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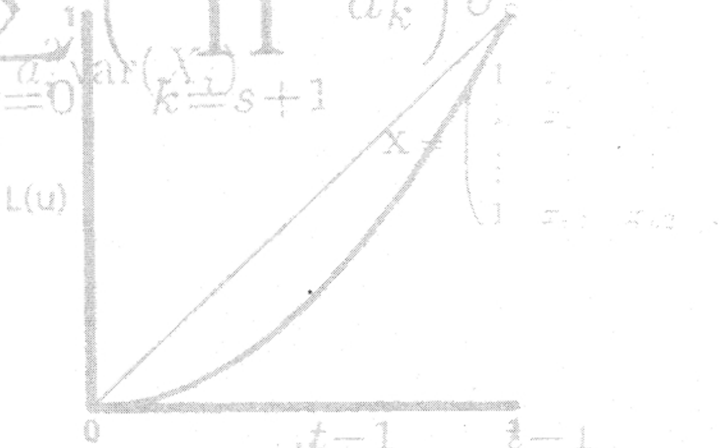

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Market Power, International CO_2 Taxation and Petroleum Wealth

Abstract:
This paper studies the effects on fossil fuel prices, extraction paths and petroleum wealth of an international carbon tax on fossil fuel consumption. We present an intertemporal equilibrium model for fossil fuels, where the main focus is on the oil market. The impacts of a global carbon tax of $10 per barrel of oil depend heavily on the market structure in the oil market. If OPEC acts as a cartel, they reduce their production to maintain the oil price. Thus, the effects on the oil wealth of the competitive fringe is minor, while OPEC's oil wealth is considerably reduced. This may explain the difference in attitudes of OPEC and other oil producing countries to international global warming negotiations. If, on the other side, the oil market is competitive, the highest relative reductions in the oil wealth are to be found among non-OPEC producers.

Keywords: International Carbon Taxes, Exhaustible Resources, Petroleum Wealth.

JEL classification: H23, Q30, Q40.

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1. Introduction

The greenhouse effect is today recognised as a severe threat to our global environment, see IPCC (1995). Carbon dioxide (CO_2) is the most important greenhouse gas, and has therefore been in the focus of debate. The main source of anthropogenic CO_2 emissions is the combustion of fossil fuels, i.e., natural gas, oil and coal. A country with large reserves of fossil fuels may therefore influence the accumulation of CO_2 in the atmosphere. On the other hand, an international treaty on CO_2 emissions reductions will influence the markets of fossil fuels, and hence the nation's income from the reserves. In this paper we focus on the latter problem, and study how an international carbon tax on the consumption of fossil fuels effects the petroleum wealth of fossil fuel producers. Most studies analysing the costs of emissions reductions ignore the reduction in the petroleum wealth. National studies of the costs of carbon abatement often focus on introducing a unilateral tax on a national level (see, e.g., Hoeller *et al.* (1992) for a survey), and do not take into account price effects in international markets if the tax is imposed in other countries too. An international carbon tax, where the tax revenue is collected by the governments of the consuming countries, has a distributional effect between fossil fuel producers and consumer countries.[1] This may prove to be a significant cost for many oil and gas exporting countries. One of the first international studies concerned with the distributional issue of a carbon tax, is Whalley and Wigle (1991).

To determine the effects of a global carbon tax, we are focusing on two important features of the fossil fuel markets, i.e., market power and dynamic behaviour. These features have earlier been included in theoretical analyses of fossil fuel markets (see e.g. Ulph (1982)). However, the theoretical models are too complex to give sufficient knowledge about the impact of a carbon tax. On the other hand, as far as we know no numerical studies have been performed combining market power and dynamic behaviour, in order to study the effects of a carbon tax.[2] Hence, our contribution is one of the first including these important issues.

The oil market, which will be in focus in this paper, is dominated by OPEC, and the consequences of a carbon tax is very much dependent on the reaction of the cartel. To illustrate this point, we have modelled the oil market in two different ways, depending on the market power of OPEC. In the first

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[1] Alternatively, the tax could be charged by an international agency, and the the revenue reimbursed to the countries according to some specified criteria. This would probably still give a significant cost to oil and gas producing countries.

[2] Dahl and Yücel (1995) combine dynamic behaviour and market power in a study of different policies for increasing energy security in the USA.

model, the oil market consists of a cartel and a fringe, where all producers act as Cournot players. In the other model, the oil market is assumed to be competitive, i.e., OPEC no longer acts as a cartel. This could either be that OPEC has been formally disorganised, or that the member countries in fact are operating on their own, ignoring their qoute dicipline. As we will see, OPECs reaction to a carbon tax is very dissimilar in the two cases.

From market theory, we know that in a competitive *static* market, the introduction of a tax will generally establish a new market equilibrium with a higher consumer price and lower producer price compared to the original equilibrium. Thus, both consumers and producers bear some of the tax burden, and the share is determined by the demand and supply elasticities.[3] However, to fully analyse the market of an exhaustible resource, the analysis should be *dynamic* to cover the intertemporal aspects. In a dynamic model of exhaustible resources, the supply is depending on (expected) market conditions in future periods, and the impacts on the consumer and producer prices of a tax cannot be *separately* determined in each period. Dasgupta and Heal (1979) shows within a traditional Hotelling model that introducing a unit tax in a competitive market of an exhaustible resource may have counterintuitive impacts in the longer term. Initially, the tax burden is shared between producers and consumers, however, after some time both the producer and the consumer price is reduced. The reason is that in order to sell the whole resource, the consumer price must either not change at all, or it must sometime fall below the original price path. Thus, an analysis ignoring the dynamic aspects of a fossil fuel market, is in danger of overlooking an important factor of the producers' behaviour. In this study we find that the intertemporal element is crucial to understand the response of competitive producers, whereas OPECs reaction as a cartel is mainly determined by static market conditions. Taxation of exhaustible resources has also been examined theoretically in, e.g., Burness (1976), who considered the traditional Hotelling model, and Heaps (1985) and Lasserre (1991), who examined more extended models as well.

This particular, intertemporal feature of fossil fuel markets has lead Sinclair (1992), as one of the first studies to combine the theory of exhaustible resources with the theory of greenhouse externalities, to state that an optimal ad valorem carbon tax should be falling over time in order to encourage producers to delay depletion. However, as shown in Ulph and Ulph (1994) and Hoel and Kverndokk (1996), the issue of an optimal carbon tax is more complex.

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[3] For a study on the distributional effects of carbon taxes on consumer and producer prices within a static model, see Berger *et al.* (1992).

In empirical energy models, the dynamic aspects associated with the imposition of a carbon tax are still often ignored. In dynamic models, the oil price is usually set exogenously. Hence, it is not possible to determine within the model how a tax will be shared between producers and consumers. Some exceptions are however GREEN (Burniaux *et al.* 1992), an extended version of Global 2100 (Manne and Rutherford 1994) and MERGE (Manne *et al.* 1995). In GREEN the oil price is endogenous. However, the supply side is modelled as being independent of future expectations. Hence, the present extraction is not changed by anticipations of future carbon taxes. This means that the supply function is not fully intertemporal (see Burniaux *et al.* (1992)). One of the first intertemporal energy models, a general equilibrium version of Global 2100, is presented in Manne and Rutherford (1994). But in the paper they focus on specific stabilisation goals and not on carbon taxes. Further, the oil market is modelled as a competitive market. MERGE is an integrated assessment model including an intertemporal energy module. Emissions, concentrations and temperature change as well as costs and benefits are analysed under five alternative policy scenarios in the MERGE model, but no attention is paid to the impacts on petroleum prices or petroleum wealth (see Manne *et al.* (1995)). Finally, Rosendahl (1996) presents one of the first numerical analyses on the impacts of CO_2 taxes on the petroleum wealth within an intertemporal energy model. He concentrates on a single fossil fuel, oil, and studies the consequences for the oil wealth of an average cost producer and for a high cost Non-OPEC producer, of different international carbon taxes, assuming perfect competition in the oil market, and no interaction with other markets.

The aim of this paper is to analyse the impacts on the petroleum wealths of fossil fuel producers of introducing an international carbon tax within an intertemporal equilibrium model for the global energy markets. In particular, we are interested in the impacts on the oil wealth of OPEC and Non-OPEC producers of a global carbon tax under different assumptions about the market power of OPEC, e.g., how would the effects of international carbon taxation differ with a strong OPEC cartel compared to a situation where the cartel has fallen apart? Compared to Rosendahl (1996), who only studies one fossil fuel, we model the markets for natural gas, oil and coal. Moreover, extraction costs are assumed to be functions of accumulated production and time (through technological change). While the main focus of the paper is the oil market, results are also given for different regional gas markets.

The paper is structured in the following way. In section 2 we describe the model. Numerical specifications are given in section 3, and simulation results are presented in sections 4 and 5. The paper ends with sensitivity analyses and conclusions.

2. Description of the model

We are modelling the international markets for fossil fuels in an intertemporal and deterministic way. 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 *demand* for fossil fuels is divided into three regions. First, we distinguish between OECD and Non-OECD. Second, we divide OECD into OECD-Europe and Rest-OECD because of market conditions for natural gas, which will be explained later.

To represent the demand for the three fossil fuels oil, gas and coal, we use log-linear demand functions. The demand for each fuel is a decreasing function of the price of that fuel and an increasing function of the prices of the two other fossil fuels. Hence, the three fuels are imperfect substitutes of each other. Moreover, we assume that there exists a single carbon-free backstop technology (e.g., solar, wind or biomass) which serves as a perfect substitute for fossil fuels. This means that if the consumer price of, e.g., oil exceeds this backstop price, then no oil will be demanded. The backstop technology is available in copious supply at a fixed price at each point of time in all regions. Over time, however, we assume that the backstop price is reduced by a constant rate to reflect technological change. Finally, the demand function may change exogenously over time to reflect income effects due to economic growth.

Carbon taxes are levied on consumption of fossil fuels globally, where the relative proportions depends on the carbon content of the fuel. Moreover, there may already exists other taxes or subsidies on consumption of fuels in each region. Hence, for the demand, the relevant price of a specific fuel in a specific region is the sum of the producer price, costs due to transportation, distribution and refining and the average tax (subsidies are considered as negative taxes). A carbon tax will be added to existing taxes. However, as a result of a more integrated world economy, we assume that existing energy taxes and unit costs due to transportation, distribution and refining for each fuel will be harmonised after 40 years to a global weighted average, using initial demand as weights.

The *maximum producer prices* in the different regional markets are defined as the backstop price minus additional regional costs due to transportation, distribution and refining of the fossil fuels, and regional fuel and carbon taxes. When energy taxes and the costs of transportation, distribution and refining are harmonised, the maximum producer price for each fuel will be equal within every region.

As fossil fuels are non-renewable resources, their allocation over time is important for the suppliers. Extracting one more unit today changes the *supply* conditions in the future. Hence, a rational producer will not only consider the current price or market condition before the optimal supply of today is chosen. We therefore model the supply of fossil fuels in an intertemporal way, where the producers maximise the present value of their resource wealth.

To analyse the importance of market power, the international *oil market* is modelled in two different ways; as a market with a cartel (corresponding to OPEC) and a competitive fringe on the supply side, and as a competitive market with low cost producers (OPEC) and high cost producers (Non-OPEC). While the first model is an approximation to the current situation, the second model may illustrate what can happen if the OPEC cartel falls apart.

In the first specification, the fringe always considers the oil price path as given, while the cartel regards the price as a function of its supply. Hence, the marginal revenue for the fringe is equal to the price, whereas for the cartel marginal revenue is in general less than the price. There are at least two different methods of modelling the supply in an intertemporal way in this case, either using a Cournot approach or a Stackelberg approach. The former assumes that both the fringe producers and the cartel take the supply of all other producers as given when deciding their own production profile (Salant 1976). 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. Thus, a powerful cartel would obviously follow the latter strategy if feasible. However, as is shown by Ulph (1982), the Stackelberg equilibrium may be dynamically or time inconsistent. Hence, we choose to concentrate on the Nash-Cournot model of a dominant firm, using the term of Salant (1976), to calculate the open loop solution of the game.[4]

The cost functions of both the cartel and the fringe are assumed to be increasing functions of cumulative production. Instead of considering their resources as strictly exhaustible, we assume that unit costs approach infinity as cumulative production approaches infinity. Hence, with a finite backstop price the economic reserves are finite (see, e.g., Heal 1976). The scarcity rent of a producer then reflects that extracting one more unit today increases costs tomorrow. Thus, this is a model of economic exhaustion (zero long-term scarcity rent) rather than physical exhaustion. The cost level of the two producer groups differs, reflecting that extraction costs in OPEC-countries generally are lower than in the rest of the world. Furthermore, one of the main reasons behind the low oil prices the last decade is probably technological change. We therefore assume that unit costs are reduced by a constant rate each year, independent of production. This means that over time unit costs may be reduced or increased, depending on the production rate.

Both the cartel and the fringe maximise the present value of their resource wealth over time, taking the supply of the other as given. It follows that the fringe also takes the price as given, whereas the cartel regards the price as a function of its own supply. In equilibrium, then, as long as the fringe produces, the price change over time must equal the scarcity rent times the discount rate, minus the unit cost times the technological rate of change (see Appendix 1). The first part reflects the standard Hotelling rule on price increase based on alternative resource allocations, while the second part reflects that the price does not have to increase that fast in optimum as the costs are falling due to technological change. If this condition is not satisfied, it is optimal for the fringe producers to delay or accelerate extraction, as this will increase the present value of the resource. Similarly, as long as the cartel produces, the change in its marginal revenue over time must equal the scarcity rent times the discount rate, minus the unit cost times the technological rate of change. If not, the cartel may increase the value of its resource by allocating it's extraction backwards or forwards in time.

The same cost conditions are employed when the oil market is modelled as a competitive market. Thus, the only difference between the two oil models is the market structure. With perfect competition, the marginal revenue for OPEC producers is equal to the price.

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[4] It can be shown that this Nash-equilibrium is time consistent but not subgame perfect, see, e.g., Hoel (1992).

Because of large transport costs, *natural gas* is mainly traded in regional markets. As we are particularly interested in the impact on producer prices in Europe, OECD-Europe is considered as a single region. The rest of the OECD is taken together, despite separate markets in North-America and the Pacific area. In this region the gas price and demand must be viewed as an average of the prices and the demand in the different gas markets, where North-America is clearly dominating. The same applies to Non-OECD, where the former Soviet Union is a dominating market. The oil market is the main focus in this paper. Therefore, we simplify and model the gas markets as competitive.

As for oil, extraction costs for gas are assumed to be increasing in cumulative production, so that costs approach infinity as cumulative production approaches infinity. The costs may differ between the regions. Moreover, an exogenous technological change occurs in gas extraction too.

Table 1. The production side of the model

Oil	Natural gas	Coal
International market. Alt. 1: Nash-Cournot approach: OPEC Competitive fringe Alt. 2: Perfect competition Low cost producers High cost producers	Regional competitive markets: OECD Europe Rest-OECD Non-OECD Trade only within regions	International competitive market
Unit costs increasing in accumulated production, decreasing in technological change	Unit costs increasing in accumulated production, decreasing in technological change	Unit costs decreasing in technological change

Table 1 summarises the production side of the model, while the model equations are given in Appendix 1.

To study CO_2 emissions from fossil fuel combustion as well as substitution effects, the *coal market* is also modelled. It is considered as an international market. However because the coal resources in the world are huge compared to oil and gas, and we are mainly concerned with the impacts on oil and gas prices and the petroleum wealths, we simply assume that the producer price of coal is fixed at each point of time. However, the price is exogenously reduced over time as a result of technological change.

3. Numerical specifications

3.1 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.[5] 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

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[5] The definition of AEEI implies the relation

$$\mathrm{GDP} = k\mathrm{E} * \mathrm{AEEI} \Rightarrow \frac{\dot{\mathrm{GDP}}}{\mathrm{GDP}} = \frac{\dot{\mathrm{E}}}{\mathrm{E}} + \frac{\dot{\mathrm{AEEI}}}{\mathrm{AEEI}}$$

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

$$\varepsilon l = \frac{\dot{\mathrm{E}}/\mathrm{E}}{\dot{\mathrm{GDP}}/\mathrm{GDP}} \Rightarrow \varepsilon l = \frac{\dot{\mathrm{GDP}}/\mathrm{GDP} - \dot{\mathrm{AEEI}}/\mathrm{AEEI}}{\dot{\mathrm{GDP}}/\mathrm{GDP}}$$

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 (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 (1994).

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

3.2 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.[6] 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

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

gas to be regarded as economically recoverable, the convexity parameter is determined by using the cost function without technology change.

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

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 1.5% 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 in Appendix 2.

3.3 The carbon tax

If a climate agreement imposing a global carbon tax is agreed upon, it is difficult to know how large such a tax eventually will be, and how it will evolve over time. However, both the US Administration and the EU have made proposals of specific carbon/energy taxes, which are not imposed, but may give rough estimates of possible sizes of a global carbon tax. The US proposal made by the Clinton Administration in 1993, which was opposed by the Congress, suggested a tax of about \$3.2 per barrel of oil.[7] The EU proposal suggested originally that a combined carbon/energy tax should increase from \$3 per barrel of oil in 1993 to \$10 in the year 2000. A comparison of several global carbon/energy models presented in Dean and Hoeller (1992), may also indicate relevant carbon tax levels. Focusing on the average of the four dynamic, long-term models that are studied, requires carbon taxes in the OECD area rising from about \$15 per barrel of oil in the year 2000 to about \$25 in 2010 to achieve the medium reduction scenario.[8]

In this study we consider a carbon tax of \$10 per barrel of oil, corresponding to \$90.3 per ton of carbon, which is set according to the carbon content of the different fuels. Moreover, the tax is assumed to be constant over time. For natural gas this means a tax of 7.1\$/boe, and in the coal market the tax is 12.4\$/boe (carbon coefficients are taken from Manne and Richels 1990). To study the impacts of a global carbon tax, results are presented for the two different assumptions of OPEC behaviour in *reference scenarios* where there are no carbon taxes, and in *tax scenarios* where the carbon tax is introduced globally.

Simulations were carried out for the time period 1995-2135 with ten year periods, i.e., 14 periods, using the GAMS/MINOS system (see Brooke *et al.* 1992). Thus the result in each period is the average over the ten years. In the graphs below, the results for the year 2000 is therefore the average over the period 1995-2005 etc.

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[7] The tax was actually intended to be based on the BTU content of various energy sources, and was therefore an energy tax rather than a carbon tax.

[8] The referred scenario consists of a reduction (from the Business as Usual path) in the rate of growth of carbon emissions by 2% per annum in each region, and would require absolute cuts in emissions in the OECD and the former Soviet Union, while allowing some continued, albeit very low growth elsewhere (see Dean and Hoeller 1992).

4. OPEC acts as a cartel

4.1 The reference scenario

Price and extraction paths for the *oil market* in the reference scenario are presented in the figures 1 and 2. The producer price of oil increases from $21.2 per barrel in the first period to its maximum at $39 in 2040, see figure 1. This is the period when the price reaches the maximum producer price set by the backstop price, energy taxes, and costs of transportation, distribution and refining. Thus, from then on, the fall in the producer price of oil is determined by the rate of technological change for the backstop technology. The price development in the first two periods corresponds well with the assumptions made by IEA (1995c) which gives a price interval from $18-28 in 2010. Figure 1 also shows the unit costs of production for OPEC and the competitive fringe. While the unit costs of OPEC is $3.5 per barrel of oil over the first period, the corresponding cost for the fringe is $12.0. The increase in costs over time is higher for the fringe than for OPEC, reflecting a higher production in the fringe initially, as well as larger oil resources in OPEC which can be extracted at lower costs.

The production of OPEC and the competitive fringe are given in figure 2. Total production in 2000 is 3,067 million tonnes of oil (mtoe/year), where 34% is produced in OPEC and 66% outside OPEC. Thus the share of OPEC is somewhat lower than the 1994 share of 41%, see BP (1995), which may be due to a more effective cartel in the model than in reality. This gives a daily OPEC production of 21 million barrels, while the OPEC quotas in 1995 are 24.5 million barrels per day. The production in the fringe is slightly rising for the first 40 years, before it starts falling, and reaches zero when the unit cost reaches the maximum producer price between 2040-50. OPEC also increases its production slightly in the beginning of the next century, and takes over the whole market when the fringe stops producing. The last period of OPEC production is 2060. From 2070 onwards, the price of the backstop technology is so low that further production is not economically viable. The accumulated production in OPEC and the fringe over the entire time horizon is 154,941 mtoe and 104,995 mtoe respectively. This is higher than proved reserves reported in BP (1995), which were 104,700 mtoe and 32,600 mtoe, but is reasonable due to technological change and increasing prices in our model.[9]

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[9] Proved reserves of oil in BP (1995) are defined as «those quantities which geological and engineering information indicate with reasonable certainty can be recovered in the future from known reservoirs under existing economic and operating conditions».

Figure 1. Price and unit cost in oil production - reference scenario

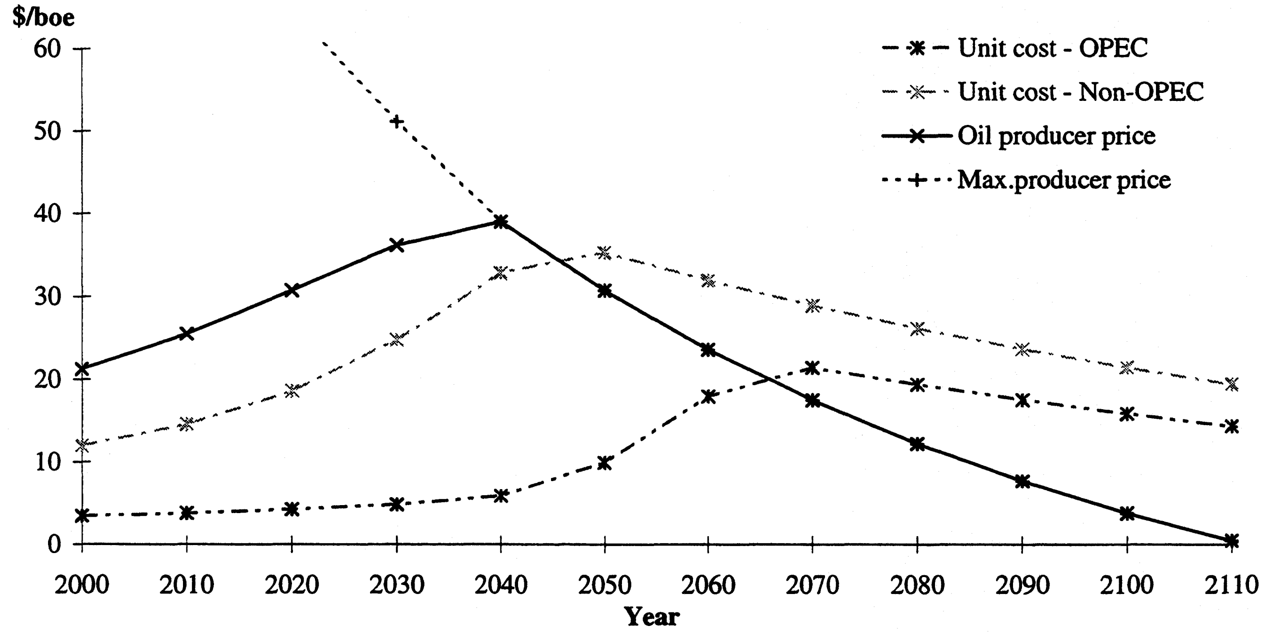
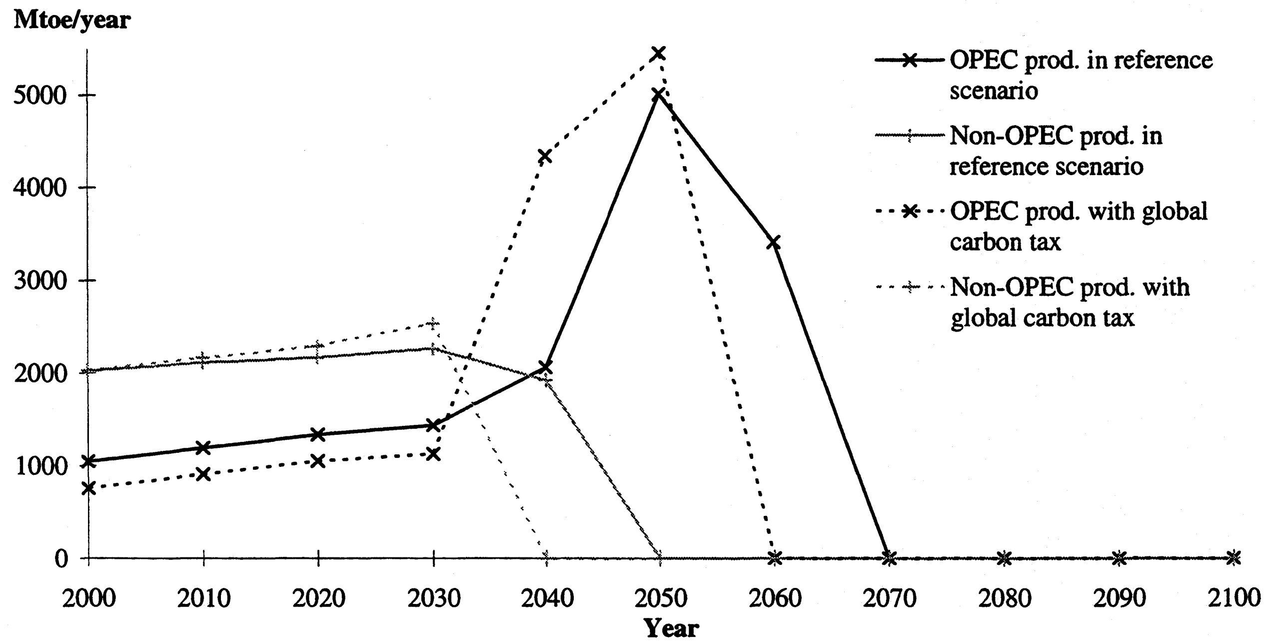
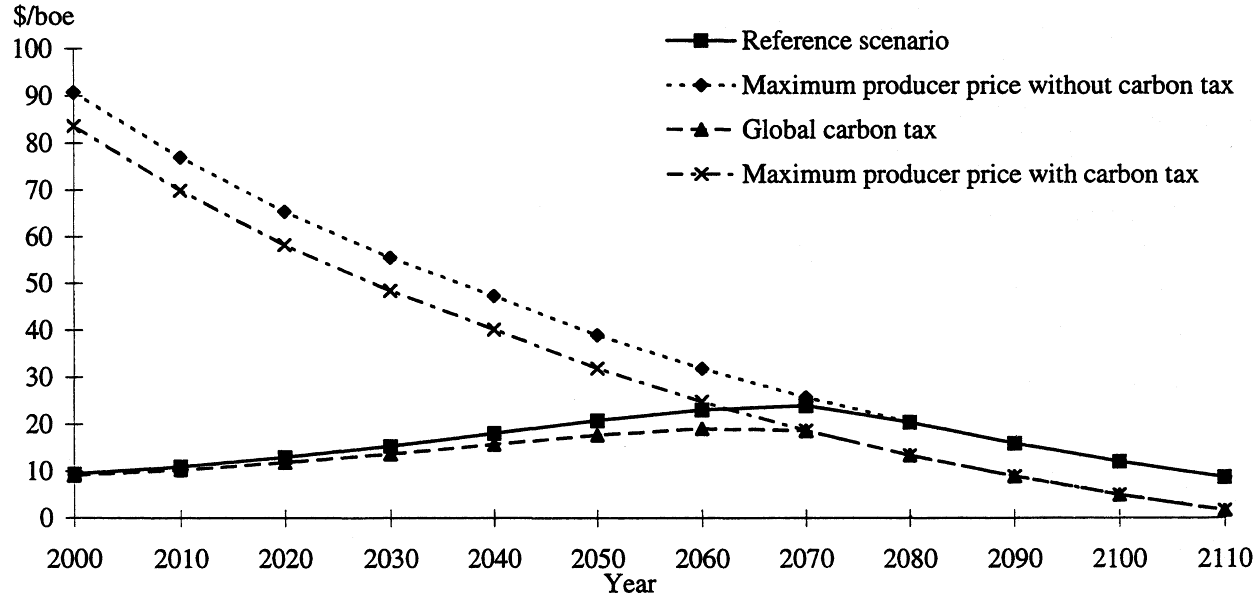


Figure 2. Production of oil in OPEC and Non-OPEC in different scenarios

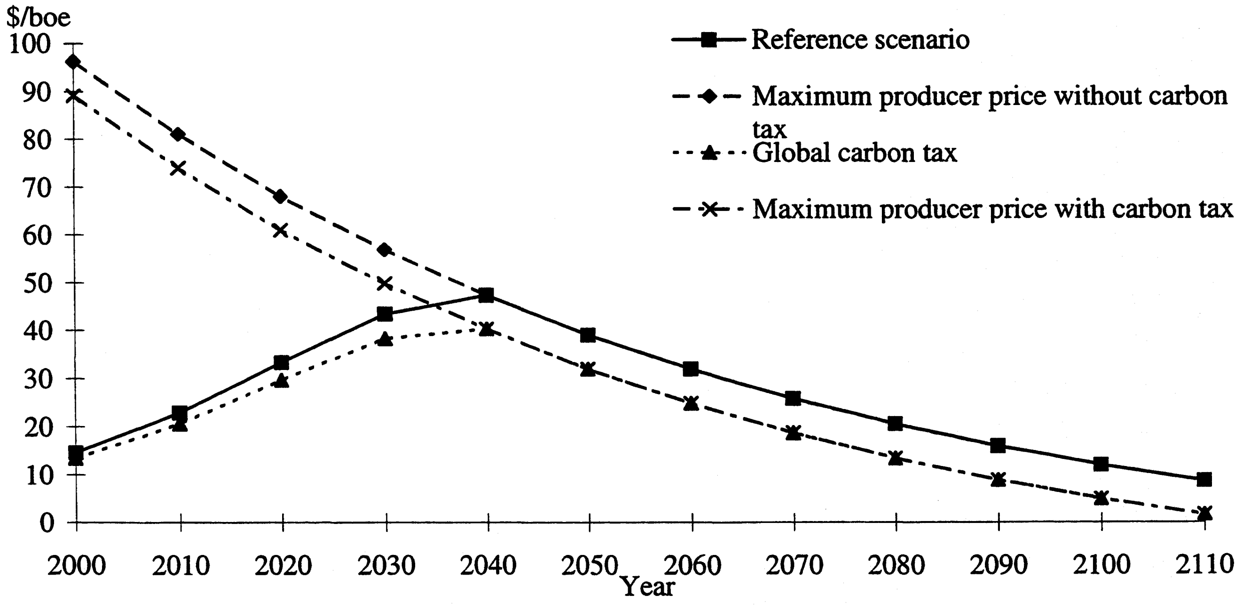


Rest-OECD has the highest consumption of oil initially, i.e., about 40% of the global consumption. OECD-Europe and Non-OECD consume about 21% and 39% in the same period. The corresponding shares of oil consumption when demand reaches its peak in 2050 are 35%, 22% and 43%. In this period, global oil production and consumption is 63% higher than in 2000. High economic growth combined with higher income elasticity than other regions are the main reasons for the large energy demand in Non-OECD. The share of OECD-Europe has also increased slightly, mainly because their energy taxes are reduced as they are harmonised across regions. Due to the harmonisation of energy taxes and additional costs, the long run regional maximum producer prices are equal, and all regions therefore consume oil as long as it is produced.

Figure 3A. Producer prices of natural gas in OECD-Europe



3B. Producer prices of natural gas in Rest-OECD



3C. Producer prices of natural gas in Non-OECD

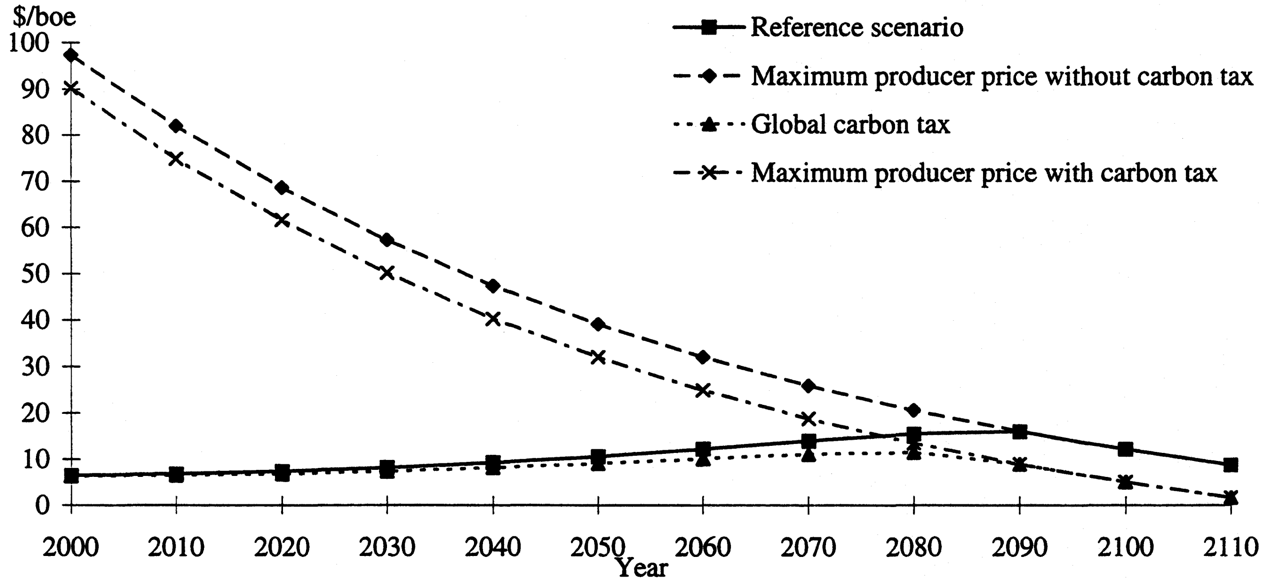


Figure 3 shows the producer prices in the three regional *natural gas markets*. Initially the producer price of natural gas is 14.6$/boe (2.68 $/MMBtu) in Rest-OECD, while it is 9.4$/boe (1.73 $/MMBtu) and 6.4$/boe (1.18 $/MMBtu) in OECD-Europe and Non-OECD respectively. The scarcity rent, the difference between the producer price and the unit cost, is highest in Rest-OECD. The reason for this is partly the relatively small gas resources in OECD compared to Non-OECD; total production over the entire time horizon is 25,207 mtoe, 22,323 mtoe and 160,529 mtoe in OECD-Europe,[10] Rest-OECD and Non-OECD respectively (which are all higher than proved reserves in BP 1995). The more scarce the resource is, the higher will the scarcity rent be *ceteris paribus*. In addition to this, demand for gas is higher in Rest-OECD than in OECD-Europe, which also explains the difference in scarcity rent and production between these regions, as no trade occurs between the regions.

The production of gas is given in figure 4. In OECD-Europe the production increases from 276 mtoe in 2000 to 335 mtoe in the peak period 2040. The production is higher in Rest-OECD, but falls from 646 mtoe in 2000 to 484 mtoe in 2030. Non-OECD produces 958 mtoe initially, and has both an increasing production over time and a longer period of production compared to the other regions. The reason is the large amount of relatively cheap gas resources in this region combined with no taxes. The consumption of gas in each region is equal to the production since there is trade only within the regions. 2030 is the last year of production in Rest-OECD, while gas is produced and consumed to 2070 in OECD-Europe, and 2080 in Non-OECD. As seen from figure 4, gas increases its importance in Non-OECD over time compared to the other regions.

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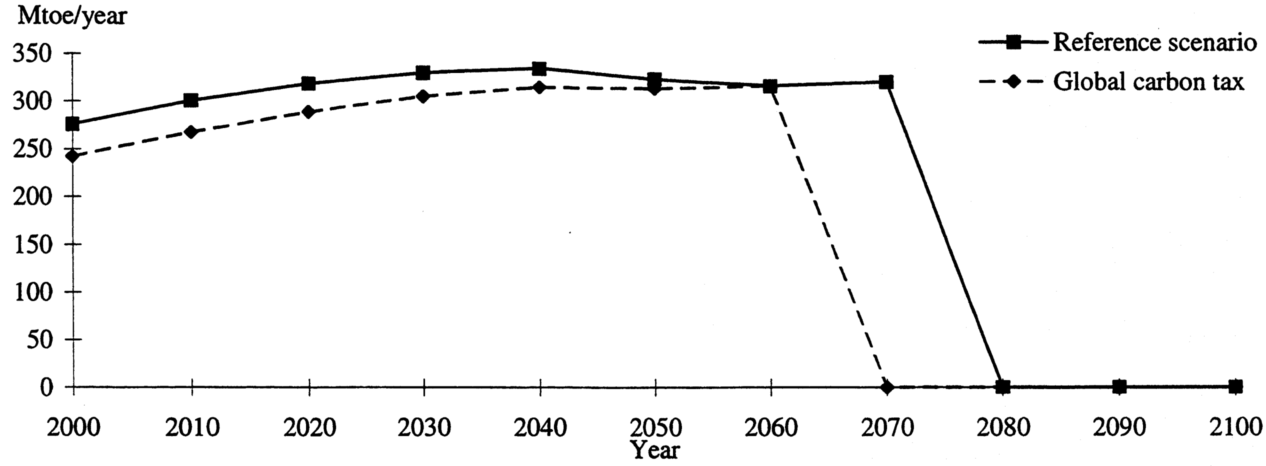
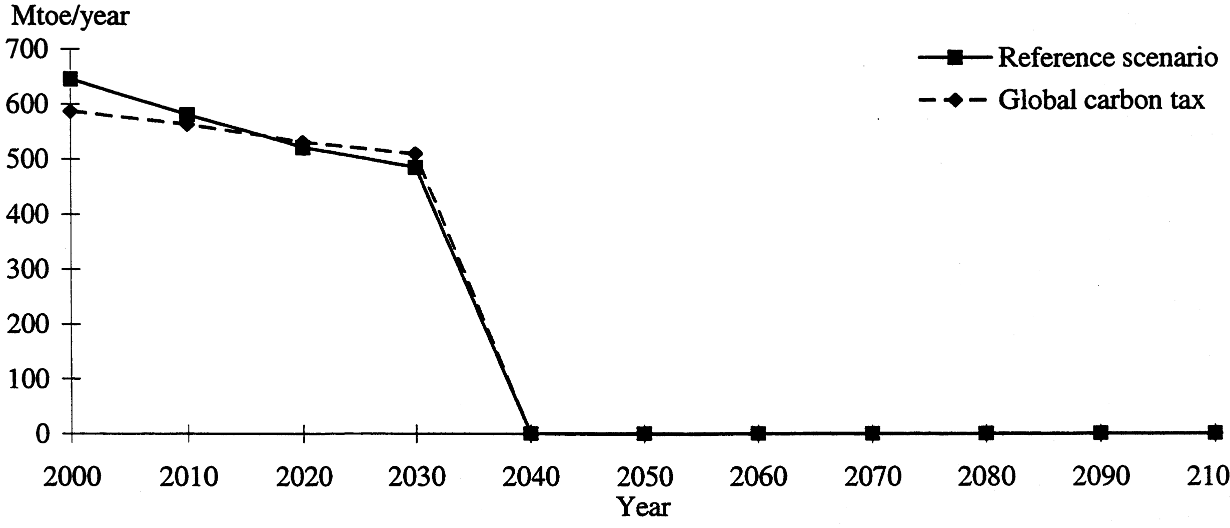
[10] Including exports from Russia and Algeria.

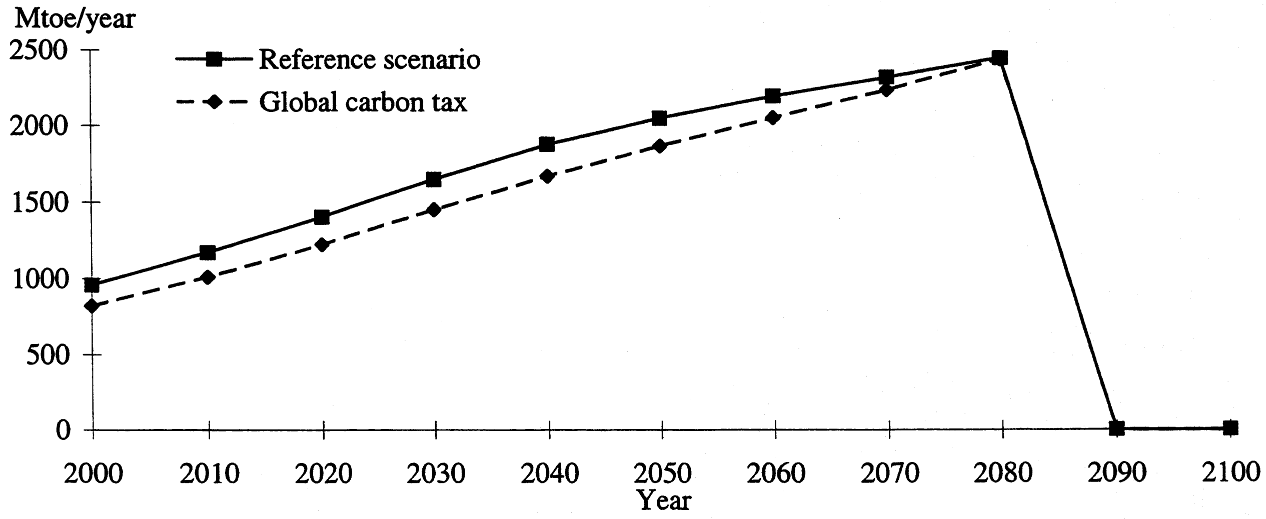
Figure 4A. Production of natural gas in OECD-Europe



4B. Production of natural gas in Rest-OECD



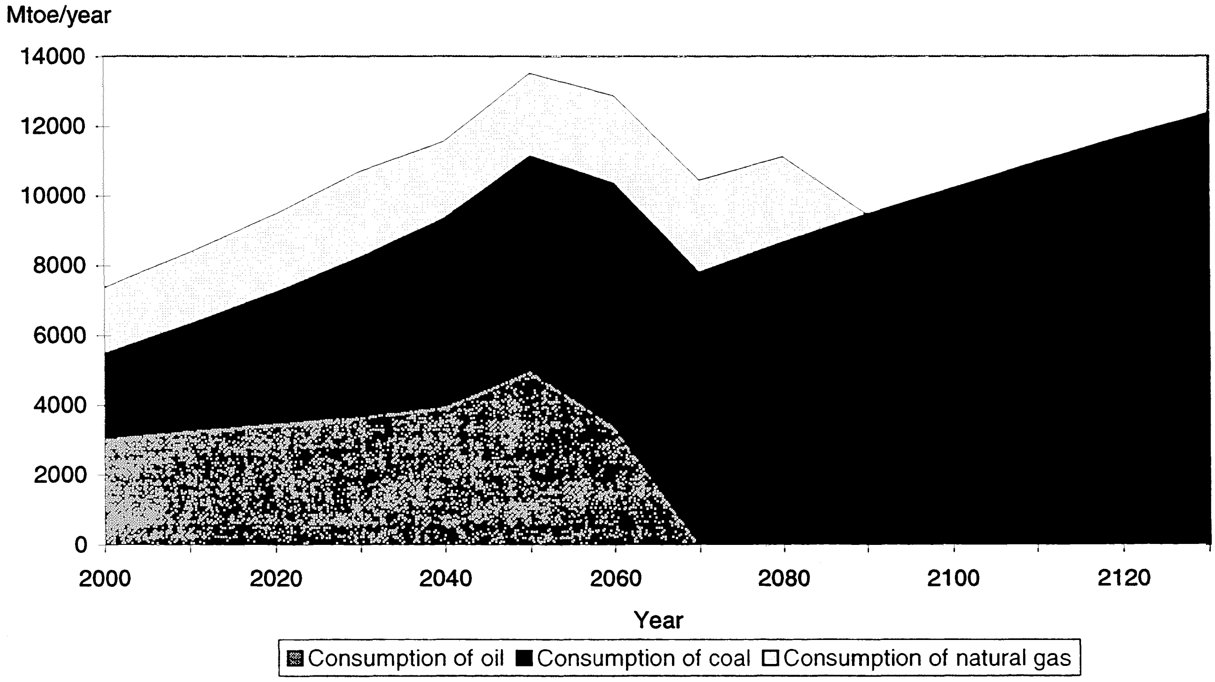
4C. Production of natural gas in Non-OECD



Global production of *coal*, which is equal to total consumption, increases from 2,411 mtoe/year in 2000 to 12,380 mtoe/year in 2130, an increase of 413%. Coal is produced and consumed over the entire time horizon, and will not be substituted by the backstop due to low prices and taxes. The accumulated production of coal over the time periods is 1,035,000 mtoe, which is almost the same as proved reserves reported in BP (1995). Initially, the relative share of coal consumption is 11.6% in OECD-Europe, 29.5% in Rest-OECD and 58.9% in Non-OECD. While the consumption increases in all regions over the time horizon, the highest increase is outside OECD due to higher economic growth and income elasticity. Thus in the last period the relative share of coal consumption across the regions has changed to 6.8%, 17.0% and 76.3%.

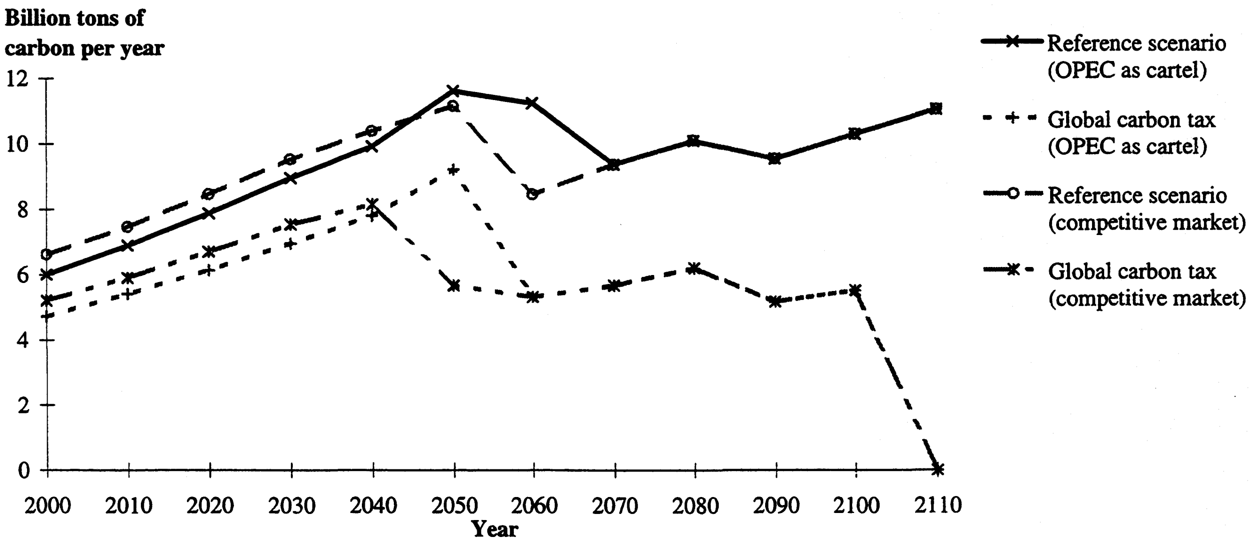
Figure 5 shows the *total consumption* of the three fossil fuels. Initially the share of oil is 41.7%, while the share of gas and coal is 25.5% and 32.8% respectively. The total fossil fuel consumption increases to the middle of the next century, but starts decreasing when the backstop becomes economically attractive. At the end, coal is the only fossil fuel consumed.

Figure 5. Consumption of fossil fuels in the reference scenario



Global *carbon emissions* are shown in figure 6. They increase from 6 billions tonnes of carbon per year in 2000, and peak at 11.6 billions in 2050. However, as oil consumption is gradually substituted by the backstop from 2050 to 2070, the emissions decrease in this period. Due to increasing coal consumption, the emissions rise thereafter, with a small drop from 2080 to 2090 when the backstop replaces natural gas globally. Our estimates agree with emission estimates from other long term studies to the middle of the next century, see, e.g., Dean and Hoeller (1992) and Cline (1992), and are in the lower range of the IPCC IS92 scenarios (IPCC 1992). However, opposed to our analysis, most other studies estimate increasing CO_2 emissions over the entire time horizon, mainly due to lack of exhaustibility constraints, backstop technologies or a falling backstop price.

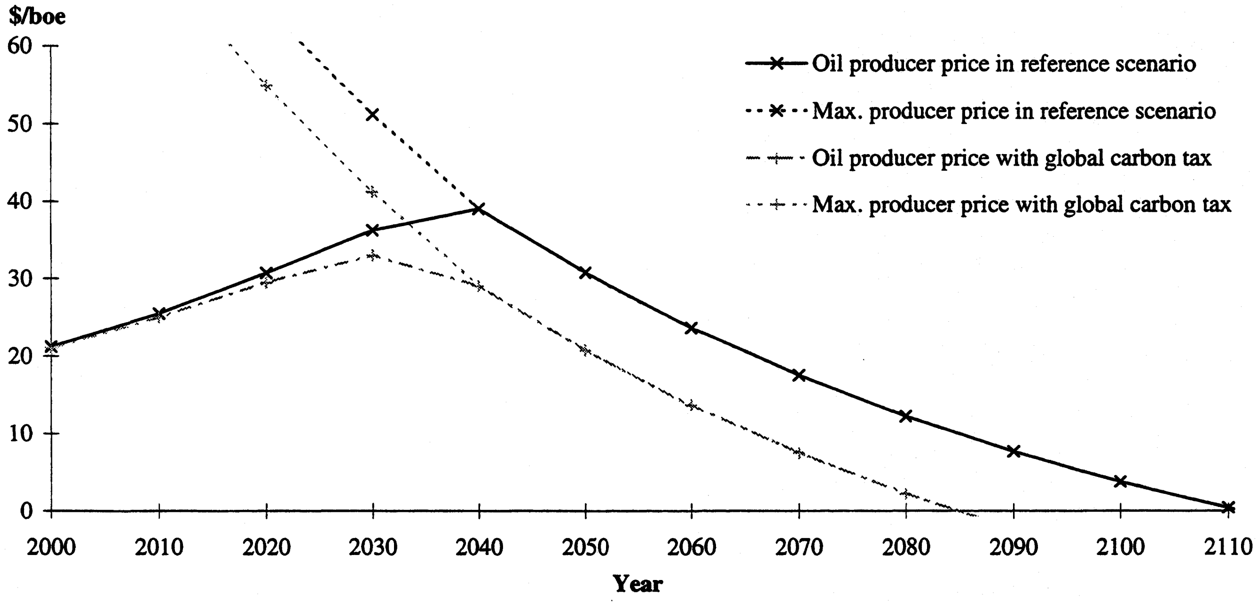
Figure 6. Global carbon emissions from fossil fuel combustion



4.2 Impacts in the oil market of a global carbon tax

When a global carbon tax of $10 per barrel of oil is introduced in all periods, we obtain a new dynamic equilibrium. In the oil market, the producer price of crude oil is reduced by merely $0.2 per barrel in the first period (see figure 7). Thus, the consumer price increases by $9.8 per barrel, i.e., the tax burden is initially born almost completely by the consumers. The explanation for this is not that oil demand is very inelastic. Total oil demand, and supply, actually falls by 9% initially. Hence, an explanation must be found on the supply side, as the producers find themselves decreasing extraction significantly although their price is almost unchanged. From figure 2 we see that OPEC's production is considerably reduced, whereas the fringe's production *increases* somewhat. To understand this, we have to look at two important aspects, i.e., the intertemporal supply and the role of OPEC.

Figure 7. Oil price in different scenarios



As the supply side is modelled intertemporally, the producers allocate the extraction of their oil according to present and future market conditions. Increased production in a specific period implies higher costs in future periods, and this induces the producers to restrain their extraction rate. The more rapid the price rises, the more profitable it is to restrain production in early periods. Thus, in order to understand the equilibrium in the first period, we must also focus on the equilibria in the other periods. Let us have a look at the new price path.

In figure 7 we see that the new equilibrium price path increases more slowly than the reference price path. With a carbon tax, the price reaches its peak level in 2030, when the new price is $3.2 per barrel less than in the reference case. Thus, until this period the carbon tax burden is born mainly by the consumers. In 2040 both price paths have reached their maximum producer price paths. Since the maximum producer price has fallen by $10 per barrel in the global carbon tax scenario, the producers bear the entire tax burden from 2040.

The fringe views the oil price as given. We can, therefore, use the price paths to explain its new production profile. We observed above that the slope of the new price path is lower than in the reference scenario, i.e., a carbon tax reduces the difference between future and current oil price. Hence, it is optimal for the fringe to produce relatively more in the first periods compared to the reference case, even though the producer price is somewhat reduced. We see this in figure 2, where the fringe moves its production profile nearer in time, and stops producing one period earlier than in the reference scenario. Thus, the intertemporal aspect is crucial in explaining the behaviour of the fringe. Further, as the producer price path is always below the original price path, total cumulative production for the fringe decreases (by 14%). The oil wealth of the fringe is reduced by around 8% due to the carbon tax.

OPEC is assumed to take the production path of the fringe as given. Then, the price in each period is a decreasing function of OPEC's production. Thus, when OPEC decides on its optimal production path, it has to weight increased production versus lower price, as well as increased production versus higher future costs, while the fringe only focuses on the latter. Both these factors induce OPEC to restrain the extraction rate, and explain why OPEC initially only produce about one third of total production in the reference scenario. In the carbon tax scenario we see that OPEC restrains production even more, particularly in the first periods, whereas in some later periods production is higher than in the reference scenario. Moreover, the oil price is mostly reduced in the latter periods.

In order to understand OPEC's initial behaviour, it is expedient to study the cartels oil rent, which can be split into a scarcity rent and a cartel rent. The former corresponds to the dynamic aspect, i.e., that production today increases costs in the future.[11] The cartel rent corresponds to OPEC's market power. In the first periods, we find that the oil rent is clearly dominated by the cartel rent. Initially, this rent is $16.0 per barrel, whereas the scarcity rent is merely $1.7. By looking at OPEC's cost curve in figure 1, we see that it is quite flat until around 2040. Hence, OPEC's costs in the near future are not very influenced by the initial production, and this explains why the scarcity rent is small. In the carbon tax scenario the scarcity rent in the year 2000 is reduced by $0.25. Thus, we conclude that OPEC's initial behaviour is not very influenced by the dynamic aspect, as opposed to the fringe. What is important for OPEC, is that their production affects the oil price. With almost constant unit costs, and a marginal change in fringe production, OPEC reacts to the carbon tax by restricting its production in order to retain the marginal revenue (net of taxes) at the same level as without the tax. In our model this implies almost the same producer price, which also could be demonstrated in a static model with similar demand functions.[12] It is important to stress that increases in consumer prices on gas and coal also contributes to this outcome.

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[11] For the fringe, this rent covers the complete oil rent.

[12] A recent study by Bråten and Golombek (1996) also finds a similar result within a static model. Their aim is to analyse OPEC's response to international climate agreements, where OPEC is either a leader or a follower in a game between OPEC and a group of countries having signed an international climate agreement.

From 2040 the fringe has no more valuable reserves, and it is optimal for OPEC to charge as high a price as possible, which is the maximum producer price. Now OPEC satisfies demand completely at this price as long as the unit cost do not exceed it. As the consumer price of oil in these periods is the same as without the carbon tax, and the coal and some gas consumer prices have increased in 2040 and 2050 compared to the reference scenario, the introduction of a carbon tax actually increases oil demand in these two periods.

Since OPEC acts to restrain its production, the impacts on OPEC's oil wealth is more dramatic than that of the fringe. Yet it is the best OPEC can achieve, given the production profile of the fringe. OPEC's oil wealth is reduced by around 23% (see Table 2 below), whereas its cumulative production is decreased by about 12%.

4.3 Impacts of a global carbon tax on the natural gas markets

The producer prices of natural gas in different scenarios are presented in figure 3. In all regions, the producer prices of gas are reduced under the carbon tax scenario. As in the oil market, the main burden falls on the consumers apart from in the last period of production.

The extraction rate of natural gas is reduced over the entire time horizon in the global tax regime in OECD-Europe and Non-OECD, and OECD-Europe stops producing natural gas one period earlier than in the reference scenario, see figure 4. The production profile in Rest-OECD is however different. While this region reduces its production compared to the reference scenario in the first two periods, it increases the production in 2020 and 2030. However, as the producer price path is always below the original price path, total cumulative production is reduced in all regions, with 19% in OECD-Europe, 8% in Non-OECD, and only 2% in Rest-OECD.

As in the oil market, a slower rise in the price compared to the reference scenario gives an incentive to move production nearer in time. Still, the production is initially lower under the tax scenario compared to the reference case for all gas producers. This may be explained by the substitution effects. The carbon tax will give relatively higher increases in the prices of gas and especially coal, than in the oil price, i.e., offsetting the fact that gas is a cleaner fuel, as oil has the highest price per boe initially. Thus, in the beginning, there will be a substitution in demand towards oil, while the effect on gas demand is less clear. However, the price of gas in Rest-OECD increases rapidly, and in 2020 and 2030, the consumer gas price in the reference scenario is higher than the consumer oil price. Moreover, a carbon tax increases gas prices less than oil and coal prices in absolute terms.

Thus in these periods, the relative increase in the consumer price of oil is higher than in the consumer price of gas, and there will be a large substitution in demand from coal and oil towards gas in this region when a carbon tax is introduced. This explains the increase in gas production in 2020 and 2030 in Rest-OECD.[13]

The resource wealths for the natural gas producers are reduced in all three regions. The greatest reduction is seen in Non-OECD (about 31%) and OECD-Europe (about 26%), while the wealth of producers in Rest-OECD is reduced by 18% (see Table 2). The reason that the largest reduction in gas wealth is found in Non-OECD is due to lower initial consumer price on natural gas. Thus, the carbon tax leads to a much higher percentage increase in the consumer price in this region. Hence demand falls and the producer price is reduced. One reason for the low reduction in the gas wealth in Rest-OECD is that this is the region with the highest scarcity rent initially. The same absolute reduction in producer price will reduce the resource wealth relatively most where the initial scarcity rent is smallest. The reduction in producer price caused by the carbon tax is not very different in Rest-OECD and the other regions. Further, Rest-OECD has a low reduction in accumulated production. However, the change in the production profile towards more production in later periods gives a lower gas wealth because of the discounting.

4.4 The impacts on global CO_2 emissions

A carbon tax of $10 per barrel of oil has quite large impacts on global CO_2 emissions in the model, especially in the long run, see figure 6. In 2000, emissions are 4.7 billion tonnes of carbon, which is a reduction of more than 21% compared to the reference scenario. But with a constant tax, emissions will increase and reach 9.2 billion tonnes in 2050. Thus, to reduce emissions below the current level in the long run, an increase in the tax is needed. Our emission reductions are in the range of other studies, see, e.g., Dean and Hoeller (1992) which compares six global energy-economy models. Even though the tax is constant, it may have a huge impact in the long run when there is a falling backstop price. Actually the tax decreases the maximum producer price below the coal price from 2100 onwards, making coal production not economically viable. Thus, there is no consumption or production of fossil fuels after this period, and consequently there are no carbon emissions from fossil fuels.

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[13] The change in the production path of Rest-OECD due to the carbon tax equals the traditional result in the theory for exhaustible resources for a given resource base, see, e.g., Dasgupta and Heal (1979).

5. Perfect competition in the oil market

5.1 The reference scenario

If the OPEC cartel breaks down and the *oil market* becomes a competitive market, it may have dramatic impacts on oil prices and production, see figures 8 and 9. Consider two groups of producers; low cost producers called OPEC, and high cost producers called Non-OPEC. In the competitive market, OPEC no longer restrains its production to keep a high oil price, and the OPEC production will be 3,968 mtoe in 2000, or almost 80 million barrels of oil per day, see figure 9. This high production level, which is almost 30% higher than the global production when OPEC acts as a cartel, brings the oil price down to $10.9 per boe in 2000. The price is too low for Non-OPEC producers to profit from oil production, and they will therefore *not* produce initially. However, as the oil price increases over time, Non-OPEC will enter the market. Due to the high initial production, OPEC producers terminate their production one period earlier than in the cartel model, while Non-OPEC produces one period longer. With perfect competition, accumulated production in OPEC is 6.5% higher than in the cartel model, while total Non-OPEC production is reduced by 7.5%. Furthermore, the oil wealth is reduced by 15% and 71% in OPEC and Non-OPEC, respectively. The large reduction in the oil wealth of Non-OPEC is mainly a result of the changed production profile, with the bulk of production in the later periods. This result confirms the conclusion in Salant (1976) that the fringe has the highest benefit from the formation of a cartel, since the fringe enjoys the benefits from a higher price, due to the market power of the cartel, without having to restrict supply.

A lower oil price gives a substitution in demand away from coal and gas towards oil. In the *gas markets* the prices are marginally lower, and so is production initially compared to the cartel model. However, production increases in the second half of the production period where the oil price follows the maximum producer price as in the cartel model, while the gas prices are somewhat lower. Compared to the cartel model, the gas wealths are reduced by 3% in Rest-OECD, and by 4% in OECD-Europe and Non-OECD.

In the *coal market*, production falls by 2-3.5% for the next 60 years. Thereafter, the production changes are only marginal.

Global *carbon emissions* from fossil fuel consumption are 0.6 billion tonnes of carbon or 10% higher in 2000 in this model compared to the former model, see figure 6. The emissions are higher in the first half of the next century, but falls below the emissions in the cartel model in 2050 and 2060 due to lower oil production in these periods. When oil is not produced, the emission paths are equal in the two models.

Figure 8. Oil price with competitive oil market

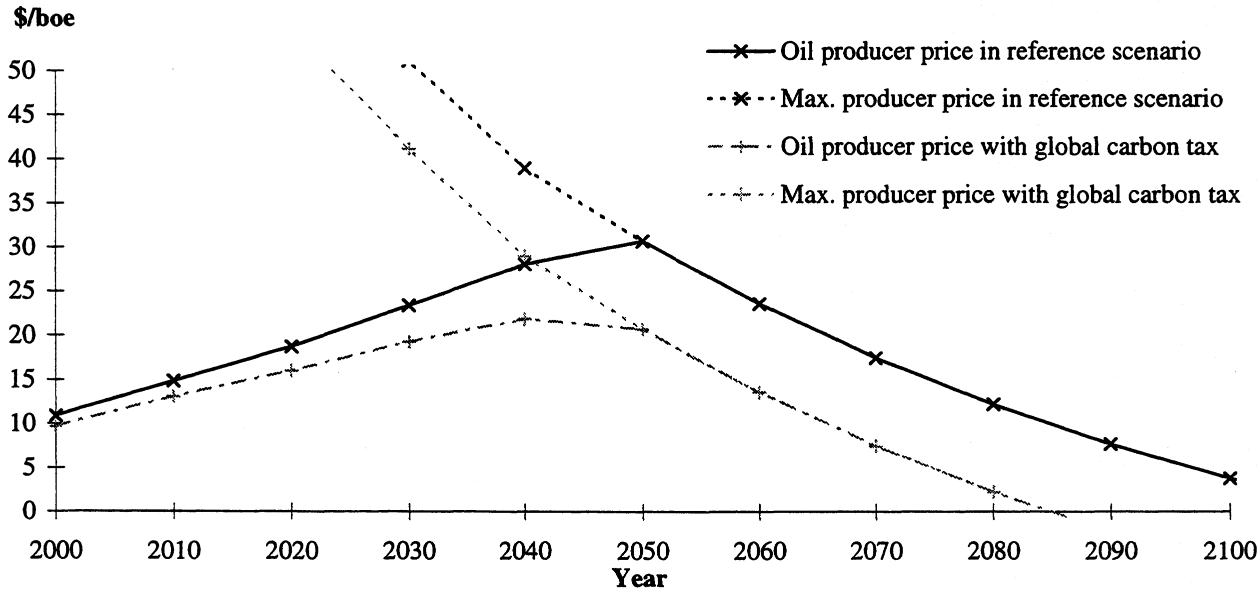
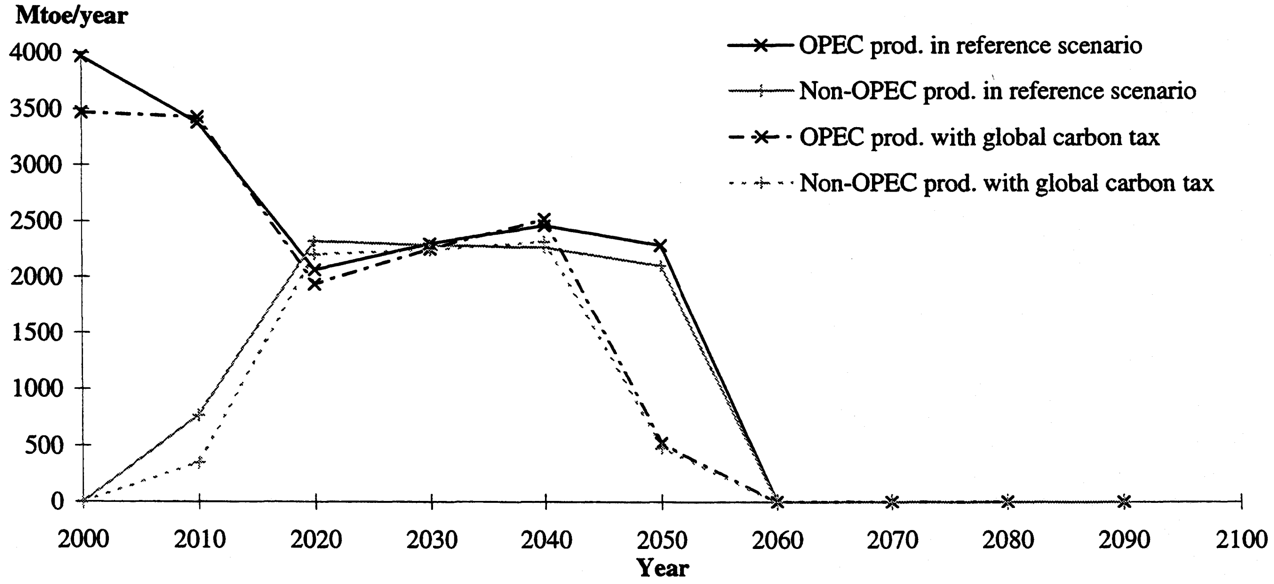


Figure 9. Production of oil in OPEC and Non-OPEC with competitive oil market



5.2 The global carbon tax scenario

Figures 8 and 9 show the consequences of a carbon tax in the competitive *oil market.* A carbon tax of $10 per boe reduces the initial oil price by $1.2, and the difference between the oil price in the reference scenario and the tax scenario is in general larger than in the cartel model. This means that a higher burden is born by the producers. As in the cartel model, the price increases less with a carbon tax than in the reference scenario. This gives incentives to move production to earlier periods, resulting in larger reductions in production in later periods. But oil production is mostly lower than in the reference scenario since the introduction of a tax gives no substitution from gas to oil because of the low oil price, i.e., a carbon tax gives a relative higher increase in the price of oil than in the price of gas. Actually, the consumer price of oil increases relatively more than the gas price after the introduction of a tax, giving a substitution in demand from oil to gas. The loss in oil wealth with a carbon tax is 25% for OPEC producers, and 39% for Non-OPEC (see Table 2). While this is a substantial increase in relative numbers for Non-OPEC compared to the cartel model, as no producers act to maintain the producer price with perfect competition, the loss in absolute numbers is not much higher as Non-OPEC's oil wealth is considerably lower in the competitive market model. Compared to the cartel model, OPEC does not reduce its production as much in the first periods, which means a smaller loss in OPEC's oil wealth in this model. However, this is offset by the fact that a larger tax burden is born by the producers. Hence, the relative impact on OPEC's oil wealth from a carbon tax is about the same in the two models. To sum up, the market structure does not make a big difference for OPEC producers when it comes to the relative impact on oil wealth from a carbon tax, while for Non-OPEC producers, the OPEC behaviour is of great importance.

These results can be compared to Rosendahl (1996). He found that the reduction in the oil wealth of an average oil producer in a competitive market of a global carbon tax of $10 per barrel, was 33-42%. Moreover, the Norwegian oil wealth was found to be reduced by 47-68%, because of higher unit costs and exogenous production profile. Thus, even if the losses in our study are a bit less than those found in Rosendahl (1996), which can partly be explained by lack of substitution effects in Rosendahl's partial model, this study confirms the major impact of a carbon tax on the oil wealths in a competitive market.

Due to the substitution in demand from oil to gas, the impacts on *gas wealths* from a carbon tax are marginally but insignificantly less in this model, compared to the cartel model.

With a carbon tax, the *carbon emissions* follow the same profile as in the reference case, however at a lower level. The reduction is, e.g., 21% initially, and the emissions peak one period earlier than in the reference case due to the low oil consumption in the last period of oil production.

Finally, table 2 summarises the impacts on the oil and gas wealths of the carbon tax in the two models.

Table 2. Percentage reductions in the petroleum wealth of fossil fuel producers in the tax scenario compared to the reference scenario

	OPEC acts as a cartel	Competitive oil market
Oil - OPEC	23%	25%
Oil - Fringe	8%	39%
Gas - OECD-Europe	26%	26%
Gas - Rest-OECD	18%	18%
Gas - Non-OECD	31%	31%

6. Sensitivity analyses

In analyses with a long time horizon, the uncertainties surrounding the parameters are huge. Therefore, sensitivity analyses are carried out to test the robustness of the model results. We concentrate on sensitivity analyses for the oil market in the cartel model.

A more pessimistic view of the future, at least from an environmentalist's point of view, may support a higher *backstop price*. Doubling the initial backstop price leads to a higher oil price. The oil price will also increase slightly for the first 50 years with a carbon tax, due to higher substitution in demand towards oil in this case. A higher backstop price will also increase the period of production, and therefore postpone the time periods when the oil price follows the maximum producer price, and the whole tax burden is born by producers. This reduces the effects of the carbon tax on the oil wealths, and Non-OPEC may actually gain by 0.5% from the carbon tax policy. Higher *technological change* in the backstop technology may be a more optimistic view of the future. However, increasing the rate of technological change from 1.5% to 2%, gives slightly higher losses for oil producers. Increasing the initial technological change for Non-OPEC producers to 5%, reduces the initial oil price in the reference scenario to $19 per barrel, and the unit costs for these producers actually falls from the first to the second period. However, the relative effects of the carbon tax remains. This is also true when the technological change in the oil market in the long run increases from 1% to 1.5%.

The model is more sensitive to changes in *price elasticities*. Increasing all cross price elasticities to 0.3, while keeping the direct price elasticities are unchanged, makes energy demand less sensitive to price changes.[14] Thus, the producer price of oil will be $0-3 higher the first 40 years with a tax due to higher substitution towards oil, especially from coal. The oil wealth of Non-OPEC will actually increase by 20% from this policy, while OPEC will face a loss of 2%. With cross price elasticities of 0.5, but higher direct price elasticities (in absolute value) such that the total price elasticity of energy demand remains unchanged, we obtain similar results, but with a slight increase in OPEC's oil wealth with the carbon tax policy. It can be argued that cross price elasticities should vary among the different fuel types as, e.g., gas and coal may be closer substitutes for each other than for oil. Increasing the cross price elasticities in the demand function for gas and the cross price elasticity between coal and gas in coal demand to 0.2, given that the total price elasticities are unchanged, reduces the losses in gas wealths, while there is little change in the oil market.

A lower *discount rate* will give a higher loss in oil wealth for Non-OPEC. For instance with a 5% discount rate, the loss in Non-OPEC will be 13%, while the OPEC loss is almost unchanged at 22%. The reason is that with a lower discount rate, the future counts more, and Non-OPEC moves the production profile nearer in time with a carbon tax. The loss for OPEC producers are less sensitive to the discount rate, as a tax make them increase production in the middle of their production period. Correspondingly, a 10% discount rate reduces the loss of Non-OPEC, while the OPEC loss increases slightly.

The shaping of the *carbon tax* policy has of course also impacts on the oil wealth. It may be reasonable that a carbon tax is first introduced in OECD. If for instance a carbon tax of $10 per barrel of oil is only levied on OECD in the four first periods, but thereafter on all regions, the loss in OPEC's oil wealth will be reduced to 16%, while the Non-OPEC loss will be 9%. As the tax policy gives a lower oil price, the oil demand outside OECD increases when a tax is put on OECD demand

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[14] With a direct price elasticity of -0.9 and cross price elasticities of 0.1 as used for the OECD region, a doubling of all energy prices will reduce the energy demand by 40% in this model. However, if we use cross price elasticities of 0.3, the reduction will only be 20%. To get an equal reduction in demand, the direct price elasticity should be changed to -1.3.

only. This increased demand is covered by OPEC. An increasing carbon tax may be a realistic alternative to a constant tax. Consider a tax starting at \$5 per barrel of oil in the first period, and thereafter increases to \$35 in period 5. From this period onwards the tax is constant. With this tax, the carbon emissions will always be below the starting level in the reference scenario, i.e., 4-20% in the four first periods. This tax system gives a loss in the oil wealths of OPEC and Non-OPEC of 38% and 28% respectively.

To conclude, the relative higher loss in OPEC's oil wealth compared to Non-OPEC countries when an international carbon tax is introduced, is a robust result when OPEC acts as a cartel.

7. Conclusions

In this paper, we have analysed the dynamic impacts on fossil fuel prices of introducing carbon taxes globally. We have taken into account the intertemporal optimisation problem fossil fuel producers are facing. In contrast to ordinary Hotelling models, our model has included important aspects, such as market power in the oil market, and cost functions increasing with cumulative production and decreasing with technological change.

Our results indicate that behaviour of OPEC is very important when analysing the impacts on petroleum wealth due to a carbon tax. When OPEC acts as a *cartel*, the crude oil price is almost unchanged initially by a global carbon tax. Moreover, in the first 40 years the tax burden is born mainly by the consumers, as OPEC reduces its production in order to maintain a high price level. This reduces the growth in the producer price of oil compared to the reference case, and the fringe accelerates it's oil production. While the market structure is important in explaining OPEC behaviour in the cartel model, the dynamic aspect explains the behaviour of the fringe. The oil wealth of the fringe is reduced by merely 8%, whereas OPEC's wealth is reduced by more than 20%. Thus, if we do not consider the environmental benefits, the main losers under the carbon tax regime will be the consumers and OPEC, while the tax revenue is collected by the governments in the consuming countries. With *perfect competition* and no carbon tax in the oil market, low cost producers (OPEC countries) increase their production significantly initially, which lowers the oil price and makes oil production unprofitable in the first period for high cost producers (Non-OPEC). In this case, the oil wealth of Non-OPEC will be reduced considerably, by more than 70%, compared to the situation where OPEC acts as a cartel. Thus, Non-OPEC has much more to fear if

OPEC breaks down even in absence of carbon policy, than if a carbon tax is implemented with OPEC as a cartel. In addition to this, a tax will have a much higher relative impact on the Non-OPEC oil wealth in the competitive model compared to the cartel model, as nobody will act to maintain the price under perfect competition, and the relative loss will also be higher than for OPEC countries.

In the gas markets the tax burden is also born most heavily by the consumers, as the scarcity rent is quite low initially. Hence, the producer prices cannot be reduced too much. However, the gas wealth is significantly reduced, especially in Non-OECD. The impact of a carbon tax is not very dependent on the behaviour of OPEC.

The oil market today is probably better described by the cartel model than the competitive model. Thus, the results from the cartel model may explain why OPEC countries are reluctant to introducing global carbon taxes, or other restrictions on carbon emissions. On the other side, other oil producers seem to have less to fear if such an agreement were reached, and this seems to be partly consistent with their positions towards carbon restrictions. Therefore, economic factors may be important in explaining attitudes of oil producers in global warming negotiations.

Finally, in a global context the standard definition of petroleum wealth is a business conception, as the external effects of utilising petroleum are not taken into account. Hence, if petroleum wealth were defined in terms of true social costs and benefits, and if carbon taxes were optimally chosen, the carbon tax would, *ceteris paribus*, not reduce petroleum wealth.

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Appendix 1

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 three regions: OECD-Europe (1), Rest-OECD (2), and Non-OECD (3). There is a natural gas market with perfect competition in each region, and 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, i=1,2,3
Q_j^i	consumer price of fuel j in region i, i=1,2,3
$\overline{P}$	international backstop price
z_j^i	unit costs of transportation, distribution and refining of fuel j in region i, i=1,2,3
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^k_j	parameter of convexity in the cost function for fuel j for producer k
$a^i_j, b^i_j, c^i_j, d^i_j$	price and income elasticities in demand function for fuel j in region i
ω^i_j	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^k_j	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 $\hat{X}^i_j$ be defined by

$$\text{(A1)} \quad \ln \hat{X}^i_j = \ln \omega^i_j + a^i_j \ln Q^i_O + b^i_j \ln Q^i_K + c^i_j \ln Q^i_G + d^i_j \ln Y^i$$

where

$$\begin{aligned} & Q^i_O = P_O + z^i_O + v^i_O \\ \text{(A2)} \quad & Q^i_K = P_K + z^i_K + v^i_K \\ & Q^i_G = P^i_G + z^i_G + v^i_G \end{aligned}$$

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

$$X_j^i = \hat{X}_j^i, Q_j^i < \overline{P}$$

$$\text{(A3)} \quad X_j^i = 0, Q_j^i > \overline{P}$$

$$X_j^i \in [0, \hat{X}_j^i], Q_j^i = \overline{P}$$

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

$$\text{(A4)} \quad x_O^C + x_O^F = \sum_{i=1}^{3} X_O^i$$

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

$$\text{(A5)} \quad P_O = P_O\left(x_O^C + x_O^F, z_O^1 + v_O^1, z_O^2 + v_O^2, z_O^3 + v_O^3, Q_K^1, Q_K^2, Q_K^3, Q_G^1, Q_G^2, Q_G^3, \overline{P}, Y^1, Y^2, Y^3\right)$$

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).

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

s.t.

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

$$\text{(A8)} \quad x_O^C \geq 0$$

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

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

4. Solving the problem

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

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

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 $\pi_{O_t}^C = -\lambda_t$.

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

$$\text{(A12)}\quad \dot{\lambda} - r\lambda = -\frac{\partial H^c}{\partial A_O^C} = \frac{\partial C_O^C}{\partial A_O^C} x_O^C$$

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

$$\text{(A13)}\quad \dot{\pi}_O^C = r\pi_O^C - \frac{\partial C_O^C}{\partial A_O^C} x_O^C$$

x_O^C maximises the Hamiltonian for all $x_O^C \geq 0$ which for an interior solution requires

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

which gives the producer price of oil when OPEC produces

$$\text{(A15)}\quad P_O = C_O^C + \pi_O^C - \frac{\partial P_O}{\partial x_O^C} x_O^C$$

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

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

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.

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

s.t.

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

(A21) $x_O^F \geq 0$

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

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

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

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

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

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

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=1,2,3. Each producer faces the following optimisation problem:

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

s.t.

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

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

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

The first order conditions give

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

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

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

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

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

Appendix 2

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
Non-OECD	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	Non-OECD
Tax on oil	34.02	12.21	3.52
Tax on gas	3.60	0.00	0.00
Tax on coal	0.74	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
Non-OECD	8,390	4,011	4,598

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	1.5	--

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

	OECD-Europe	Rest-OECD	Non-OECD
oil			
transportation	1.64	1.53	1.06
distribution	3.4	3.4	3.4
refining costs	2.28	2.53	2.16
total	7.32	7.46	6.62
natural gas			
transportation	5.1	3.16	2.1
distribution	6.8	6.8	6.8
storing and load balancing	2.0	2.0	2.0
total	13.9	11.96	10.9
coal			
transportation	3.79	1.43	0.57
distribution	3.4	3.4	3.4
total	7.19	4.83	3.97

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