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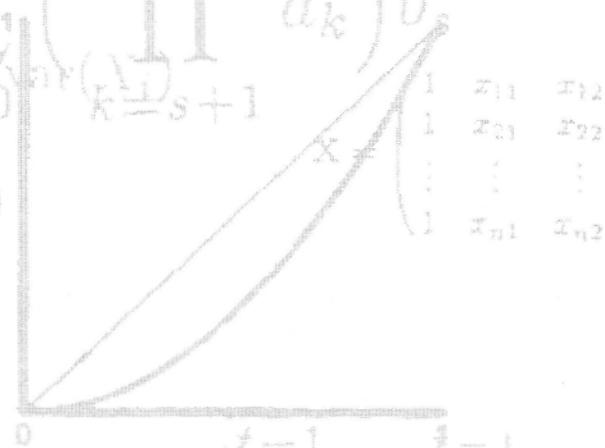
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# Gains from Cartelisation in the Oil Market

# Discussion Papers

$$+ \frac{2}{dt} \sum_{i>j} \sum_{j=1} \text{COV}_t(X_i, X_j)$$

$$\text{var}\left(\sum_{i=1}^n a_i X_i\right) = \sum_{s=0}^{t-1} \sum_{k=s+1}^{t-1} \left(\prod_{k=s+1}^{t-1} a_k\right) b_s$$



$$\text{var}\left(\sum_{i=1}^n a_i X_i\right) = \sum_{i=1}^n a_i^2 \sum_{s=0}^{t-1} \left(\prod_{k=s+1}^{t-1} a_k\right) \sum_{j=1}^n (y_j - (ax_j + b))$$



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## **Gains from Cartelisation in the Oil Market**

**Abstract:**

In this paper we ask whether OPEC still gains from cartelisation in the oil market despite low producer prices and a modest market share. We apply two intertemporal equilibrium models of the global oil market; one consisting of a cartel and a fringe, and one describing a hypothetical competitive market. Comparing the outcome of these models we conclude that there are positive cartelisation gains of about 18 per cent in the oil market. In comparison with what Pindyck (1978) found for the 1970s this may be considered as quite modest. Moreover, we study whether the cartelisation gains to OPEC are altered by different moves by non-OPEC producers or consumer countries. Generally, we find that the relative cartelisation gains are unchanged. One exception is exploration activities, where we find that a major increase in non-OPEC reserves could remove the cartelisation gains to OPEC completely. In this case, the OPEC-countries could find themselves better off without the cartel.

**Keywords:** Cartelisation Gains, Petroleum Wealth, Exhaustible Resources.

**JEL classification:** Q30, Q40.

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# 1. Introduction

Since 1973 the power of OPEC has been an important determinant in the global oil market. By curbing its production the cartel has to a large degree managed to obtain high oil prices, presumably to the benefits for their member countries, but even more so for producers outside OPEC. In the 1970s oil prices were high, and OPEC's market share was about one half. Pindyck (1978) then concluded that OPEC's cartelisation gains were tremendous. In the 1990s real oil prices have been halved compared to the 1970s, while OPEC's market share has shrunk to about 40 per cent. Thus, the market situation seems to have changed to the worse for OPEC over the last 20 years, and one may ask whether there still are cartelisation gains left in the current oil market. A persisting question for OPEC should therefore be whether sustaining the cartel is advantageous, or whether the total revenue of the OPEC-countries may be increased if the cartel is dissolved.<sup>1</sup>

Of course, with a given supply from other producers, OPEC as a whole could do no better than utilising its market power. However, with more realistic assumptions about the behaviour of non-OPEC, this may not hold universally. Moreover, even though OPEC as a group may benefit from keeping the cartel alive, separate member countries may be tempted to break out in order to grasp the free-rider gains to non-OPEC countries. Ecuador and Gabon did so in 1992 and 1996, respectively, and this issue is certainly a difficult one for central member countries like Saudi-Arabia, Kuwait and the UAE. If the total gains from cartelisation are small, there is little to lose for single members by leaving OPEC, i.e., the cartel is not a stable coalition.

In this paper we investigate whether OPEC profits from cartelisation in the current and the expected future oil market. Moreover, we study how different moves by producers outside the cartel may influence this gain. If, e.g., steps are taken to increase production or reserves of non-OPEC producers, this may reduce or even erode the cartelisation gains, and may eventually lead to the collapse of OPEC. The main losers from these events may ultimately be non-OPEC. We will also study whether moves by consumer countries, like the introduction of global carbon taxes, may trigger a breakdown of the cartel. If so, the environmental effect of the taxes may be undesirable, as global oil production would probably increase.

There are several ways of modelling the game between a cartel and a fringe, of which the Nash-Cournot approach and the Stackelberg approach are the most familiar. 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 optimal production profile.

Thus, a powerful cartel would obviously follow the latter strategy if feasible, and, as indicated above, the gains from cartelisation depends crucially on how the market power of OPEC is viewed. If production from other producers are thought to be exogenously determined, or if the cartel's role can be described as being a Stackelberg leader, OPEC will never lose from its cartelisation. The cartel is

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<sup>1</sup> This is illustrated by the title of a speech held by the Secretary General of OPEC: «Can OPEC survive?» (Lukman 1996).

then able to choose between several strategies *including* a strategy giving the same outcome as a competitive equilibrium. On the other hand, Ulph and Folie (1978)<sup>2</sup> have shown that a cartel may possibly be worse off in an open-loop Nash equilibrium than if the market is perfectly competitive. The intuition behind this result is that if a cartel is dissolved, the supply from the cartel producers will increase, lowering the price, which in turn induces the other producers to restrict their supply. Being a cartel, however, implies that such a supply increase may not be credible, which means that the fringe will not be driven to restrict its supply. This applies in particular to a Nash equilibrium, where the producers are supposed to take the other producers supply as given. Thus, there are no feasible Nash strategies for the cartel leading to a competitive equilibrium. Hence, even though the cartel responds optimally to the actual market situation, there is a possibility that breaking up the cartel may increase its profits.

As shown by Ulph (1982), there are shortcomings with both the Nash and the Stackelberg solution concepts, and the choice of concept should be endogenous to the model. One important shortcoming with the Stackelberg solution is that the equilibrium may be dynamically inconsistent (Ulph 1982). Moreover, it may be argued that OPEC has not enough credibility in the oil market to act as a market leader in the term of Stackelberg. Hence, the Nash solution concept may seem more appropriate in the current market situation. We therefore choose to concentrate on the Nash-Cournot model of a dominant firm to calculate the open loop solution of the game.<sup>3</sup> Moreover, as shown in Figures 1 and 2, initially the reference case of our model seems to fit well with the actual market conditions (the reference case of the model is further documented in Berg et al. (1996)). It should be emphasised, however, that the choice of solution concept is crucial for the results.<sup>4</sup>

An important aspect of our model is the intertemporal behaviour of the supply side. Only recently has this been implemented into some empirical energy models (e.g. Manne *et al.* (1995) (MERGE) and Manne and Rutherford (1994) (extended version of Global 2100)). The relevance of such behaviour may of course be discussed, but the alternative, i.e., ignoring future expectations, seems inappropriate in the market of an exhaustible resource.

In Pindyck's (1978) study mentioned above, the gains to OPEC from cartelisation were found to be 50-100 per cent, and potentially even higher. The study was based on market information from around 1975, i.e., just after the first oil shock in the 1970s. He used a model where the fringe acts in a static manner, while the cartel operates intertemporally as a Stackelberg leader. In a later study Griffin (1992) found that the return from cartelisation is about 25 per cent. This result is based on a simple Hotelling model, and the choice of price path in the monolithic case seems somewhat ad hoc. Compared to these two studies, our study utilises a more sophisticated model, particularly compared to the model used by Griffin. The time schedule has also shifted, especially compared to Pindyck's study. Moreover, as opposed to the other studies, we also focus on how the cartelisation gains may be altered by different moves by other producers or consumer countries.

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<sup>2</sup> According to Ulph (1982).

<sup>3</sup> It can be shown that this Nash-equilibrium is time consistent, but not subgame perfect, see, e.g., Hoel (1992).

<sup>4</sup> According to Teece (1982) and Gülen (1996) OPEC did not behave at all as a cartel until the early 1980's. Yet from 1982 Gülen finds evidence of co-ordination among the member countries. On the other hand, Griffin (1985) and Youhanna (1994) find support for a partial market sharing cartel model in the periods 1971-1983 and 1983-1989, respectively.

The structure of the paper is as follows. In the next section the model is briefly described. In section 3 we discuss the cartelisation profits in the current market. Then, the two subsequent sections deal with effects of moves by producers outside OPEC; in section 4 production restrictions in Norway are discussed, and in section 5 more general moves are discussed. The impacts on the cartelisation gains of moves by consumer countries are studied in section 6. The paper ends with conclusions and policy recommendations.

## 2. Model description

The model we apply is based on Berg et al. (1996), which models 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. We focus on OPEC and the oil market in this paper, while Berg et al. (1996) also discusses specific features of the coal and natural gas markets.

The *demand* for fossil fuels is divided into three regions, i.e., OECD-Europe, rest-OECD and non-OECD. For each fuel the demand is represented by a log-linear function, which is decreasing in the price of the fuel and increasing in the prices of the two other fossil fuels. Hence, the three fuels are imperfect substitutes. The relevant price of a specific fuel by region equals the sum of the producer price, costs due to transportation, distribution and refining, and the average net fuel tax.<sup>5</sup> The demand function changes exogenously over time due to economic growth. Moreover, we assume that there exists a 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 the price of the backstop technology, then no oil will be demanded.<sup>6</sup> 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 cost of applying the backstop technology is reduced by a constant rate to reflect technological change.

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. We therefore assume that the producers maximise the present value of their resource wealth, i.e., they solve an intertemporal optimisation problem.<sup>7</sup>

To analyse the gains from cartelisation, the international oil market is modelled in two different ways. The *cartel model* describes a market with a cartel (corresponding to OPEC) and a competitive fringe on the supply side, whereas the *competitive model* describes a competitive market with low (OPEC)

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<sup>5</sup> As a result of a more integrated world economy, we assume that existing energy taxes and unit transportation, distribution and refining costs for each fuel will be harmonised after 40 years to a global weighted average, using initial demand as weights.

<sup>6</sup> This is of course a very simplifying, though common, assumption, especially because oil have alternative areas of application than as a fuel.

<sup>7</sup> This is not done for coal, as the global coal reserves are so huge that the resource rent in coal extraction will probably be marginal in the foreseeable future.

and high cost producers (non-OPEC), respectively. In the former specification, which corresponds to the current market situation, the fringe always considers the oil price path as given, while the cartel regards the price as a function of its supply.<sup>8</sup> 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. As explained in the introduction, we have chosen to model this market as a Nash-Cournot game.

We do not consider the resources as strictly exhaustible. However, the cost functions of both the cartel and the fringe are assumed to be exponentially increasing functions of cumulative production. This implies that unit costs approach infinity as cumulative production approaches infinity. Hence, at any given price there is a limited amount of reserves that are economically valueable. The cost level of the two producer groups differs, reflecting that extraction costs in OPEC generally are lower than in the rest of the world. Moreover, the shape of the cost functions also differs, depending on initial reserves. Furthermore, we assume that unit costs are reduced by a constant rate each year to reflect technological change and new discoveries.

Some important parameter choices in the model should be mentioned. First, we assume a universal discount rate of 7 per cent per year in both OPEC and non-OPEC. Second, the technological rate of change is assumed to be 1 per cent in OPEC. In non-OPEC the rate is assumed to start at 2 per cent due to major cost reductions lately, and then gradually fall to 1 per cent after 30 years. Finally, the parameters in the cost functions are determined so that the marginal cost of the last unit of the current oil reserve (BP 1995) equals \$20 per barrel.

Further discussions of features of the model and numerical specifications are given in Berg et al. (1996). A formal model description is found in the appendix.

### **3. Gains from cartelisation in the current oil market**

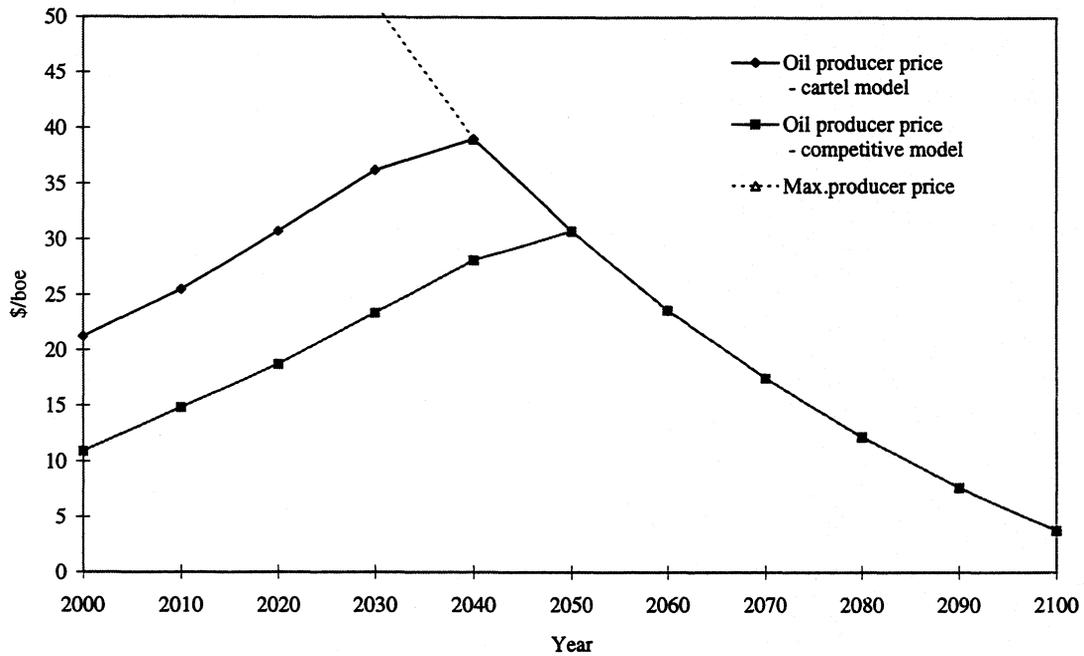
To investigate OPEC's profits from cartelisation, we compare the outcome of the cartel model with the outcome of the competitive model. We start by briefly describing the reference scenarios in the two models (see Berg et al. (1996) for a more detailed description). The price and production profiles in both reference scenarios are illustrated in Figure 1 and 2.<sup>9</sup> With the cartel model the real oil price starts at \$21 per barrel in the year 2000 and increases to \$39 in 2040, which equals the maximum producer price due to the backstop technology. Initially, OPEC has a market share of about one-third, which is somewhat less than their real market share in the current oil market. In the period 2030-2050 OPEC gradually takes over the whole market.

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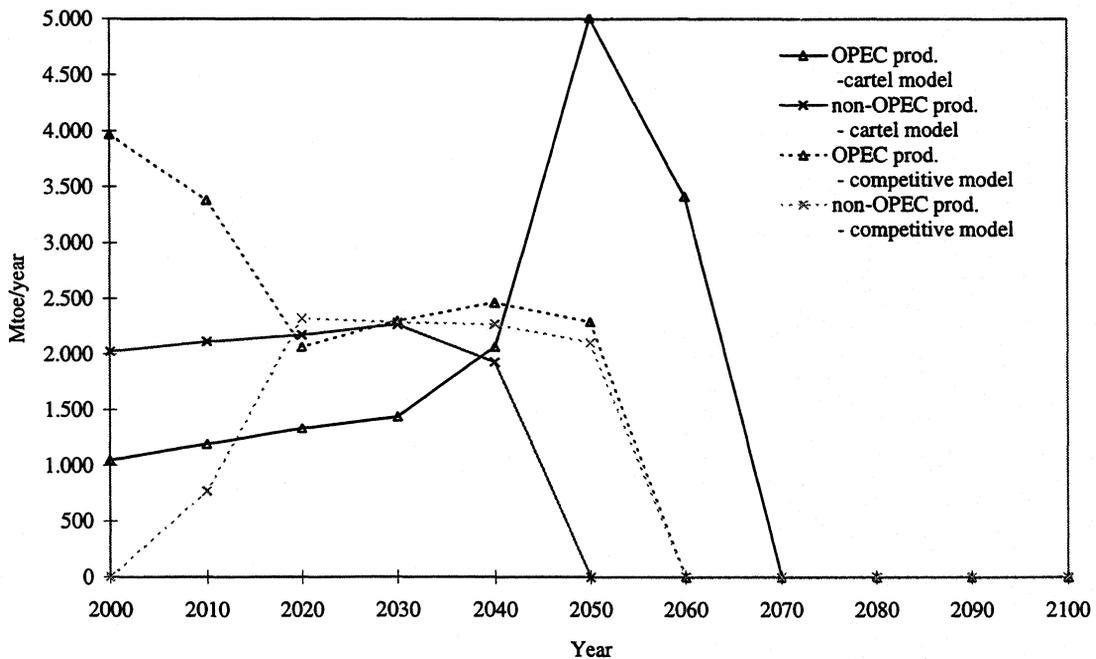
<sup>8</sup> An alternative approach is to consider a core of the cartel (i.e., consisting of Saudi Arabia and some other central member countries), and assume that the rest of the cartel operates as price takers.

<sup>9</sup> The model operates with periods of ten years, so that, e.g., the year 2000 refers to average levels in the period 1995-2004. The maximum producer prices in the different regional markets are defined as the backstop price net of regional transportation, distribution and refining costs, and regional taxes.

**Figure 1. Producer price of oil in the reference scenarios - cartel and competitive model**



**Figure 2. Production of oil in OPEC and non-OPEC in the reference scenarios - cartel and competitive model**



In a competitive market, the countries that currently constitute OPEC find it optimal to increase production substantially (i.e., almost a quadrupling in the first period), as they are assumed to ignore their own impact on the price. Hence, initially the oil price is reduced from \$21 to \$11 per barrel, and non-OPEC is squeezed out of the market, see Figure 1 and 2 (the realism of this outcome is discussed below). The effect on producers outside OPEC is clearly disastrous.

We notice that dissolving the cartel has significant impact on both the oil price and the fringe production. Clearly, for the OPEC-countries the break up has had a favourable influence on non-OPEC

production. The question is whether or not OPEC gains from this, i.e., whether or not its oil wealth has increased. The wealth is defined as the present value of the net revenue, i.e., price minus unit cost times production. In the cartel model OPEC's oil wealth is found to be \$ 4,030 billions. In the competitive model, however, the oil wealth of OPEC as a group is reduced to \$ 3,431 billions.<sup>10</sup>

Thus, according to our results, there are still positive gains from cartelisation in the current oil market (i.e., 17.5 per cent).<sup>11</sup> The results seem to underpin earlier results found by Griffin (1992), who, based on a much simpler model, found that the gains from cartelisation are 25 per cent. However, compared to the results of Pindyck (1978), who found cartelisation gains of at least 50-100 per cent around 1975, we may conclude that the profits of being a cartel have been considerably reduced. This result reflects the change in market situation described in the introduction.<sup>12</sup> Thus, being a cartel may no longer seem an obvious strategy in economic terms for the OPEC-countries.

It should be emphasised that the model we apply is a long term equilibrium model, and the reference scenario of the competitive model presented should be viewed as a hypothetical long term scenario. Hence, the model does not present *short term effects* of an eventual break up of OPEC. In reality production in non-OPEC will only gradually be reduced, as the main costs are sunk capital costs. Moreover, it may take time for OPEC-countries to build up capacity from their current levels. Thus, the ultimate impact on the initial price level will depend on the flexibility of OPEC and non-OPEC production. Moreover, demand is more inelastic in the short run, which means that an increased supply will have difficulties being sold in the nearest future. This puts further downward pressure on the initial price level. It is difficult to conclude in which direction these short term effects go. If non-OPEC production is inflexible and short term demand is inelastic, the cartelisation gains are presumably higher than indicated above, as the price is forced further down if OPEC breaks up. However, if OPEC's capacity is somewhat inflexible, this may actually be a gain for the OPEC-countries as a whole, as production is not increased too much.

As the gains from cartelisation seem to be modest for OPEC as a whole, there is a clear temptation for individual countries to withdraw from the cartel. Ecuador did so in 1992, and Gabon has recently done the same. If a single member country has the option to produce more than the agreed quota, the direct gains of increasing production, e.g., by leaving the cartel or cheating on its quota, may be large. However, the country has to bear in mind that its behaviour may trigger a dissolution of the cartel, which ultimately may lead to a loss for the country. According to our analyses, this loss is not very serious, and hence in this regard the cartel may be characterised as relatively unstable. The production increases in Venezuela over the last year seem to support this conclusion.

For producers outside OPEC this picture is probably alarming. Our model simulations indicate a loss of 71 per cent of their oil wealth if OPEC breaks down as a cartel. This is due to much lower oil prices, which makes the relatively expensive non-OPEC production almost unprofitable initially.

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<sup>10</sup> The numbers that are referred are of course highly dependent on some key parameters, like the choice of discount rate, and should be interpreted with caution. However, we focus on the comparison of the two models under identical parameter choices. For a comparison, Griffin (1992) finds that the net present value of OPEC's oil resources are about twice as high as our figures. This is probably due to much higher oil prices.

<sup>11</sup> This result is robust to, e.g., increases in the discount rate, which presumably is a pivotal parameter.

<sup>12</sup> The discrepancy may of course also be due to modelling differences.

Thus, they should indeed care about how their behaviour may influence OPEC's future role in the oil market. That is what the rest of this paper discusses.

#### 4. The effects of reductions in the Norwegian oil production

The North Sea is an expanding region in oil production, illustrated by the fact that 62 per cent of the increase in non-OPEC production from 1990 to 1994 came from higher production in Norway (35 per cent) and the United Kingdom (27 per cent), see BP (1995), and a further rise in North Sea production is expected. As a result, OPEC applies pressure to these two countries to lower their production, warning that the implication of increased North Sea supply may be that the cartel loosens its production quotas, or, in the worst case, ceases to restrict production. Thus, it is of interest to study whether this warning has a root in economic rationality, i.e., whether a reduction in North Sea production increases the cartelisation gains for OPEC, so that a disorganisation of OPEC is prevented.

In this analysis, we look specifically at a reduction in Norwegian extraction, which we for the time being assume to be exogenous. The other fringe producers, however, are modelled as before. In the *planning scenario*, we assume that the Norwegian oil production follows the scenarios of the Norwegian Government, see Norwegian Ministry of Industry and Energy (1996). This extraction path includes oil fields currently in production, oil fields decided to be put into production, discoveries under consideration, production due to better resource utilisation, and prospects. In the *reduction scenario* we assume that this production is reduced by one third in the first period (1995-2004), corresponding to 1 million barrel per day, and by one sixth in the next period (2005-2014) corresponding to a reduction of about 0.6 million barrels per day. However, total cumulative production in Norway is the same in the two scenarios, which in the end implies an increase in the Norwegian production in the reduction scenario compared to the planning scenario, i.e., the production profile in the former scenario is somewhat flatter, see Figure 3.

Figure 3. Production of oil in Norway - two alternative scenarios

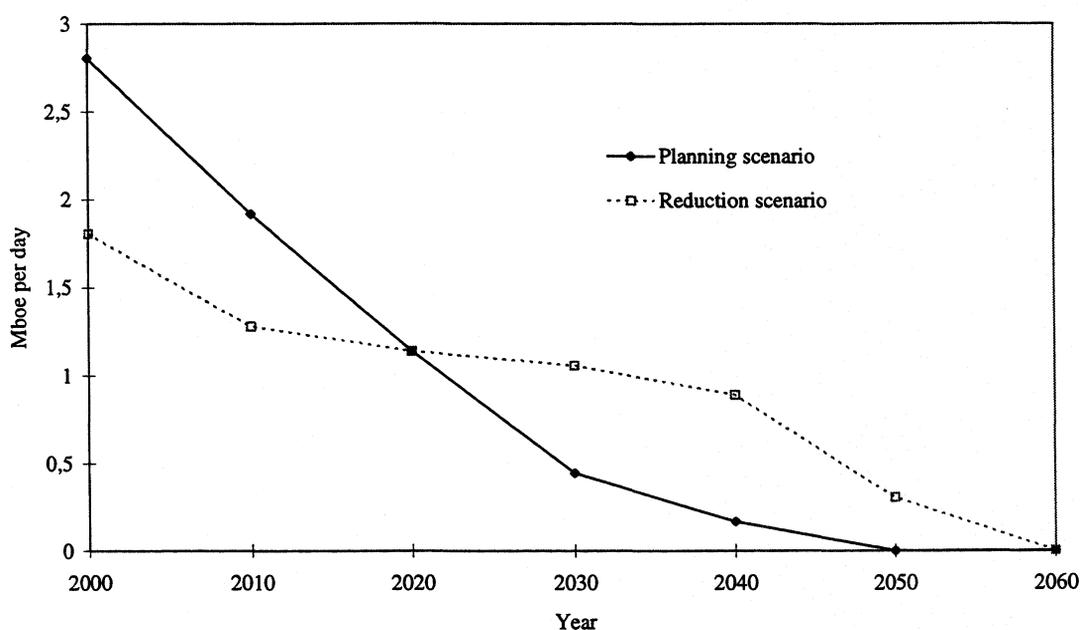
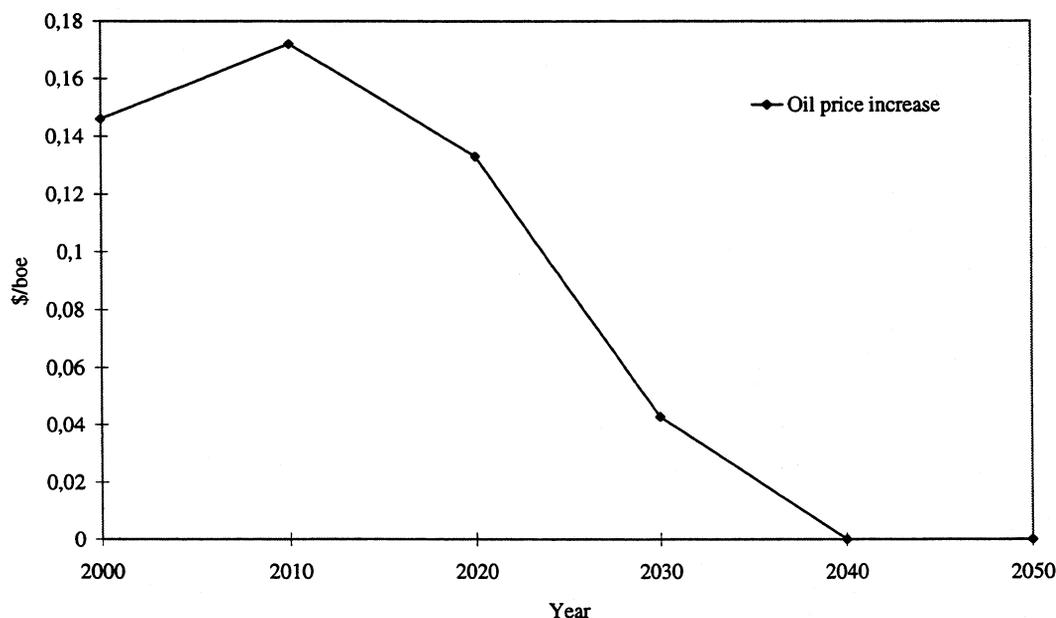


Figure 4 shows the difference between the producer price of oil in the two scenarios, with OPEC being a cartel. The price increase due to reduced Norwegian production is relatively small, i.e., \$0.15 per barrel. However, note that the price path of the reduction scenario is always above the price path of the planning scenario, even though the Norwegian production increases from 2020 onwards in the reduction scenario. The reason is that in response to a higher oil price with reduced Norwegian supply, the rest of the fringe (ROF) increases production initially by 0.75 million barrels per day. However, due to the intertemporal aspects of the model, increased current production gives higher future costs, and lower future production. The changed Norwegian production profile therefore leads to an almost equivalent opposite change in the production profile of ROF. The ROF production is very price sensitive, initially 75 per cent of the Norwegian reduction is offset by increased production in ROF.

This active response from ROF means that there is little room for OPEC to exploit the reduced North Sea supply. The cartel increases its production initially by 0.04 million barrels of oil, which means that 79 per cent of the Norwegian production decline is offset by increased production from other producers, i.e., a leakage rate of 79 per cent in 2000. Thus, while the production of ROF is very price sensitive, OPEC chooses to keep production rather unchanged to obtain somewhat higher prices. OPEC's oil wealth increases only marginally, i.e., by 0.6 per cent, with a flatter Norwegian production profile. The reason is of course that the ROF to a large degree counteracts the change in Norwegian supply.

**Figure 4. Oil price increase in reduction scenario compared to planning scenario**



In section 3 we observed that in a *competitive* equilibrium, it would not have been optimal for the fringe to produce at all in the first 10-years period. Thus, the two alternative Norwegian production profiles described in Figure 3 may seem a bit irrelevant in the competitive scenarios.<sup>13</sup> We therefore

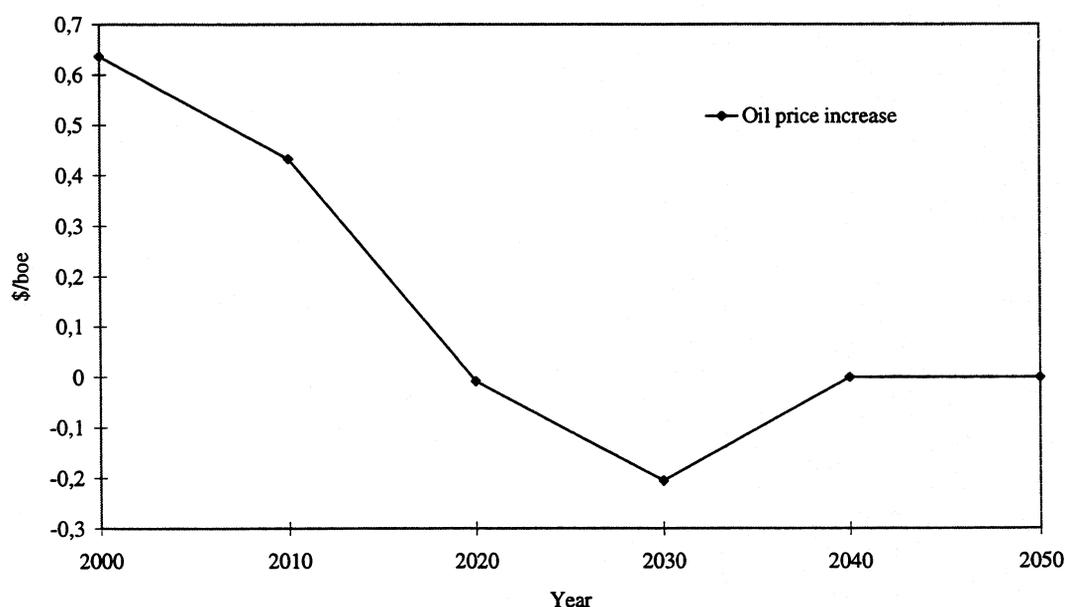
<sup>13</sup> Of course, as explained in section 3, in the short term production in non-OPEC is not as flexible as indicated by our model results. Short term effects are discussed later in this section.

assume that if OPEC were dissolved as a cartel, we would have the competitive equilibrium earlier shown in Figures 1 and 2, i.e., with Norway as an integrated part of the fringe, no matter what the Norwegian production profile looks like with OPEC being a cartel. This means that the cartelisation gains only depend on the different outcomes of the Nash Cournot model, as the outcome of the competitive model is fixed.

Therefore, as OPEC's oil wealth in the cartel model is somewhat increased with a more conserving Norwegian production profile, the cartelisation gains also rise. However, as the wealth increase is small, the impact on the cartelisation gains is also small, i.e., from 17.3 to 18.0 per cent. Thus, a more conserving Norwegian production profile may slightly increase the profitability of OPEC, but probably not as much as to influence OPEC's future market role. This indicates that although psychological aspects should play a role in this matter, OPEC's warning to the North Sea producers may be somewhat groundless, and rather hide the fear of losing revenues.<sup>14</sup>

Short term inflexibilities that are not captured by the model may however lead to a greater shift in the oil price than indicated above, when Norwegian production is reduced initially. We now take a closer look at one of the short term effects, i.e., we assume that the ROF production is totally inflexible, and thus unchanged, in the first three periods, while total non-OPEC production (including Norway) is adjusted optimally from period four onwards. This scenario is called the *new reduction scenario*.<sup>15</sup> OPEC is assumed to have idle capacity and therefore responds optimally to reduced North Sea extraction.

**Figure 5. Oil price increase in new reduction scenario compared to planning scenario**



<sup>14</sup> Actually, Norwegian oil wealth is also increased in the reduction scenario, i.e., by 14 per cent or 67 billion NOK. Thus, according to the model there seems to be joint benefits to OPEC and the North Sea producers if this scenario is chosen.

<sup>15</sup> In this case the planning scenario is identical to the reference scenario of the cartel model described in section 3. That is, Norway is not modelled independently of the ROF, as in first part of this section.

Figure 5 shows the changes in the producer price of oil when the ROF production meets an upper limit. The effect on the oil price is considerable compared to the scenario in Figure 4. Initially, a reduction of 1 million barrel of oil per day from the North Sea increases the price by \$0.64 per barrel. However, the difference between the planning scenario and the new reduction scenario diminishes with time, and the oil price in the reduction scenario will in this case fall below the planning scenario price between 2020 and 2040. This is due to increased production in the fringe, including Norway, in this period.

As the ROF production is unchanged initially, OPEC increases its production slightly more in this scenario, by 0.18 million barrels per day, giving a total leakage rate by 18 per cent. However, in order to defend the oil price, OPEC's production is reduced significantly between 2030 and 2050 when non-OPEC production increases. In this reduction scenario the oil wealth of OPEC is increased by 1.8 per cent, which is slightly more than under the previous reduction scenario above. Again, taking the competitive scenario as given, the cartelisation gains increase from 17.5 to 19.5 per cent. That is, this short term effect of a more conserving North Sea extraction may reduce the temptation for OPEC-countries to break up the cartel. However, the increase in cartelisation gains is still relatively small.

## 5. The effects of more general moves by non-OPEC

In this section we generalise the discussion in the previous section by focusing on more general moves by non-OPEC producers, and how such moves may influence the cartelisation gains to OPEC. We are especially interested in whether there are realistic assumptions about the fringe behaviour under which the cartelisation gains become negative, so that it may be profitable for OPEC to disintegrate. Moreover, if the cartelisation profits are greatly diminished, but still positive, it might also induce the disintegration of OPEC for at least three reasons. First, it is possible that when the total cartelisation gains are small, for certain member countries the gains may be negative. Second, even a small gain may not be enough to conquer the temptation of grasping the free-rider gains to competitive producers. Third, we neither take account of costs associated with cartelisation such as political costs, costs of coordinating output and price and the costs to the individual cartel members stemming from the risk of being undercut and losing significant short term profits, see Pindyck (1978). These costs may be significant and may thus outweigh the cartelisation gains under certain conditions, making it difficult for OPEC to maintain cartel discipline when the gains from adhering to the cartel rules are small.

The changes in the fringe behaviour are brought about by different assumptions about the *discount rate* of the fringe producers, the rate of *technological change* outside OPEC and the *reserve bases* of the fringe. (In the next section we look at the impact of moves by consumer countries.) The results are summarized in Table 1.

**Table 1. OPEC's oil wealth and cartelisation gains with different moves by non-OPEC**

Scenario	Parameter <sup>1</sup>			OPEC oil wealth in billion \$		Cartelisation gains (per cent)
	R2 <sup>2</sup>	T2 <sup>3</sup>	C2 <sup>4</sup>	Nash Cournot model	Competitive model	
<i>Reference/competitive scenario</i>	0.07	0.02	0.025	4,030	3,431	17.5
SCEN 1	0.10			3,769	3,183	18.4
SCEN 2	0.15			3,561	3,008	18.4
SCEN 3	0.20			3,463	2,932	18.1
SCEN 4		0.03		3,715	3,182	16.8
SCEN 5		0.05		3,160	2,678	18.0
SCEN 6		0.07		2,692	2,258	19.2
SCEN 7			0.020	3,421	3,127	9.4
SCEN 8			0.015	2,778	2,745	1.2
SCEN 9			0.010	2,039	2,305	-11.5
SCEN 10	0.20		0.020	2,848	2,642	7.8
SCEN 11	0.20		0.015	2,269	2,260	0.4
SCEN 12		0.07	0.020	2,163	1,941	11.4
SCEN 13		0.07	0.015	1,594	1,578	1.0

<sup>1</sup> We enter the parameter estimates only where they differ from the reference scenario assumptions.

<sup>2</sup> R2 - discount rate of non-OPEC

<sup>3</sup> T2 - initial technological change in non-OPEC

<sup>4</sup> C2 - convexity parameter for non-OPEC

### 5.1. Changes in the discount rate of the fringe

The appropriate discount rate depends on whether the development rate of new oil fields are determined by national governments or by the private oil industry, and the social and private discount rates. In non-OPEC countries there seems to be a more or less mixed influence by governments and private agents, whereas oil production in OPEC traditionally has been managed by the states.<sup>16</sup> The private industry generally demands a higher rate of return than the discount rate of societies, and they also face the possibility of losing the property right of the resources they currently have in control. However, several developing countries including major OPEC-countries face severe budget crises (see e.g. Adelman (1993)), which implies that the need for current money may be overwhelming. Hence, the social discount rate may also be high.

Based on the reasoning above, in the reference scenario both the fringe and the OPEC-countries are assumed to have a discount rate of 7 per cent. However, if the trend towards more privatisation continues outside OPEC, meaning that the oil resources are getting more or less controlled by private

<sup>16</sup> In the last years there has been a move towards more privatisation in some OPEC-countries, too, like Venezuela.

companies, this rate may become too low for non-OPEC. Moreover, if the need for current money becomes stronger due to budget crisis etc., this may also lead to a higher discount rate in non-OPEC.<sup>17</sup>

We see from Table 1 (SCEN 1-3) that when the discount rate of the fringe is gradually increased from 7 to 20 per cent,<sup>18</sup> the oil wealth of OPEC is reduced monotonically in both models. The reason why the OPEC wealth is reduced is clearly seen from Figures 6-7. Figure 6a shows that when the discount rate of the fringe is 20 per cent, the producer price of oil is well below the corresponding price in the reference scenario in the first three periods. This is also the case with perfect competition, see Figure 7a. The price is lower initially because the higher discount rate for the fringe producers will induce them to move production forward in time, see Figures 6c and 7c. According to the Hotelling rule for optimal extraction of exhaustible resources, the price of oil must rise faster with a higher discount rate, for the producer to be willing to postpone production to future periods.

From Figure 6b we see that in the Nash Cournot model OPEC reduces its production only marginally in the early periods as a response to the change in non-OPEC behaviour. This means that OPEC does not find it optimal to use its cartel power to reduce production in order to maintain a high price of oil. The explanation for this might be that with an initial increase in non-OPEC production, the market share of OPEC is reduced from 34.0 per cent in the reference scenario to 28.3 per cent in SCEN 3. Hence, the cartel power has diminished, so that the gains from restricting supply have become smaller.

In the situation with perfect competition, the OPEC-countries take the price as given and reduce production significantly in the second period as a response to increased non-OPEC production. With a faster increase in the oil price this induces the OPEC-countries to delay production. However, as non-OPEC still doesn't produce in the first period, it is profitable for the OPEC-countries to move some production to this period.

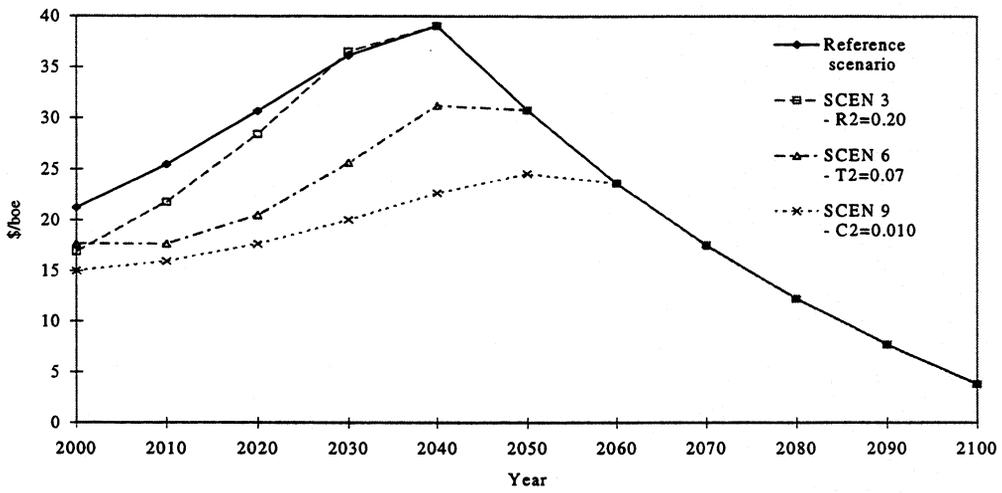
With OPEC's market share being shrunk to less than 30 per cent with a discount rate of 20 per cent in non-OPEC, one would naturally think that the cartelisation gains were diminished, too. However, as OPEC's oil wealth is negatively affected in both models, the impacts on the cartelisation gains are not tremendous. The absolute cartelisation gains are somewhat reduced, i.e., by 11.6 per cent in SCEN 3 compared to the reference scenario. The relative cartelisation gains are, however, roughly the same. Hence, the more offensive behaviour of non-OPEC does not seem likely to spur on the disintegration of OPEC. This confirms the more specific conclusions reached in the previous section.

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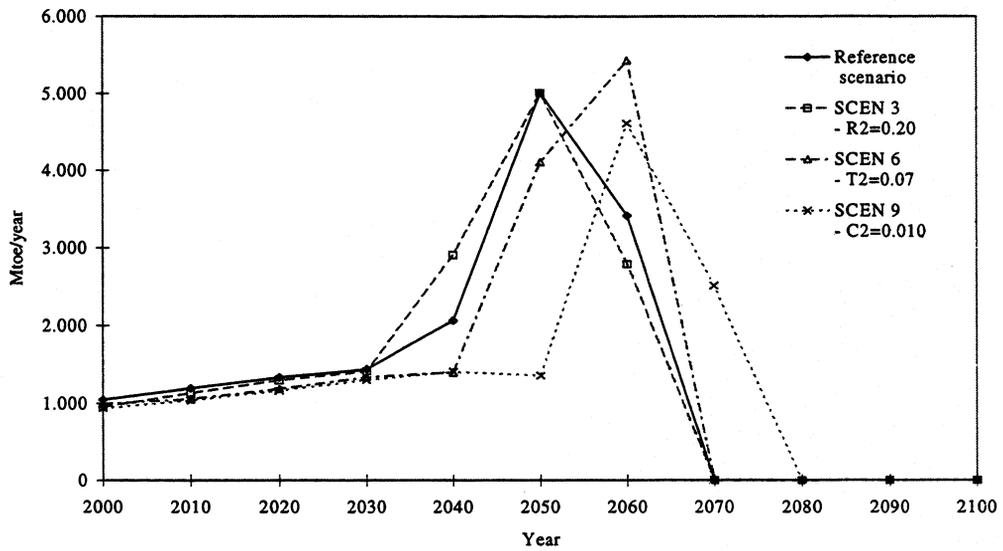
<sup>17</sup> Both these arguments may also be put forward for OPEC. If we assume that the discount rate of OPEC rather than non-OPEC becomes higher, the relative cartelisation gains actually increase as the competitive outcome is characterised by strongly depressed prices.

<sup>18</sup> Higher discount rates probably imply higher unit costs, as investment costs are particularly important in oil production. This is however not taken into account in the analyses, as cost data are taken directly from the literature.

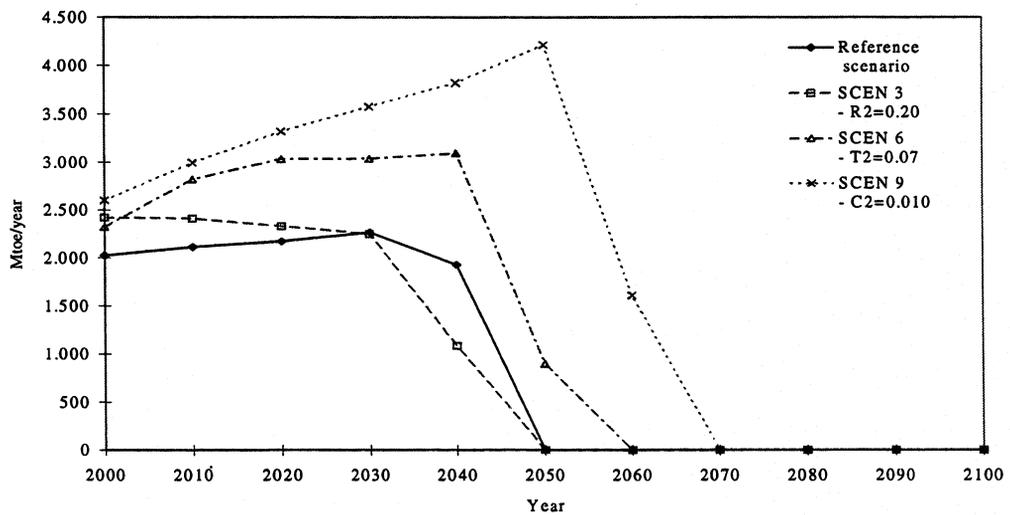
**Figure 6a. The producer price of oil under cartelisation**



**Figure 6b. Oil production in OPEC under cartelisation**



**Figure 6c. Oil production in non-OPEC under cartelisation**



## 5.2. Changes in technological progress outside OPEC

The technological progress has been impressive in some of the non-OPEC areas lately, notably in the North Sea, where the estimates of economically valueable reserves have been revised upwards for several fields. However, it is not certain that this progress will last for a very long time, and it is questionable whether this progress will be apply to other parts of non-OPEC as the exploration areas differ<sup>19</sup>. Thus, in the reference scenario we have assumed an initial rate of technological progress of 2 per cent p.a. in non-OPEC, which is gradually reduced to 1 per cent after 30 years.<sup>20</sup>

However, if governments and companies outside OPEC choose to invest large resources in R&D in the oil sector, the technological progress may be faster than we have assumed in the reference scenario. As OPEC's share of the global reserves probably will become constantly higher in the years to come, the OECD-countries might find the future oil market a bit frightening. Financing R&D in the oil sector may therefore become a higher priority.<sup>21</sup>

Thus, we look at increases in the initial rate of technological change for the fringe producers, and study the cartelisation gains in this case.<sup>22</sup> From Table 1 (SCEN 4-6) we see that the oil wealth of OPEC is reduced monotonically in both models when the technological progress in the fringe increases. When the initial rate of technological change is 7 per cent, the oil wealth in OPEC is reduced by one third in the Nash Cournot model. The same wealth reduction applies to the competitive model. From Figures 6a and 7a we see that the producer price of oil is strictly lower than in the reference scenario in all periods until the price reaches the maximum producer price. The reduction in the resource wealth of OPEC is a result of the general cost reduction for the fringe producers implied by the increased technological progress. The fringe will now produce a greater amount of oil at any given price. From Figures 6c and 7c we see that when the initial rate of technological change is 7 per cent, the fringe indeed produces more than in the reference scenario in all periods in both models. Thus, there is a shift in the *level* of production, whereas the *profile* is quite unchanged, although the fringe produces one period longer than in the reference case. This is different from the outcome of higher discount rates in non-OPEC, as described in the previous subsection. In that case the production profile of non-OPEC was changed, giving OPEC market dominance earlier than in the reference scenario, whereas *cumulative* production was almost unchanged.

From Figure 6b we note that in the Nash Cournot model OPEC production is almost unchanged the first 40 years by higher technological change in non-OPEC. This is the same reaction as with a higher discount rate in non-OPEC, see the previous subsection. In the competitive model, however, OPEC production in 2010 and 2020 is significantly reduced as OPEC loses some of the original cost advantage, see Figure 7b.

Even though increased technological progress in non-OPEC severely reduces the oil wealth of OPEC, as well as the cartel's market share, the cartelisation gains are not particularly altered. The reason is of course that the profitability of being competitive producers also diminishes. Since the wealth reductions are quite huge, however, the absolute cartelisation gains are reduced by 27.7 per cent in SCEN 6 compared to the reference scenario. However, the relative cartelisation gains are quite stable, so that the relative importance of cartelisation is roughly the same as in the reference case.

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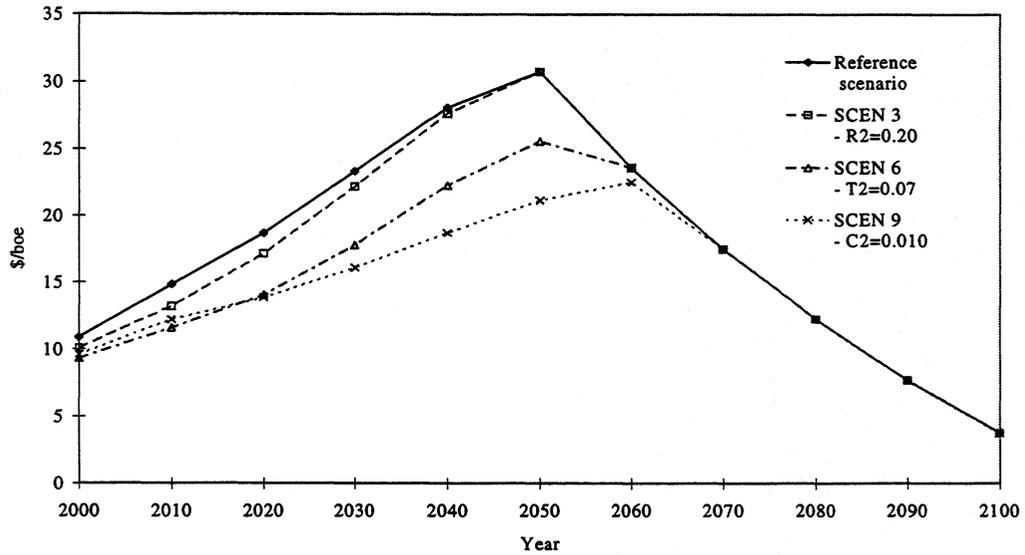
<sup>19</sup> This is, e.g., discussed by four contributors in Oxford Energy Forum (1996).

<sup>20</sup> In OPEC we have assumed a constant rate of 1 per cent p.a.

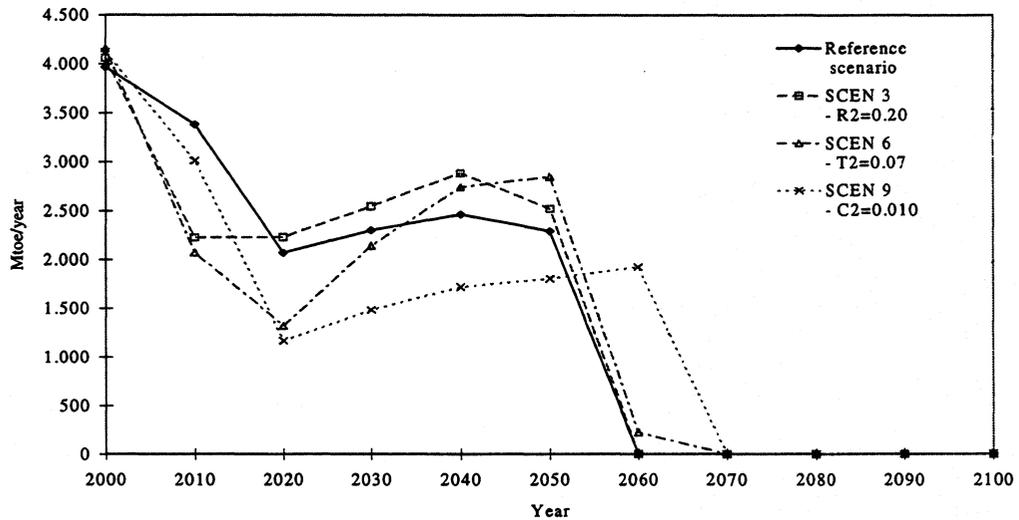
<sup>21</sup> This argument may also be put forward for OPEC, as several OPEC-countries are getting more connected to the international oil industry. If we assume that the initial technological rate of change is increased in OPEC rather than non-OPEC, the cartelisation gains are increased. This is due to a higher market share for OPEC in this case.

<sup>22</sup> The technological change is still gradually reduced to 1 per cent after 30 years.

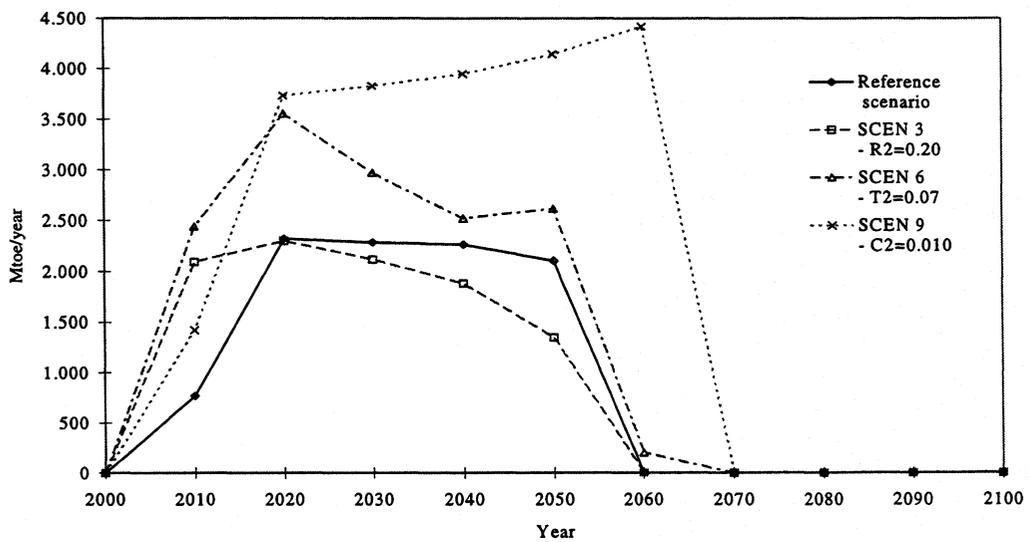
**Figure 7a. The producer price of oil under perfect competition**



**Figure 7b. Oil production in OPEC under perfect competition**



**Figure 7c. Oil production in non-OPEC under perfect competition**



### 5.3. Changes in non-OPEC reserves

In the reference scenario the shape of our cost functions are based on data from BP (1995) for proved reserves, which indicates that the fringe has initial reserves of 239 billion barrels of oil, while OPEC is endowed with 770 billion barrels, i.e., about three quarters of the global reserves. As pointed out in the previous subsection, these circumstances may not be satisfactory for governments in the OECD-countries. One strategy, then, may be to intensify the exploration activity outside OPEC, in order to increase non-OPEC reserves. Thus, we would like to study whether such a move influences the cartelisation gains to OPEC.

As explained in section 2, the cost functions are assumed to be exponentially increasing functions of cumulative production, where the convexity parameter determines the slope of the function. This parameter is determined so that the marginal production cost of the last unit of the current oil reserve equals \$20 per barrel. This choice reflects that there is no universal rule to estimate reserves, beyond the vague definition «quantities which can be extracted under existing economic and operating conditions». With the reserve estimates above, and initial unit costs of \$10.9 and \$3.3 per barrel in non-OPEC and OPEC, the convexity parameters are respectively 0.025 and 0.023 in the reference scenario. The similarities in these parameters reflect that the higher the initial reserves and unit cost, the lower is the convexity parameter in the cost function.

We look at three different scenarios. A convexity parameter for non-OPEC of 0.020 implies an initial amount of reserves equal to 300 billion barrels of oil, while 0.015 implies reserves of 400 billion barrels. Finally, a convexity parameter of 0.010 implies that non-OPEC has reserves of about 600 billion barrels of oil, which is 2.5 times their current reserves. This last scenario seems rather unrealistic even if there were a considerable amount of exploration activity outside OPEC. However, for purpose of illustration the scenario is presented in the Figures 6-7.

Increasing the level of non-OPEC reserves is seen to have an important impact on the oil wealth of OPEC, particularly in the Nash Cournot model. From Table 1 (SCEN 7-9) we see that the resource wealth of OPEC decreases monotonically when the reserves of non-OPEC increases, i.e., when the convexity parameter of the fringe decreases. This is a similar conclusion as in the previous subsections.

However, whereas the relative cartelisation gains have been quite stable in the foregoing analyses, in this case *the profitability of being a cartel is greatly affected*. We see from Table 1 that if the initial oil reserves of non-OPEC are assumed to be 300 billion barrels, i.e., an increase of 25 per cent, the cartelisation gains are halved. Moreover, with initial reserve estimates being increased to 400 billion barrels, the gains become almost zero.<sup>23</sup> Finally, with an initial non-OPEC reserve of 600 billion barrels of oil the cartelisation gains have become negative and the OPEC members would receive a higher resource wealth if they would disintegrate and act as price takers in the oil market.

The intuition behind these results is that as the reserves of non-OPEC producers are expanded, they increase production of oil in all periods of extraction, see Figures 6c and 7c. OPEC thus loses market shares. The price effect of supply restrictions in OPEC is consequently smaller and thus the gains of

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<sup>23</sup> The absolute cartelisation gains are reduced by 94.5 per cent compared to the reference scenario.

cartelisation to OPEC members are smaller. In the Nash Cournot model the change in OPEC supply is only minor in the first four periods, see Figure 6b. However, the time when OPEC takes over the dominance of the market, and enjoys the benefits from cartelisation, is postponed by one period. This implies that the gains from cartelisation in future periods do not outweigh the costs from restricting supply and foregoing revenue in earlier periods when the fringe has such considerable reserves. Hence, OPEC is in fact better off acting as a price taker in this scenario.

We conclude this section by stating that the amount of reserves in non-OPEC is of major importance for the cartelisation gains to OPEC. This conclusion is strengthened by the results of SCEN 10-13, see Table 1. They state that when we combine increases in the fringe reserves with increases in the discount rate or the rate of technological progress, the reserve amount is clearly the most important factor. This might imply that increases in the level of exploration activity outside OPEC is the type of fringe behaviour most inductive to the disintegration of OPEC.

## 6. The effects of moves by consumer countries

The cartelisation gains to OPEC are not only dependent on the behaviour of other oil producers, but also by moves on the demand side, e.g., taken by consumer countries. One such move may be the introduction of carbon taxes in order to curb the emissions of CO<sub>2</sub>. Another step could be to invest R&D in energy savings equipment or alternative energy supply sources in order to be less dependent on oil. In this section we look at the significance of such moves for the oil wealth of OPEC and for the cartelisation gains. The results are presented in Table 2.

**Table 2. OPEC's oil wealth and cartelisation gains with different moves by consumer countries**

Scenario	Parameter <sup>1</sup>		OPEC oil wealth in billion \$		Cartelisation gains (per cent)
	CO <sub>2</sub> <sup>2</sup>	Y1 <sup>3</sup>	Nash Cournot model	Competitive model	
<i>Reference/competitive</i>					
<i>scenario</i>	0	0.5	4,030	3,431	17.5
SCEN 14	10		3,121	2,581	20.9
SCEN 15	25		1,979	1,662	19.1
SCEN 16	35		1,461	1,266	15.3
SCEN 17		0.4	3,873	3,307	17.1
SCEN 18		0.2	3,591	3,027	18.6
SCEN 19		0.0	3,353	2,804	19.6

<sup>1</sup> We enter the parameter estimates only where they differ from the reference scenario assumptions.

<sup>2</sup> CO<sub>2</sub> - global carbon tax in \$ per barrel of oil equivalent

<sup>3</sup> Y1 - income elasticity of fossil fuels in the OECD area

### 6.1. Introduction of global carbon taxes

The threat of global warming is becoming more and more topical (IPCC 1995), and the implication of this may be an international agreement to curb the emissions of CO<sub>2</sub> and other greenhouse gases. One of several strategies to curb such emissions could be to introduce international carbon taxes on the consumption of fossil fuels. An interesting question, then, is whether such a move could alter the

cartelisation gains to OPEC. One possibility could in fact be that the gains become so small that OPEC breaks down, implying that the production of oil, and thus the emissions of CO<sub>2</sub>, accelerates.

We introduce global carbon taxes in the range \$10-35 per barrel of oil, where the tax is put on the fossil fuels according to their carbon content. As one would guess, this reduces the oil wealth of OPEC dramatically, see Table 2 (SCEN 14-16). However, the effect on the cartelisation gains to OPEC is ambiguous, as the reduction in oil wealth is big in the competitive model, too. Still, even though the relative cartelisation gains are only partly changed, OPEC's oil wealth diminishes so much that the absolute level of cartelisation gains is considerably reduced. Hence, although there has not become more to gain by leaving the cartel, the benefits of sustaining the cartel are reduced in this scenario. If there are fixed costs unaccounted for by maintaining the organisation, the introduction of large carbon taxes may thus have adverse effects on the unity of OPEC.

## 6.2. Changes in income elasticities in the OECD area

There are much debate about energy savings and research in alternative energy sources in several OECD-countries. Several explanations could be mentioned for this attention. The traditional argument in favour of such strategies has been related to the availability of oil reserves; both the fact that oil is an exhaustible resource, and that the major stocks of these resources are situated in a politically unstable area. In recent years the focus on air pollution has also called attention to the negative externalities of consuming fossil fuels.

If these factors induce the OECD countries to more actively encourage energy savings or research in alternative energy sources, the income elasticities of oil, and probably other fossil fuels, may decrease in the OECD area from its current level.<sup>24</sup> Hence, we would like to study the impact of this on the oil wealth of OPEC. In the reference scenario the income elasticities in the OECD area were assumed to be 0.5 for alle three fossil fuels. In Table 2 (SCEN 17-19) results are presented for income elasticities of fossil fuels in the range 0.4-0.0.<sup>25</sup> Again, OPEC's oil wealth is negatively affected in both models. The oil price is reduced, and the production profile of OPEC is decreased, especially in the midterm period from 2020 to 2050, when the energy savings have become more effectual. In the final periods, when the maximum producer price is reached and the reserves have diminished, production lasts somewhat longer since unit costs are lower due to less accumulated production.

Nevertheless, the impacts on OPEC's oil wealth are not as dramatic as with, e.g., large carbon taxes, see Table 2. Moreover, the cartelisation gains are almost unchanged, both in relative and absolute terms. Although the energy savings mainly affect the later periods, when OPEC dominates the market as a cartel, and not the early periods, which would be dominated by the OPEC-countries if the market were competitive, the profits of sustaining the cartel have in fact not decreased. There are two possible explanations for this. First, the intertemporal feature of the model ensures that negative effects on the profitability in the future also affect earlier periods, as there is a wish to increase present production, which in turn depresses the initial price level. Second, although the midterm

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<sup>24</sup> Intensified research in alternative energy sources may also increase the rate of technological change in the backstop technology.

<sup>25</sup> In each scenario the income elasticities of the three fossil fuels are assumed to be identical in the OECD-area. The results are more or less the same if only the income elasticity of oil is changed, with income elasticity of gas and coal being the same as in the reference scenario.

periods seem to be more important for OPEC as a cartel than if the market were competitive, the marginal profits of one unit may not be different. This is also particularly related to the intertemporal aspect. As production is reduced by almost the same magnitude in the midterm periods in both models, the impacts on the oil wealth may be quite similar. Thus, we may conclude that encouraging energy savings in the OECD area will not lead to any break up of OPEC.

## 7. Conclusions

In this study we have found that there are still positive cartelisation gains to OPEC in the oil market, despite the combination of a relatively small market share to the cartel and low prices compared to earlier decades. More specifically, our results indicate that OPEC's oil wealth is about 18 per cent higher than it would have been if the cartel didn't exist, i.e., if the market were competitive. However, these gains may be considered as quite modest compared to the 1970s, when Pindyck (1978) calculated the gains to be at least 50-100 per cent.

The paper has also focused on different moves taken by non-OPEC producers or consumer countries which could lead to major reductions in the oil wealth of OPEC. In general, we find that these moves nevertheless do not alter the relative size of the cartelisation gains to OPEC significantly. This conclusion applies to the effects of higher discount rates (through privatisation or the acute need for current revenue) and more rapid technological progress on the supply side, as well as the introduction of global carbon taxes and increased energy savings on the demand side. However, as the oil wealth is reduced, so is the absolute value of the cartelisation gains, which implies that the monetary benefits of maintaining the cartel diminish.

The only move that significantly alters the relative cartelisation gains to OPEC, seems to be increases in the oil reserves in non-OPEC. If increased exploration activity leads to an increase in non-OPEC reserves of 25 per cent, we find that the relative cartelisation gains to OPEC are almost halved. Moreover, doubling the reserves implies that the cartelisation gains completely vanish, and in fact become negative. This confirms the theoretical result by Ulph and Folie (1978) that a cartel may be worse off in an open-loop Nash equilibrium than in a competitive market.

Although the relevance of this last scenario may be discussed, it points to the risk that seemingly rational exploration activity may in the end be severely detrimental for the producers if the total exploration activities in non-OPEC are massive. This risk is strengthened by the fact that OPEC consists of several heterogeneous member countries, so that positive cartelisation gains for the cartel as a whole may not be sufficient to prevent a dissolution of the cartel.

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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 $i$ , $i=1,2,3$
$\bar{P}$	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 $k$
$\bar{A}_j^k$	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 $k$
$\lambda$	the shadow cost associated with cumulative extraction up to the current time
$\pi_j^k$	scarcity rent in production of fuel $j$ for producer $k$
$MR^C$	marginal revenue of OPEC
$\tau^k, \gamma^i, \psi$	rate of technological change in production of oil, gas and coal respectively
$\mu$	rate of technological change in backstop technology
$\eta_j^k$	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 $i$
$\omega_j^i$	constant in demand function for fuel $j$ in region $i$
$\alpha, \beta, \sigma^i, \theta$	constants in cost functions
$\kappa$	initial backstop price
$r$	discount rate

t time  
 $T_j^k$  last period of production of fuel j for producer k

## 2. Demand

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

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

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

where

$$\begin{aligned} Q_o^i &= P_o + z_o^i + v_o^i \\ (A2) \quad Q_K^i &= P_K + z_K^i + v_K^i \\ Q_G^i &= P_G + z_G^i + v_G^i \end{aligned}$$

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

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

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

$$(A4) \quad x_o^C + x_o^F = \sum_{i=1}^3 X_o^i$$

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

$$(A5) \quad P_o = P_o(x_o^C + x_o^F, z_o^1 + v_o^1, z_o^2 + v_o^2, z_o^3 + v_o^3, Q_K^1, Q_K^2, Q_K^3, Q_G^1, Q_G^2, Q_G^3, \bar{P}, Y^1, Y^2, Y^3)$$

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

$$(A6) \max_{x_o^c} \int_0^{\infty} [P_o(\cdot) - C_o^c] x_o^c \cdot e^{-rt} dt$$

s.t.

$$(A7) \dot{A}_o^c = x_o^c$$

$$(A8) x_o^c \geq 0$$

$$(A9) C_o^c = \alpha e^{\eta_o^c A_o^c - \tau^c t}$$

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

#### 4. Solving the problem

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

$$(A11) H^c = [P_o(\cdot) - C_o^c(A_o^c, t)] x_o^c + \lambda x_o^c$$

where  $\lambda_t (<0)$  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

$$(A12) \dot{\lambda} - r\lambda = -\frac{\partial H^c}{\partial A_o^c} = \frac{\partial C_o^c}{\partial A_o^c} x_o^c$$

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

$$(A13) \dot{\pi}_o^c = r\pi_o^c - \frac{\partial C_o^c}{\partial A_o^c} x_o^c$$

$x_o^c$  maximises the Hamiltonian for all  $x_o^c \geq 0$  which for an interior solution requires

$$(A14) \frac{\partial H^c}{\partial x_o^c} = P_o - C_o^c + \frac{\partial P_o}{\partial x_o^c} x_o^c + \lambda = 0$$

which gives the producer price of oil when OPEC produces

$$(A15) \quad P_o = C_o^c + \pi_o^c - \frac{\partial P_o}{\partial x_o^c} x_o^c$$

where  $-\frac{\partial P_o}{\partial x_o^c} x_o^c$  is the cartel rent. The marginal revenue of OPEC is defined as

$$(A16) \quad MR^c = P_o + \frac{\partial P_o}{\partial x_o^c} x_o^c = C_o^c + \pi_o^c$$

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

$$(A17) \quad \dot{MR}^c = r\pi_o^c - \tau^c C_o^c$$

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  $\bar{A}_o^c$  be the aggregate production of OPEC over the entire time horizon. The transversality condition is then

$$(A18) \quad \max_i (\bar{P}_{T_o^c} - z_o^i - v_o^i) = C_o^c(\bar{A}_o^c, T_o^c)$$

### 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.

$$(A19) \quad \max_{x_o^f} \int_0^{\infty} [P_o - C_o^f] x_o^f \cdot e^{-\rho t} dt$$

s.t.

$$(A20) \quad \dot{A}_o^f = x_o^f$$

$$(A21) \quad x_o^f \geq 0$$

$$(A22) \quad C_o^f = \beta e^{\eta_o^f A_o^f - \tau^f t}$$

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

$$(A23) \quad P_o = C_o^f(A_o^f, t) + \pi_o^f$$

$$(A24) \quad \dot{P}_o = rP_o - (r + \tau^f)C_o^f = r\pi_o^f - \tau^f C_o^f$$

where  $\pi_o^f$  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  $T_0^F \in (0, \infty)$ , is

$$(A25) \quad \max_i (\bar{P}_{T_0^F} - z_0^i - v_0^i) = C_0^F(\bar{A}_0^F, T_0^F)$$

## 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:

$$(A26) \quad \max_{x_G^i} \int_0^{\infty} [P_G^i - C_G^i] x_G^i \cdot e^{-\pi t} dt$$

s.t.

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

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

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

The first order conditions give

$$(A30) \quad P_G^i = C_G^i(A_G^i, \gamma^i, t) + \pi^i$$

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

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

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

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

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

## 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:

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

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.

$$(A38) P_K = P_K(x_K, z_K^1 + v_K^1, z_K^2 + v_K^2, z_K^3 + v_K^3, Q_O^1, Q_O^2, Q_O^3, Q_G^1, Q_G^2, Q_G^3, \bar{P}, Y^1, Y^2, Y^3)$$

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

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

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