable to analyse near-term effects of carbon taxes, as there is no short-term rigidities in the model. Still, it may be interesting to compare the emissions in Annex B in the mitigation scenarios with the obligations for Annex B countries in the Kyoto protocol. The protocol sets limits on the emissions of six greenhouse gases (GHGs). The combined result of individual country targets is estimated to result in an overall reduction in Annex B parties' GHG emissions of 5.2 % from the 1990 levels by the commitment period 2008-2012 (averaged across the period). As CO_2 accounts for most of the GHG emissions in the region, it may be reasonable to assume that the reduction of CO_2 does not deviate substantially from the reduction targets for all six GHGs. In this case, we find that the mitigation scenarios A1-650 and A2-750 are almost in line with the emission targets in the Kyoto protocol. With more short-term rigidities included in the model, the protocol would have been more consistent with lower concentration targets, as such rigidities would have implied less reductions in the near-term and more reductions in the long-term for a given concentration target. However, as constant carbon taxes over time are not necessarily consistent with a least-cost strategy, these results must be taken with special caution. Still, they illustrate that whether the Kyoto target is consistent with a longer-term goal or not, depends not only on the concentration target, but also on the baseline scenario. This is often neglected in cost analyses of the Kyoto commitments (see, e.g., several of the studies in Weyant, 1999).

Figure 5. Global carbon emissions at various mitigation scenarios, A1



[9] Although we have not used a least-cost strategy, we have used the same type of policy measure on the two baselines, i.e., a constant carbon tax over time.

Figure 6. Global carbon emissions at various mitigation scenarios, A2

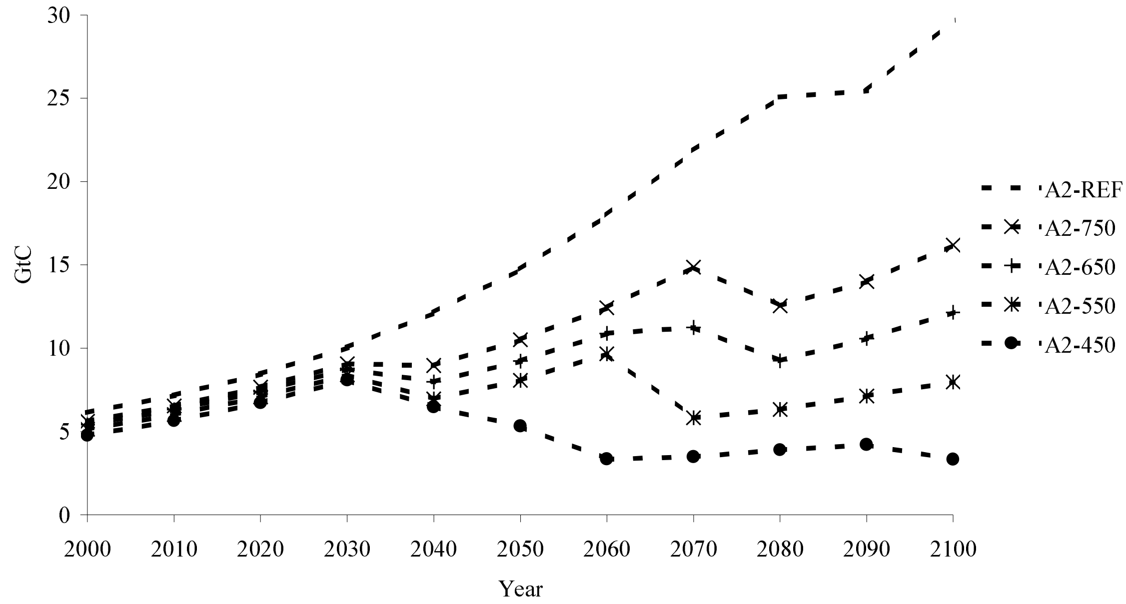


Figure 7. Global carbon emissions in A1-550, A2-550 and the two baselines.

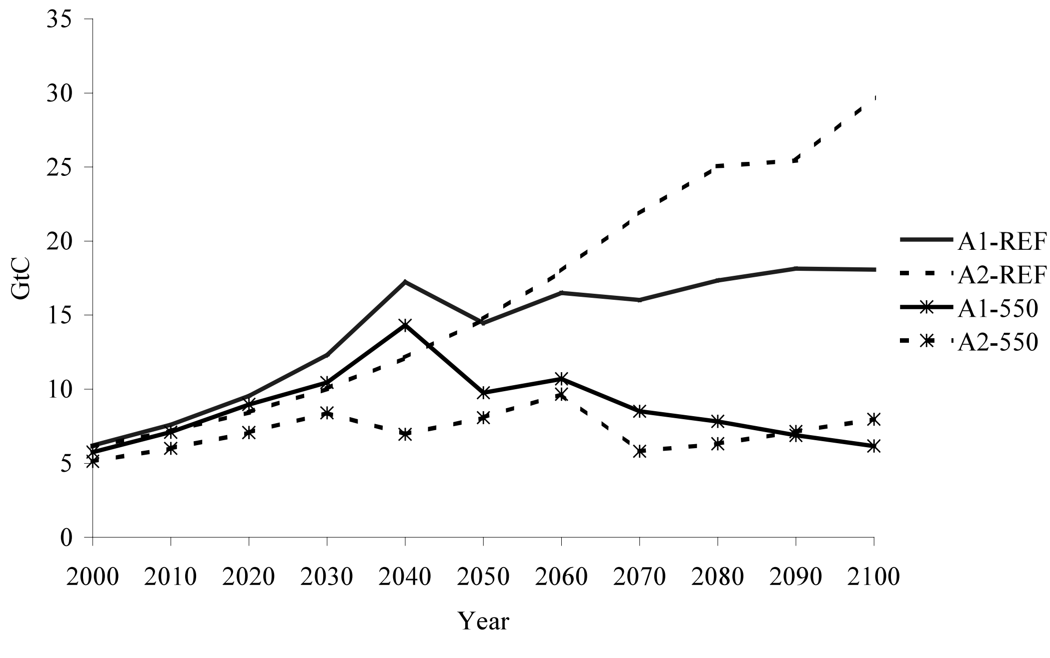
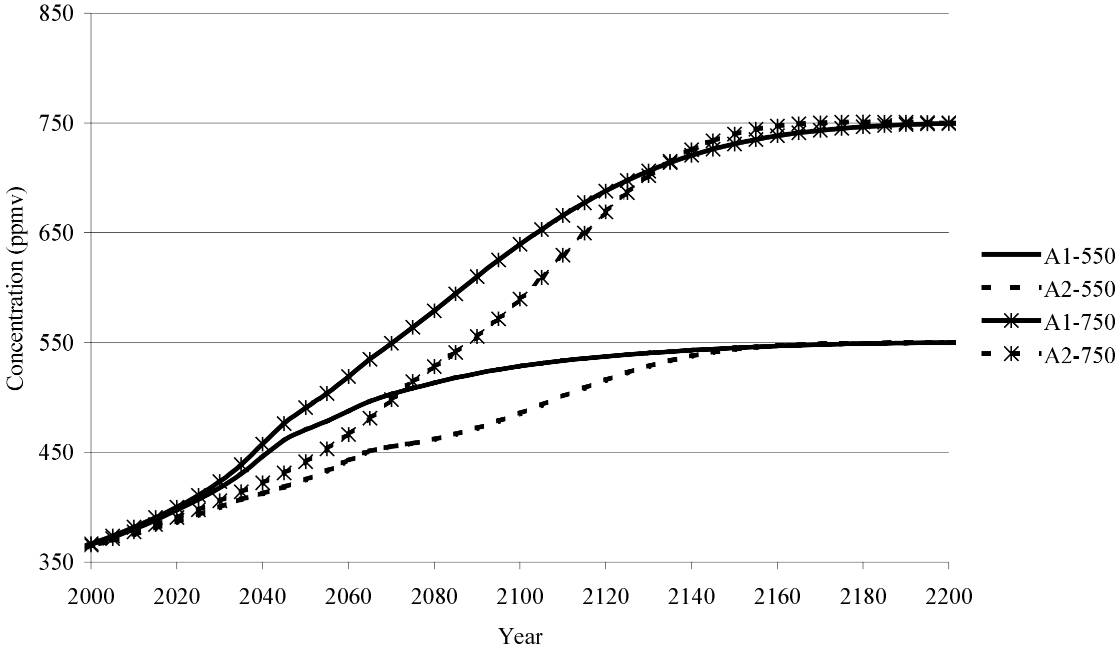


Figure 8. CO_2 concentration level at mitigation scenarios A1 and A2, 550 and 750 ppmv.



How are the emission paths in the various mitigation scenarios related to the fuel use? Figures 9-12 show the impacts on global fossil fuel and backstop consumption for both 550 ppmv mitigation scenarios. Generally the effects will be gradually stronger as the concentration target becomes tighter. Any divergence from such a tendency will be commented on.

From Figure 9 we see that oil consumption in A1-550 is approximately unchanged over the first 40 years compared to A1-REF.[10] Figure 11 shows that global gas consumption is reduced slightly from the baseline over the whole period. Both oil and gas are replaced by the backstop technology at about the same time as in the baseline, see Figure 12. On the other hand, coal consumption is more than ten per cent below A1-REF in the initial periods when the carbon tax is imposed in the Annex B countries only, and around one third below when the carbon tax becomes global (see Figure 10). Coal consumption starts to fall after 2060. Almost three quarter of the reduction in 2100 (measured in energy content) is compensated by increased use of the backstop technology, which now has a market share of 93 per cent in 2100 (80 per cent in baseline). This is the reason why the emission paths in all mitigation scenarios show a decreasing trend towards 2100. Hence, we see that the carbon tax clearly hits the most carbon intensive fuel most. The explanation for this is of course partly due to the fact that the tax on coal is higher than on oil and gas (measured in energy content). However it is also important

[10] In A1-450 oil consumption is reduced sharply in 2040, which is reflected in Figure 5 by the drop in emissions from the baseline.

that the consumer price of coal in the baseline is much lower than the price of gas and especially oil, so that the relative price increase due to the carbon tax is much higher.

As carbon taxes in the A2 mitigation scenarios are much higher than in A1, we should expect more drastic effects on the fuel use. In A2-550 the introduction of a carbon tax moves oil consumption nearer in time, with *higher* consumption compared to the baseline in the period 2040 to 2060, see Figure 9. On the other hand, the backstop technology replaces oil consumption two periods earlier than in A2-REF. As in A1 gas consumption shows minor changes over the whole century in the various mitigation scenarios (except in A2-450 where gas is replaced by the backstop in 2100). Again it is coal consumption that shows the greatest reduction. Coal consumption is one third below A2-REF in the initial periods when the carbon tax is imposed in the Annex B countries only, and as much as two third below when the carbon tax becomes global. This is due to the high level of carbon tax. As the backstop technology is more expensive than in A1, it is not able to replace coal consumption before 2100 even with such high taxes. Therefore, coal consumption increases during the second half of the century in all the A2 mitigation scenarios. This explains why emissions in all the A2 mitigation scenarios except A2-450 have rising emissions at the turn of the century. In 2100 only 30 per cent of the reduction in coal consumption is compensated by higher backstop consumption (measured in energy content). Still, the backstop technology now has a market share of 63 per cent (vs. 22 per cent in the baseline).

When we compare the mitigation scenarios in A1 and A2, we see that in both cases emissions are mainly reduced through reduction in coal consumption. Moreover, this reduction is partly compensated by increased backstop consumption. In A1 the backstop technology is competitive at an earlier stage than in A2, and so the substitution from coal to backstop is more feasible. Consequently, strong policy measures are not needed in A1 to accelerate this transition. In A2, however, substitution towards the backstop is more difficult, which implies that high carbon taxes are necessary in order to reduce emissions over the century. This leads to major reductions in coal use over the whole time horizon.

Because of larger substitution possibilities between fossil fuels in A2, the introduction of carbon taxes leads to periods of increased oil consumption compared to baseline. On the other hand, the total duration of oil consumption and production in the world is shorter. In A1 the carbon taxes have little impact on the oil consumption profile. In the next section we will discuss these effects more thoroughly by examining the behaviour of oil producers, and study how their resource wealth is affected in the mitigation scenarios.

Figure 9. Global oil consumption in mitigation scenarios A1-550 and A2-550

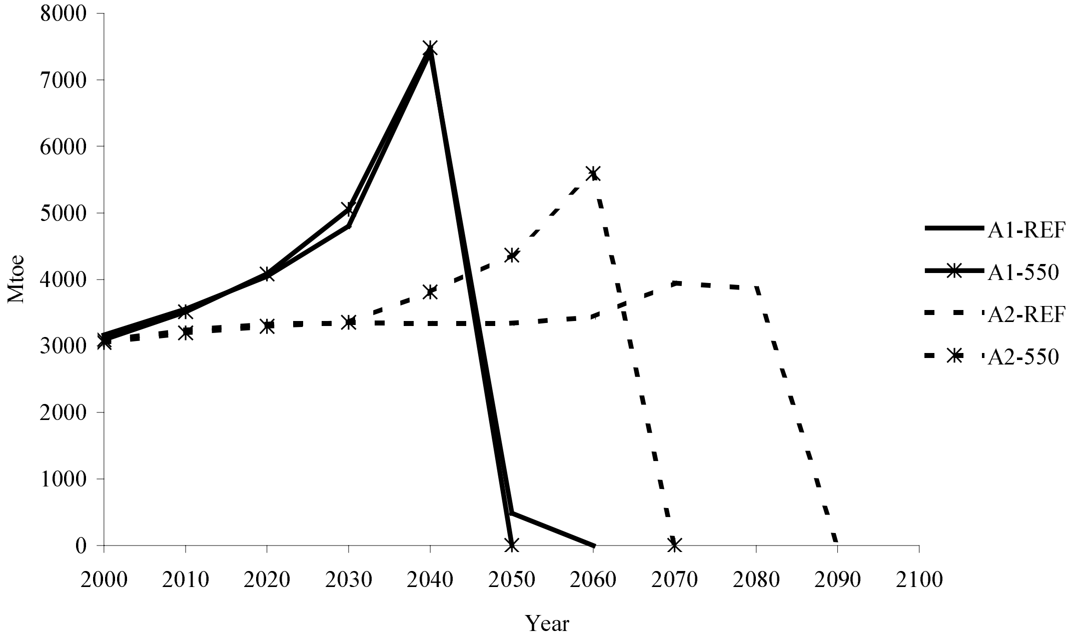


Figure 10. Global coal consumption in mitigation scenarios A1-550 and A2-550

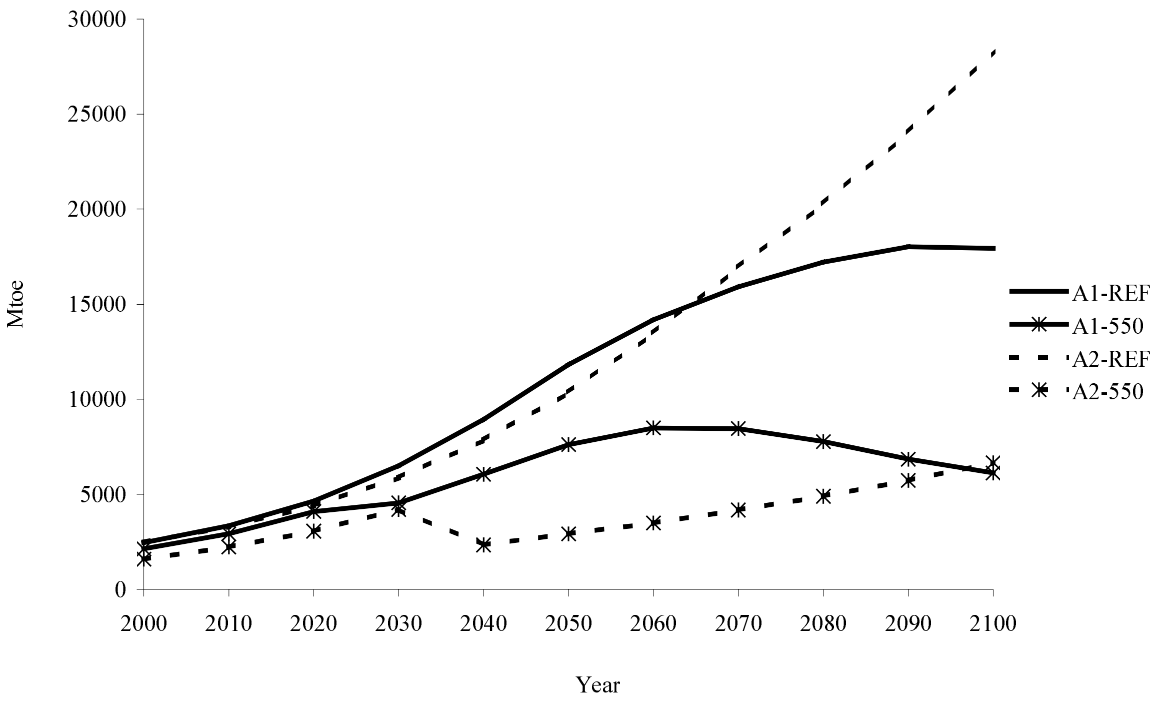


Figure 11. Global gas consumption in mitigation scenarios A1-550 and A2-550

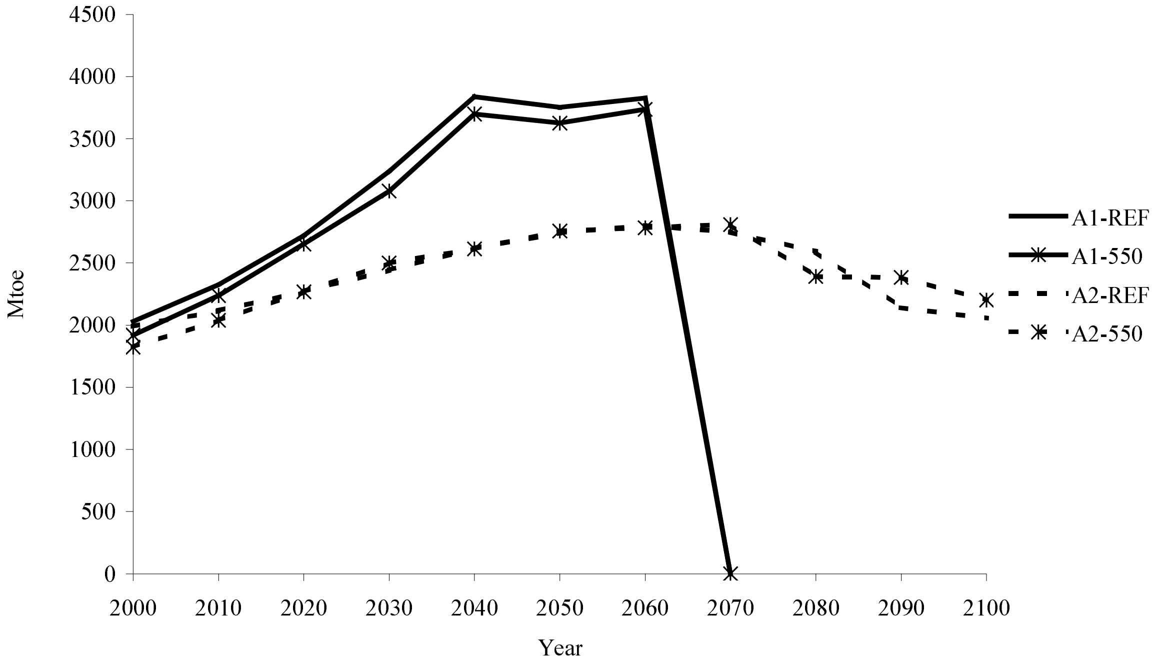
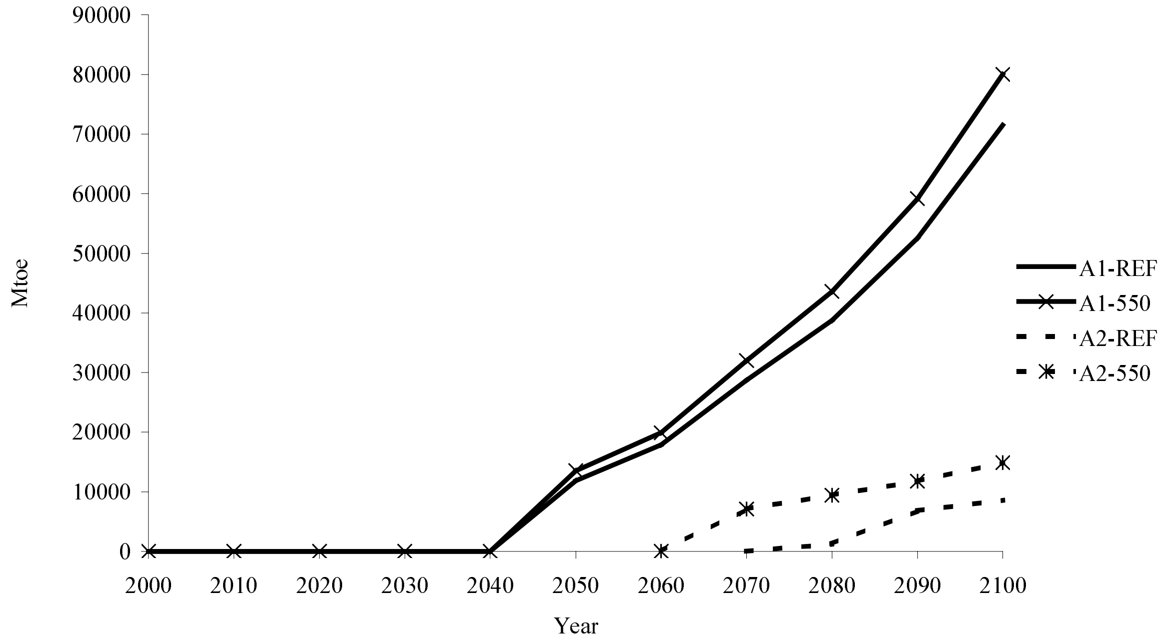


Figure 12. Global backstop consumption in mitigation scenarios A1-550 and A2-550



6. Effects in the oil market and impacts on oil producers

OPEC and other oil producers are greatly concerned with the climate change issue, particularly with respect to their oil revenues. In this section we want to investigate in what way the oil market will be affected by the various mitigation scenarios, and how the oil wealth of different oil producers will change. The Petro model is well suited for such analyses, as the market power of OPEC is implemented in the model. In Figures 13-15 we show the impacts of the 550 ppmv mitigation scenarios on oil producer prices and production in OPEC and Non-OPEC.

The producer price of oil starts at around $20 per barrel in the baseline scenarios, as shown in Figure 13.[11] Then it increases until it hits the path of the maximum oil producer price determined by the price of the backstop technology. In A1 this happens already in 2030 since the technological progress for the backstop is very rapid. Then the oil price is $34 per barrel. On the other hand, in A2 the oil price rises for four more decades until it reaches $56 per barrel in 2070.

In A1 Non-OPEC initially has a market share of about two-thirds until 2030, see Figure 14 and 15. This is almost in accordance with its real market share today of about 60 per cent. Then OPEC goes into a period of 20-30 years with monopoly power, before the backstop technology becomes so cheap that oil production is no longer profitable even in OPEC. In the A2 baseline Non-OPEC has a smaller market share initially than in A1, i.e., nearly 50 per cent. Non-OPEC's market share increases slightly towards 2060, but still it is clearly below its real market share today. After 2060 OPEC increases its production before it goes into a ten year long period with monopoly power. Then the backstop technology takes over. OPEC's low market share when Non-OPEC produces is due to the Nash-Cournot modelling, which implies that OPEC finds it profitable to restrict their supply in order to maintain a relatively high producer price. This effect is weakened in the A2 baseline when the substitution possibilities between fossil fuels are higher, implying that the direct price elasticities for oil are higher. Thus, as the price response of a shift in supply is more modest, OPEC is less willing to restrict its supply. Non-OPEC producers determine their current supply by considering the extra profits today against higher costs in the future. Their production profile is optimal at the equilibrium price path.

When the carbon tax is introduced in the mitigation scenario A1-550, the initial producer price of oil falls by $0.25 per barrel compared to baseline, whereas 20 years later the decline is $1.6. OPEC

[11] Note that the intertemporal behaviour in the model may lead to slightly different starting points for the two baseline scenarios A1 and A2 even though only future demand and production costs are different.

almost manages to prevent the oil price from falling by reducing production by around one tenth in the first two periods. This means that the consumers pay almost the whole tax increase over the first twenty years. Then from 2030 the backstop technology depresses the producer price of oil so that the producers pay the whole tax. That is, the consumer price of oil is unchanged in 2030, whereas the consumer prices of coal and gas are higher than in A1-REF. Therefore oil consumption increases in this period in A1-550 compared to the baseline scenario. Note that in this mitigation scenario Non-OPEC production is actually higher than in the baseline for the first two periods. The reason is that the price reduction is bigger in later periods, and so the producers find it optimal to move some of its extraction to an earlier time. Thus, OPEC is able to increase its market share in 2030, but stops producing a bit earlier. OPECs accumulated production increases somewhat over the production period, while Non-OPEC reduces its total production.

In the mitigation scenario A2-550 the introduction of a carbon tax actually increases the producer price of oil by $1.3-3.2 per barrel for the first 50 years compared to baseline. Then the price starts to fall earlier than in the baseline, and from 2070 the tax burden is totally born by the producers. The reason is again larger substitution possibilities between fossil fuels in A2 than in A1. As mentioned before, the carbon tax has a relatively much higher effect on the consumer price of coal than on the consumer price of oil. In A2 the increased coal price has a larger positive impact on oil demand than in A1, and this leads to a tighter oil market resulting in higher prices than without the carbon tax. In fact, oil consumption in Annex B increases and oil consumption outside Annex B decreases when the carbon tax is levied on the Annex B countries only in the initial periods. OPEC reduces production in the first four periods to keep the oil price as high as possible, while Non-OPEC increases production in the same period due to a higher level and slower increase in the oil price than in baseline. Both producers stop extracting two periods earlier than in A2-REF.

Figure 13. Oil producer price in A1 and A2 baseline and A1-550 and A2-550 mitigation scenarios

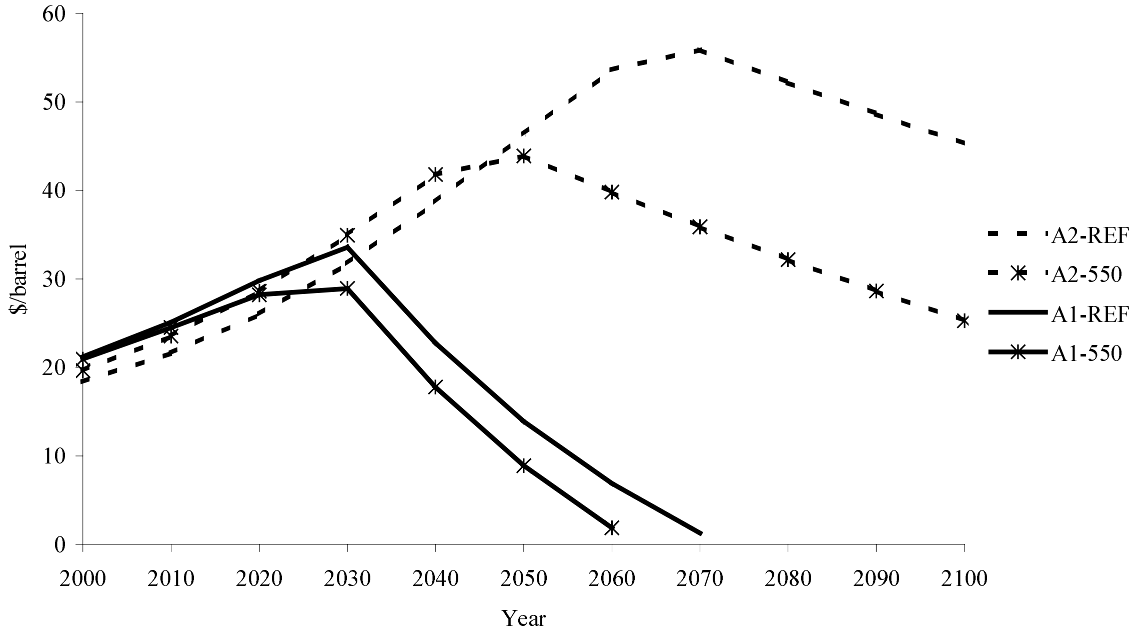


Figure 14. Production of oil in OPEC in A1 and A2 baseline and A1-550 and A2-550 mitigation scenarios

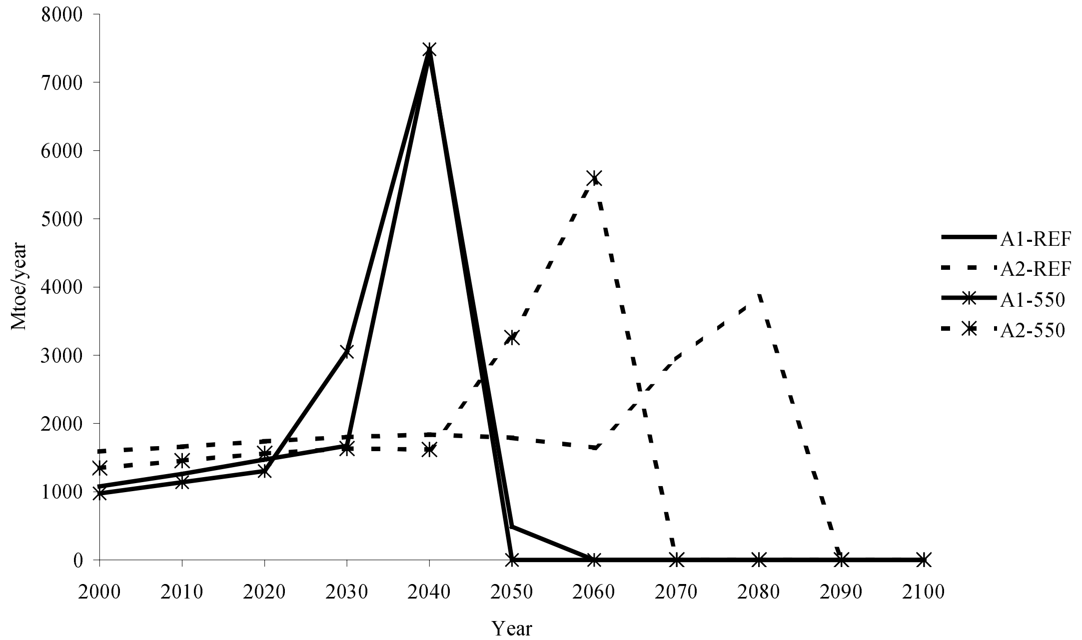
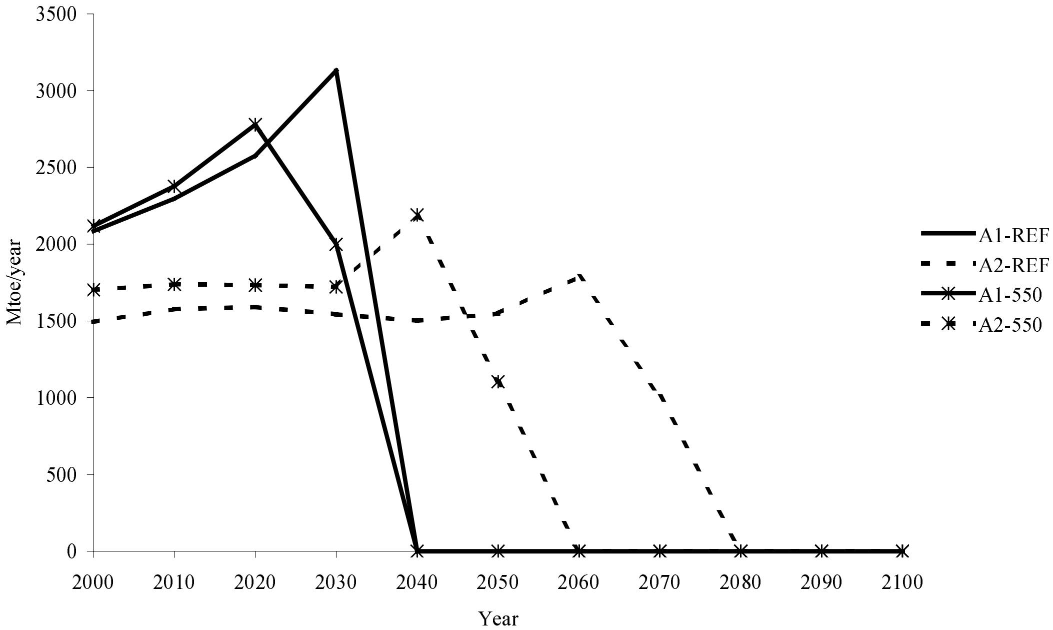


Figure 15. Production of oil in Non-OPEC in A1 and A2 baseline and A1-550 and A2-550 mitigation scenarios

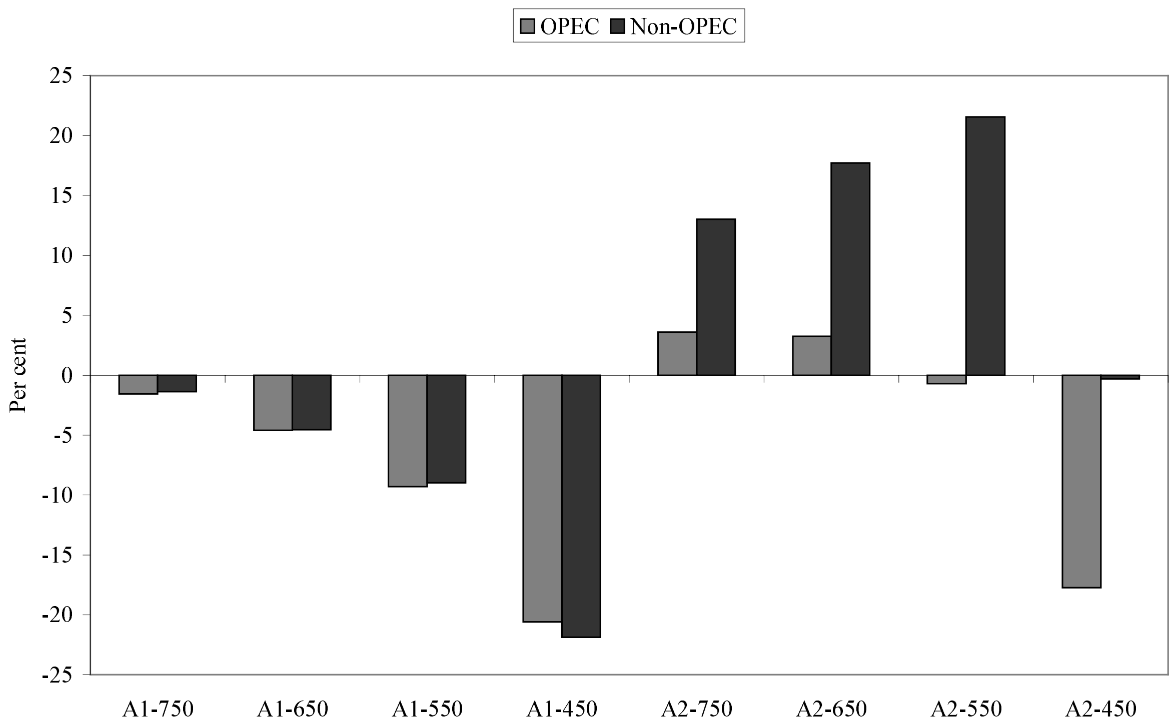


How do the mitigation scenarios affect the oil wealth of OPEC and Non-OPEC, i.e., total discounted oil revenues over the time horizon? First, note that OPEC's wealth is around 7 per cent higher in A2-REF than in A1-REF, while Non-OPEC's wealth actually is 43 per cent lower. The main reason is that OPEC has higher production in A2-REF than in A1-REF in the first three periods due to higher substitution possibilities, which implies lower prices and less production for Non-OPEC.

Figure 16 shows the consequences for the producers' oil wealth in all mitigation scenarios compared to their baseline. We see that in the A1 scenarios, both producer groups experience more or less the same relative loss in oil wealth, and that the loss is increasing when the target is tightened. For instance, in A1-550 the loss is 9 per cent for both OPEC and Non-OPEC. OPEC is hit mostly in the beginning when it finds it optimal to reduce its supply, whereas Non-OPEC is mainly hit by reduced production in later periods. As a comparison, Berg *et al.* (1997a) found that a carbon tax of $10 per barrel of oil, which almost corresponds with the tax in A1-450, reduced the oil wealth of OPEC and Non-OPEC by 23 and 8 per cent, respectively. This is about the same reduction for OPEC as in A1-450, whereas Non-OPEC is hurt much more in our results. The main reason is that the production period for Non-OPEC is much shorter, so that the future effects are felt more in A1-450 than in the results of Berg *et al.*

In the A2 mitigation scenarios the oil producers are affected in a very different way. OPEC faces a slightly higher oil wealth in A2-750 and A2-650 compared to baseline, almost unchanged wealth in A2-550, and a large reduction in A2-450. Non-OPEC's oil wealth is significantly increased in all these mitigation scenarios except A2-450, where it is more or less unchanged. In A2-550 Non-OPEC experiences an increase in its oil wealth of 22 per cent. Hence, mitigation of CO_2 from the A2 baseline is generally beneficial for oil producers as long as carbon taxes are used as policy measure and the target is not too ambitious. This is quite the contrary of what oil producers seem to expect. The explanation is of course related to the price increase discussed above, which endures for half a century. Since the price increase is partly due to reduced supply from OPEC, Non-OPEC is clearly ending up as the main winners.

Figure 16. Changes in oil wealth for OPEC and Non-OPEC in various mitigation scenarios. Percentage change compared to baseline.



The discussion in this paper has illustrated that a specific concentration target may be reached through a combination of carbon taxes and the introduction of a carbon-free energy source. With rapid improvement in alternative energy technologies, carbon taxes may be quite low (as in the A1 scenarios), whereas high taxes are needed if there is slow technological progress for carbon-free energy sources (as in the A2 scenarios). An interesting question may then be how the oil wealth for oil producers is affected by the two means of reaching the target. Should oil producers opt for improved technological progress of new energy technologies, expecting carbon taxes to be lower, or should they prefer taxes? Is the answer different for OPEC and Non-OPEC?

At first glance it is tempting to compare the oil wealth in e.g. A1-550 with A2-550, as the former mitigation scenario is characterised by rapid technological progress for the backstop technology, whereas the latter scenario is characterised by high carbon taxes. However, there are several other differences between the A1 and A2 scenarios that blur the picture. For this reason, we have rather run more simulations based on the A1 and the A2 baseline, and varied the rate of technological progress and the carbon tax level so that the target of 550 ppmv is reached. In both cases we have found a scenario where the target is reached solely by increased rate of technological change in the backstop technology ("backstop scenario"), and a scenario where the target is reached solely by introducing carbon taxes ("tax scenario"). Note that in A1 the technological rate of change in the tax scenario is reduced compared to the original baseline scenario. The resulting oil wealth for OPEC and Non-OPEC is shown in Table 3, as indexes compared to the A1 backstop scenario.

We see that in both A1 and A2 Non-OPEC has a significantly higher oil wealth when the target is reached through carbon taxes than through carbon-free technologies. One explanation for this is that carbon taxes hit oil *less* than other fossil fuels, whereas alternative energy sources hit oil *more* than other fossil fuels, at least for the first half of the century. Thus, total oil extraction over the whole time horizon is more reduced by the alternative energy source than by the carbon taxes. For OPEC the results are more ambiguous. The producer group tries to maintain a high oil price initially by restricting production. This is more necessary with carbon taxes than with alternative energy sources, as taxes affect current consumption, whereas improved technological change only affects future consumption.

Table 3. Oil wealth for OPEC and Non-OPEC under different 550 ppmv mitigation scenarios. Index (A1 Backstop scenario = 1)

	Non-OPEC	OPEC
A1 Backstop scenario[a]	1	1
A1 Tax scenario[b]	1.31	0.99
A2 Backstop scenario[c]	0.61	1.05
A2 Tax scenario[d]	0.91	1.20

[a] Technological progress in backstop technology is 3.2 per cent. No carbon tax.
[b] Technological progress in backstop technology is 1.0 per cent. Carbon tax is $190/ton C.
[c] Technological progress in backstop technology is 2.3 per cent. No carbon tax.
[d] Technological progress in backstop technology is 0.5 per cent. Carbon tax is $181/ton C.

7. Carbon leakage

In our mitigation scenarios only one part of the world, i.e. the Annex B countries, mitigates carbon emissions for the first decades. This is in line with the Kyoto protocol, except for the mitigation channelled through the Clean Development Mechanism. Since there is free trade of energy and other goods between Annex B countries and other countries, the mitigation efforts in the Annex B area may indirectly affect the amount of carbon emissions in the rest of the world through changes in international prices. Most studies of this effect confirm the expected result that carbon emissions increase compared to baseline outside the mitigation area (see, e.g., the survey in Smith, 1998, and the papers collected by Weyant, 1999). Therefore, this effect has been called carbon leakage, and is generally measured as the share between emissions increase outside the mitigation area and the emissions decrease inside the area, both compared to a baseline with no mitigation. If this share is high, i.e., close to unity, the mitigation efforts in Annex B countries have little or no real impact on global emissions. One the other hand, if the share is small, i.e., close to zero, there is little reason to worry about carbon leakage.

The literature has defined three sources of carbon leakage (see, e.g., Smith, 1998).[12] The first one is the effects through the global fossil fuels markets. When the demand for fossil fuels is reduced in Annex B due to, e.g., carbon taxes, the prices of fossil fuels on the international markets may fall. This leads to higher demand for fossil fuels outside Annex B. This effect is most relevant for oil, as the international trade in gas and coal between Annex B countries and other countries is low. Since there are substitution possibilities between the fossil fuels, higher oil demand outside Annex B may lead to reductions in coal and gas demand. If oil replaces coal consumption to a large extent, there is a possibility that carbon emissions may fall rather than increase outside Annex B. Moreover, there is also a chance that oil prices might not fall in the world market at all, either because carbon taxes in Annex B hurt coal and gas demand so much that oil demand in Annex B is not reduced, or because OPEC finds it optimal to maintain high oil prices. As a result, in these two cases we may actually observe a negative carbon leakage.

The second source of leakage is through the international markets for energy-intensive products. Higher energy costs in Annex B countries make producers of such goods outside Annex B more competitive. Thus, there may be a shift in production from Annex B countries to other countries, either through increased capacity in existing firms in Non-Annex B countries or through movement of firms from Annex B to the rest of the world.

[12] A fourth, more indirectly, source of leakage is the effects on the willingness to reduce emissions in other countries when one group of countries introduce measures against CO_2 emissions (see, e.g., Fankhauser and Kverndokk, 1996).

The third source of leakage is through changes in income outside Annex B. In the literature it has been focused on income effects through changes in terms of trade, which may be either positive or negative. One important effect that is rarely mentioned explicitly in this respect is the changes in oil revenues. This may be the most important income effect of mitigation efforts in Annex B, and may lead to reduced carbon emissions, i.e., negative leakage.

Earlier studies have found very different estimates of the amount of carbon leakage. However, most new studies seem to find estimates around 10-30 per cent (see, e.g., Bernstein *et al.*, 1999, Tulpulé *et al.*, 1999, and Smith ,1998). In most cases the second source of leakage seems to be highest, when it is included. However, McKibbin *et al.* (1999) find that including international capital flows in the model dampens this effect through their impacts on the exchange rates. The first source is also generally positive, although in some special cases negative leakage has been found (Felder and Rutherford, 1993, found negative leakage due to fuel substitution).

In the Petro model we are only able to measure the first source of leakage. The third effect could partly be included through changes in oil revenues, but is not done in this study. Since the model includes a detailed modelling of the oil market with emphasis on OPECs market power and intertemporal behaviour, it should give improved insight into the first source of leakage. Most models that are used to measure carbon leakage only have a simple characteristic of the oil market, with, e.g., fixed supply elasticities. On the other hand, the Petro model has no trade of gas between the regions, and the international price of coal is exogenous. Consequently, a carbon tax in the Annex B regions has no effect on gas and coal prices outside Annex B (except second-order effects, see below). Although this is a simplification, the little amount of trade in gas and coal worldwide implies that this should not be important for our conclusions.

From the preceding chapter we have seen that the mitigation scenarios have rather little impacts on oil prices in the first decades. In the A1 scenarios, OPEC finds it optimal to reduce its supply to maintain a relatively high oil price. This has important implications for the carbon leakage in our model. With only marginal reductions in the oil price, demand for oil is only marginally increased outside the Annex B region. In the A2 scenarios, the oil producer price actually rises compared to baseline. Oil demand in Annex B increases despite high carbon taxes, which is due to large replacement of other fossil fuels, particularly coal. As a result, demand for oil outside Annex B falls.

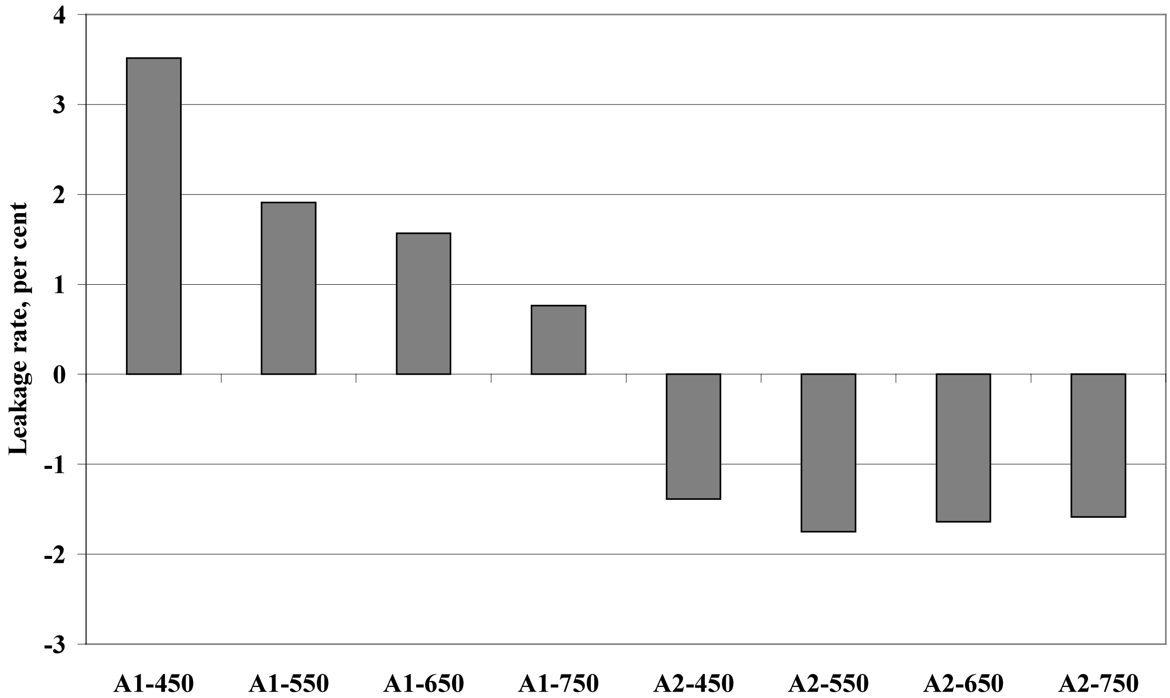
An interesting point about gas prices and demand in Non-Annex B is that these change in two ways even though gas is not traded between the regions. The most obvious one is that changes in oil prices affect the demand for gas, and so there are second-order effects on the gas prices. The other change is through the intertemporal effect of future carbon taxes in Non-Annex B. Expectations about this lead gas producers to extract more of their resources today since profits will fall in the future. This leads to lower prices of gas and higher gas demand outside Annex B. In A2, since oil prices are rising, both factors are driving gas demand in Non-Annex B upwards. In A1 the factors have opposite effects, but the results indicate that the last factor is dominating, i.e., gas demand is driven up in this scenario, too. Hence, a mitigation policy that starts in Annex B, but is anticipated to expand worldwide after some decades, seems to cause an upward pressure on gas demand outside Annex B. This is quite the contrary of what could be expected, as gas is not traded between Annex B and Non-Annex B in the model.

Although gas demand in Non-Annex B is positively affected by carbon taxes in Annex B, the main substitution takes place between oil and coal. Still, the behaviour of gas demand results in relatively small effects on leakage from fuel substitution in Non-Annex B.

In Figure 17 we show the carbon leakage in 2010 in the eight mitigation scenarios. The leakage is small in all scenarios as indicated above. In A1 the leakage rate varies from 0.8 in the least ambitious scenario (A1-750), to 3.5 per cent when the concentration target is 450 ppmv (A1-450). That is, the leakage rate seems to be an increasing function of the emission constraint. The leakage rate also appears to increase somewhat over time, from 1.9 per cent in 2010 to 4.6 in 2020 in A1-550. The impact of fuel substitution is small - it contributes to a negative leakage of merely 0.2 per cent in A1-550 in 2010.

In A2 the leakage is negative in all scenarios due to higher oil prices. It varies between -1.4 and -1.8 per cent, and there is no clear tendency when the stabilisation target is changed. In 2020 the leakage rate is closer to zero, e.g., in A2-550 it is -0.3 per cent. Here, too, the overall substitution effect is small and contributes to 0.2 per cent leakage in A2-550 in 2010. This may seem strange owing to the much larger substitution possibilities between fossil fuels in A2. However, as oil is replaced by both coal and gas, i.e., one more and one less carbon intensive fuel, the overall impact on emissions is quite little. In A2-450 we find that the upward pressure on gas demand is so high that the substitution effects have the opposite sign of what is usually expected.

Figure 17. Carbon leakage to Non-Annex B in 2010 in eight mitigation scenarios. Per cent



8. Conclusions

Mitigation scenarios do not only depend on concentration targets, but also on the baseline chosen. By focusing on two quite different future worlds (called A1 and A2), as presented in Nakicenovic *et al.* (forthcoming), we find that necessary carbon taxes as well as the emission and concentration paths vary across concentration targets and baselines. This calls for caution with respect to judging whether a medium-term target like the Kyoto protocol is consistent or not with the more long-term goal of stabilising concentration of greenhouse gases in the atmosphere at levels that prevent dangerous climate changes.

Our analyses are based on an intertemporal model of fossil fuels markets, Petro. The results clearly indicate that one of the most important determinants for future emissions and necessary policy measures is the availability and costs of carbon-free energy sources. With slow improvements in such technology (e.g., the A2 world), high carbon taxes (or other policy measures) are needed to stabilise concentration at low or moderate levels. On the other hand, rapid technological change in carbon-free energy sources (e.g., the A1 world) implies that small carbon taxes are sufficient to reach the same target. For instance, the same tax is needed to stabilise concentration at 450 ppmv in A1 and at 650 ppmv in A2, according to our analyses. Moreover, the results indicate that carbon taxes are generally about four times higher in A2 than in A1, and two times higher for each 100 ppmv reduction in the concentration target.

Differences in baseline were also found to have significant impact on emission and concentration paths for a given concentration target. With expectations of cheap carbon-free energy from the middle of the century, emissions are allowed to be higher initially compared to a situation with less optimistic expectations. Actually, we found that the emission paths under the A1 mitigation scenarios were lying above the corresponding emission paths under the A2 scenarios until around 2090. The reason is that with emissions turning downward at the turning of the century (as in A1), more emissions are permitted up to 2100 than if emissions are turning upwards (as in A2). This implies that the concentration level in 2100 is much higher in A1 mitigation scenarios than in A2 for the same long-run concentration target.

Although the mitigation scenarios require very different size of policy measures, one common effect is that almost all reductions in emissions are due to reduced coal use. There are several reasons for this. One is that coal has a higher carbon content than oil and gas, so the coal price is increased more by a carbon tax. Moreover, since consumer prices for coal are lower than for gas and particularly oil, the relative price increase is much higher. A third reason that is often forgotten in this matter is that conventional oil and gas resources are expected to be more or less depleted during the next century. Moreover, most of the resources are profitable even if prices are falling somewhat. Therefore, as long as carbon taxes are not too high, overall extraction of these resources over the century is only partly reduced. This implies that efforts to reduce CO_2 emissions in the long run must include measures against coal consumption.

According to our results, carbon leakage is not a problem although carbon taxes initially are imposed in Annex B countries only. The leakage rate is always below 4 per cent, and in the A2 world the leakage is negative. However, the model does not capture all sources of leakage, especially those coming from trade in energy intensive goods.

A final conclusion drawn from our analyses is that OPEC and other oil producers will not face major reductions in their revenues as long as the concentration target is not too tight. Actually, the oil wealth may increase rather than decrease in some mitigation scenarios based on the A2 world, particularly for Non-OPEC. Moreover, choosing between carbon taxes and increased competition from carbon-free energy sources as a mean to stabilise CO_2 concentration in the atmosphere, we found that carbon taxes is preferable for oil producers, at least Non-OPEC. Carbon taxes hit oil consumption less than other fossil fuel use, whereas carbon-free energy sources hit oil consumption somewhat more.

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Appendix A

Formal model description

In the model there are three fossil fuels produced: Oil (O), natural gas (G) and coal (K). We consider the model of the world oil market with OPEC as a cartel (C) and a competitive fringe (F). Consumers are situated in four regions: OECD-Europe (1), Rest-OECD (2), EIT (3) and Non-Annex B (4). There is a natural gas market with perfect competition in each region, that is region i=1,2 and 3+4 together. The coal market is assumed to be a competitive world market.

All variables are functions of time. However we will suppress the time notation in the following. The functional forms are constant over time.

1. List of symbols

P_O	international producer price of oil
P_K	international producer price of coal
P_G^i	producer price of natural gas in region i,
Q_j^i	consumer price of fuel j in region i,
$\overline{P}$	international backstop price
z_j^i	unit costs of transportation, distribution and refining of fuel j in region i,
v_j^i	existing taxes on fuel j in region i
Y^i	gross national income in region i
x_j^k	production of fuel j by producer k
X_j^i	consumption of fuel j in region i
A_j^k	accumulated production of fuel j by producer k
$\overline{A}_j^k$	accumulated production of fuel j by producer k over the entire time horizon
C_j^k	unit cost of production of fuel j for producer k
λ	the shadow cost associated with cumulative extraction up to the current time
π_j^k	scarcity rent in production of fuel j for producer k
MR^C	marginal revenue of OPEC
τ^k, γ^i, ψ	rate of technological change in production of oil, gas and coal respectively
μ	rate of technological change in backstop technology

η_j^k parameter of convexity in the cost function for fuel j for producer k

$a_j^i, b_j^i, c_j^i, d_j^i$ price and income elasticities in demand function for fuel j in region i

ω_j^i constant in demand function for fuel j in region i

$\alpha, \beta, \sigma^i, \theta$ constants in cost functions

κ initial backstop price

r discount rate

t time

T_j^k last period of production of fuel j for producer k

2. Demand

On the demand side we assume loglinear demand functions in all regions. Demand takes into account the imperfect substitution possibility between the different fossil fuels.

First, let $\hat{X}_j^i$ be defined by

(A1) $$\ln \hat{X}_j^i = \ln \omega_j^i + a_j^i \ln Q_O^i + b_j^i \ln Q_K^i + c_j^i \ln Q_G^i + d_j^i \ln Y^i$$

where

(A2) $$\begin{aligned} Q_O^i &= P_O + z_O^i + v_O^i \\ Q_K^i &= P_K + z_K^i + v_K^i \\ Q_G^i &= P_G^i + z_G^i + v_G^i \end{aligned}$$

Then the demand for energy type j in region i is given by

(A3) $$\begin{aligned} &X_j^i = \hat{X}_j^i, Q_j^i < \overline{P} \\ &X_j^i = 0, Q_j^i > \overline{P} \\ &X_j^i \in [0, \hat{X}_j^i], Q_j^i = \overline{P} \end{aligned}$$

The restriction of market clearing in the world oil market can then be written

(A4) $x_O^C + x_O^F = \sum_{i=1}^{4} X_O^i$

From (A1)-(A4), we can derive the producer price of oil:

(A5)

$$P_O = P_O\left(x_O^C + x_O^F, z_O^1 + v_O^1, z_O^2 + v_O^2, z_O^3 + v_O^3, z_0^4 + v_0^4, Q_K^1, Q_K^2, Q_K^3, Q_K^4, Q_G^1, Q_G^2, Q_G^3, Q_G^4, \overline{P}, Y^1, Y^2, Y^3, Y^4\right)$$

In a similar way, we can derive the producer prices of natural gas and coal.

3. The optimisation problem for OPEC in the Nash-Cournot model

When the oil market is modelled as a Nash-Cournot model, the cartel (OPEC) is facing a downward sloping demand schedule at each point of time, and takes the extraction path of the fringe as given. OPEC seeks to maximise the present value of the net revenue flow. The control variable in the optimisation problem is the extraction path of the cartel, and the state variable is accumulated production. $P_O(\cdot\cdot)$ in (A6) is the producer price given in (A5).

(A6) $\max_{x_O^C} \int_0^{\infty} \left[P_O(\cdot\cdot) - C_O^C\right] x_O^C \cdot e^{-rt} dt$

s.t.

(A7) $\dot{A}_O^C = x_O^C$

(A8) $x_O^C \geq 0$

(A9) $C_O^C = \alpha e^{\eta_O^C A_O^C - \tau^C t}$

(A10) $\overline{P} = \kappa e^{-\mu t}$

4. Solving the problem

The current value Hamiltonian in the optimisation problem of OPEC, H^c, is given by

(A11) $H^c = \left[P_O(\cdot) - C_O^C\left(A_O^C, t\right)\right] x_O^C + \lambda x_O^C$

where λ_t (<0) is the shadow cost associated with cumulative extraction up to time t. The scarcity rent for the cartel is defined as $\pi_{Ot}^C = -\lambda_t$.

The necessary conditions for an optimal solution are given by the Pontryagin's maximum principle. From this maximum principle we get the time path of the shadow cost

(A12) $$\dot{\lambda} - r\lambda = -\frac{\partial H^{c}}{\partial A_{O}^{C}} = \frac{\partial C_{O}^{C}}{\partial A_{O}^{C}} x_{O}^{C}$$

(A12) can be rewritten using the definition of the scarcity rent

(A13) $$\dot{\pi}_{O}^{C} = r\pi_{O}^{C} - \frac{\partial C_{O}^{C}}{\partial A_{O}^{C}} x_{O}^{C}$$

x_{O}^{C} maximises the Hamiltonian for all $x_{O}^{C} \geq 0$ which for an interior solution requires

(A14) $$\frac{\partial H^{c}}{\partial x_{O}^{C}} = P_{O} - C_{O}^{C} + \frac{\partial P_{O}}{\partial x_{O}} x_{O}^{C} + \lambda = 0$$

which gives the producer price of oil when OPEC produces

(A15) $$P_{O} = C_{O}^{C} + \pi_{O}^{C} - \frac{\partial P_{O}}{\partial x_{O}^{C}} x_{O}^{C}$$

where $-\frac{\partial P_{O}}{\partial x_{O}^{C}} x_{O}^{C}$ is the cartel rent. The marginal revenue of OPEC is defined as

(A16) $$MR^{C} = P_{O} + \frac{\partial P_{O}}{\partial x_{O}^{C}} x_{O}^{C} = C_{O}^{C} + \pi_{O}^{C}$$

Using (A13) and (A16) we find the time path of the marginal revenue

(A17) $$\dot{MR}^{C} = r\pi_{O}^{C} - \tau^{C} C_{O}^{C}$$

The cartel will stop producing at time $T_O^C \in (0,\infty)$ when the unit cost reaches the backstop price minus region specific costs and taxes. Let $\overline{A}_O^C$ be the aggregate production of OPEC over the entire time horizon. The transversality condition is then

$$\text{(A18)} \qquad \max_i (\overline{P}_{T_O^C} - z_O^i - v_O^i) = C_O^C\left(\overline{A}_O^C, T_O^C\right)$$

5. The optimisation problem for the competitive fringe

The optimisation problem of a competitive fringe producer in the oil market is similar to the one of OPEC above, with the exception of the producer price which is regarded exogenously. In a competitive market, the optimisation problem of OPEC producers is again similar to this.

$$\text{(A19)} \qquad \max_{x_O^F} \int_0^\infty \left[P_O - C_O^F\right] x_O^F \cdot e^{-rt} dt$$

s.t.

$$\text{(A20)} \qquad \dot{A}_O^F = x_O^F$$

$$\text{(A21)} \qquad x_O^F \geq 0$$

$$\text{(A22)} \qquad C_O^F = \beta e^{\eta_O^F A_O^F - \tau^F t}$$

From the first order conditions of this maximisation problem, we get for an interior solution

$$\text{(A23)} \qquad P_O = C_O^F\left(A_O^F, t\right) + \pi_O^F$$

$$\text{(A24)} \qquad \dot{P}_O = rP_O - \left(r + \tau^F\right)C_O^F = r\pi_O^F - \tau^F C_O^F$$

where π_O^F is the scarcity rent for the fringe defined as the negative of the shadow cost associated with cumulative extraction.

In a market equilibrium, OPEC's first order and transversality conditions as well as the market condition (A4) and the development in the backstop price (A10) must be satisfied.

The transversality condition of the fringe, where $T_O^F \in (0,\infty)$, is

$$\text{(A25)} \qquad \max_i (\overline{P}_{T_O^F} - z_O^i - v_O^i) = C_O^F\left(\overline{A}_O^F, T_O^F\right)$$

6. The optimisation problems in the natural gas markets

As in the oil market, the gas producers also maximise the present value of the net revenue flow. We consider three separate regional natural gas markets with perfect competition. There are similar restrictions and first order conditions for the optimisation problems for all markets i=1,2 and 3+4 together. Each producer faces the following optimisation problem:

(A26) $$\max_{x_G^i} \int_0^\infty \left[P_G^i - C_G^i\right] x_G^i \cdot e^{-rt} dt$$

s.t.

(A27) $$\dot{A}_G^i = x_G^i$$

(A28) $$x_G^i \geq 0$$

(A29) $$C_G^i = \sigma^i e^{\eta_G^i A_G^i - \gamma^i t}$$

The first order conditions give

(A30) $$P_G^i = C_G^i\left(A_G^i, \gamma^i, t\right) + \pi_G^i$$

(A31) $$\dot{P}_G^i = rP_G^i - \left(r + \gamma^i\right) C_G^i = r\pi_G^i - \gamma^i C_G^i$$

In a market equilibrium the development of the backstop price (A10) and the market condition (A32) must hold.

(A32) $$P_G^i = P_G^i\left(x_G^i, z_G^i + v_G^i, Q_O^i, Q_K^i, \overline{P}, Y^i\right)$$

The transversality conditions in the natural gas markets, where $T_G^i \in (0, \infty)$, are similarly

(A33) $$\overline{P}_{T_G^i} - z_G^i - v_G^i = C_G^i\left(\overline{A}_G^i, T_G^i\right)$$

7. The optimisation problem in the coal market

We assume that there is one global coal market with perfect competition. Since the coal resources in the world are so huge compared to those of oil and gas, we ignore the dynamic aspect of the resource extraction and treat the optimisation problem in the coal market as a static problem, where the coal producers maximise the profit in every period. Each producer faces the following problem:

(A34) $$\max_{x_K} \int_0^{\infty} [P_K - C_K] x_K \cdot e^{-rt} dt$$

s.t.

(A35) $$x_K \geq 0$$

(A36) $$C_K = \theta e^{-\psi t}$$

The unit cost in coal production is assumed to be independent of accumulated production. The first order condition is simply,

(A37) $$P_K = C_K$$

In a market equilibrium, (A10) and the market condition (A38) must hold.

(A38)
$$P_K = P_K\left(x_K, z_K^1 + v_K^1, z_K^2 + v_K^2, z_K^3 + v_K^3, z_K^4 + v_R^4, Q_O^1, Q_O^2, Q_O^3, Q_0^4, Q_G^1, Q_G^2, Q_G^3, Q_G^4, \overline{P}, Y^1, Y^2, Y^3, Y^4\right)$$

The transversality condition, where $T_K \in (0, \infty)$, is

(A39) $$\max_i (\overline{P}_{T_K} - z_K^i - v_K^i) = C_K(T_K)$$

Numerical specifications and results

Table B1. Price and income elasticities

	OECD	EIT	ROW
A1			
Direct price elasticity	-0.9	-0.75	-0.75
Cross price elasticity	0.1	0.1	0.1
Income elasticity	0.50	0.22	0.64
A2			
Direct price elasticity	-1.6	-1.45	-1.45
Cross price elasticity	0.45	0.45	0.45
Income elasticity	0.53	0.39	0.69

Table B2. Average yearly GDP growth rates

	OECD	EIT	ROW
A1			
2000-2050	2.0	4.2	6.0
2050-2100	1.6	2.1	2.4
A2			
2000-2050	1.5	3.1	3.8
2050-2100	1.6	2.7	2.6

Table B3. Technological rate of change in energy supply

	A1	A2
Oil[a] and gas	1.5	0.5
Coal	1.0	0
Backstop	2.3	0.5

[a] Initially higher for Non-OPEC, i.e., 2.5 in A1 and 1.5 in A2.

Table B4. Average growth rates of CO_2 emissions and energy use in the two baseline scenarios

	2000-2040		2040-2100	
	A1	A2	A1	A2
CO_2 emissions				
Annex B	1.2 %	0.9 %	-1.2 %	0.5 %
Non-Annex B	3.9 %	2.7 %	0.5 %	2.1 %
World	2.6 %	1.7 %	0.1 %	1.5 %
Energy demand - world	2.5 %	1.5 %	2.5 %	1.7 %
Oil demand - world	2.2 %	0.2 %	-100 %	-100 %
Gas demand - world	1.6 %	0.7 %	-100 %	-0.4 %
Coal demand - world	3.3 %	2.9 %	1.2 %	2.2 %

Table B5. Percentage change in CO_2 emissions and energy use in A1-550 and A2-550 compared to baseline

	2000		2040		2100	
	A1-550	A2-550	A1-550	A2-550	A1-550	A2-550
CO_2 emissions - world	-7 %	-16 %	-17 %	-43 %	-66 %	-73 %
Energy demand - world	-7 %	-14 %	-15 %	-37 %	-4 %	-39 %
Oil demand - world	-2 %	-1 %	1 %	14 %	-	-
Gas demand - world	-5 %	-8 %	-4 %	0 %	-	7 %
Coal demand - world	-13 %	-35 %	-32 %	-70 %	-66 %	-76 %