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Beyond Kyoto: CO_2 permit prices and the markets for fossil fuels

Abstract:
This paper analyses the markets for fossil fuels given that the limits that the Kyoto Protocol sets on CO_2 emissions from Annex B countries extend beyond 2008-2012. To our knowledge we are the first to apply a forward-looking model with endogenous prices for fossil fuels in analysis of specific CO_2 emission targets, under different assumptions concerning OPEC behaviour. We calculate both the time-path of the international permit prices needed for the Kyoto targets as well as the implications through reduced demand and lower producer prices for fossil fuels. Irrespective of the assumption concerning OPEC behaviour, the permit price has to rise for the first 30 to 40 years in order to fulfil the Kyoto targets in Annex B. The permit price can be reduced substantially, dependent on when a backstop technology starts to replace oil. The Kyoto targets will result in a loss of petroleum wealth for oil and gas producers by 15 to 20 % as long as OPEC acts as a cartel. If the developing countries are included in the Protocol, OPEC will lose much more of their wealth. The competitive fringe has far more to lose if OPEC breaks down in the absence of these emission targets, than the implementation of the targets with OPEC as a cartel.

Keywords: The Kyoto Protocol, International CO_2 permits, Exhaustible Resources, Petroleum wealth.

JEL classification: H23, Q30, Q40.

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1. Introduction

The Kyoto Protocol to the Framework Convention on Climate Change (FCCC) was completed in December 1997. The most prominent feature of the Kyoto Protocol is the quantified emissions limitation and reduction commitments of greenhouse gases (GHGs) in Annex B countries[1]. The combined result of individual country targets is estimated to result in an overall reduction in Annex B parties' GHG emissions by 5.2 % from the 1990 levels by the commitment period 2008-2012 (averaged across the period).

The most important GHG is CO_2. The main source of anthropogenic CO_2 emissions is the combustion of fossil fuels, such as oil, natural gas and coal. The point of departure in this study is that emissions of CO_2 shall be reduced by 5.2 % in the Annex B area. 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 emission reduction targets for all six GHGs.

One of the specific features of the Kyoto Protocol is the explicit introduction of emission trading among Annex B countries. The implementation of a trading scheme is still being discussed, but in our study we assume an efficient international tradable permit market. In the model we impose a regional-wide tax, but we define the shadow cost of reducing emissions as a permit price. With an efficient international tradable permit market, assumed to be perfectly competitive, the permit price will correspond to the tax necessary to achieve the same reduction in emissions.

In this study, we look at the CO_2-permit prices necessary in order to fulfil the Kyoto Protocol commitments. This has been done in various studies, e.g., OECD (1998). Our findings indicate that irrespective of the assumption concerning OPEC's behaviour, the permit price will rise from about \$14-24 per tonne CO_2 in 2010 up to \$25-41 in 2020, before it reaches \$36-57 in 2030. The lower figures are indicating a situation where OPEC is acting as a cartel and the higher figures a situation with perfect competition on the oil market. Rising permit prices is necessary in order to reduce in particular a steadily rising consumption of coal in Annex B. In comparison, estimates of the permit price in nine different models in OECD (1998) were in the range of \$5.5-33.5 in 2010. Our estimate is thus within the price interval provided by these studies, but in addition our study points to possible development paths after 2010 under different assumptions concerning the cartel's market power. We show that the permit prices can be reduced substantially as global oil production begins to fall dependent on when the backstop starts to replace oil 30-40 years after the turn of the millennium. Such a hump-shaped CO_2-tax or permit price over time is in accordance with studies like Ulph and Ulph

[1]This is OECD-countries (except Mexico, Korea and Turkey), Russian Federation, Ukraine, Estonia, Latvia, Lithuania, Bulgaria, Croatia, Romania, Slovakia, Slovenia.

(1994) and Kverndokk (1994b). Their starting point is that the damage done is related to the stock of carbon in the atmosphere. They find that to combat global warming the *optimal* time path of a tax should rise over time when the initial stock of carbon is small, but fall later on when the stock of fossil fuels nears exhaustion[2].

In contrast to other analysis we focus on two important features of the markets for fossil fuels, i.e., *market power* and *dynamic behaviour* (see Salant, 1982, for an early numerical model). A long-term model for oil, natural gas and coal markets (PETRO) is used in this study in order to analyse the effect of the emission targets on supply, demand and prices for fossil fuels, thereby allowing us to derive the impact on the producers' oil and gas wealth. The PETRO model is a dynamic model where the producers take into account future market conditions. All prices and quantities are determined simultaneously in the model. We make the analysis under different assumptions concerning OPEC's behaviour.

The study is a follow up of Berg et al. (1997b), who look at how a CO_2 tax of $10 per barrel of oil equivalents influences the petroleum wealth of oil and gas producers. In our new version of the PETRO model we include an additional region on the demand side in order to study the Annex B area. In addition to obtain the time-path of the CO_2-permit prices that are necessary to fulfil the specified exogenous emission targets, our main contribution is to derive the consequences for the fossil fuel markets.

The dynamic aspect is often ignored in empirical energy models. In dynamic models the oil price is usually set exogenous making it impossible to determine how the burden of a permit or tax is shared between the producers and consumers. Some exceptions are however GREEN (Burniaux et al., 1992) and an extended version of Global 2100 (Manne and Rutherford, 1994). In GREEN the oil price is endogenous, but the supply side is not fully intertemporal because it is modelled as being independent of future expectations. One of the first intertemporal energy models, a general equilibrium version of Global 2100, is presented in Manne and Rutherford (1994). They focus on specific stabilisation goals different from the Kyoto targets and the oil market is modelled as a competitive market. Chakravorty et al. (1997) also use an intertemporal model with endogenous prices for fossil fuels, and study the impact of constant CO_2-taxes on competitive markets. GREEN is among nine models in OECD (1998), an analysis of the consequences of the Kyoto Protocol. GREEN and GLOBAL 2100 are in the portfolio of six models in Dean and Hoeller (1992) that focuses on global emission targets. These

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[2] Sinclair (1994) argues that the optimal carbon tax should decline over time to get the fossil fuel producers to postpone production. Farzin and Thavonen (1996) also combine the stock externality aspect of CO_2 in the atmosphere and the exhaustible nature of fossil fuel reserves. They find that the time-path of an optimal carbon tax can have different shapes dependent on, first of all, how the stock of carbon decays in the atmosphere.

studies apply measures of welfare like GNP, failing to take account of changes in terms of trade, which can be especially important for fossil fuel producing countries.

Petroleum wealth for an oil and gas producer is defined as the present value of future petroleum rent; equal to the difference between production revenues and the costs of oil and gas production. Oil and gas extraction normally provides an excess return to capital compared with other economic activity because they are non-renewable resources (Hotelling, 1931). In this context the *scarcity rent* refers to the nature of exhaustibility of the resource. In addition, OPEC's market power on the oil market gives a *cartel rent.* If an international CO_2 tax (or a system with tradable permits) results in a reduction in the prices of fossil fuels, petroleum wealth will be reduced. From standard tax incidence theory it is well known that the distribution of the tax burden in terms of lower producer prices and higher consumer prices depends on the relative price responsiveness in supply and demand. If the supply varies substantially as a result of a change in prices, the effect on the consumer price will be greatest whereas the price for producers will be affected to a lesser extent. As fossil fuels are non-renewable resources, producers will take into account that extraction today will reduce the availability of the resource in the future. The distribution of the CO_2 tax burden between consumers and producers may therefore change over time.

OPEC is an important agent in the oil market. By reducing its production the cartel is able to obtain high oil prices. As a starting point we model OPEC as a cartel, where the members have coinciding interests. To illustrate the importance of OPEC's market power we also study an oil market with perfect competition, where all producers consider the price as given. This is done because the assumption concerning the situation in the oil market will influence both the level of the CO_2 permit price and the loss of oil and gas wealth as a result of a climate treaty. The current situation can be said to share features from both market descriptions, although modelling OPEC as a cartel clearly gives the most reasonable results.

The developing countries were not subject to any commitments in the Kyoto Protocol, or on the subsequent conference in Buenos Aires. However, these countries may be facing emission reduction requirements at a later stage. We will therefore also look at a scenario with global emission targets. In the scenario involving Global Kyoto targets, it is assumed that the entire world shall achieve the Kyoto targets by reducing the emission level in 1990 by 5.2 % in 2010. In order to estimate the costs of implementing emission cuts in the commitment period, assumptions are required concerning the longer-term requirements in both scenarios, since the model is intertemporal. As the international negotiation process offers little guidance on this issue, we simply assume that emissions are held constant when the targets have been reached.

The structure of the paper is as follows. Section two describes the model, and in Section three we look at the reference scenario with no CO_2 tax in the model version where OPEC acts as a cartel. We then examine the effects of an implementation of the Kyoto Protocol, before examining the consequences of a Global Kyoto treaty in Section five. This is followed by a discussion in Section six of the effects of perfect competition in the oil market. We turn to sensitivity analysis and caveats in Section seven, and a conclusion ends the paper.

2. Description of the model

The model has a long time horizon and describes the international markets for oil, gas and coal in an intertemporal and deterministic way (see Appendix A for a more formal model description, based on Berg et al. 1997b). Compared with Berg et al., the model has been expanded to include Economies In Transition (EIT). The EIT region on the demand side consists of the Russian Federation, the Ukraine, and the former Central and Eastern European countries. Some central parameter values will be mentioned in the following (otherwise see Appendix B for numerical specifications).

As fossil fuels are finite and non-renewable resources, the extraction of one unit today will reduce the availability of the resource in the future. Producers will therefore demand a petroleum rent for selling the resource today. It is assumed that producers have perfect (i.e. model consistent) knowledge, and in the model they therefore take account of not only existing prices and market conditions, but also future movements in these variables. Producers attempt to extract their resources at a rate that maximises their petroleum wealth. Consumer demand, on the other hand, is assumed to depend only on income and prices in each period. All prices and quantities at each point in time are determined simultaneously in the model.

There are four demand regions in the model: OECD-Europe, Rest of OECD, EIT and a region consisting of the rest of the world (Non-Annex B). The model specifies three fossil fuels: oil, gas and coal. The demand for a fossil fuel declines with the price of this fuel and increases with the price of the other two fuels. The direct price elasticities are set equal to -0.9 and -0.75 for the OECD-regions and the Non-OECD regions, respectively. All cross price elasticities are set equal to 0.1. Demand rises over time due to economic growth, which is determined exogenously for each region. Annual GDP growth is highest in Non-Annex B and lowest in OECD-Europe. A certain relative rise in income outside the OECD area results in a slightly higher relative increase in demand than in the OECD.

A carbon-free alternative energy source (backstop-technology) exists at a specific cost at any given time in all regions. Due to technological progress, this cost is reduced over time. It is available in unlimited quantities and is a perfect substitute for fossil fuels. Hence, there will be no consumer demand for a fossil fuel if the consumer price of the fuel is higher than the price of the backstop.

The relevant consumer price of a fuel in a region is the sum of the producer price, delivery costs (due to transport, distribution and refining) and existing taxes and subsidies. The CO_2 tax comes in addition to delivery costs and existing taxes. They are imposed on the consumption of fossil fuels and vary with the carbon content of the fuel. The price of the backstop less these taxes and delivery costs represents a ceiling for the producer price of each fuel at any given time, and will in the following be referred to as the *maximum producer price*. As a result of a more integrated world economy, we assume that existing taxes and delivery costs for each fuel will be harmonised after 40 years to a global weighted average. When these costs and taxes are harmonised, the maximum producer price for each fossil fuel will be equal across the regions.

The oil market is divided into two groups of producers: OPEC, which has low costs, and a fringe of high-cost producers. In order to examine the importance of market power, two different situations are studied. In the first model version, OPEC acts as a cartel and takes into account that their own production influences prices. They consider the production from the fringe as given, and this entails a Cournot approach (see e.g., Salant, 1976). The fringe is a competitive producer, deciding production on the basis of the given price. In the second version, the entire oil market is a competitive market. The prices and volumes that satisfy the maximisation problem of both types of producers are the equilibrium solution. Initial unit costs are set equal to \$3.30 and \$10.90 per barrel of oil for OPEC and the fringe, respectively. The unit costs of producers are assumed to rise as oil resources are gradually depleted. The parameters in the cost functions are determined so that the marginal cost of the last unit of the current reserves (BP, 1995) equals \$20 per barrel. Moreover, technological progress independent of the production lowers the unit costs. This means that depending on the production rate unit costs can increase or decrease over time. The technical progress is assumed to be higher in the fringe for the first 30 years. We assume a universal discount rate of 7 %.

Both the gas and coal markets are modelled in a more simple fashion, and they are not analysed under various market conditions. The market for natural gas is divided into three regions: OECD-Europe, Rest of OECD, and Non-OECD. Because gas is costly to transport, no trade takes place between the regions. The producers' cost structure is modelled in the same way as for the oil market. All three regions are modelled as competitive markets. Initial unit costs are set equal to \$7.00, \$5.45 and \$5.53 per barrel of oil equivalents (boe) for OECD-Europe, Rest-OECD and Non-OECD, respectively.

The coal market is modelled as a global competitive market. Due to substantial international coal reserves, extraction today is not assumed to increase costs at a later time. Producers will therefore focus on each individual period. Technological progress results in lower costs over time. Initial unit costs are set equal to \$8.80 per boe.

Due to differing carbon contents, a tax of \$1 per barrel of oil will correspond to \$0.71 per boe for gas and \$1.24 per boe for coal. Simulations are carried out up to 2100 with periods of 10 years using the GAMS/MINOS system (Brooke et al., 1992). For example, the result for the year 2010 can be interpreted as an average for the period 2005-2015.

3. Reference scenario with OPEC as a cartel

Figure 1 shows the model's projections of movements in the oil price and unit costs for OPEC and the fringe, in the scenario without emission reduction targets and where OPEC acts as a cartel. The price starts from \$21 per barrel in the year 2000. This is higher than the current oil price. In the current situation, it cannot be said that OPEC is acting as a completely coherent cartel where participants have coinciding interests. In reality, members of the cartel will therefore be somewhat less willing to reduce production to achieve a higher price. Moreover, the model provides a long-term price path, entailing that short-term changes are not captured. The current low price of oil partly reflects the prevailing market, with lower demand for oil due to the crisis in Asia[3].

The price rises until it reaches a peak of \$41 in 2040[4]. In this period, the producer price is at its maximum level, determined by the price of the backstop, existing taxes and delivery costs. After this time, the producer price is reduced due to technological progress for the backstop-technology. The figure shows that unit costs increase faster in the fringe. The reason is that they produce more than the cartel in the first periods while, at the same time, OPEC has greater resources that can be extracted at lower costs.

[3] After OPEC's decision on new production cuts in March-99, the oil price reached \$19-\$20 in June and July.

[4] The oil price follows closely to the median price of a poll survey which is presented for the period 2000-2020 by the International Energy Workshop (Schrattenholzer, 1998).

Figure 1. Oil producer price and unit costs with OPEC as a cartel

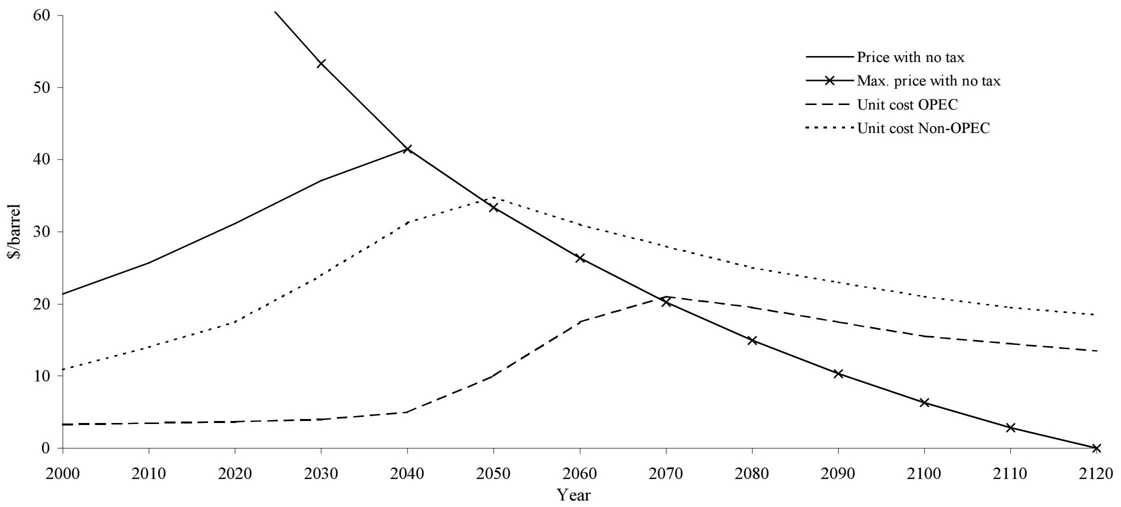
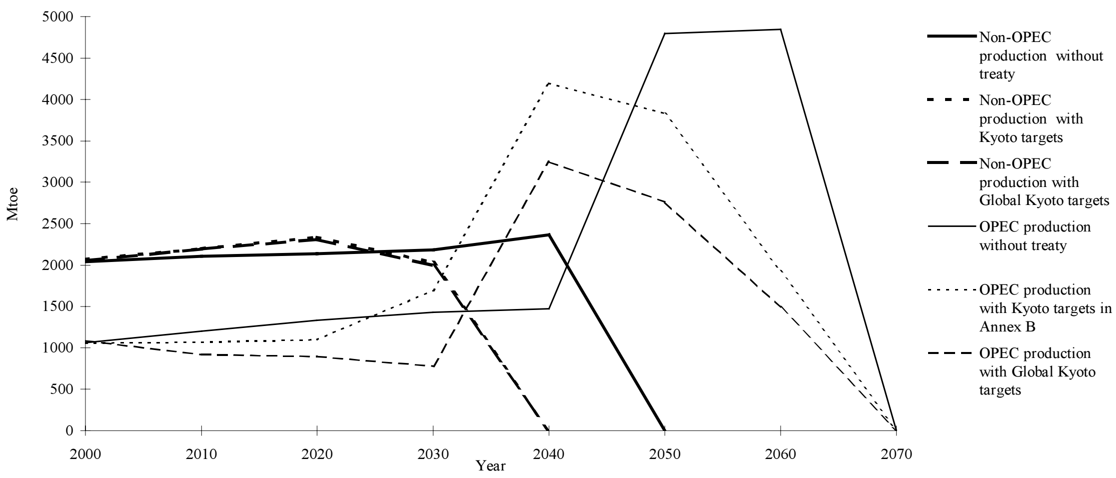


Figure 2 shows production in the fringe and OPEC prior to the *introduction of taxes*. The fringe produces approximately twice as much as the cartel in the first period[5]. Because higher production in a period increases costs in the future, both OPEC and the fringe have incentives to limit production. In addition the cartel has market power and takes into account that higher production results in a lower price in the same period. This is the reason why OPEC produces less than the fringe, even though costs are lower. The fringe produces the first 50 years until its unit costs reach the maximum producer price between 2040 and 2050. Further extraction is then no longer profitable. OPEC also increases production somewhat in the first periods before the cartel takes over the entire market. The cartel stops extracting in 2070 when it is no longer profitable for the cartel to produce oil, as the price of the backstop has become lower than the cartels unit costs.

Figure 2. Oil production with and without climate treaties, and with OPEC as a cartel



[5] OPEC's share of total production is slightly lower than its real market share today of about 40 %. The reason may be that the cartel is more effective in the model than in reality.

Developments in gas markets vary between regions (as shown later in Figure 5). The producer price of gas in OECD-Europe rises from a little less than $10 per boe until it reaches its maximum level of $25 in 2070 in the reference scenario. Production is relatively stable until gas production is no longer profitable in 2080, and the backstop takes over. The gas price in Rest-OECD also starts from about $10 and reaches $36 in 2050. The production is higher in this region, but falls over time until it ceases in 2060. The gas price in Non-OECD rises from $6.5 in 2000 until it reaches a peak of $15 in 2090. In contrast to the other regions, the production increases over time until it stops in 2100. Natural gas is produced and consumed over a longer period because the region has considerable gas resources that can be extracted with lower costs[6].

Coal is produced and consumed throughout the whole period and will not be replaced by the backstop due to low prices and low existing taxes on coal. The consumption of coal in Annex B is almost three times higher in year 2100 as in 2000.

Figure 3 shows carbon emissions in Annex B in the reference scenario with no taxes when OPEC operates as a cartel. Oil's share of total consumption is almost constant for the first fifty years, while coal's share has increased somewhat on the expense of natural gas. Total emissions rise from 3.92 billion tonnes of carbon a year in 2000 and reach a peak of 6.38 billion in 2050. The carbon emissions in the reference case are crucial in determining the tax level needed to implement specific reductions. Among the key factors underlying the reference scenario are GNP growth rates, (autonomous) improvements in energy efficiency, technological progress, developments in relative prices of fossil fuels and the availability and price of the backstop. Compared to 1990, the carbon emissions are about 10 % higher in 2010 and 21 % higher in 2020. This is in the lower range of Annex B emissions scenarios in the reference case in other studies, e.g., OECD (1998). Part of the explanation is that we have OPEC as a cartel that reduces oil production compared to a situation with a competitive market[7]. However, opposed to our analysis, many studies estimate increasing Annex B (and global) CO_2-emissions over the entire time horizon due to lack of exhaustibility constraint and a falling backstop price.

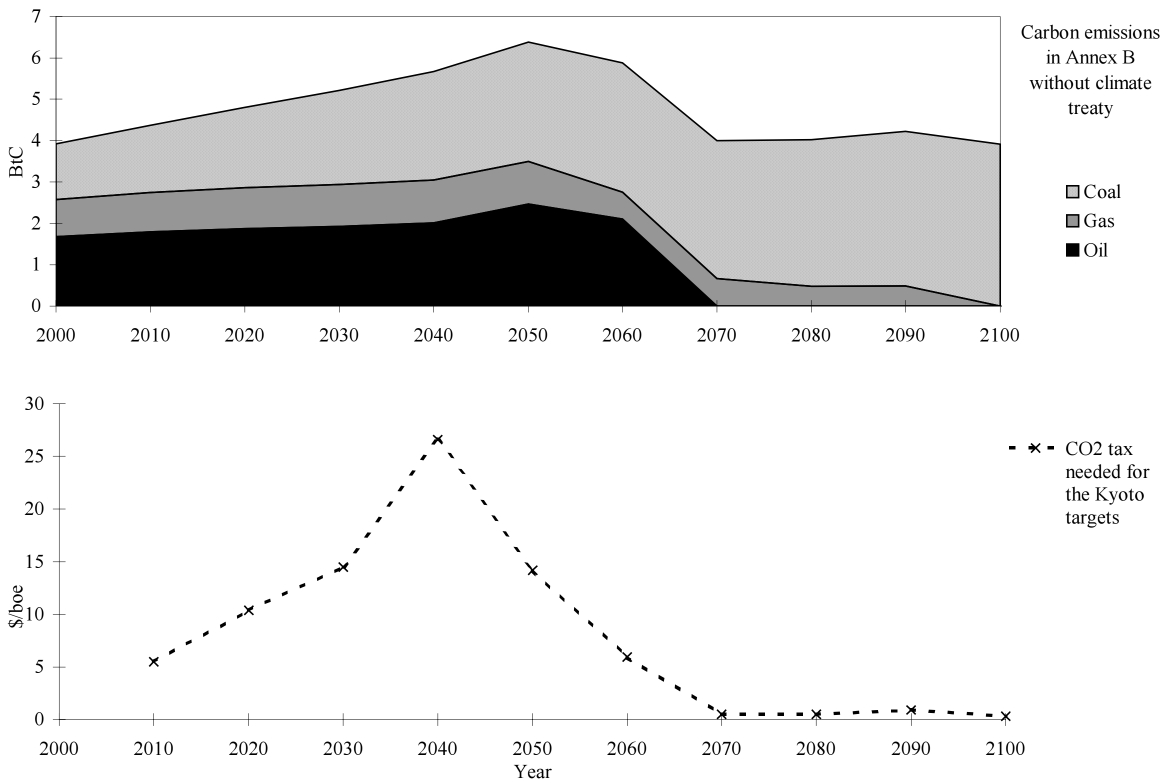
Carbon emissions from coal more than double in the period up to 2050. The cost of the backstop falls over time (and leads to a steadily lower maximum producer price for oil). As a result the emissions

[6] Total accumulated production of oil is greater than "proven" reserves in BP (1995), as pointed out in Berg et al. (1997b). This is also true for natural gas, and is ascribable to the fact that technological progress and increasing prices expands the resource base in our model.

[7] Another explanation may be that we use a lower GDP growth in the EIT-region compared to some other analysis. It should be mentioned that the US Department of Energy's Energy Information Administration (EIA) has substantially reduced forecasts of world energy consumption out to the year 2020 owing to continued economic troubles in Russia (and partly Asia) (Global Environmental Change Report No. 7, 1999).

from oil are reduced after 2050, until global oil production ceases in 2070. Total emissions also decline in this period. The consumption of gas in Annex B is reduced when production in Rest-OECD and OECD-Europe ceases in 2060 and in 2080, respectively. The consumption of gas in Annex B (i.e., EIT) stops in 2100, and coincides with the last period of production in Non-OECD. Due to the harmonisation of taxes and costs the long run regional maximum producer price is equal, and all regions therefore consume a fuel as long as it is produced, except for the gas markets where no trade takes place between the regions. Emissions are almost constant after 2070, with a small drop in 2100 when the backstop displaces gas.

Figure 3. Carbon emissions in Annex B in the reference scenario and time-path of a CO_2 tax needed for the Kyoto targets



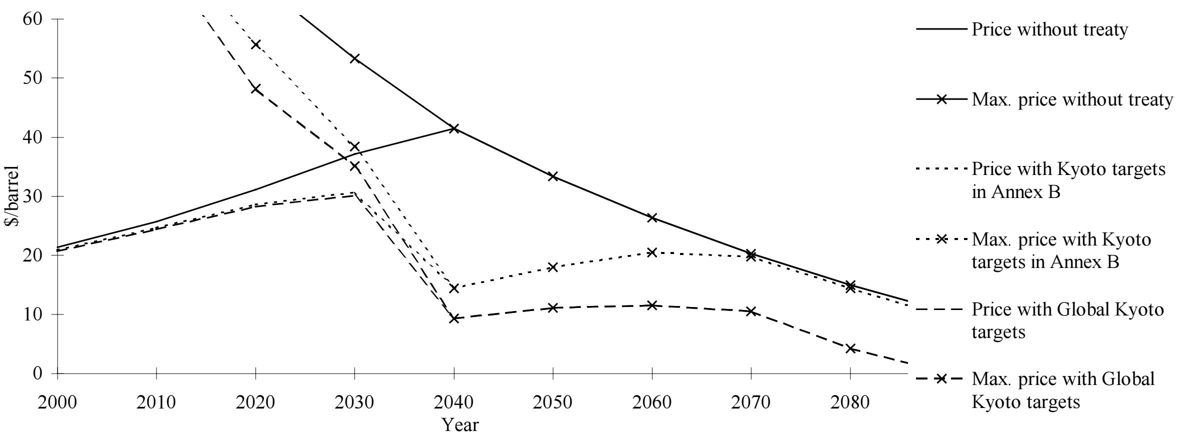
4. Effects of an implementation of the Kyoto Protocol

In order to achieve the Kyoto targets, Annex B countries must reduce emissions to 3.77 billion tonnes of carbon from 2010. It is presupposed that emissions should be kept at this level in subsequent periods. A CO_2-tax is imposed on the consumption of fossil fuels in each period. We derive the tax profile that is just necessary for the targets to be reached. Due to the intertemporal aspect of the model, the taxes must be introduced simultaneously in all periods. Figure 3 shows the development in the CO_2 tax per boe over time, which is necessary if Annex B countries are to fulfil the commitments in the Kyoto Protocol[8]. It is assumed that the tax is first introduced in 2010.[9] In order to limit steadily rising emissions in the first periods, as shown in Figure 3, the tax will first rise. As emissions gradually decline due to the backstop technology, the taxes will be reduced. The tax must increase from about \$6 per boe in the year 2010 to \$15 in 2030, thereafter rising faster to a peak level of \$27 in the year 2040. The tax then declines slightly to just under \$1 in 2070. It is then no longer profitable to produce oil because OPEC's unit cost exceeds the price of the carbon-free energy source. From then on the tax remains at this low level. The reason is that the falling backstop price makes the unconstrained emissions almost constant and generally not much higher than the target of 3.77 billion tonnes of carbon. But why does the tax reach a peak in 2040, one period before the emissions in Annex B reach its highest level? To answer this we have to look more closely at the oil market.

Effects in the oil market

Figure 4 shows changes in the producer price of oil after the tax has been introduced. Since the maximum producer price is the price of the backstop less taxes, the maximum producer price is reduced by the entire tax in each period.

Figure 4. Oil producer price with and without climate treaties, and with OPEC as a cartel



We see that the effect on the producer price is minimal at the beginning. In the year 2000 the price is reduced marginally because the tax is not introduced until 2010. In the year 2010 the producer price is reduced by only \$1.10. The tax is \$6.20, which means that the consumer price rises by \$5.10. Consumers will thus bear almost the entire tax burden at the beginning. The introduction of the tax entails that the oil price reaches its peak level in 2030, one period earlier than in the scenario with no

[8] In the scenario with Kyoto targets, the tax is not imposed on consumption *outside* Annex B until 2040. In order to study the direct effect of the Kyoto Protocol, we let Non-Annex B exist without CO_2-taxes for as long as possible. In 2040 the taxes must be placed outside Annex B due to model technical reasons, but it may nevertheless be realistic under a more global economy. Besides, the development of a more global economy was the reason for letting existing taxes and costs be harmonised across regions up to 2040.

[9] If the tax was introduced in 2000, this would have resulted in a marginally lower tax level in the first two periods.

tax. The price is then $6.50 lower than it would have been without a tax. It is not until 2040 that the producer price is reduced by the entire tax of $27. This means that in the first 40 years the consumer price shows the greatest change as a result of the tax, whereas it is the producers who bear the entire tax burden after this time. The reason for this is found on the intertemporal aspect of the supply side in the model and from OPEC's behaviour, which we will now examine more closely.

Figure 2 in the previous section shows how the production profiles of OPEC and the fringe change as a result of the necessary CO_2 tax for the Kyoto targets. OPEC takes the production of the fringe as given. OPEC take into consideration that reduced production gives a higher oil price now (the "cartel effect"). Because the costs stay fairly constant in the first periods, it is not so essential for the cartel to weight reduced production versus lower future costs (the "scarcity effect"). OPEC reduces production by 11 % in 2010 and by 18 % in 2020. The cartel reduces production to maintain oil prices at about the same level that prevailed before the tax was introduced. The fringe considers the oil price as given. For the high-cost fringe it is crucial to weight increased production versus higher future costs. The fringe finds it optimal to increase production in 2000, 2010 and 2020 when the reduction in the producer price is less than in 2030. When the price is reduced by the entire tax in 2040, it is no longer profitable for the high-cost fringe to produce oil, and so the production ceases one period earlier than in the reference case. Oil wealth outside OPEC is reduced by about 15 % (as measured by the present value of future petroleum rent). Beginning in 2040 it is optimal for OPEC to charge as high a price as possible that is the maximum producer price, and the cartel produces as long as its unit costs do not exceed this price. In 2070 the backstop has become cheaper than oil, and it is no longer profitable for OPEC to extract. OPEC's total production is reduced by only 8 %, but the oil wealth by as much as 19 %. The reason is that the bulk of OPEC production comes in the last periods, when OPEC can't prevent the drop in producer prices.

Effects in natural gas markets

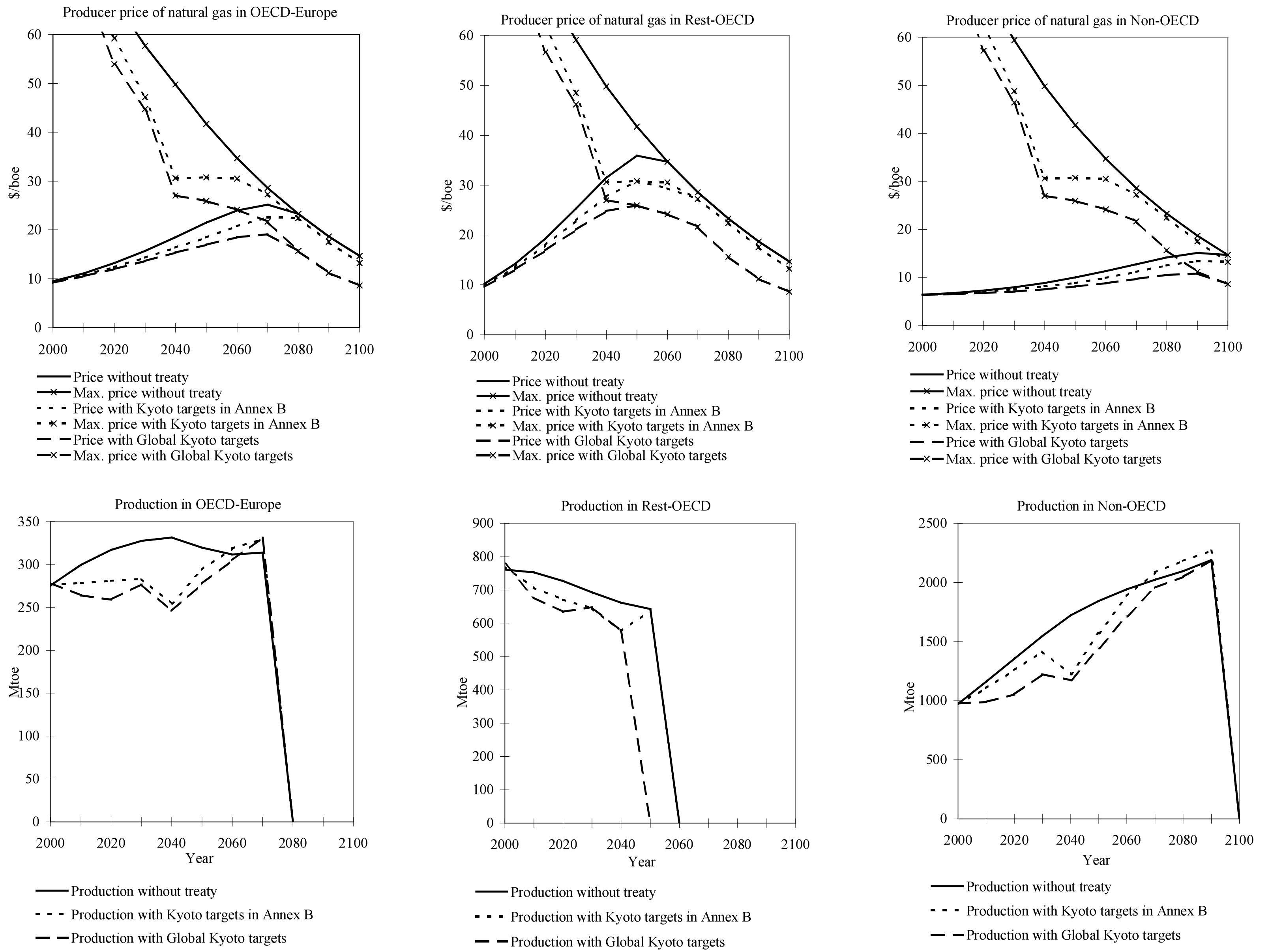
When taxes are introduced, the producer price of gas is reduced somewhat over the entire horizon in the three production regions, as shown in later in figure 5. As in the oil market, however, most of the burden falls on consumers in the first periods (and for a longer period than in the oil market). The level of extraction is reduced almost over the whole production period in the three regions. The reduction in extraction increases up to 2040, when the tax leads to the highest consumer price. From 2040 the tax is reduced and production increases in all three regions. As for the fringe in the oil market a slower rise in the producer price compared to the reference scenario will give an incentive to move production nearer in time. Still, production is lower with the emission targets compared to the reference case for all gas producers. Some of the decline in production can be explained by a substitution effect from gas to oil that will be commented on later. Total production is reduced by 7 % in OECD-Europe, 5 % in Rest of OECD and 7 % in Non-OECD. Gas wealth in the three regions is reduced by about 18, 15 and 17 %, respectively, following the introduction of the CO_2 tax. (The reduction in oil and gas wealth is summarised in Figure 10, at the end of Section 6).

Effects on consumption in Annex B

The effects on the consumption of fossil fuels in Annex B are shown in Figure 6. As the CO_2-tax increases up to 2040, so does the reduction in gas and coal consumption from the reference situation. Oil consumption is only marginally reduced in 2010 and 2020, and is actually higher than in the reference scenario in 2040, as is the case with global oil production. We see from Figure 6 that it is particularly the consumption of coal that is reduced after taxes have been introduced. In 2020, coal consumption has already been reduced by half in relation to the reference scenario. 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). The reason for the larger reduction in gas than oil consumption is due to the fact that the consumer price of gas (and also coal) is lower than on oil, so that the relative price increase due to the CO_2-tax is higher. This occurs even though gas is a cleaner fuel.

When the tax reaches a peak in 2040, Figure 2 showed that the fringe stops producing oil and the cartel takes over the whole market and its oil production starts to decline (as is the case with consumption in Annex B). In 2040 the oil producers bear the whole tax burden, as the taxes have no effect on the consumer price. The consumer price of gas and coal, on the other side, has increased in 2040 compared to the reference case. As a consequence, the introduction of the CO_2-taxes increases oil demand from the reference situation. In the following periods it is optimal for OPEC, as in the reference scenario, to charge as high a price as possible which is the maximum producer price. But due to a rising producer price up to 2060/70 it is not optimal for the cartel to satisfy all demand. This leads to a faster introduction of the carbon-free backstop technology than in the reference scenario.

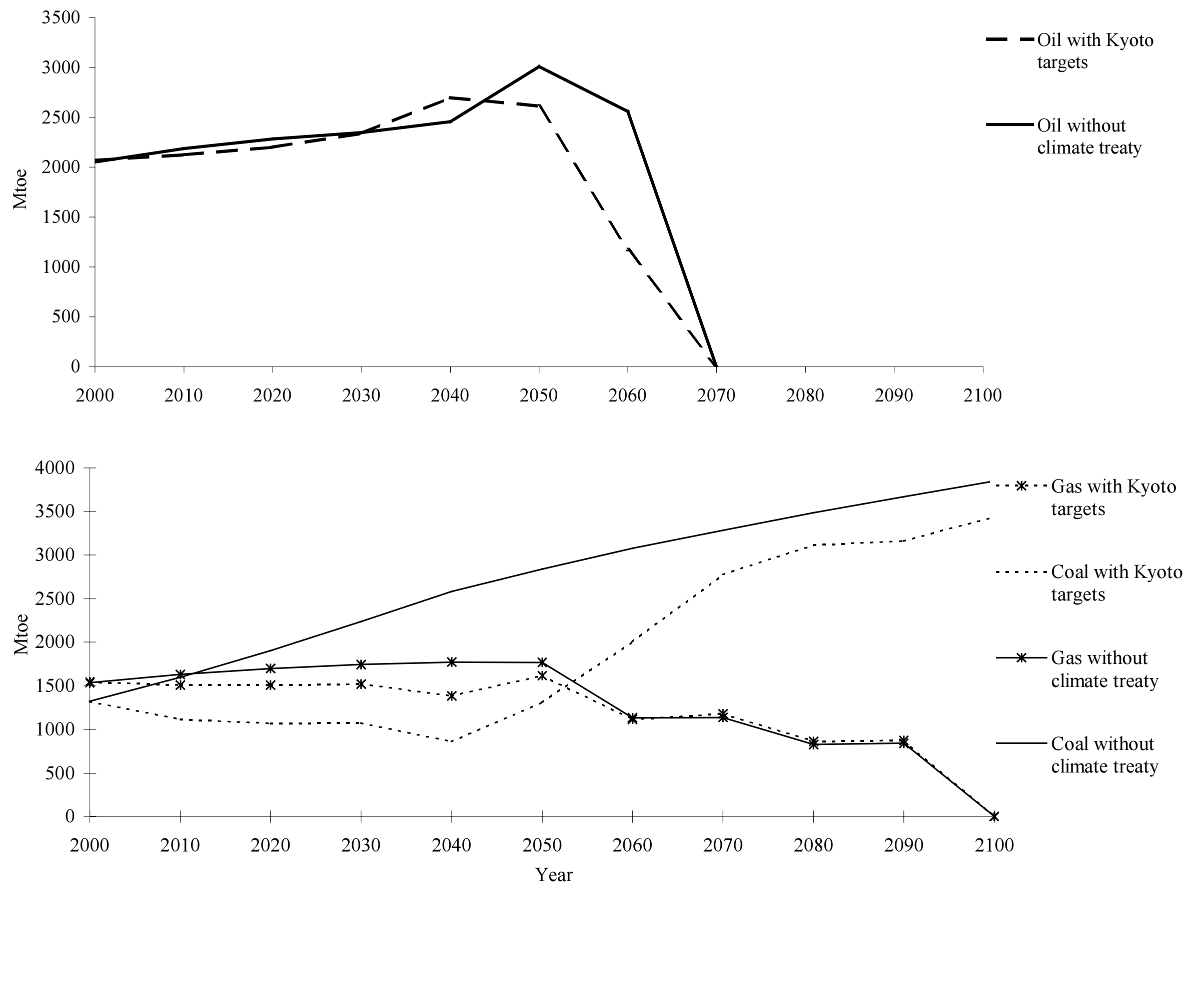
Figure 5. Producer price and production in the natural gas regions with and without climate treaties, and with OPEC as a cartel



Backstop consumption in Annex B increases from 12 % in 2040 to over 200 % of the oil consumption in 2060[10]. The reduction in oil consumption after 2040 and the introduction of the backstop are the reasons for the CO2-tax to reach its maximum level in 2040, one period before the emission level peak in the reference scenario.

Inasmuch as oil production falls until it comes to a complete halt in 2070, the CO_2-tax is also reduced in this period. Figure 6 shows that from 2050 coal consumption begins to increase in line with the decline in the CO_2-tax. Gas consumption in Annex B moves along approximately the same path as in the reference scenario beginning in 2050. Gas consumption falls gradually from then on because gas production becomes unprofitable and is phased out in the three production regions.

Figure 6. Effects on oil, gas and coal consumption in Annex B with Kyoto targets, and OPEC as a cartel



[10] It is assumed that the relative amount of backstop consumption is equal inside and outside Annex B. Because the backstop is a perfect substitute for oil, just small shifts in the tax lead to relatively large shifts in demand between the two energy goods in 2050 and 2060. This makes it difficult to find the exact CO_2-tax needed for the emission target. As a consequence the emissions in Annex B in 2050 are marginally higher and in 2060 marginally lower than the target. A correct tax would only have to be slightly higher for 2050 and lower for 2060.

A key point is that if only the OECD had been subject to emission reduction targets in Kyoto, the CO2-tax (or permit price) would initially have to be higher. If an efficient tradable permit market is assumed, the model shows that the OECD can actually increase emissions by 2.4 % from 1990 to 2010 due to substantial emission reductions in EIT. As a result of the collapse and dissolution of the Soviet Union at the beginning of the 1990s, emissions from this category of Annex B were about 26 % lower in 1994 than in 1990. These countries have thus been allocated commitments they may be able to fulfil by a wide margin in 2010 without having to implement measures (with this phenomenon referred to as “hot air”). The magnitude of this "hot air" in various models is crucial in determining the costs of the Kyoto emission targets.

5. Consequences of Global Kyoto targets

Global emissions rise from 6.15 billion tonnes of carbon in 2000 and reach a peak level in the reference scenario of 12.11 billion in 2060, as shown in Figure 7. The estimated emissions are in accordance with other long term studies to the middle of next century, see, e.g., Dean and Hoeller (1992)[11] and Cline (1992), and are in the lower range of IPCC scenarios (IPCC 1992, 1996). In our model the emissions rise more rapidly outside Annex B due to stronger economic growth and higher income elasticity for fossil fuels. In particular, the consumption of coal rises faster outside Annex B.

The Global Kyoto targets refer to a situation where the entire world reduces emissions by 5.2 % in 2010 compared with the level in 1990. In order to achieve these targets the global emissions have to be reduced to 5.59 billion tonnes of carbon from 2010. The global tax is imposed on consumption from 2010.

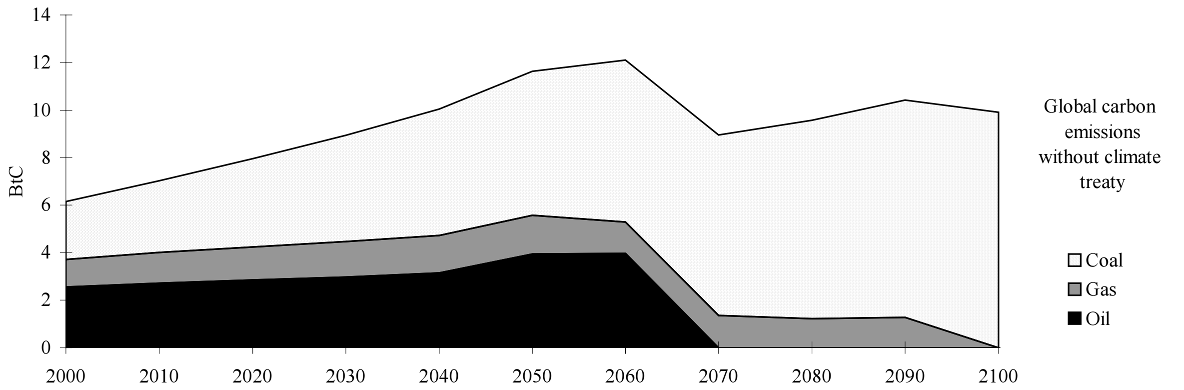
As a result of these reduction targets, the tax must in all periods be higher than the tax level in the case with commitments only for Annex B. This is particularly due to the much higher consumption of coal inasmuch as we are considering consumption in Non-Annex B. The tax now rises sharply from $10.5 per boe in 2010 and up to an almost steady level of $17-18 in 2020 and 2030, before it reaches a maximum level of $32 in 2040; this time two periods before the emission level peaks. For OPEC, it is now profitable to reduce production twice as much in 2010 and 2020 to maintain oil prices, compared to the situation with Kyoto targets in Figure 2. In 2030 OPEC actually reduces production with 45 % compared to the reference case. The cartel production is lower than with Kyoto targets in Annex B throughout the whole extraction period. Even if the tax is higher, the producer price is almost the same as with Kyoto targets in Annex B up to 2030. This leads to almost the same production profile for the

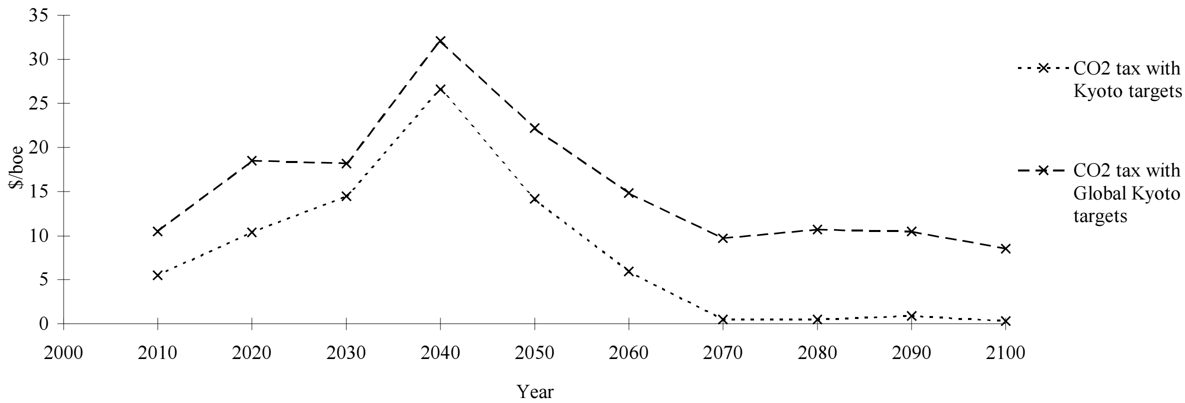
[11] Our estimated global emissions *up to 2010* with OPEC as a cartel are actually in the lower range of the scenarios in Dean and Holler. This study that uses standardised values for exogenous variables across the different models. But the reference scenarios that were calibrated to match the actual 1990 levels, indicates an overshooting of the level of global emissions already in 1995. See also footnote 7.

fringe in the three periods it produces. With global reduction targets, the fringe's oil wealth is reduced with 17.5 %, compared to 15 % with targets for Annex B. OPEC's oil wealth is reduced with as much as 32 %, an increase of about two-thirds of the loss with Kyoto targets in Annex B.

With regards to the natural gas markets as shown in Figure 5, the producer price is reduced further compared with the case with Kyoto targets, and production is lower. Gas wealth in OECD-Europe, Rest-OECD and Non-OECD is now reduced by 27 %, 24 % and 33 %, respectively. While the wealth loss in the two OECD regions increases with 50-60 %, the loss in Non-OECD is almost doubled compared to loss with Kyoto targets in Annex B. Non-OECD now experiences the largest reduction in wealth first of all because this region includes Non-Annex B and this region is not included in the Kyoto Protocol. The wealth effects are summarised in Figure 10.

Figure 7. Global carbon emissions and time-path of a CO_2 tax with Global Kyoto targets, and OPEC as a cartel

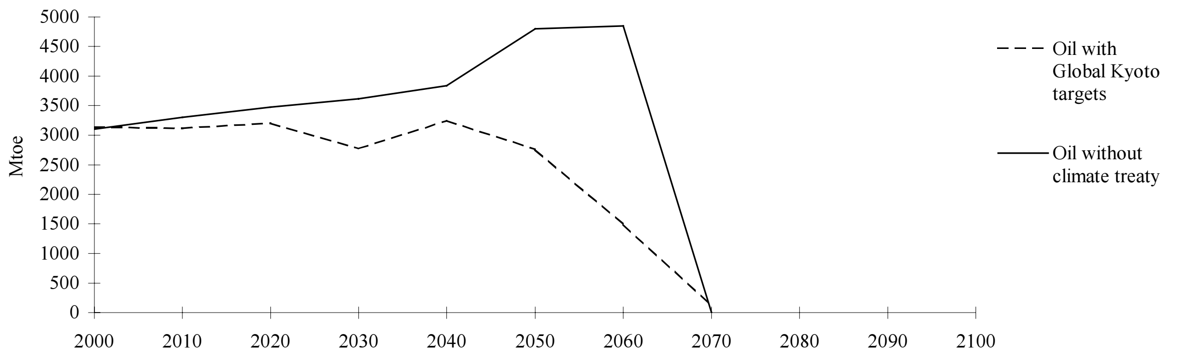


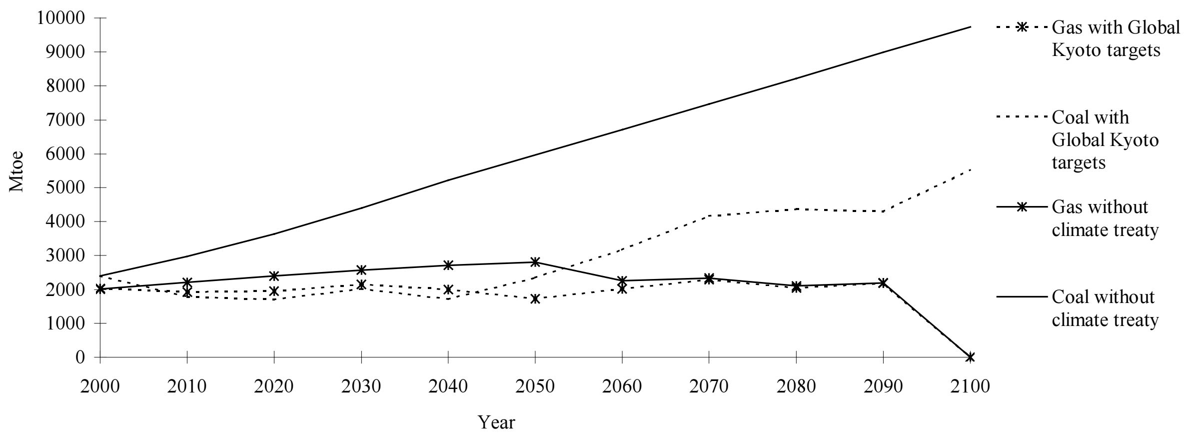


We now turn to the effect of the introduction of CO_2-taxes on the *global consumption* of fossil fuels, as shown in Figure 8. We see that the higher tax leads to a larger reduction in the consumption of fossil fuels compared to the Kyoto targets. Figure 4 shows that the oil producer price is almost the same for the first three periods as with Kyoto targets in Annex B, while the producer price of gas and coal is reduced further. An extension of the Kyoto targets to the whole world will therefore lead to a relatively larger increase in the oil consumer price. As a consequence the substitution towards oil consumption that was present with Kyoto targets is reduced.

Beginning in 2040 the oil consumer price is the same as in the reference case, while the consumer price of gas and coal has increased. This leads to a larger reduction in gas and coal consumption than for oil in 2040. As with Kyoto targets in Annex B, the relatively large demand after oil in 2040 is partly satisfied by the backstop and at an increasing rate in the following periods. The backstop replaces gas consumption in Rest-OECD in 2050, and in 2060 the reduction in the oil consumption is actually larger than for coal. After oil consumption is phased out in 2070 the CO_2-tax reaches a level of about \$10 to keep the global coal consumption low (compared a level of less than \$1 with Annex B targets).

Figure 8. Effects on oil, gas and coal consumption with Global Kyoto targets, and OPEC as a cartel





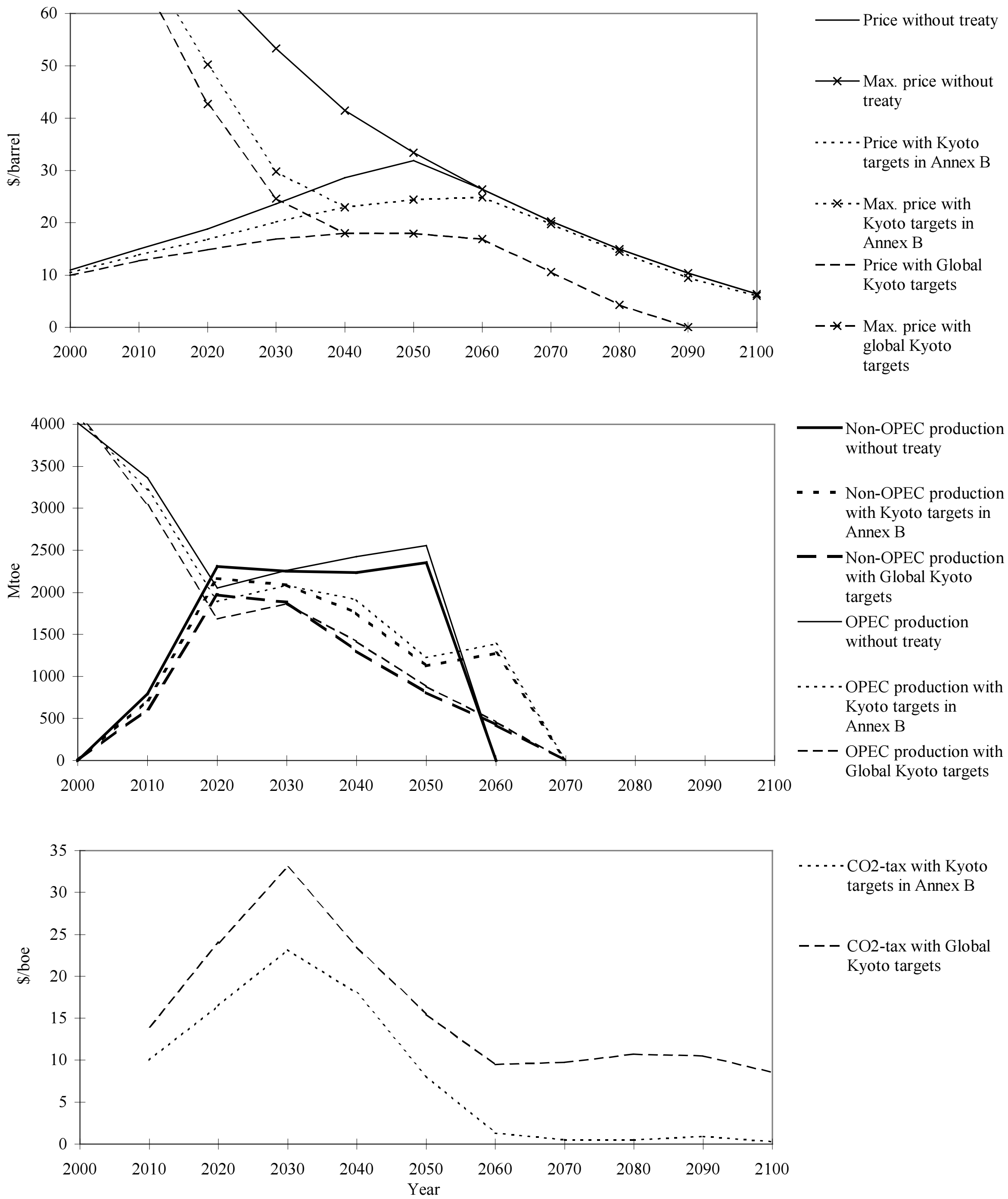
6. Perfect competition in the oil market

The oil market is probably best described with OPEC as a cartel. But the discussion of who shall reduce production may, for example, result in such considerable strains that the various member countries completely disregard the production quotas. If OPEC is dissolved and the oil market becomes a competitive market, the calculations show that this will have major consequences for prices and production, see Figure 9. OPEC no longer restrains production in order to maintain oil prices. They now quadruple their production in the first period, bringing the initial oil price down to about \$11 in the year 2000. The oil producer price does not reach the maximum producer price until 2060, two periods later than when OPEC acts as a cartel.

The low oil price entails that high-cost countries find it optimal to postpone production until a later period, and it is not until the third period that these countries achieve the same production level that they have when OPEC operates as a cartel. Due to high production initially, OPEC halts production one period earlier, while Non-OPEC produces one period longer compared with the cartel case. The dissolution of OPEC has major negative consequences for the other producer countries. Non-OPEC's oil wealth is reduced with as much as 71 % before any emission targets are introduced. The reason is that the producers outside OPEC now cannot enjoy the benefits from a higher oil price. The change in production profile towards more production in later periods contributes also to the large reduction in wealth because of discounting. OPEC loses about 15 % of its wealth, and so Non-OPEC has far more to lose from a dissolvement of the cartel (see also Berg et al. 1997a). OPEC does not have to reduce production to keep the oil price high, and actually moves some of its production to earlier periods. With perfect competition in the oil market, both Annex B and global CO_2-emissions are in the range of the scenarios from other studies, also up to 2020. Hence, the costs of reducing emissions from the reference situation in this period is also probably more comparable with other studies than in the case with OPEC acting as a cartel.

We see from Figure 9 that global oil production is higher in the case with perfect competition in the first four periods compared to the cartel situation in the reference case. It also appears that oil *consumption* in Annex B is higher in this period. For this reason the CO_2-tax in Annex B must be higher up to 2030 with perfect competition. The tax must increase from about \$10 in 2010 to a peak level of \$23 in 2030. Figure 9 also shows that the CO_2-tax declines after 2030, and is lower than in the cartel case from 2040 to 2060.

Figure 9. Effects of climate treaties on oil producer price and production, with a competitive oil market



In a situation with perfect competition the introduction of a tax necessary for the Kyoto targets in Annex B results in a further reduction in the producer price. We see from Figure 9 that the relative impact is marginally greater up to 2030 than in a situation with OPEC acting as a cartel. The tax is higher and OPEC countries do not find it optimal to limit their production to the same extent in the first four periods as in the cartel case. This leads to a higher loss for Non-OPEC because this region has the lowest petroleum rent initially. A certain reduction in the producer price will give a relatively higher loss of wealth when the extraction costs are closer to the price, i.e. a lower petroleum rent. A larger burden therefore falls on producers in high-cost countries, and the reduction in Non-OPEC's oil wealth as a result of the tax is greater, about 30 %. OPEC loses about 15 % of its wealth from the reference case under perfect competition. Figure 9 also shows that because the producer price is higher in 2060 than in 2050, it is profitable for both OPEC and Non-OPEC to postpone oil production so that they produce one period longer than in the case without a tax.[12]

The higher tax and the lack of substitution effect from gas to oil up to 2030 lead to a larger reduction in oil consumption in Annex B than in the cartel model. The CO_2-tax now peaks in 2030, two periods before the maximum emission level in the reference scenario. The tax is lower than in the cartel case from 2040 to 2060, because the reduction in oil consumption in Annex B now is greater in this period. The reason is that in the cartel case the tax did not have any effect on the consumer price from 2040, but it is not until 2060 that the producers bear the whole tax burden with perfect competition. The relative backstop consumption in Annex B is twice as large in 2040 compared to the cartel case (and in 2050 it is three times as high). Emissions, and thereby the tax, are the same in the case with perfect competition as with OPEC operating as a cartel when oil production ceases in 2070.

We now define the shadow cost of reducing emissions as a permit price. A CO_2 tax of \$1 per barrel of oil with an efficient international tradable permit market will be equivalent to about \$2.5 per tonne CO_2. If we sum up the consequences of the Kyoto Protocol, it may generally be said that irrespective of the assumption concerning OPEC's behaviour, the permit price will rise from about \$14-24 per tonne CO_2 in 2010 up to \$25-41 in 2020, before it reaches \$36-57 in 2030. The lower figures are indicating a situation where OPEC is acting as a cartel. In comparison, estimates of the permit price in nine different models in OECD (1998) were in the range of \$5.5-33.5 in 2010. Our estimate is thus within the price interval provided by these studies, but in addition our study points to possible development paths after 2010 under different assumptions concerning the cartel's market power.

As in the case with a cartel situation, *Global Kyoto targets* entail that the tax, and thus the permit price, must be higher in all periods than the tax level in the case with the Kyoto targets. The producer price of oil is now lower during the whole production period compared with the situation with perfect competition and emission targets for Annex B, as shown in Figure 9. This leads to a further reduction in the production of both OPEC and Non-OPEC through the entire period. As a result, Non-OPEC's oil wealth is now reduced with as much as 55 %, against 30 % with the current Kyoto targets. OPEC

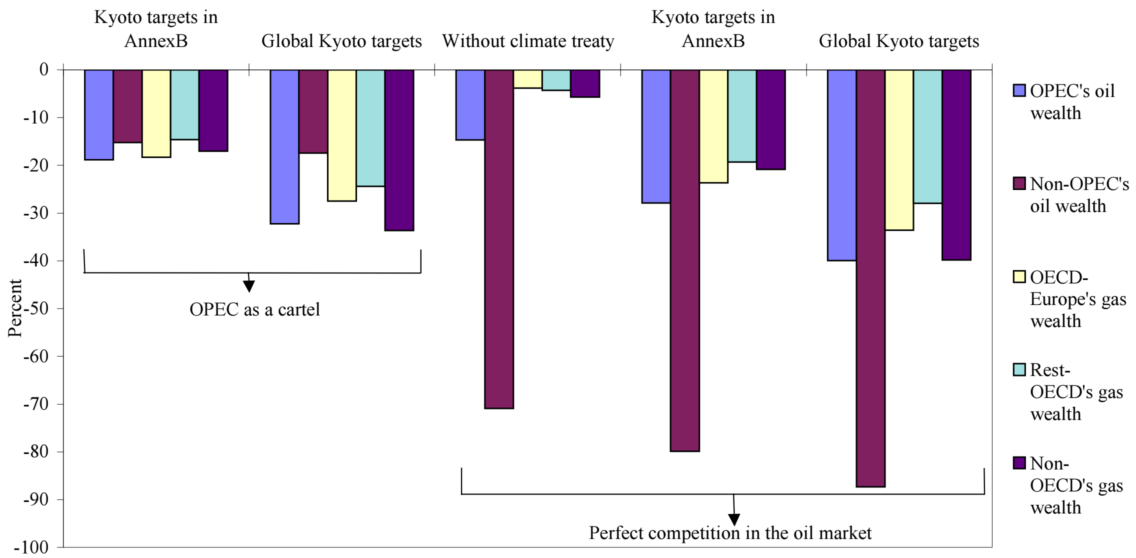
[12] This is in line with Sinclair's argument that a carbon tax should decline over time to get producers to postpone extraction (see footnote 2).

looses 29 % compared to 15 %. In a situation with perfect competition in the oil market the emission targets will lead to a relative loss for Non-OPEC about twice as high than for the low-cost producers that belonged to the cartel. Even though a larger tax burden is born by the producers, the relative loss in wealth for OPEC is marginally less than in the cartel situation. The reason is that OPEC does not reduce production in the first periods as much as in the cartel model. Therefore, market structure is not so important for OPEC when it comes to the *relative* impact of emission targets, while for Non-OPEC it is of great importance.

To sum up the consequences of including developing countries in the Protocol, the permit price rises from $33-35 in 2010, up to $52-59 in 2020 before it reaches $49-81 in 2030. The higher figures are indicating the permit price with perfect competition in the oil market. Our estimates are in the lower range of about $50-85 in 2020 in Dean and Hoeller (1992)[13]. As in our study, the availability of the backstop after 2030 is a major factor in determining possible time-paths of emissions and permit prices after 2030.

This section has been focusing on the oil market because the results in natural gas markets are approximately the same as in the cartel model. The gas wealth in the reference case is slightly smaller than in the cartel case, because the lower oil price leads to a substitution from gas to oil before targets are introduced. The relative effects in the gas market of the emission targets are not substantially different from the cartel case.

Figure 10. Reductions in oil and gas wealth from the reference case with OPEC as a cartel and no climate treaty



7. Sensitivity analyses and caveats

There is considerable uncertainty associated with the value of several parameters. Some sensitivity analyses have been carried out to examine the degree to which the results depend on special numerical assumptions. The simulation results apply to the oil market in the cartel case (see also sensitivity analysis in Berg et al., 1997b).

Technological growth has been remarkable in many Non-OPEC countries. More rapid *technological progress* in the fringe for the first 30 years will result in lower unit costs, higher production and this leads to a lower oil price. Inasmuch as OPEC's production is almost unchanged, total production and thereby emissions also increase, and the permit price must be higher if the emission targets are to be achieved. More rapid technological progress for the backstop technology will clearly change the time-path of the permit prices. When the backstop price falls faster, total production will increase for the first periods but the production period will be shortened. This will increase the permit price for the first periods, but eventually lead to a lower permit price as oil production is phased out.

All cross-price elasticities are set equal to 0.1. Higher cross-price elasticities, while keeping the direct price elasticities unchanged, makes total energy demand less sensitive to price changes. The permit price must then be increased to get the same increase in consumer price (and fall in demand). In general will lower substitution elasticities between fossil fuels lead to an overestimation of the costs of mitigation, because this makes switching between fossil fuels more difficult. Still, different consumer prices of fossil fuels in our model are an important factor in determining substitution. Differences in existing prices determine "the leverage" of any particular tax rate, and hence induce fuel switching. It is uncertain whether there should be an even larger substitution between the fuels than in our simulations.

Several developing countries including major OPEC members face severe budget crises (see, e.g., Salameh, 1997). This can imply that the need for current money may be overwhelming. Hence, the discount rate for OPEC may be high. A higher discount rate in the model indicates that the future counts less, but the production profile for OPEC (and the fringe) shows minor changes in the first periods. With a higher discount rate, the emission targets makes the cartel increase their production in the middle of their production period. Due to low extraction costs the intertemporal aspect is not so important for OPEC during the first decades of the next century.

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[13] These permit prices are roughly estimated through interpolation of different reduction scenarios in 2020, and by looking at graphs.

A characteristic feature of markets for fossil fuels is that there is imperfect competition. Since natural gas markets are modelled as competitive markets, there is greater uncertainty associated with the results here. Greater criticism may perhaps be made of the description of the coal market, which is also modelled as a competitive market with a very simple cost function. As coal consumption constitutes a large fraction of total CO2-emissions, particularly in the long run and outside Annex B, the characteristics of this market is obviously important for the permit price. However, it is uncertain in which direction this affects the results.

There is uncertainty about the emission targets after 2010. There is little doubt that the Kyoto Protocol itself is just an initial step in a sequential series of agreements to deal with climate change. The emission targets in our study are just one possible development. See, e.g., Lindholt (1998) for the consequences of a more ambitious goal of 20 % reduction in global emissions in 2020 compared to the level in 1990.

Intertemporal optimisation models assume that decision-makers have perfect foresight. That is, we assume that the producers are fully informed about the nature of future conditions, and act accordingly. Given the present state of uncertainty this is a highly debatable idea. In addition, asides from financial markets, there are no actual markets for purchases and sales in the distant future.
But as perfect foresight into the distant future is an implausible assumption, myopia in the context of energy markets seems even worse. Investments in energy production are typically long-lived. Today's decisions about energy production are not only influenced by what happens next year, but also what happens thereafter. Hence, analyses that focus only on the short term may be overlooking an important factor of decision about the production of energy. In addition, it seems reasonable that producers of exhaustible resources, at least to some extent, are looking forward and take into account that extraction today will reduce the availability of the resource in the future.

The modelling of the backstop as a perfect substitute for fossil fuels is a simplification. Even though our results show that oil production is gradually substituted by the backstop, oil production is the first fossil fuel to be completely replaced by the backstop. In reality there are specific end uses for oil, like transportation, which will possibly endure the competition with the backstop for a longer period (see, e.g., Chakravorty et al. (1997) for a more sophisticated modelling of the backstop).

The Cournot approach assumes that both the fringe producers and the cartel take the supply of all other producers as given, when deciding on their production profile. In a Stackelberg model with the cartel as a leader, the cartel knows that the fringe reacts to its supply decisions, and takes this into account when choosing its production profile. In addition the cartel can take into consideration how the consequences of the permits differ with its own production choice. Thus, a powerful cartel would obviously follow this strategy if feasible. Future plans for expanding the PETRO model involve both such a Stackelberg approach, as well as a more realistic modelling of the backstop-technology.

8. Conclusion

In this study we have analysed the dynamic aspects on fossil fuel prices of introducing CO_2 emission targets. We show that in order to achieve the emission reduction targets for Annex B parties in the Kyoto Protocol, international CO_2 permit prices must rise in the 30-40 years after the turn of the millennium. This is necessary in order to reduce in particular a steadily rising consumption of coal in Annex B. If the rest of the world were to be subject to the same relative emission reduction commitments, the result is higher permit prices. Irrespective of the emission reduction targets, permit prices can be reduced substantially as global oil production begins to fall dependent on when a backstop technology starts to replace oil. In contrast to a regime with a constant permit price, the introduction of the targets leads to a gradual substitution from oil to the backstop.

With an efficient international tradable permit market, the results indicate a CO_2 permit price that rises from $14 per tonne in 2010 to $36 in 2030. If the oil market becomes competitive, oil production will be higher in the first periods, resulting in a higher permit price in order to achieve a given emission target. The results indicate that the permit price in this case will rise from $24 per tonne CO_2 in 2010 to $57 in 2030. If the developing countries are included in the Protocol, the results indicate that the permit price rises from $33-35 in 2010, up to $52-59 in 2020 before it reaches $49-81 in 2030. The higher figures are indicating the permit price with perfect competition in the oil market.

The results for the oil market show that in the first periods it is consumers who bear the greatest burden of the introduction of the CO_2 permits if OPEC functions as a cartel. The reason is that OPEC reduces production to maintain oil prices, entailing that the reduction in the producer price is not as great as in the first periods. As long as OPEC acts as a cartel, the simulations show that the Kyoto commitments result in a reduction in the wealth of oil and gas producers of 15-20 %. OPEC will not lose much more than the fringe, even if the cartel reduces production to keep the oil price high. The reason is that OPEC goes earlier into a period with monopoly power while the fringe stops producing one period earlier. Global Kyoto targets will result in higher CO_2 permit prices and a greater reduction in the producer's oil and gas wealth. OPEC reduces production further to keep the oil price high, as demand from Annex B and especially Non-Annex B falls. As a result OPEC will lose relatively more than the fringe if the developing countries are included in the Kyoto Protocol. Compared to a situation with Kyoto targets in Annex B the loss for OPEC increases from 19 to 32 %, but for the fringe the loss only increases from 15 to 17,5 %. The loss for the OECD gas producers increases with 50-60 %, while Non-OECD loses almost the double of its gas wealth if the Kyoto commitments become global.

Non-OPEC will lose considerably more if OPEC is dissolved than if the Kyoto Protocol is fulfilled. If OPEC was to be dissolved, or the various member countries begin to disregard their production quotas, the producers outside OPEC might lose about 70 % of its oil wealth in the case *without* emission targets. Non-OPEC is now in a situation where it cannot enjoy the benefits of a higher oil price. In addition to a lower oil price than in the cartel model, the reason is that the price-reduction makes it optimal for Non-OPEC to move production to later periods and this leads to a larger loss because of discounting. OPEC only loses 15 % of the wealth it had as a cartel in a situation without a climate treaty. OPEC does not reduce production to keep the oil price high, and hence moves some of its production to earlier periods. If emission targets are introduced with perfect competition in the oil market, the relative loss for OPEC will be slightly lower than when it operates as a cartel, but for the high-cost producers the relative loss will be about twice as high. Even though the fall in the producer price is greater under perfect competition because the producers consider the oil price as given, the market structure is not so important for OPEC when it comes to relative loss, but for the fringe it is of major importance. The main reason is that the fall in the producer price of oil will have a relative greater effect on Non-OPEC's wealth because their petroleum rent is smaller for the first 30 years. All in all, the combination of perfect competition and the Kyoto emission targets result in a reduction of as much as 80 % in Non-OPEC's oil wealth compared with the cartel situation in the reference case. Global Kyoto targets will lead to a loss of almost 90 %.

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Appendix A

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 $\overset{i}{X}_j$ be defined by

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

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

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. $P_O(\ )$ in (A6) is the producer price given in (A5).

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

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

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 $\pi^c_{O_t} = -\lambda_t$.

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) $$\dot{\lambda} - r\lambda = -\frac{\partial H^c}{\partial A^C_O} = \frac{\partial C^C_O}{\partial A^C_O} x^C_O$$

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

(A13) $$\dot{\pi}^C_O = r\pi^C_O - \frac{\partial C^C_O}{\partial A^C_O} x^C_O$$

x^C_O maximises the Hamiltonian for all $x^C_O \geq 0$ which for an interior solution requires

(A14) $$\frac{\partial H^c}{\partial x^C_O} = P_O - C^C_O + \frac{\partial P_O}{\partial x_O} x^C_O + \lambda = 0$$

which gives the producer price of oil when OPEC produces

(A15) $$P_O = C^C_O + \pi^C_O - \frac{\partial P_O}{\partial x^C_O} x^C_O$$

where $-\frac{\partial P_O}{\partial x^C_O} x^C_O$ is the cartel rent. The marginal revenue of OPEC is defined as

(A16) $$MR^C = P_O + \frac{\partial P_O}{\partial x^C_O} x^C_O = C^C_O + \pi^C_O$$

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

(A17) $$\dot{MR}^C = r\pi^C_O - \tau^C C^C_O$$

The cartel will stop producing at time $T_O^C \quad (0,\infty)$ 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.

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

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 $T_O^F \quad (0,\infty)$, 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:

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

s.t.

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

$$\text{(A28)} \qquad x_G^i \geq 0$$

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

The first order conditions give

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

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

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

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

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

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

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) $$\max_{x_K} \int_0^{\infty} \left[P_K - C_K\right] x_K \; e^{-rt} dt$$

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 $T_K \quad (0,\infty)$, is

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

Appendix B

Numerical specifications

Demand side

Both the direct and cross price elasticities and the income elasticity are constant as we use log-linear demand functions. There is much variation across empirical studies and hence it is difficult to come up with representative elasticities, see, e.g., Dahl and Erdogan (1994). The *price elasticities* in this study are taken from Golombek and Bråten (1994). For the OECD-regions all direct price elasticities are set equal to -0.9, while in the Non-OECD-region the direct price elasticities are set equal to -0.75. Their choice of elasticities is partly based on the conventional wisdom that demand is less elastic in developing countries where fossil fuels are used to satisfy basic needs. All cross price elasticities are set equal to 0.1.

It is often assumed that the *income elasticities* are somewhat higher in developing countries than in developed countries. However this difference should not be exaggerated as there is more potential for energy-efficiency improvement in developing countries. The higher the energy saving potential, the smaller is the income elasticity for any given growth rate in gross domestic product (GDP). Consider the «Autonomous Energy Efficiency Index» (AEEI) invented by Manne and Richels (1990). A GDP growth rate of 2.5% per year combined with a 1 % increase in the AEEI is equivalent to an income elasticity of 0.6.[14] Based on this we assume that the income elasticity is 0.5 in the OECD-Regions and 0.6 in Non-OECD.

The existing *tax structure* varies greatly between different countries. Energy taxes in the OECD-countries are based on ECON (1995). In Non-OECD existing taxes on coal and natural gas are mostly insignificant or unavailable (see IEA 1995b), thus they are set equal to zero. The tax on oil in Non-OECD is calculated from Gupta and Mahler (1995). The consumption figures in 1994, taken from BP

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[14] The definition of AEEI implies the relation

$$\mathrm{GDP} = \mathrm{kE} * \mathrm{AEEI} \qquad \frac{\dot{\mathrm{GDP}}}{\mathrm{GDP}} = \frac{\dot{\mathrm{E}}}{\mathrm{E}} + \frac{\dot{\mathrm{AEEI}}}{\mathrm{AEEI}}$$

where *k* is a constant and *E* is total energy demand. For constant energy prices the elasticity of income (εI) is then given by

$$\varepsilon I = \frac{\dot{\mathrm{E}}/\,\mathrm{E}}{\dot{\mathrm{GDP}}/\,\mathrm{GDP}} \qquad \varepsilon I = \frac{\dot{\mathrm{GDP}}/\,\mathrm{GDP} - \dot{\mathrm{AEEI}}/\,\mathrm{AEEI}}{\dot{\mathrm{GDP}}/\,\mathrm{GDP}}$$

(1995), are used as weights. As mentioned above, all energy taxes are harmonised to the global average of 1994 after 40 years, where the consumption figures in 1994 are used as weights.

The annual *GDP growth rates* are based on Burniaux et al. (1992) and Kverndokk (1994a).

Finally, the demand functions are calibrated to agree with consumption of the respective fuels in 1994 given prices and taxes this year.

Supply side

The unit cost function in fossil fuel extraction has the following functional form

$$(1)\ C_t = C_0 e^{\eta A_t - \tau t}$$

where C_0 is the initial unit costs of production, A is cumulative production, τ is the rate of technological change, t is time and η is the convexity parameter of the cost function.

The *initial unit costs* of oil production in OPEC and Non-OPEC are calculated from Ismail (1994). The corresponding cost estimates for the production of gas in OECD-Europe and Rest-OECD are based on Golombek *et al.* (1995) and IEA (1995a) respectively, while the unit cost of production of gas in Non-OECD is taken from ECON (1990). In 1994, Russia exported 10% and Algeria 56% of their gas production to Europe. These shares are therefore considered as production in OECD-Europe in the model, and are taken into account when calculating the initial unit cost.[15] We assume that there is no scarcity rent in coal production, and the initial unit cost of production of coal is therefore set equal to the fob price in 1994 based on IEA (1995b).

The *convexity parameter* is calculated using estimates of the unit costs in the base year, and data from BP (1995) for proved reserves, R, defined as quantities which can be extracted under existing economic and operating conditions. There is no universal rule to estimate the reserves. However, assuming resources with unit costs less than $20 per barrel of oil equivalents (boe) for both oil and gas to be regarded as economically recoverable, the convexity parameter is determined by using the cost function without technology change.

[15] Similar shares of the reserves in Russia and Algeria are added to the proved reserves of OECD-Europe, see below.

(2) $20 = C_0 e^{\eta R}$

For coal η is set equal to zero.

The rates of *technological change* are very uncertain. We have generally assumed the rate of technological change in oil and gas production to be 1%. Initially, however, as oil producers outside OPEC have had impressive technological improvements lately, we assume a rate of 2% in Non-OPEC (see, e.g., Ismail 1994). This rate is reduced to 1% after 30 years. The technological change in coal production is assumed to be lower, i.e., 0.5% per year. This is based on the development in past coal prices, see Ellermann *et al.* (1995).

Finally we assume that there is a higher technological progress in the backstop technology with a decrease in the backstop price of 1.4 % per year. The initial *backstop price* is taken from Manne *et al.* (1995) and is set equal to \$108.2/boe.

In addition to the unit costs of production specified in equation (1), there are costs of transportation*, distribution etc*. Refining and transportation costs for oil are calculated from ECON (1990). The costs of transportation and distribution of natural gas in OECD-Europe are taken from Golombek *et al.* (1995). Due to lack of data, we assume that the costs of national transportation, distribution, storage and load balancing of natural gas are the same in Rest-OECD and Non-OECD as in OECD-Europe. We further assume that there are no costs of international transportation of gas outside OECD, while for Rest-OECD we have taken account of the costs of LNG transport to Japan and the natural gas trade in North America. The costs of transportation of coal are based on ECON (1990). Finally we assume that the costs of distribution of oil and coal are half the costs of distribution of natural gas. Even if these costs differ across regions initially, we assume that they are harmonised after 40 years to the average global level, using consumption figures in 1994 from BP (1995) as weights.
A market rate of 7% is used as a *discount rate* in all markets. All data are presented below.

Table A1. GDP growth rates, in per cent.

	1995 2004	2005 2014	2015 2024	2025 2034	2035 2044	2045 2054	2055 2064	2065 2074	2075 2084	2085 2094	2095 2104	2105 2114	2115 2124	2125 2134
OECD-Europe	2.2	1.9	1.6	1.4	1.3	1.2	1.1	1.05	1.0	0.95	0.9	0.85	0.8	0.75
Rest-OECD	2.8	2.5	2.2	1.9	1.6	1.4	1.2	1.1	1.0	0.95	0.9	0.85	0.8	0.75
EIT	2.8	2.5	2.2	1.9	1.6	1.4	1.2	1.1	1.0	0.95	0.9	0.85	0.8	0.75
Non-AnnexB	3.6	3.4	3.2	2.95	2.7	2.4	2.2	2.0	1.8	1.7	1.6	1.45	1.3	1.2

Table A2. Price and income elasticities

	OECD	Non-OECD
Direct price elasticities	-0.90	-0.75
Cross price elasticities	0.10	0.10
Income elasticities	0.50	0.60

Table A3. Existing taxes on fossil fuels in 1994, 1994$/boe

	OECD-Europe	Rest-OECD	EIT	Non-Annex B
Tax on oil	34.02	12.21	3.52	3.52
Tax on gas	3.60	0.00	0.00	0.00
Tax on coal	0.74	0.00	0.00	0.00

Table A4. Constant parameter in demand function, ω, mtoe/year

	Oil	Natural gas	Coal
OECD-Europe	13,506	2,524	1,596
Rest-OECD	17,735	6,126	3,465
EIT	1.596	2,128	1,160
Non-Annex B	7,312	1,992	3,465

Table A5. Parameters in the cost functions

$C = C_0 e^{\eta A - \tau t}$	initial unit cost of prod., C_0, 1994$/boe	technological change, τ, per cent	convexity parameter, η
oil			
OPEC	3.32	1.0	0.023
Fringe	10.91	2.0 → 1.0	0.025
natural gas			
OECD-Europe	7.00	1.0	0.122
Rest-OECD	5.45	1.0	0.088
Non-OECD	5.53	1.0	0.017
coal	8.80	0.5	--
backstop technology	108.20	1.4	--

Table A6: Initial unit costs of transportation, distribution and refining, 1994$/boe

	OECD-Europe	Rest-OECD	EIT	Non-Annex B
oil				
transportation	1.64	1.53	0.68	1.18
distribution	3.4	3.4	3.4	3.4
refining costs	2.28	2.53	2.16	2.16
total	7.32	7.46	6.24	6.74
natural gas				
transportation	5.1	3.16	2.1	2.1
distribution	6.8	6.8	6.8	6.8
storing and load balancing	2.0	2.0	2.0	2.0
total	13.9	11.96	10.9	10.9
coal				
transportation	3.79	1.43	0.73	0.51
distribution	3.4	3.4	3.4	3.4
total	7.19	4.83	4.13	3.91