Optimal Oil Exploration under Climate Treaties

by

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Abstract

In this paper we focus on how an international carbon treaty will influence the exploration of oil in Non-OPEC countries. We present a numerical intertemporal global equilibrium model for the fossil fuel markets where the world is divided into three demand regions: OECD-Europe, Rest-OECD and Non-OECD. An initial resource base for oil is given in the Non-OPEC region, however, the resources change over time due to depletion, exploration and discovery. As OPEC as a whole has vast resources, we do not consider oil exploration in this region. The international oil market is modelled with a cartel (OPEC) and a competitive fringe on the supply side. To determine optimal exploration and production, we follow a Nash-Cournot approach. In addition to the oil market, we also model the markets for natural gas and coal to cover substitution effects in demand. When studying the effects of different climate treaties on oil exploration, two contrasting incentives apply. If a constant international carbon tax is introduced, the producer price of oil will fall giving an incentive to delay oil production and exploration. However, the rise in the oil price will also be less which gives an incentive to accelerate production, and, therefore, also to find new oil fields. The last incentive proves to be the strongest which means that an international carbon treaty will accelerate oil exploration in Non-OPEC countries.

Keywords: International Carbon Treaties, Exhaustible Resources, Optimal Oil Exploration

JEL classification: H23, Q30, Q40

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Introduction

A climate treaty, like the Kyoto Agreement, that regulates the emissions of carbon dioxide (CO$_2$), the most important greenhouse gas, will have important impacts on the oil market. Combustion of the fossil fuels, natural gas, oil and coal, is the main source for anthropogenic CO$_2$ emissions, and such a treaty will influence the magnitude and composition of fossil fuel consumption, and therefore also production pattern and exploration activity.

The impacts of a carbon treaty on the oil market have been studied in, e.g., Whalley and Wigle (1991), Wirle (1994,1995), Tahvonen (1996) and Berg et al. (1997a,b). But none of these studies have analysed the effects on oil exploration. The importance of exploration activity may be illustrated by the study of Berg et. al (1997b) where exploration activity outside OPEC is found to be important for the cartelisation gains to OPEC. While they conclude that the relative cartelisation gains are unchanged by other moves from Non-OPEC producers or consumer countries, a major increase in Non-OPEC reserves could remove the cartelisation gains to OPEC completely. Thus, a high successful exploration activity outside OPEC may lead to the dissolution of the OPEC cartel resulting in dramatically lower oil prices and therefore, higher oil consumption and CO$_2$ emissions.

Exploration activity has been examined theoretically either as a problem of constrained intertemporal maximisation or as a problem of stochastic optimisation under uncertainty (see, e.g., Pindyck, 1978; Gilbert, 1979; Arrow and Chang, 1982; Devarajan and Fisher, 1982; Livernois and Uhler, 1987; and Swierzbinski and Mendelsohn, 1989).\(^1\) The seminal paper of Pindyck (1978) introduced exploration into a model of optimal extraction of non-renewable resources, and became a standard for modelling oil exploration in the years to come. Pindyck recognised that producers

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\(^1\) An important part of the literature on oil exploration are econometric studies. For a survey on econometric models on oil exploration, see, e.g., Rodriguez Padilla (1992).
are not «endowed» with reserves, but instead must develop them through the process of exploration. The resource base is treated as the basis for production, and exploration activity as the means of increasing or maintaining reserves. «Potential reserves» are unlimited, but as depletion ensues, given amounts of exploration activity result in ever smaller discoveries. Given these constraints, resource producers must simultaneously determine their optimal rates of exploration activity and production. The desired level of reserves depends in part on the behaviour of production costs. If production costs were independent of reserves (and if there were no uncertainty about the discoveries resulting from exploratory activity), producers would postpone their exploratory activity (thereby discounting its costs) and maintain no reserves. However, production costs rise as reserves decline, although the exact relationship may be complex. The optimal reserve level balances revenues with exploration costs, production cost, and the «user cost» of depletion.

Solow and Wan (1976) shows that in the absence of new discoveries, an aggregate extraction cost function can be defined and indexed by either the level of reserves or the amount of cumulative extraction. However, when new discoveries occur, the proper specification of the aggregate extraction cost function depends on the exploration technology and is in general different from that which is appropriate in the no-discovery case. Thus, according to Swierzbinski and Mendelsohn (1989) the common practice of including an aggregate extraction cost function from the no-discovery case in a model with exploration results in a misspecification as long as the quality of the resource is not homogeneous. This is the procedure in Pindyck (1978), where the extraction costs at the time of a new discovery will determine the extraction costs of the new resources added to the resource base, i.e., the extraction costs of new discoveries are set equal to those of initial reserves at the time of discovery. This will encourage early exploration to «find» cheap oil.

Jin and Grigalunas (1993) examines the impacts of environmental regulations on firms in the oil and gas industry by incorporating the environmental compliance costs into
the exploration and production stages, and concludes that the total investment in exploration and oil production will decrease as a result of rising compliance costs. They do, however, not study the effects an international climate treaty may have on the oil price path and, therefore, also on exploration. This will be the focus in this study where we look at the optimal exploration activity in Non-OPEC countries under different climate treaties like the introduction of carbon taxes. Although there is also some exploration activity by OPEC members such as Venezuela, Indonesia, Nigeria, compared to Non-OPEC countries, OPEC as a whole has vast resources that are easily accessible so that such activity is not an important concern.

We use an extended version of the PETRO model (see Berg et al., 1997a,b) which is a numerical intertemporal global equilibrium model for the fossil fuel markets. Opposed to the original version of the model, exploration in Non-OPEC is explicitly modelled based on Swierzbinski and Mendelsohn (1989). We do not consider uncertainty as we assume a deterministic relationship between exploration effort and new discoveries. As Non-OPEC countries are considered as price takers, their production activity and, therefore, also their exploration activity depends on the price path of oil which is consistent with Hotelling’s theory of exhaustible resources.

In this paper we find that a climate treaty implemented by an international CO₂ tax will reduce the producer price of oil giving an incentive to reduce the oil production and thus delay exploration activity. However, the price of oil is increasing at a lower rate after the introduction of a carbon tax. An increasing price gives an incentive to delay production. Thus the flatter oil price development gives the competitive producers an incentive to move production nearer in time. As this incentive shows to be the strongest, Non-OPEC countries will actually accelerate oil exploration. Thus, the impacts on oil exploration are very different from the results found in Jin and Grigalunas (1993) where local environmental regulations on firms are considered.
The paper is organised as follows. In Section 2, the model is outlined, while data are given in Section 3. The simulation results are presented in Section 4. We provide some sensitivity analyses in Section 5 to test the robustness of the results. In the final section, the paper concludes.

2. The model

The PETRO-model was first introduced in Berg et al. (1997a,b). This new version of the model includes oil exploration activity in Non-OPEC countries. It models the international markets for fossil fuels in an intertemporal way, taking into account that the fuels are nonrenewable resources. All prices and quantities at each point of time are determined simultaneously in the model. Consumers determine their demand according to current income and prices of the fuels, whereas producers determine their supply and exploration activity according to the market conditions in all periods assuming perfect foresight.

Let $j$ denote a fossil fuel type and let $i$ denote a geographical region. We specify three fossil fuels in the model; oil (O), natural gas (G) and coal (K), thus $j = O, G, K$.

Consumers are situated in three regions, $i = 1, 2, 3$, where region 1 is OECD-Europe, region 2 is Rest-OECD, and Non-OECD is region 3. $k$ denotes the producer type in the world oil market. We define two producers namely OPEC which acts as a cartel (C), and a competitive fringe (F). There are three regional natural gas markets with perfect competition, 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.

2.1 The demand side

The consumer price of a specific fuel in a specific region, $Q^i_j$, is the sum of the producer price, $P_o, P_k$ or $P_g^i$, fixed unit costs due to transportation, distribution and
refining, \( z^i_j \), existing fuel taxes (subsidies are considered as negative taxes), \( v^i_j \), and, eventually, a carbon tax. Thus before a climate agreement is imposed, we have
\[
Q^i_O = P^i_O + z^i_O + v^i_O \\
Q^i_K = P^i_K + z^i_K + v^i_K \\
Q^i_G = P^i_G + z^i_G + v^i_G
\]

The demand of each fuel, \( X^i_j \), is represented by a log-linear demand function, and is a decreasing function of the consumer price of that fuel and an increasing function of the consumer prices of the two other fossil fuels. Finally, the demand functions change exogenously over time to reflect economic growth. 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. The technology is available in copious supply at a fixed price, \( P \), at each point of time in all regions. Over time, however, the backstop price is reduced by a constant rate to reflect technological change, \( \mu \). \( \kappa \) is the initial backstop price.
\[
(2) \quad P = \kappa e^{-\mu t}
\]

Analytically, the demand structure is specified as follows. Let \( \hat{X}^i_j \) be defined by
\[
(3) \quad \ln \hat{X}^i_j = \ln \omega^i_j + a^i_j \ln Q^i_O + b^i_j \ln Q^i_K + c^i_j \ln Q^i_G + d^i_j \ln Y^i
\]

where \( \omega^i_j \) is a constant coefficient, \( a^i_j, b^i_j, c^i_j, d^i_j \) are price and income elasticities, and \( Y^i \) is the gross national income. Then the demand for fuel type \( j \) in region \( i \) is given by
\[
(4) \quad X^i_j = \hat{X}^i_j, \quad Q^i_j < P \\
X^i_j = 0, \quad Q^i_j > P \\
X^i_j \in [0, \hat{X}^i_j], \quad Q^i_j = P
\]

Consider the oil market, and let \( x^k_O \) denote the production of oil by producer \( k \). Then the restriction of market clearing in the world oil market can be written
\[ (5) \quad x^C_o + x^F_o = \sum_{\nu=1}^{3} X \]

From (1)-(5), we can derive the producer price of oil:
\[ (6) \quad P_o = P_o(x^C_o + x^F_o, z_o^1 + v_o^1, z_o^2 + v_o^2, z_o^3 + v_o^3, Q^K, Q^G, P, Y, Y^2, Y^3) \]

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

### 2.2 Oil production

The supply side of the international oil market consists of a cartel (corresponding to OPEC) and a competitive fringe. While the fringe always considers the oil price path as given, 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. We choose the Nash-Cournot model of a dominant firm to calculate the open loop solution of the game, where both the fringe producers and the cartel take the supply of all other producers as given when deciding their own production profile.

Instead of considering the resources as strictly exhaustible, we assume that the unit extraction costs of both the cartel and the fringe are increasing functions of cumulative production which approach infinity as cumulative production approaches infinity. However, the competitive fringe has an opportunity to influence its extraction costs by finding oil of better quality (meaning lower extraction costs) than those already included in the initial resources. This is done by exploration activity. Hence, with a finite backstop price the economic reserves are finite (see, e.g., Heal, 1976).

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2 There exists two versions of the original model, differing only with respect to the treatment of the global oil market; one consisting of a cartel and a fringe, and one describing a hypothetical competitive market. By comparing the oil wealth of OPEC in the two model versions, we can investigate the cartelisation gains of OPEC, see Berg et al. (1997a,b).

3 The term Nash-Cournot-model of a dominant firm was used by Salant (1976). It can be shown that this Nash-equilibrium is time consistent but not subgame perfect, see, e.g., Hoel (1992).
2.2.1 The optimisation problem for OPEC

Let \( C^k_j \) be the unit cost of production of fuel \( j \) for producer \( k \). The cost level of the two oil producer groups differs as extraction costs in OPEC-countries are generally lower than in the rest of the world. To describe the cost structure of OPEC we have chosen the following exponential function

\[
C^C_O = \alpha e^{\eta_j A^C_O - \tau^C t}
\]

where \( \alpha \) is the initial unit cost, \( A^C_j \) is cumulative production and \( \eta_j \) is a constant coefficient. 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, \( \tau^C_k \), each year (\( t \) is time), independent of production. This means that over time unit costs may be reduced or increased, depending on the production rate.

OPEC seeks to maximise the present value of the net revenue flow, i.e., the oil wealth. It is facing a downward sloping demand schedule at each point of time, and takes the extraction path of the fringe as given. The control variable in the optimisation problem is the extraction path and the state variable is accumulated production. Let \( r \) be the discount rate, and \( P_O(\cdot) \) is the producer price given in (6). With an infinite planning horizon, the optimisation problem is as follows:

\[
\max_{x^C_O} \int_0^\infty \left[ P_O(t) - C^C_O(t) \right] x^C_O(t) \cdot e^{-rt} \, dt
\]

s.t.

\[
\begin{align*}
A^C_O &= x^C_O \\
x^C_O &\geq 0 \\
C^C_O &= \alpha e^{\eta_j A^C_O - \tau^C t} 
\end{align*}
\]

The current value Hamiltonian, \( H^C \), is given by

\[
H^C = \left[ P_O(t) - C^C_O(A^C_O, t) \right] x^C_O + \lambda^C x^C_O
\]
where $\lambda^k(t) (<0)$ is the shadow cost associated with cumulative extraction up to time $t$. The scarcity rent for the cartel is defined as $\pi^c_t = -\lambda^c$, and 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 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

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

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

$$\pi^c_o = r\pi^c_o - \frac{\partial C^c}{\partial x^c_o} x^c_o$$

$x^c_o$ maximises the Hamiltonian for all $x^c_o > 0$ which for an interior solution requires

$$\frac{\partial H^c}{\partial x^c_o} = P_o - C^c_o + \frac{\partial P_o}{\partial x^c_o} x^c_o + \lambda^c = 0$$

This gives the producer price of oil when OPEC produces

$$P_o = C^c_o + \pi^c_o - \frac{\partial P_o}{\partial x^c_o} x^c_o$$

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

$$MR^c = P_o + \frac{\partial P_o}{\partial x^c_o} x^c_o = C^c_o + \pi^c_o$$

Using (14) and (17) we find the time path of the marginal revenue

$$\dot{MR}^c = r\pi^c_o - \tau^c C^c_o$$
In equilibrium, then, as long as the cartel produces, the change in the marginal revenue over time must equal its scarcity rent times the discount rate, minus its unit cost times the technological rate of change. The first part reflects the standard Hotelling rule, while the second part reflects that the marginal revenue does not have to increase that fast in optimum as the costs are falling due to technological change.

In each demand region there is a maximum producer price for each fossil fuel, which is defined as the backstop price minus regional costs due to transportation, distribution and refining of the fuel, and regional fuel and carbon taxes. The cartel will stop producing at time $T^c_0 \in (0, \infty)$ when the unit cost reaches the maximum producer price. Let $A^c_0$ be the aggregate production of OPEC over the entire time horizon. The transversality condition is then

$$\max_i (P^c_i - z^i_0 - v^i_0) = C^c_0 (A^c_0, T^c_0)$$

2.2.2 The optimisation problem for Non-OPEC

The competitive fringe has an opportunity to influence its extraction costs by finding oil of better quality (meaning lower extraction costs) than those already included in the resources. This is done by exploration activity. Thus, we introduce a separation of resources into initial resources and discoveries. The specification of the Non-OPEC optimisation problem is based on Swierzbinski and Mendelsohn (1989).

The undiscovered oil is located in several deposits within different oil fields in the Non-OPEC region. New deposits are discovered via random search in different oil fields. At each point of time, there is a constant exploration unit cost for each unit discovered within each field, $G$, which is known to the fringe. Thus, we assume a deterministic relationship between exploration effort and new discoveries. However, the unit costs increases over time as more oil is discovered, reflecting that the most accessible fields are searched first. The unit cost is known prior to any exploration. Let $D$ be the aggregated discovery and $w$ be the new discoveries at specific point of time. Thus
(20) \( \dot{D} = w \)

Further, let \( \delta \) be the rate of technological progress in exploration costs, \( \beta \) is the initial unit exploration cost, and \( \gamma \) is a constant coefficient. Then, we can specify the following exploration unit cost function for Non-OPEC countries:

(21) \( G = \beta e^{\gamma D - \delta t} \)

By paying the exploration unit cost, the fringe will discover a unit of oil and learn the quality of it, i.e., its unit extraction cost. Only units that have been identified may be extracted. The quality of oil within a deposit can be described by a deposit-cost profile, \( F(C) \), which gives the fraction of oil within a deposit with a unit extraction cost less than \( C \). We specify the deposit-cost profile as follows:

(22) \( F(C) = 1 - e^{-1/\phi(Cr^\tau - C_{min})} \)

where \( C_{min} \) is the lowest possible unit extraction cost. Thus \( F \to 1 \) as \( C \to \infty \). \( \phi \) is a constant coefficient, while \( \tau \) is a technology parameter. Assume that the deposit-cost profile is identical in every deposit and in all fields in the Non-OPEC region. Further, assume that this profile also applies to the initial resources, \( R_0 \), which also includes deposits not economically profitable today. As the fringe will extract the cheapest units first, we see that the cumulative extraction at a specific period of time is equal to the fraction of the total available resources since initial time with extraction costs less than the current extraction cost, i.e.,

(23) \( A^F = (R_0 + D) F(C) \)

Thus, we get

(24) \( F(C) = \frac{A^F}{R_0 + D} \)
Equating (22) and (24) gives after some calculation, the unit extraction cost from old resources, i.e., the resources available at the beginning of the time period, for the fringe:

\[ C_{\text{OF}} = C_{\text{min}} - \varphi \ln \left( \frac{R_0 + D - A_{\text{OF}}^F}{R_0 + D} \right) e^{-\tau F t} \]

However, the fringe can also extract from newly discovered resources, as some of the units in the new deposits have lower extraction costs than units in old resources. Let \( f(C) = F'(C) \). By using this and employing (22), the total extraction costs from extracting from newly discovered deposits are given by

\[ w \int_{C_{\text{min}}}^{C_{\text{OF}}} C f(C) dC = w \left[ e^{-\frac{1}{\varphi}(C_{\text{min}} - C_{\text{OF}})(e^{\tau F t} - 1)} (C_{\text{min}} + \varphi e^{-\tau F t}) - e^{-\frac{1}{\varphi}(C_{\text{min}} + \varphi e^{-\tau F t})(e^{\tau F t} - 1)} (C_{\text{OF}} + \varphi e^{\tau F t}) \right] \]

As \( wF(C_{\text{OF}}) \) is the extraction rate from newly discovered deposits, the unit extraction cost from newly discovered deposits is:

\[ \frac{1}{F(C_{\text{OF}})} \int_{C_{\text{min}}}^{C_{\text{OF}}} C f(C) dC \]

The total oil production in Non-OPEC at a specific point of time is then the sum of the extraction from newly discovered deposits, \( wF(C_{\text{OF}}) \), and extraction from old resources, \( q \).

\[ x_{\text{OF}}^F = wF(C_{\text{OF}}) + q \]

The fringe maximises its resource wealth taking the producer price as given. The optimisation problem with an infinite time horizon is then described by equations (29). All variables are functions of time.

\[ \max_{q,w} \int_0^\infty \left\{ P_o \cdot (w \cdot F(C_{\text{OF}}) + q) - w \int_{C_{\text{min}}}^{C_{\text{OF}}} C f(C) dC - q \cdot C_{\text{OF}}^F - w \cdot G \right\} e^{-\pi t} dt \]
subject to

\begin{align*}
(30) \quad A_o &= wF + q \\
(31) \quad \dot{D} &= w \\
(32) \quad P &\leq F
\end{align*}

given \( q \geq 0, w \geq 0 \), and the functional forms in (2), (21), (22), (25), and (26).

Let \( \lambda^F \) and \( \mu^F \) be the shadow values corresponding to \( A_o^F \) and \( D \). Then the current value Hamiltonian, \( H^F \), of this maximisation problem is:

\[ H^F = P_o \cdot (wF + q) - \int_{\epsilon_{\min}}^{c^F_o} Cf(C)dC - q \cdot C_o^F - w \cdot G + \lambda^F (wF + q) + \mu^F w \]

Hence, the necessary conditions for an optimum are

\[ \frac{\partial H^F}{\partial q} = P_o - C_o^F + \lambda^F \leq 0 \quad (= 0 \text{ for } q > 0) \]

\[ \frac{\partial H^F}{\partial w} = P_o F - \int_{\epsilon_{\min}}^{c^F_o} Cf(C)dC - G + \lambda^F F + \mu^F \leq 0 \quad (= 0 \text{ for } w > 0) \]

\[ \lambda^F - r \lambda^F = -\frac{\partial H^F}{\partial A_o^F} = q \frac{\partial C_o^F}{\partial A_o^F} - wF(C_o^F) \frac{\partial C_o^F}{\partial A_o^F} \cdot \frac{\partial H^F}{\partial q} \]

\[ \mu^F - r \mu^F = -\frac{\partial H^F}{\partial D} = q \frac{\partial C_o^F}{\partial D} + wG \frac{\partial G}{\partial D} - wF(C_o^F) \frac{\partial C_o^F}{\partial D} \cdot \frac{\partial H^F}{\partial q} \]

From (34) we then see that for \( q > 0 \)

\[ P_o = C_o^F - \lambda^F \]

Thus, as long as the fringe produces from old resources, the price must equal the unit cost plus the scarcity rent due to extraction from old resources, \(-\lambda^F\).
To find the time path of the price for \( q > 0 \), we use (30), (31), (36), (38) and the property that the extraction cost function is the inverse function of the deposit-cost function, i.e., \( C^F = F^{-1}(A^F_f/(R_0 + D)) \). Thus we find:

\[
(39) \quad \dot{P}_o = rP_o - (r + \tau^F)C^F_o = r(P_o - C^F_o) - \tau^FC^F_o
\]

Hence, as long as the fringe produces from old resources, the price follows a Hotelling path adjusted for technological change.

From (35) we see that for \( w > 0 \)

\[
(40) \quad P_o = \frac{1}{F}\left[\int_{c_{min}}^{c^F_o} Cf(C)dC + G\right] - \lambda^F - \frac{1}{F}\mu^F
\]

By using (30), (31), (36), (37), (40) and the characteristics of the extraction cost function, we find the development in price for \( w > 0 \):

\[
(41) \quad \dot{P}_o = r\left[\frac{1}{F}\left[\int_{c_{min}}^{c^F_o} Cf(C)dC + G\right]\right] - \frac{1}{F}\delta G + \frac{1}{F}f(C)\tau^FC^F_o \frac{\partial H^F}{\partial q}
\]

Thus, the price follows a Hotelling path adjusted for technological growth, where the term in the square brackets is the unit costs of identifying and extracting a unit from new deposits.

The condition for simultaneous production from old and new deposits, i.e., \( q > 0 \) and \( w > 0 \), is found by equating (39) and (41):

\[
(42) \quad C^F_o (1 + \frac{\tau^F}{r}) = \frac{1}{F}\left[\int_{c_{min}}^{c^F_o} Cf(C)dC + G(1 + \frac{\delta}{r})\right]
\]

Thus, the cost of extracting a unit from previously identified resources adjusted for technological change, must equal the cost of identifying and extracting a unit from a new deposit adjusted for technological change.
The transversality condition for the fringe, where $T_O^F \in (0, \infty)$ is the last period of production and $\overline{A}_O^F$ and $\overline{D}$ are aggregate production and discovery over the entire time horizon, is

$$\max_i (P_{T_{O}^F} - z_{O}^i - v_{O}^i) = C_{O}(\overline{A}_O^F, \overline{D}, T_{O}^F)$$

2.3 Gas production

Because of large transportation costs, natural gas is mainly traded in regional markets. As we are particularly interested 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. The third region is Non-OECD, where the former Soviet Union is a dominating market. We simplify and model the gas markets as competitive since the oil market is the main focus in this paper. However, gas producers dynamically optimise and extraction costs for gas are modelled in the same way as for OPEC. The costs differ between the regions. For more information on the optimisation problems in the gas markets, see Appendix 1.

2.4 Coal production

The coal market is considered as an international competitive market. Since coal resources in the world are huge compared to oil and gas, and we are mainly concerned with the impacts in the oil market, we simply assume that the producer price of coal is fixed at each point of time. However, the price is exogenously reduced over time due to technological change. For more information on the optimisation problem in the coal market, see Appendix 1.
3. Exploration data

The data applied in the OPEC model as well as for gas and coal markets were discussed in Berg et al. (1997a). These are given in Appendix 2. Therefore, we focus on data for Non-OPEC producers.

The initial (1995) unit exploration cost, $\beta$, is set equal to $2 per barrel of oil. This is based on information and exploration cost data in 1994 for Norway (The Norwegian Oil Directorate, 1997) and the United States (Fagan, 1997). There has been a remarkable technological change in exploration outside OPEC the last decades. For the United States, Fagan (1997) concludes that “an accelerating rate of technical change reduced average finding cost 15 percent (onshore) and 18 percent (offshore) per year by 1994”. Taking a more conservative view, we set the rate of technological change in exploration costs equal to 3 per cent per year initially, declining gradually to 1 per cent over a 30 year period. The convexity parameter in the exploration cost function, $\gamma$, is calculated given the assumption of a 3 per cent annual increase in the unit exploration cost at discovery rates of 10 billion barrels per year and 3 per cent annual technological change rate.

The deposit-cost profile is calibrated so that 1985 is the initial year, i.e., $F = 0$ in 1985. This means that in 1995 we have the following deposit-cost profile:

$F_{1995} = \frac{R}{R_{1995} + R} > 0$

where $R$ is the total production in Non-OPEC from 1985-94, and $A_{0,1995} = R$. Thus $D_{1995} = 0$ as previous discoveries are included in $R_{1995}$. This means that the deposit-cost profile of new discoveries are equal to the deposit-cost profile of initial resources in 1985. According to BP(1995), proved reserves of oil at end 1994 in Non-OPEC countries are 239 billion barrels of oil. The reserves are defined as those which can “...be recovered in the future from known reservoirs under existing economic and operating conditions”. However, initial oil resources, $R_{1995}$, also consists of known oil...
resources not yet economically recoverable. The resource/reserves fraction is based on Norwegian figures for 1995 (The Norwegian Ministry of Oil and Energy, 1996), as international estimates are hard to obtain. The parameter \( \varphi \) in the extraction cost function is calibrated under the assumption that the initial reserves are economically recoverable at an oil price equal to $20 per barrel, i.e., \( F(20) = \text{reserves/resources} \). The initial unit cost of oil production, \( C_{\text{min}} \), is calibrated given the deposit-cost profile and given unit costs in 1995 equal to $10.91 per barrel of oil (calculated from Ismail, 1994). We have generally assumed the rate of technological change in oil and gas production to be 1 per cent per year. Initially, however, as oil producers outside OPEC have had impressive technological improvements lately (see, e.g., Ismail, 1994), we assume a rate of 2 per cent in Non-OPEC. This rate is gradually reduced to 1 per cent after 30 years.

A market rate of 7 per cent is used as a discount rate in all markets. All data are presented in Appendix 2.

Results are presented in a Reference scenario where there are no carbon taxes, and in two tax scenarios where carbon taxes are introduced. In the Global carbon tax scenario a carbon tax of $10 per boe is introduced in all regions from 2000 onwards, while in the OECD carbon tax scenario the same carbon tax is introduced in the OECD regions from 2000, while it is first introduced outside OECD in 2030.

Simulations were carried out for the time period 1995-2135 with ten year periods, using the GAMS/MINOS system (see Brooke et al., 1992). Thus the results in each period are the average over the ten years, e.g., the results for the year 2000 are the average over the period 1995-2005.
4. Simulation results

4.1 The Reference scenario

In 2000 the total oil production in the world is 23.8 billion barrels of oil (boe) or 66 million barrels per day in average. OPEC produces about 7.3 billion boe, or equivalently 20.2 million barrels per day, see Figure 1. Thus the OPEC’s share of the total production is just above 30 per cent which is less than the 1994 share of 41 per cent. This means that OPEC acts as a more effective cartel in the model than in reality. The Non-OPEC production in 2000 is 16.5 billion boe or 46 million barrels per day. It increases slightly to the year 2020, where it reaches the top production of more than 19.5 billion boe. The last year of production in Non-OPEC is 2050. OPEC has a steady increase in its production as long as Non-OPEC is in the market. However, when Non-OPEC stops producing, OPEC takes over the whole market. The last year of production in OPEC is 2070 as the price of the backstop is so low that further oil production is not economically viable.

The oil exploration in Non-OPEC, or the new discoveries, start on a level of about 3.5 billion boe in 2000, see Figure 2. This is a little less than actual discoveries in Non-OPEC in 1995 of 3.962 billion boe, see Petroconsultants (1996). However, the exploration and new discoveries are quite high from 2010 to 2040, i.e., on a level between 12 and 16 billion boe per year. The reason for the low exploration in the first period is the relatively large initial resource base, as well as the difference between extraction costs from old resources and new discoveries are increasing over time as the lowest-cost deposits are extracted first. Non-OPEC has a simultaneous exploration and production in all periods apart from in 2050 when its production is very small. Due to the low discoveries in the first period, most of its extraction is taken from old resources. However, for the next three decades, between 50 and 60 per cent of the extraction each year come from new discoveries. As there is no exploration in 2050, extraction in this period is from old resources only. Total discoveries in Non-OPEC over the time horizon is about 597 billion boe.
The oil price starts at $18.2 and increases to almost $39 in 2040, where it meets the maximum producer price of oil, see Figure 3. From 2040 onwards, the producer price follows the maximum producer price. Due to the simultaneous exploration and production from old resources in Non-OPEC from 2000 to 2040, the price path satisfies equations (39) and (41) simultaneously as long as the price is less than the maximum producer price.

Global CO₂ emissions increase from 6.17 billion tons of carbon in 2000 and reach the top of about 12 billion tons in 2050, see Figure 4. Emissions fall from 2060 as oil is substituted by the backstop. Due to increasing coal consumption, the emissions rise
thereafter, with a small drop from 2080 to 2090 when the backstop replaces natural gas globally. Coal is consumed and produced over the entire time horizon.

**Figure 3: Oil price**

<table>
<thead>
<tr>
<th>Year</th>
<th>Reference scenario</th>
<th>Global carbon tax scenario</th>
<th>OECD carbon tax scenario</th>
<th>Maximum producer price in Reference scenario</th>
<th>Maximum producer price in Global carbon tax scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2010</td>
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<td>2100</td>
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**Figure 4: Global CO2 emissions**

<table>
<thead>
<tr>
<th>Year</th>
<th>Reference scenario</th>
<th>Global carbon tax scenario</th>
<th>OECD carbon tax scenario</th>
</tr>
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<tr>
<td>2000</td>
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<tr>
<td>2020</td>
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<tr>
<td>2100</td>
<td></td>
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</tbody>
</table>

**4.2 The Global carbon tax scenario**

In the Global carbon tax scenario, a carbon tax of $10 per boe is introduced in all regions from 2000 onwards. As seen from Figure 3, the producer price of oil is reduced by only $0.5 in the first period, which means that the consumer price increases with $9.5. However, the slope of the price path is lower, and from 2040 onwards, when the price path follows the new maximum producer price, the producer
price is $10 less than in the Reference scenario. See also equation (39) to understand the impacts on the slope by a fall in the price.

**Figure 5: Oil production in OPEC**

![Figure 5: Oil production in OPEC](image)

The reason for the small initial change in the oil price is the OPEC behaviour. As seen from Figure 5, OPEC reduces its production quite significantly, by about 29 per cent, as a response to this climate policy. As OPEC has market power, it knows that reducing production gives a higher price. In a static model, the optimal response by a cartel is to reduce its production to retain its marginal revenue, i.e., the cartel rent. In a dynamic model, however, OPEC must also take into consideration the exhaustability aspect, introduced by the scarcity rent, and the oil rent now consists of the cartel rent and the scarcity rent. But the marginal extraction costs in OPEC is almost constant as long as Non-OPEC is in the market, which means that the scarcity rent is rather low, and OPEC behaviour is not much influenced by the dynamic aspects. Thus for OPEC it is optimal to reduce the production to retain its cartel rent and therefore its oil rent, see also Berg et al. (1997a).

Non-OPEC is a competitive fringe, and views the oil price as given. A lower oil price gives an incentive to reduce production. However, the slope of the price path also matters. An increasing price gives an incentive to delay production. As the price increases less under the climate policy, this incentive is weakened, and Non-OPEC wants to move the production profile nearer in time, i.e., to increase production in
earlier periods and to reduce production in later periods. This explains the production profile in Figure 6. The incentive to accelerate production is stronger than the incentive to reduce production due to lower prices, apart from in the year 2000 where the production is marginally reduced. Thus, Non-OPEC increases its production in the first part of the next century and reduces production at the end of the extraction period. Over the time horizon, the aggregated Non-OPEC production is reduced by about 5 per cent to 875 billion boe.

Figure 6: Oil production in Non-OPEC

To increase Non-OPEC production in early periods, higher exploration may be necessary. This is also confirmed by Figure 2. In a similar way as the production profile, the oil exploration path has been moved nearer in time. Oil exploration is somewhat reduced in 2000, but is higher in the following periods apart from in the last period of exploration. The highest increase is in 2030 where Non-OPEC increases its discoveries with about 1 billion boe per year. Due to the fall in new discoveries in 2040, total discoveries are reduced by 7.5 per cent. This result contrasts the findings of Jin and Grigalunas (1993), where a competitive producer of fossil fuels reduces its production and exploration when an environmental regulation is introduced. Thus, if the environmental regulation effects the producer price of the fuel, as is the case with a climate treaty, the competitive producers may accelerate their production and exploration.
A carbon tax of $10 per boe introduced globally, will reduce global emissions by 21 per cent to 4.8 billion ton carbon in 2000, see Figure 4. This is about 1 billion ton less than global 1990 emissions. The emissions will, however, increase slightly and peak at 9.6 billion tons in 2050. Due to the carbon tax, coal is actually substituted by the backstop from 2110 onwards, which gives no carbon emissions.

4.3 The OECD tax scenario

In the case where the carbon tax is levied on OECD countries only until 2030, but thereafter on all countries, the price path of oil is more or less identical to the price path in the Global carbon tax scenario, see Figure 3. Thus, Non-OPEC production and exploration is also almost identical, see Figures 2 and 6. The reason for this is again the OPEC behaviour. As the Non-OECD region meets no climate restrictions, it has a higher demand for fossil fuels than in the Global carbon tax scenario. This demand is met by higher OPEC production, see Figure 5. As a result, the price paths in the two tax scenarios are almost identical.

Global CO₂ emissions in 2000 have been reduced to 5.6 billion tons of carbon, thereafter, the emissions increase, but are reduced and follow the path of the Global carbon tax scenario when all countries join the agreement, see Figure 4. As fossil fuel prices are almost identical to the Global carbon tax scenario in the OECD regions, CO₂ emissions are also almost identical. In 2000, OECD CO₂ emissions are 7.8 per cent less than 1990 level, however, they are 3.8 per cent higher than 1990 level in 2010. Thus, a carbon tax of $10 per boe in 2010 is probably not high enough to meet the Kyoto Agreement of a reduction of 5.2 per cent compared to 1990 levels of an aggregate of 6 greenhouse gases (including CO₂) measured in CO₂ equivalents.

This scenario shows that even if a carbon tax is levied only on OECD countries for a period of time, the general impacts on exploration will be the same as if the carbon tax is introduced in all regions due to the OPEC behaviour. Thus, a climate agreement will give Non-OPEC countries incentives to accelerate exploration.
5. Sensitivity analysis

As exploration or discoveries in Non-OPEC countries is the main topic in this paper, we concentrate the sensitivity analysis on this variable.

Exploration is not so sensitive to the initial resources in Non-OPEC. Increasing the initial resources from 330 billion barrels to 360 billion barrels reduces exploration somewhat in all periods apart from the first period where it is slightly increased. The reason for the increase in the first period is that we get a more convex extraction cost function, see the calibration of $\varphi$ in section 3. This means that the difference between extraction cost from old resources and the best quality deposits in new discoveries has increased. However, as more initial resources are available, the extraction will be lower over time. Reducing the initial resources gives an opposite result. Finally, by introducing a global carbon tax, the previous results are confirmed, i.e., a carbon treaty gives an incentive to accelerate exploration.

The exploration unit cost is an important variable for determining the optimal exploration. An initial unit cost of $1 actually increases exploration in the first period by as much as 180 per cent, but the increase in later periods is relatively small. If the initial unit cost increases to $5, exploration in the first period is not profitable, however, in later periods new discoveries range from 10-13 billion barrels per year. Introducing a global carbon tax gives the same exploration pattern as before, however, the incentives to accelerate exploration weakens with a low exploration unit cost and high exploration.

A high technological change in exploration, increases exploration activity in all periods, and the usual pattern remains when it comes to a global carbon tax. Exploration is very sensitive to the depletion effect in exploration costs ($\gamma$). If the parameter is halved, i.e., $\gamma = 0.03$, exploration increases considerably in all periods, and Non-OPEC extends its production with one period. In this case, a global carbon tax will only increase exploration in 2030 and 2040, and it will be lower in the other periods.
Increased technological change to 5 per cent initially in extraction will also give high exploration as high technological change increases Non-OPEC production. However, exploration in 2000 is actually non-profitable due to lower extraction costs from old resources. When a global carbon tax is introduced, exploration is increased in 2030 and 2040 but is reduced in other periods. Thus, when exploration is already high, the incentive to accelerate it under a climate treaty seems weakened.

Doubling the technological change in the backstop technology to 3 per cent per year, increases Non-OPEC exploration as they get an incentive to move production to an earlier stage. However, as the maximum producer price is reduced, Non-OPEC stops producing and exploring one period earlier. Introducing a global carbon tax gives the same exploration pattern as before.

To summarise, these sensitivity analyses show that an accelerated Non-OPEC exploration is a rather strong result.

6. Conclusions

This paper studies how an international carbon treaty influences oil exploration in Non-OPEC countries. The traditional result for a competitive producer of fossil fuels meeting an environmental regulation is that the exploration activity is reduced (see Jin and Grigalunas, 1993). However, this result is based on a constant resource price, and the environmental regulation may be interpreted as a local regulation. This assumption no longer holds when an international climate treaty is implemented. A tax on carbon emissions (or a tradeable quota system) will influence the producer price of oil. The producer price will fall, but the rise in the price over time will also be less. If Non-OPEC countries act as competitive producers, they will consider the price as given when deciding their production profile. A lower producer price gives an incentive to reduce production and, therefore, also exploration. However, the reduced increase in
future price lower the incentive to delay production. Thus, Non-OPEC may move the production profile forwards which gives an incentive to accelerate exploration.

To study which effect is the strongest, we have run simulations on a numerical intertemporal global equilibrium model for the fossil fuel markets, where the international oil market consists of a cartel (OPEC) and a competitive fringe (Non-OPEC) on the production side. Due to the optimal reactions of the cartel, we find that the incentive to accelerate exploration is the strongest apart from in the first period where exploration is slightly reduced. The exploration profile is changed so that exploration is reduced in the last period of production. However, aggregated discoveries will be lower under the climate treaty. This pattern holds even if a climate treaty is first introduced in OECD countries. The climate treaty signed in Kyoto in 1997 implies reductions in greenhouse gas emissions of about 5 per cent compared to 1990 levels in Annex 1 countries consisting of OECD and Eastern Europe. Thus, optimal reactions from OPEC to this agreement means that oil exploration in Non-OPEC countries may increase compared to a non-treaty scenario over the next few decades.
References


Appendix 1

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:

(A1) \[ \max_{x_G} \int_0^\infty \left[ P_G^i - C_G^i \right] e^{-rt} \cdot dx_G \]

s.t.

(A2) \[ \dot{A}_G^i = x_G^i \]

(A3) \[ x_G^i \geq 0 \]

(A4) \[ C_G^i = \sigma e^{\eta A_G^i - \gamma^t} \]

The first order conditions give

(A5) \[ P_G^i = C_G^i \left(A_G^i, \gamma^t, t\right) + \pi_G^i \]

(A6) \[ \dot{P}_G^i = rP_G^i - (r + \gamma^t)C_G^i = r\pi_G^i - \gamma^t C_G^i \]

In a market equilibrium the producer price is

(A7) \[ P_G^i = P_G^i \left(x_G^i, z_G^i + v_G, Q_O^i, Q_K^i, P, Y^i\right) \]

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

(A8) \[ \overline{P}_{T_G^i} - z_G^i - v_G^i = C_G^i \left(\overline{A}_G^i, T_G^i\right) \]
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:

\[
\text{(A9)} \quad \max_{x_k} \int_0^{\infty} \left[ P_K - C_K \right] x_k \cdot e^{-rt} \, dt
\]

s.t.

\[
\text{(A10)} \quad x_k \geq 0
\]

\[
\text{(A11)} \quad C_k = \theta e^{-\psi t}
\]

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

\[
\text{(A12)} \quad P_k = C_k
\]

In a market equilibrium we get the following producer price of coal

\[
\text{(A13)} \quad P_k = P_k (x_k, z_k, v_k, z_{1k}, v_{1k}, z_{2k}, v_{2k}, z_{3k}, v_{3k}, Q_{O_1}, Q_{O_2}, Q_{O_3}, Q_{G_1}, Q_{G_2}, Q_{G_3}, P, Y_1, Y_2, Y_3)
\]

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

\[
\text{(A14)} \quad \max_{i} (\bar{P}_{T_k} - z_k - v_k) = C_k (T_k)
\]

\[31\]
Appendix 2

Table A1: GDP growth rates, in per cent.

<table>
<thead>
<tr>
<th>Year</th>
<th>OECD-Europe</th>
<th>Rest-OECD</th>
<th>Non-OECD</th>
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<tr>
<td>1995</td>
<td>2.2</td>
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<td>2094</td>
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<td>2114</td>
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<td>0.75</td>
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Table A2: Price and income elasticities

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<th>Non-OECD</th>
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<tbody>
<tr>
<td>Direct price elasticities</td>
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<td>-0.75</td>
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<tr>
<td>Cross price elasticities</td>
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<td>0.10</td>
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<tr>
<td>Income elasticities</td>
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<td>0.60</td>
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Table A3: Existing taxes on fossil fuels in 1994, 1994$/boe

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<th>OECD-Europe</th>
<th>Rest-OECD</th>
<th>Non-OECD</th>
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</thead>
<tbody>
<tr>
<td>Tax on oil</td>
<td>34.02</td>
<td>12.21</td>
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<tr>
<td>Tax on gas</td>
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<td>Tax on coal</td>
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Table A4: Constant parameter in demand function, ω, mtoe/year

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<th>Oil</th>
<th>Natural gas</th>
<th>Coal</th>
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<tbody>
<tr>
<td>OECD-Europe</td>
<td>13,506</td>
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<td>Rest-OECD</td>
<td>17,735</td>
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<td>Non-OECD</td>
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<td>4,011</td>
<td>4,598</td>
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Table A5: Parameters in the cost functions (Non-OPEC not included)

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<tr>
<th></th>
<th>Initial unit cost of prod., C₀, 1994$/boe</th>
<th>Technological change, τ, per cent</th>
<th>Convexity parameter, η</th>
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<tr>
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<td><strong>natural gas</strong></td>
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<td>OECD-Europe</td>
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### Table A6: Cost data in oil production for Non-OPEC

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<tr>
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<th>initial unit cost, $1994/boe</th>
<th>convexity parameter, $γ$ and $φ$</th>
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<td>exploration costs</td>
<td>2.00</td>
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<td>extraction costs</td>
<td>8.36</td>
<td>7.05</td>
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### Table A7: Production and resources in Non-OPEC, billion barrels of oil

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<tr>
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<td>Non-OPEC</td>
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<td>330</td>
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### Table A8: Initial unit costs of transportation, distribution and refining, $1994/boe$

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<tr>
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