Oil Exploration and Technical Progress in Backstop Technology

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Abstract: This paper examines the impact of endogenous technological change in backstop technology on the optimal exploration and extraction of an exhaustible resource. An intertemporal optimization model is developed and simulated using data for global oil and renewable energy supply and demand. The results indicate that the presence of renewable energy and research in this field alter the optimal time path of oil exploration. Less resources are developed in favor of alternative energy production. However, as long as oil is extracted the share of renewable energy in total production remains relatively small, while the utilization of the resource is shifted from the future towards the present.

Key Words: *exhaustible resources; oil exploration; backstop technology; technological change.*

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1 Introduction

In view of currently high oil and natural gas prices, growing energy demand, and the ongoing unstable political situation in the Middle East, politicians and researchers have called for increasing oil exploration and development activity outside the OPEC cartel. The International Energy Agency (IEA) estimated that investments of about 5 trillion US-$ plus intensified R&D effort are necessary to secure oil supply during the next decades (IEA, 2004). However, since the earth's fossil resources are ultimately exhaustible and the use of conventional energy mainly contributes to global warming, alternative energy technologies must be developed in the long run. Thus, the question arises if the proposed enhancement of exploration and development activity is socially optimal, or, if it would be socially preferable to increase public and private research funds for the development of renewable, environmentally friendly energy technology. This paper examines this problem focussing on the long-term impact of endogenous technological change in renewable energy technology on the optimal exploration of oil.[1]

There is a vast theoretical and empirical literature on exhaustible resource exploitation and exhaustible resource markets (reviewed, e.g., in Krautkraemer, 1998). Resource exploration and discovery has been investigated either as a deterministic or as a stochastic process (see, e.g., Arrow and Chang, 1982; Cairns and Quyen, 1998; Devarajan and Fisher, 1982; Gilbert, 1977; Pindyck, 1978a, 1978b; and Swierzbinski and Mendelsohn, 1989). The following analysis builds upon the well-known exploration model developed by Pindyck (1978a). I assume a 'social planner' with perfect foresight whose objective is to maximize the present value of social net benefits from consumption of oil and the backstop substitute. The reserve base can be replenished through exploration and discovery of new fields, while renewable energy technology

[1] Although the study applies wherever production can be based either on a finite resource stock or a backstop resource, I find it useful to conduct the exposition in the concrete terms of oil and renewable energy due to the problem mentioned above.

can be improved through R&D. Both forms of investment lower marginal energy production cost. This model is used to investigate the following questions: What impacts have the incorporation of a backstop technology on the optimal time profile of oil exploration and extraction? How does endogenous technical change in renewable energy technology influence these effects? How important is endogenous renewable energy R&D compared to the case of substitution?

Due to the complexity of the model only a few results can be obtained analytically. I therefore conduct numerical simulations using data for global oil and renewable energy supply and demand.[2]

In Pindyck's framework the incentives for resource exploration are very similar to the incentives to invest in technical progress. Since there is a stock effect in the aggregate extraction cost function, explorers have an incentive to search for and find new deposits in order to offset the increase in aggregate cost of oil production caused by depletion of known deposits. As Livernois and Uhler (1987) and Swierzbinski and Mendelsohn (1989) have shown, this assumption is only suitable when the quality of the resource is homogenous.[3] However, for the purpose of this study the simplifying assumption is advantageous because it reduces the complexity of the model and allows us to interpret the discovery process as technical progress in extraction technology. Thus, the following analysis also provides insights into the optimal development and allocation of two competing technologies over time.

The majority of earlier works studying the transition from a nonrenewable resource to a backstop substitute considers a 'bang-bang' solution where the transition to the backstop occurs once and for all, when the marginal cost of resource production reaches that of the substitute (see, e.g., Heal, 1976;

[2]Previous applications of Pindyck's model for numerical simulation are, e.g., Deacon (1993) and Yücel (1986, 1989), who study the effects of severance taxes on resource exploration.

[3]Extensions of Pindyck's model that account for the critique can be found, e.g., in Jin and Grigalunas (1993) and Marvasti (2000).

Dasgupta and Heal, 1979; Owen and Powell, 1985). In this modeling approach, technological progress in the backstop technology generally affects the arrival date of the backstop (see, e.g., Dasgupta and Stiglitz, 1981, 1982; Deshmukh and Pliska, 1985; and Kamien and Schwartz, 1978). The more plausible case of a smooth transition, where the resource and the backstop are used simultaneously over a time interval, has been investigated only by a few authors (see, e.g., Kemp and Long, 1980; Chakravorty et al. 1997; Tsur and Zemel, 2003). Endogenous technical pogress in the backstop technology as modeled here has been studied, e.g., by Tsur and Zemel (2003), but they do not account for resource exploration.

The following analysis extends the literature in that it includes both exploration and endogenous technical change in the backstop technology. In addition, it is one of only a few studies that consider global oil exploration activity.[4] I find that the availability of a backstop for oil influences the optimal time path of exploration only indirectly by reducing the scarcity rent (i.e., 'user cost') of oil *in situ*. This generally lowers the incentives for the discovery of new oil fields. The numerical simulations reveal that not only the level but also the shape of the optimal time path of oil exploration is altered in the presence of renewable energy. Technical improvements in the substitute technology reinforce these effects but the impact is smaller that that of energy substitution. An important result for energy policy is that the price path becomes more flat, i.e., the energy price remains nearly constant over time when the share of alternative energy increases due to technical change.

The rest of the paper is organized as follows. In the next section the model is introduced. Results of the numerical simulations and sensitivity analysis are presented in Section 3. Section 4 summarizes the main findings

[4]Due to the lack of data most numerically and/or empirically oriented works focus on regional oil industries, as, e.g., Deacon (1993). An exception is Berg et al. (2002), who study the impact of international climate treaties on the global oil market and on oil exploration in non-OPEC countries.

and concludes.

2 The model

Consider the problem of choosing the optimal rate of consumption of energy, denoted by $q(t)$, that can be produced in each period of time, t, either by using oil, $q^R(t)$, or renewable energy technology, $q^B(t)$, which are assumed to be perfect substitutes. Utility consumers derive from energy consumption is described by a function $U(q(t))$ that satisfies the standard curvature properties: $U_q > 0$, $U_{qq} < 0$, $U_q(0) \leq \infty$, and $U_q(\infty) = 0$.[5] It is further assumed that consumers are indifferent with respect to energy production from fossil fuels, $q^R(t)$, or using the backstop technology, $q^B(t)$, so that $U(q(t)) = U(q^R(t) + q^B(t))$. In a market environment then, the marginal willingness to pay for energy, U_q, represents the inverse aggregate energy demand function, $D^{-1}(q(t))$, and utility is given by gross consumer surplus, $U(q(t)) = \int_0^{q(t)} D^{-1}(x)dx$.

Let $R(t)$ denote the stock of proven reserves at time, t. Following Pindyck (1978a), total costs of conventional energy production, $C^1(R(t))q^R(t)$, are linear in the rate of extraction, $q^R(t)$, while the unit cost of extraction increases as the stock of proven reserves, $R(t)$, is depleted ($C^1_R < 0$). Additional reserves can be attained through exploration and discovery. Denoting $X(t)$ as cumulated discoveries the proven reserve base changes over time according to

$$\dot{R}(t) = \dot{X}(t) - q^R(t) , \quad (1)$$

$$\dot{X}(t) = F(w(t), X(t)) , \quad (2)$$

where $F(w(t), X(t))$ is the discovery function satisfying the properties: $F_w > 0, F_{ww} < 0, F_X < 0, F_{wX} < 0$. These assumptions imply that the number of

[5]First (second) derivatives are denoted by single (double) subscripts to function symbols. Dots over function symbols refer to time derivatives.

discoveries, $F(\cdot)$, depends positively on exploratory effort, $w(t)$, and negatively on cumulative discoveries, $X(t)$. The latter reflects the idea that it becomes more difficult to make new discoveries the more fields have already been found. If we consider exploration as research activity to improve extraction technology the assumption $f_X < 0$ represents the concept of 'fishing' innovations out of an exogenously given pool of inventions, which is depleted through the research process.[6] With both interpretations searching for future opportunities involves that resources must be allocated to the search process. The costs of exploratory effort, $C^2(w(t))$, are assumed to be convex in $w(t)$, i.e., $C^2_w > 0, C^2_{ww} \geq 0$.

Described so far, the model is alike the framework developed by Pindyck (1978a). Adding a backstop resource and endogenous technical progress requires further assumptions concerning the associated costs and the process of technological change.

I assume that the costs of backstop production, $C^3(q^B(t), H(t))$, depend on output, $q^B(t)$, as well as on the level of knowledge pertaining to alternative energy exploitation, $H(t)$. The function $C^3(\cdot)$ is assumed to exhibit the common properties: $C^3_{q^B} > 0, C^3_{q^B q^B} > 0, C^3_H < 0, C^3_{HH} > 0$, $C^3_{q^B H} < 0$, and $C^3_{q^B} > 0$ for $H \to \infty$, implying that total and marginal backstop production cost increase with output and decrease with increasing knowledge.

The process of knowledge accumulation is determined by investments in R&D, denoted by $r(t)$, and the level of knowledge in period t:

$$\dot{H}(t) \quad = \quad \Psi(r(t), H(t)) \ , \tag{3}$$

where $\Psi_r > 0, \Psi_H > 0$. This is the well-known 'standing-on-shoulders' approach, which, in contrast to the discovery process, implies that research activity in one period leads to a larger stock of knowledge in the next period. I assume that there are diminishing returns to R&D, both within and across

[6]See, e.g., Nordhaus (2002), p. 187, on the difference between the 'depletable-pool' and the 'standing-on-shoulders' approach in modeling the innovation-possibility frontier.

time periods: $\Psi_{rr} < 0, \Psi_{HH} < 0$.[7] Research expenditures are described by a function $C^4(r(t))$ that satisfies the properties: $C^4_r > 0, C^4_{rr} \geq 0$.

Given the assumptions above the social planning problem is to choose optimal time paths for extraction, exploration, backstop production, and research so as to maximize discounted social net benefits from energy consumption. Formally, the optimization problem is:

$$\max_{q,w,r} \int_0^\infty [U(q(t)) - C^1(R(t))q^R(t) - C^2(w(t)) - C^3(q^B(t), H(t)) - C^4(r(t))] \, e^{-\rho t} \, dt \tag{4}$$

subject to (1), (2), (3), and $\lim_{t\to\infty} R(t) \geq 0$, $q^R(t), q^B(t), w(t), r(t) \geq 0$, $R(0) = R_0, X(0) = X_0, H(0) = H_0$ given.

Requirement (4) represents a dynamic optimization problem with four control variables, $q^R(t)$, $w(t)$, $q^B(t)$, and $r(t)$, and three state variables, $R(t)$, $X(t)$, and $H(t)$. The current-value Hamiltonian $\mathcal{H}$ for this problem is given by:

$$\begin{aligned} \mathcal{H} \;=\; & U(q^R(t) + q^B(t)) - C^1(R(t))q^R(t) - C^2(w(t)) - C^3(q^B(t), H(t)) \\ & -C^4(r(t)) + \lambda^1(t)\big(F(w(t), X(t)) - q^R(t)\big) + \lambda^2(t)F(w(t), X(t)) \\ & +\mu(t)\Psi(r(t), H(t)) \;, \end{aligned}$$

where $\lambda^1(t)$, $\lambda^2(t)$, and $\mu(t)$ denote the costate variables associated with resource extraction (1), exploration (2), and knowledge accumulation (3), respectively. From the maximum principle one obtains the following necessary

[7] This assumption is consistent with empirical findings on energy R&D. See, e.g., Popp (2002).

conditions:

$$\begin{aligned}
\mathcal{H}_{q^R} &= U_q(\cdot) - C^1(R(t)) - \lambda^1(t) \ \le 0 \quad (=0 \ \text{ if } \ q^R(t) > 0), &(5)\\
\mathcal{H}_{w} &= -C^2_w(w(t)) + (\lambda^1(t)+\lambda^2(t))F_w \ \le 0 \quad (=0 \ \text{ if } \ w(t) > 0), &(6)\\
\mathcal{H}_{q^B} &= U_q(\cdot) - C^3_{q^B}(q^B(t), H(t)) \ \le \ 0 \quad (=0 \ \text{ if } \ q^B(t) > 0), &(7)\\
\mathcal{H}_{r} &= -C^4_r(r(t)) + \mu(t)\Psi_r(r(t), H(t)) \ \le \ 0 \quad (=0 \ \text{ if } \ r(t) > 0), &(8)\\
\dot\lambda^1(t) &= \rho\lambda^1(t) + C^1_R(R(t))q^R(t) \ , &(9)\\
\dot\lambda^2(t) &= \rho\lambda^2(t) - \big(\lambda^1(t)+\lambda^2(t)\big)F_X \ , &(10)\\
\dot\mu(t) &= \rho\mu(t) + C^3_H(q^R(t), H(t)) - \mu(t)\Psi_H(\cdot) \ , &(11)
\end{aligned}$$

and the transversality conditions:

$$\lim_{t\to\infty} e^{-\rho t}\lambda^1(t) = 0 \ , \quad \lim_{t\to\infty} e^{-\rho t}\lambda^2(t) = 0 \ , \quad \lim_{t\to\infty} e^{-\rho t}\mu(t) = 0 \ . \qquad (12)$$

In the following, I assume $U_q(0) > C^1(0) > C^3_{q^B}(0,\cdot)$, which rules out the trivial solution $q^R = q^B = 0$ as well as the well-known 'bang-bang' solution ($q^B = 0$ (>0) if $q^R > 0$ $(=0)$) that would arise when backstop production cost were linear in output. I further assume that at least a small amount of backstop energy can always be competitively supplied, i.e., $C^3_{q^B}(0, H_0) < C^1(R_0) + \lambda^1(0)$.

The equations of motion (9)-(11) can be solved using the corresponding transversality conditions (12) and the first order conditions (6) and (8), yielding:

$$\lambda^1(t) = -\int_t^\infty C^1_R\, q^R\, e^{-\rho(s-t)} ds \ , \qquad (13)$$

$$\lambda^2(t) = \int_t^\infty F_X \frac{C^2_w}{F_w}\ e^{-\rho(s-t)} ds \ , \qquad (14)$$

$$\mu(t) \ = \int_t^\infty \big(-\ C^3_H + \Psi_H \frac{C^4_r}{\Psi_r}\big) e^{-\rho(s-t)} ds \ . \qquad (15)$$

Note that the shadow values $\lambda^1(t)$ and $\mu(t)$ are positive, while $\lambda^2(t)$ is negative.

The equations governing the dynamics of system (4) can be easily interpreted. Equation (5) states that along the optimal extraction path of oil marginal benefits from energy consumption should always equal marginal extraction cost, $C^1(R(t))$, plus the shadow value, $\lambda^1(t)$, of the proven reserve base. Here, the shadow price of oil represents the discounted sum of marginal cost that one extracted unit in period t inflicts over all future extractions of the remaining reserve base (cf. equation (13)). Similarly, from equation (14) we see that the shadow cost of cumulative discoveries, $\lambda^2(t)$, reflects the increase in marginal cost of future reserve additions due to exploratory activity in t. Given these interpretations, equation (6) says that in the optimum new discoveries should be made up to the point where *marginal discovery cost*, C_w^2/F_w, plus the shadow cost of cumulative discoveries, $\lambda^2(t)$, equal the discounted sum of future marginal extraction cost savings, $\lambda^1(t)$, that result from one additional unit of proven reserves. Thus, the incentives to invest in oil exploration are very similar to the incentives to invest in improved technology, which generally comprise all future marginal cost savings from research (see below). The difference here is that the discoveries *themselves* can also be consumed once they are extracted.

Since backstop energy is indefinitely available by definition there are no scarcity costs related to this activity. Consequently, the first order condition (7) for optimal renewable energy production implies that marginal utility from energy consumption and marginal backstop production cost should be balanced out in each time period.

Finally, the condition (8) for the optimal level of renewable energy R&D requires that in the optimum *marginal innovation cost*, C_r^4/Ψ_r, equals the marginal rate of return to the knowledge stock, $\mu(t)$. The latter covers the discounted sum of all future marginal backstop production cost savings and marginal innovation cost savings resulting from a marginal increase of the knowledge stock (see equation (15)).

The dynamics of system (4) with renewable energy production and R&D

consist of two phases: an initial phase where conventional and renewable energy is consumed simultaneously, followed by a phase where the backstop resource is the single source for energy production. Exploratory activity occurs only during the first phase, while renewable energy R&D is undertaken in both time intervals.

The two-phase solution to (4) follows directly from the assumptions on marginal cost of backstop production. According to the first order conditions (5) and (7), simultaneous production of conventional and backstop energy requires that marginal cost of backstop production equals marginal cost of resource extraction plus rent:

$$C^3_{q^B}(q^B(t), H(t)) = C^1(R(t)) + \lambda^1(t) \ . \tag{16}$$

Since it is assumed that marginal cost of renewable energy production increases with output and that renewable energy is initially competitive, this condition holds from $t = 0$ onward. As oil reserves are used up marginal extraction cost rises during this phase (despite exploration), while marginal cost of renewable energy production decreases due to the accumulation of knowledge. From equation (16) follows that marginal extraction cost cannot rise infinitely since they are always bounded from above by marginal cost of renewable energy production. This implies that conventional energy production ceases in finite time, in general before oil reserves are exhausted. At the optimal terminal date of conventional energy production, T^*, condition (16) reduces to $C^3_{q^B}(q^B(T^*), H(T^*)) = C^1(R(T^*))$, since the scarcity rent $\lambda^1(T^*)$ is zero according to the transversality condition (12). In the second phase following T^* only renewable energy is consumed.

The end conditions for exploration activity remain unchanged in the presence of renewable energy. As Pindyck (1978a, p. 846-7) has shown the optimal shutdown date of exploration depends on the value of marginal discovery cost for $w = 0$. If $C^2_w/F_w = 0$ as $t \to T^*$, exploration and extraction will end at the same time. If $C^2_w/F_w > 0$ as $t \to T^*$, exploration will stop before oil extraction shuts down.[8]

What impact have renewable energy production and R&D on resource exploration? From the first order condition (6) one obtains the following equation of motion that describes the dynamics of oil exploration:[9]

$$\dot{w}(t) \;=\; \frac{C_w^2\left(\frac{F_{wX}}{F_w}F(\cdot) - F_X + \rho\right) + C_R^1 q^R(t) F_w}{C_{ww}^2 - \frac{C_w^2}{F_w}F_{ww}} \,. \tag{17}$$

Expression (17) is identical to equation (13) in Pindyck (1978a), which implies that renewable energy production and R&D does not affect the optimal time path of exploratory effort *directly*. However, both substitute production and R&D do influence exploratory activity in that they alter the optimal time profile of oil extraction. Although the impact on exploration cannot be derived analytically, some conclusions can be drawn from the terminal conditions for oil extraction and exploration. As noted earlier, since marginal cost of renewable energy production places an upper bound on marginal extraction cost, the presence of the renewable energy shortens the optimal time horizon of conventional energy production. Both effects lower the scarcity rent, $\lambda^1(t)$, of the proven reserve base over the whole time horizon the exhaustible resource is used. As a consequence, the incentives for oil exploration, which comprise the discounted sum of future marginal extraction cost savings, i.e., $\lambda^1(t)$, are also lowered. Moreover, since it is not optimal to discover new oil fields after conventional energy production has been shut down, exploration is undertaken over a shorter period of time too. These impacts together imply that cumulative discoveries are likely to be smaller in the presence of renewable energy than without a backstop. Endogenous technical change in the

[8]The terminal conditions follow directly from the Kuhn-Tucker condition (6). In case of $C_w^2(0)/F_w(0,\cdot) = 0$, $C_w^2/F_w - \lambda^2(T^*) = \lambda^1(T^*) = 0$ holds so that $w(T^*) = 0$. If exploration stopped before T^* social benefits could be increased by enhancing exploratory activity in each period up to the point where $C_w^2/F_w - \lambda^2(t) = \lambda^1(t) > 0$. After T^* no further benefits can be obtained from exploration since $\lambda^1(t) = 0$ for all $t \geq T^*$. In case of $C_w^2(0)/F_w(0,\cdot) = \overline{c} > 0$, optimal exploratory activity stops in $T' < T^*$ where $C_w^2/F_w = \overline{c} = \lambda^1(T')$ holds, since $\lambda^2(T') = 0$ according to (12). In $t > T'$, $C_w^2/F_w = \overline{c} > \lambda^1(t)$ holds so that $w(t) = 0$ for all $t > T'$.

[9]See Appendix for details.

backstop technology strengthens these effects in that it lowers the boundary on marginal extraction cost over time.

In the following section the model is applied to the development of renewable energy technologies and the optimal extraction and exploration of global oil reserves in order to investigate numerically how renewable energy production and R&D influence the dynamics of the model.

3 Numerical simulation

In this section numerical simulations are carried out to study the impact of renewable energy R&D on oil exploration over time, given reasonably realistic parameter values. Throughout the analysis the assumptions made in the previous section are maintained. World petroleum resources are considered as the exhaustible resource stock, while the different renewable energy technologies are viewed as an aggregated backstop technology. It is assumed that the energy industry is fully competitive. Therefore, the simulated paths do not forecast future energy price and supply of oil and renewable energy. However, the simplified model is sufficient to answer the questions raised in the introduction.

In the following, I first describe the functional forms and parameter values used in the simulation. Then, the optimal time paths for oil extraction and exploration without and with backstop technology and renewable energy R&D are calculated and compared to each other. Since most 'real' parameter values are relatively uncertain I also perform sensitivity analysis to test the robustness of the model outcome. Finally, the results obtained throughout this section are summarized and discussed.

3.1 Functional and parametric specifications

The numerical model is initially calibrated using available data of the world crude oil market and global primary renewable energy supply and development, where the year 2000 has been chosen as the base year.

As described earlier, gross consumer's surplus is taken as a measure for (gross) social welfare derived from energy consumption. I assume that aggregate annual energy demand, $D(P(t))$, depends negatively on energy price, $P(t)$, and positively on aggregate income, $Y(t)$. The functional form assumed for energy demand is:[10]

$$D(P(t)) = \alpha_D P(t)^{\beta_{D_1}} Y(t)^{\beta_{D_2}} \ , \tag{18}$$

where α_D is a constant coefficient and β_{D_1} and β_{D_2} denote, respectively, the long run price and income elasticities of demand.

Several empirical studies on price and income elasticities of energy demand exist in the literature (see, e.g., Cooper, 2003; Gately and Huntington, 2002). In general, these studies have found inelastic demand responses to changes in energy prices, both in the short and in the long run, but the estimated values vary substantially across the analyzes. In this study, the long-run price elasticity of demand, β_{D_1}, is set to -0.6, a value used for OECD countries in the *OECD Economic Outlook No. 76* (OECD, 2004). With respect to the long-run income elasticity, β_{D_2}, I follow the suggestion of Gately and Huntington (2002) for OECD countries and assume a value of 0.5.[11]

The third parameter in the demand function, α_D, is computed from equation (18) using the initial values for $D(t), P(t)$, and $Y(t)$ described below. This yields $\alpha_D = 1.28$.

Aggregate income, $Y(t)$, is measured as gross world product (GWP), which was $31,746$ billion US-\$ in the year 2000 (World Bank, 2006). In the

[10]This function is commonly used in the literature. See, e.g., Berg et al. (2002) and Chakravorty et al. (1997).

[11]In the context of a long-run planning model as used here, short-term responses of energy demand are typically neglected (i.e., 'smoothed out'), since the focus of the analysis is on long-term developments. However, short-term responses of energy demand could be easily integrated in the model by assuming a partial adjustment demand function in equation (18). For an application of such a function in the context of a nonrenewable resource model see, e.g., Pindyck (1978b) and Rauscher (1988), (1992).

base case scenarios, GWP and, thus, energy demand is held constant over time. This assumption is relaxed in the sensitivity analysis, where the effects of growing energy demand on oil exploration and renewable energy R&D are studied.

In 2000, oil remained one of the most important energy resources of the world. According to the IEA (2002) crude oil accounted for about 39% ($\approx$ 27.5 Gb)[12] of global primary energy demand, while the share of renewable energy was only 5% ($\approx$ 3.5 Gboe).[13] The average price for oil increased to about $28 per barrel, which is taken as the initial price for total energy consumption in the simulation. The initial stock of proven oil reserves is set to $R_0 = 1115.8$ Gb (BP, 2005).

As in Pindyck (1978a), I assume that average extraction cost increases hyperbolically with decreasing oil reserves. The extraction cost function is given by:

$$C^1(R(t)) = c_0^1 R_0 / R(t) \; , \tag{19}$$

where c_0^1 denotes initial production cost per barrel.

Oil production cost range worldwide from $2 to more than $15 per barrel depending on reservoir characteristics and economic conditions. I assume an initial cost of $10 per barrel, which lies in the range of values commonly used in the literature for a competitive oil industry (see, e.g., Berg et al., 2002).

Since there is no empirical study on global oil exploration and discovery, several assumptions are made regarding exploratory activity. The discovery

[12] In 2000, demand was partly met with oil from stocks on hand. In addition, there is no single number for oil consumption in the literature; see, e.g., EIA (2004) and IEA (2002). The extraction rate used for the base year, $q^R(0) = 27.5$, is therefore the average of oil production and consumption reported by BP (2005) for 2000.

[13] The relatively small share of renewable energy contains only commercial energy demand and excludes biomass consumption in developing countries (IEA, 2002). The share of renewable energy consumption including bioenergy use in developing countries was about 13.8% in 2000 (IEA, 2002). The smaller number is used in the simulation, because bioenergy consumption in developing countries mainly refers to the combustion of biomass for cooking and heating, which is not a backstop *technology* in the sense of the definition used here.

function is of the form used by Pindyck (1978a):

$$F(w(t), X(t)) = \alpha_F w(t)^{\beta_{F_1}} e^{-\beta_{F_2} X(t)} \ , \tag{20}$$

where the parameter α_F can be interpreted as total exploratory productivity, β_{F_1} refers to marginal well productivity, and β_{F_2} is a depletion parameter. Exploratory effort, $w(t)$, is measured by the number of exploratory wells (i.e., new field wildcats) completed each year.

Data for global exploration and discovery is generally difficult to obtain. According to IHS (2006) worldwide exploratory activity yielded an average annual volume of 15.1 Gb of oil discoveries in the period 2000-2004 ($F(0) = 15.1$).[14] Since both total field wildcats and the rate of successful wells drilled are only reported for oil *and* gas, the initial number of exploratory wells is calculated from the data using the average number of successful exploratory wells for oil (453) and the average rate of success for oil and gas (40.94%) for the 2000-2004 period. This yields $w(0) = 1107$. The values for $F(0)$ and $w(0)$ are then used to compute the parameter α_F in the discovery function, where the remaining parameters are set to $\beta_{F_1} = 0.5$ and $\beta_{F_2} = 0.0015$. The value for β_{F_1} is taken from Yücel (1986). The depletion parameter β_{F_2} is chosen to meet the requirement that cumulative discoveries in the case without backstop technology lies in the range of values estimated by the USGS (2000). The impacts of variations of the parameters in the discovery function are investigated within the sensitivity analysis in section 3.3.

Marginal cost of exploratory effort is assumed to be constant, i.e., $C^2(w(t)) = c_0^2 w(t)$. The costs per exploratory well, c_0^2, are calculated from initial discoveries and wells drilled using finding costs per barrel of oil equivalent as a proxy for marginal discovery cost. Finding costs are defined as the ratio of three-year weighted averages of exploration and development expenditures to reserve additions. The EIA (2002) reports worldwide finding costs for oil and

[14] Since there are large fluctuations in annually discovered volumes, average values are used for exploration and discovery in the base year.

gas of selected major U.S.-based energy-producing companies of \$5.83/boe for the years 1998-2000. Over the longer period from 1987 to 2000, worldwide finding costs, excluding the U.S. Offshore region, remained relatively stable around \$5/boe (in 2000-\$). In more recent years, finding costs increased but mainly due to reserve revisions. Thus, I use the constant value of \$5 per barrel for initial marginal discovery costs (C_w^2/F_w) to compute $c_0^2 = 0.034$.

Next, specifications for backstop production and renewable energy R&D are needed. I assume a quadratic backstop cost function: $C^3(q^B(t)) = \frac{c_0^3}{H(t)}\, q^B(t)^2$, where the parameter c_0^3 is calibrated so that the initial share of renewable energy consumption equals 5% of total primary energy demand ($q^B(0) = 3.5$ Gboe). The initial stock of knowledge, H_0, is normalized to unity, so that $c_0^3 = 4$. Total and marginal cost of backstop production decrease over time as more and more knowledge is accumulated. I assume that the knowledge accumulation process is driven by both exogenous technical progress as well as (endogenous) investment in technological improvements. The function $\Psi(\cdot)$ reads:

$$\Psi(r(t), H(t)) = \alpha_{\Psi_1} H(t) + \alpha_{\Psi_2} r(t)^{\beta_{\Psi_1}} H(t)^{\beta_{\Psi_2}} \ , \quad 0 < \beta_{\Psi_1}, \beta_{\Psi_2} < 1 \ , \quad (21)$$

where $\alpha_{\Psi_1} = 0.05$ is the rate of autonomous technical change per year. The second term on the right hand side of equation (21) describes how investment in renewable energy R&D create new knowledge. The Cobb-Douglas form reflects the assumption that there are diminishing returns to R&D, both within and across time periods.[15] Following Goulder and Mathai (2000), I set $\beta_{\Psi_1} = \beta_{\Psi_2} = 0.5$ in the backstop R&D scenario. The parameter α_{Ψ_2} is chosen in order that the average annual growth rate of backstop production during the first time periods corresponds to the past average annual growth rate of 1.2% of renewable energy sources in the member countries of the IEA (OECD/IEA, 2004). The value of $\alpha_{\Psi_2} = 0.0115$ meets this requirement.

[15] The Cobb-Douglas form is a common functional form used in the literature. See, e.g., Goulder and Mathai (2000), Nordhaus (2002), and Popp (2004).

The slow growth of renewable energy sources in IEA countries during the past decade is mainly attributable to reduced public and private investment in energy R&D (see, e.g., Margolis and Kammen, 1999). In 2000 public spending on renewable energy R&D was about \$630 million (in 2000-\$) according to IEA RD&D statistics (IEA, 2006). Detailed information on global private investment in renewable energy R&D is unfortunately not available. However, data for the U.S. indicates that both the level of overall energy R&D and the share of renewable energy R&D have been declined since the 1990's.[16] Thus, although somewhat arbitrarily I increase the value for public R&D reported in the IEA database about two third in order to specify initial investment funds for renewable energy R&D: $C^4(r(0)) = 1$ billion \$.[17] Average cost of research investment are assumed to increase with scale: $C^4(r(t))/r(t) = r(t)$, which implies $r(0) = 1$ (cf. Goulder and Mathai, 2000).

Finally, the discount rate used in the simulation is 5% per annum.

3.2 Simulation results

Simulations were carried out at 10-year intervals for the time period 2000-2100.[18] This small deviation from the analytical model has two implications. First, the results obtained for each period should be interpreted as the average values over the corresponding ten years. Second, the time paths for conventional and renewable energy use are (only) optimal, given the fixed time horizon. The restriction of the time scale can be justified not only with saved computing time but also with the fact that the earth's oil reserves are expected to be depleted within a century (which is confirmed by the backstop scenarios).

[16] Cf. Jefferson et al. (2001) and Kammen and Nemet (2005).

[17] This value has also been used by Popp (2004) for the base year 1995 (in 1990-\$). Since research expenditures declined since 1995, the value seems to be still plausible for the year 2000.

[18] The model has been solved using the student version of the GAMS/MINOS software. See Brooke et al. (1998).

In order to explore the impacts of renewable energy production and R&D on oil exploration I compare the following three scenarios:

(1) oil extraction and exploration *without* backstop technology;

(2) oil extraction and exploration *with* renewable energy technology;[19]

(3) oil extraction and exploration with *endogenous* technological change in renewable energy technology.

The second scenario serves as the reference case in the sensitivity analysis below.

3.2.1 Optimal solutions without backstop technology

To begin with, I describe the most important time paths for the first scenario, i.e., oil extraction and exploration in the absence of a backstop technology. Results for optimal extraction, oil exploration and discovery, reserve changes, and energy price are shown in Figures 1-4.[20]

Consider the dotted curve in Figure 1. Without any substitution possibilities, energy is produced from conventional oil reserves over the entire time horizon. Oil production increases from 27.5 Gb in 2000 to 33 Gb in 2010 and declines thereafter until 2090.[21] Due to the fixed time horizon the extraction level in the last period is increased again up to the point where the sum of marginal extraction and discovery cost equal marginal benefits from energy consumption. Exploratory effort follows a hump-shaped path (see Figure 2) as is predicted by the analytical model in case of large initial reserves and relatively small initial unit extraction cost. Accordingly, reserves fall in all

[19] In the second scenario it is also allowed for some autonomous technical change that decreases renewable energy production cost. However, this does not affect the generality of the simulation results.

[20] In all figures dotted curves refer to case (1), broken curves to case (2), and continuous curves to case (3).

[21] Note that the initial production level is fixed so that optimal extraction increases before it follows the hotelling path.

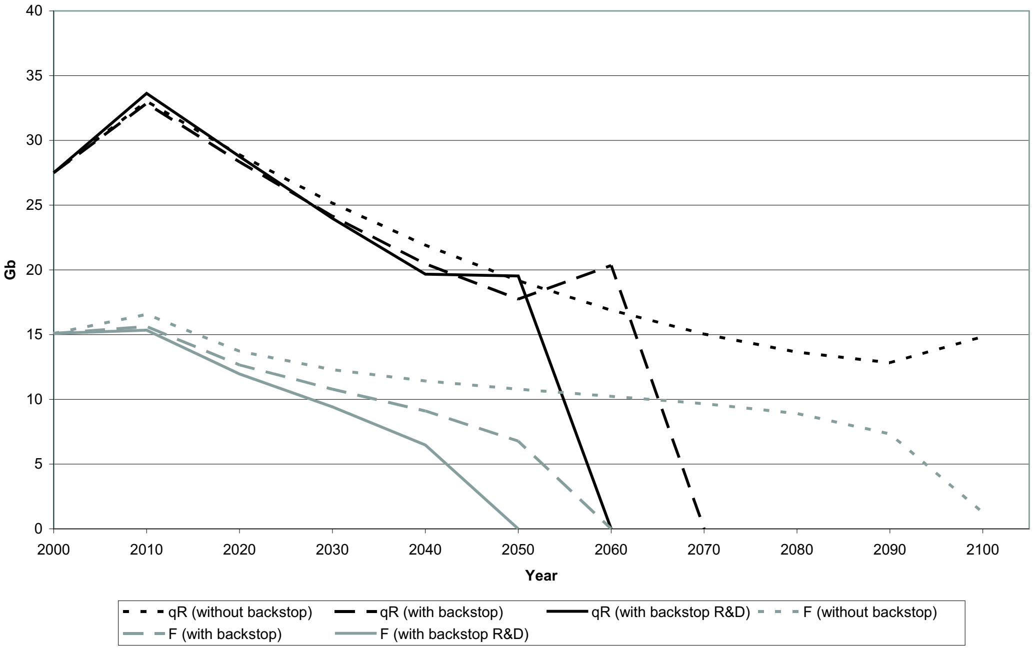

Figure 1: Optimal time paths for oil extraction and discoveries

production periods (cf. Figure 3). Oil exploration and production cease after 110 years, where oil reserves are depleted.

The optimal time profiles for energy price are shown in Figure 4. In the absence of a substitute, the price path corresponds to the extraction path: price decreases from \$34 in 2000 to \$25 in 2010 and then increases up to approximately \$122 in 2090. In the last period, oil is supplied at a lower price of \$95.6 per barrel because the level of production increases.[22]

The simulation results obtained in the first scenario are consistent with the predictions of Pindyck's (1978a) exploration model for the situation where proven reserves are large and initial unit extraction cost is small relative to price and exploration cost. Variations of the parameter values leading to this case will be studied in the sensitivity analysis below. We now turn to the results of the backstop simulations.

[22]It is important to note that the downward jumps in price are generally not a result of exploratory effort but always caused by changes in optimal oil extraction.

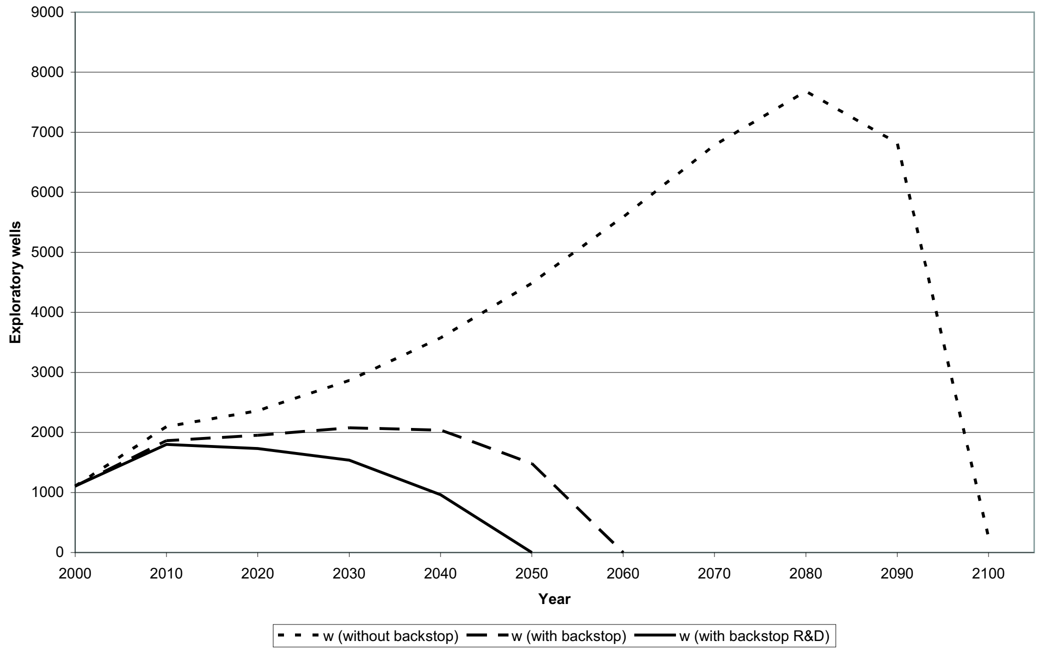

Figure 2: Optimal time paths for oil exploration

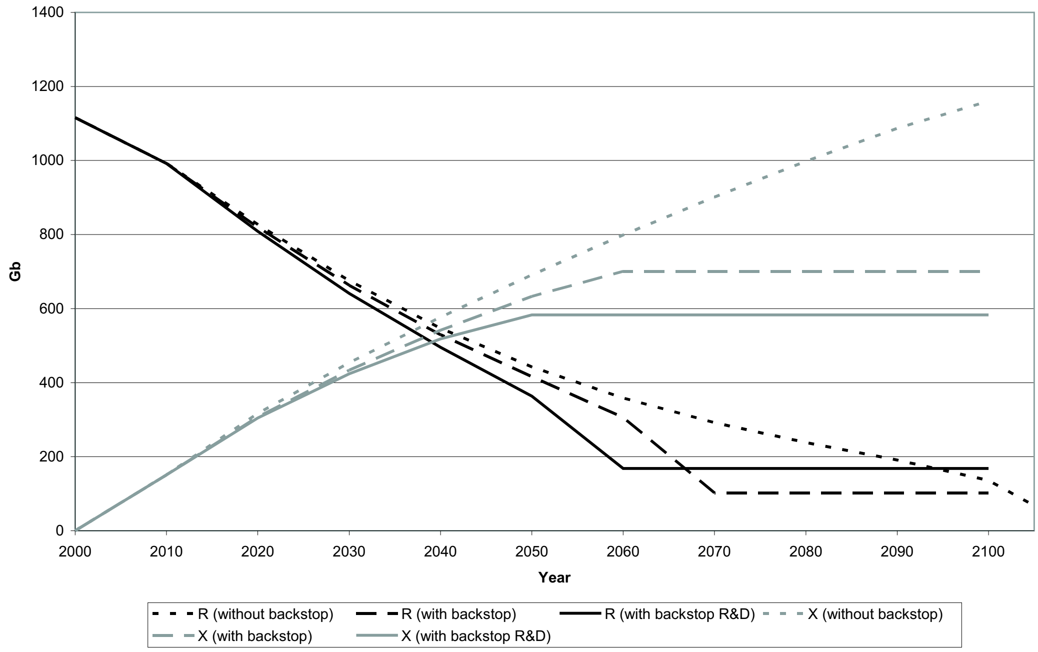

Figure 3: Proven reserves and cumulative discoveries

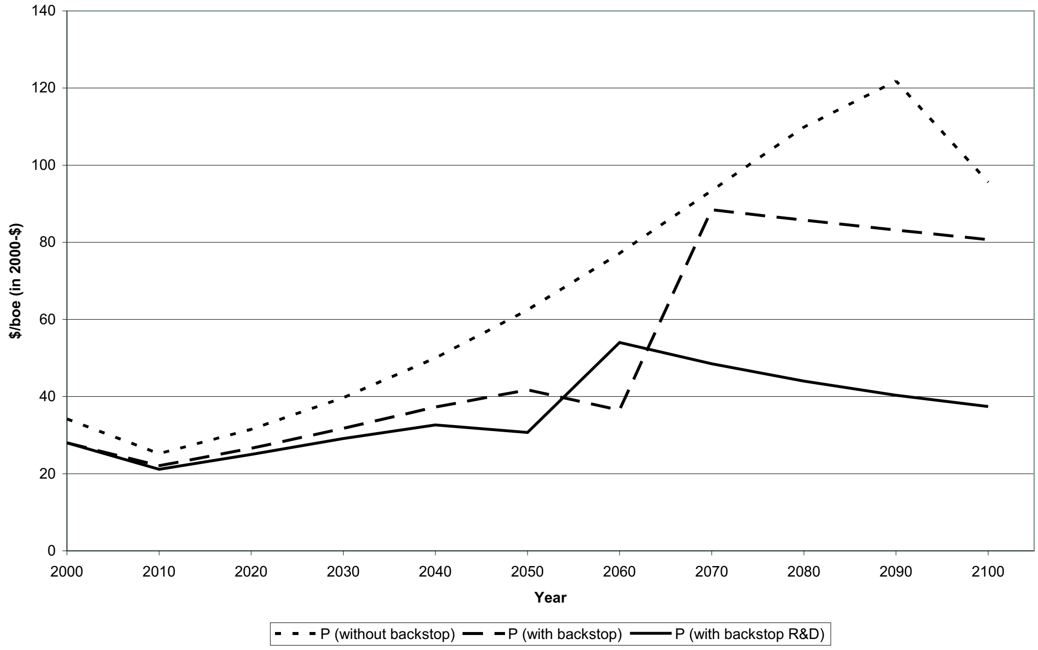

Figure 4: Optimal time paths for energy price

3.2.2 Backstop scenarios

In general, having a backstop technology for oil implies that energy is less scarce in the economy over the whole planning horizon. As a consequence, opportunity costs of oil resources *in situ* decrease when a backstop resource becomes available. More energy is produced at lower cost in each time period, which raises (discounted) social benefits from energy consumption. Cumulative oil extraction *and* exploration are lower than without the substitute.

To investigate the impacts of the presence of renewable energy production and R&D in detail consider first the optimal time paths for backstop production and oil extraction, shown in Figure 5. As predicted by the analytical model, both renewable and conventional energy is produced from period 2000 onward until oil production is no longer competitive. In both backstop scenarios, optimal renewable energy production declines slightly in 2010, grows slowly until the mid of the century, and jumps upward when

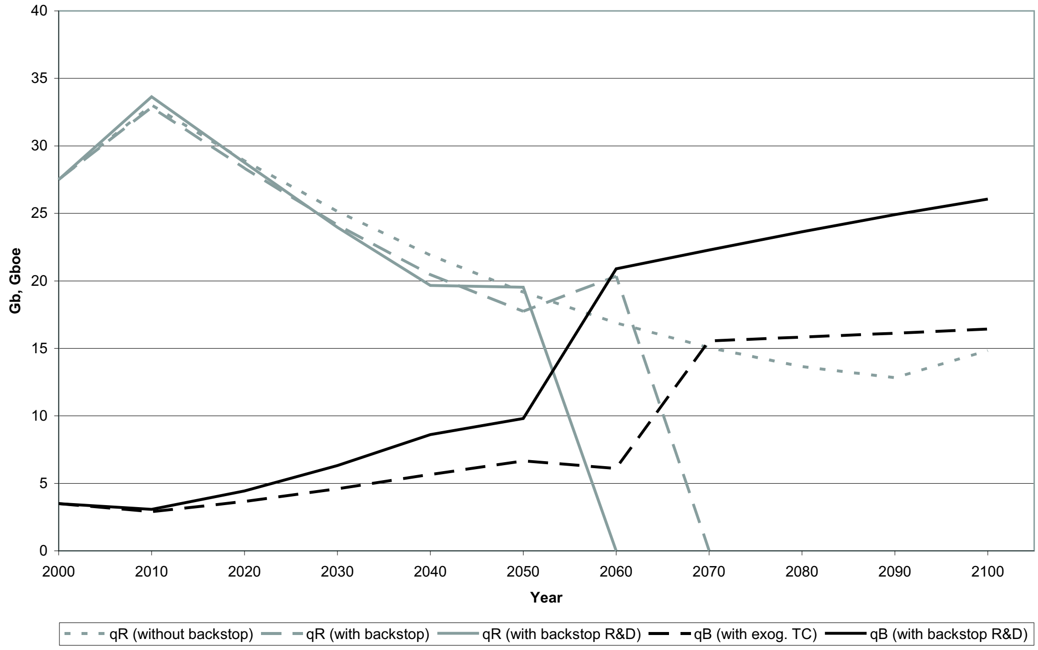

Figure 5: Optimal renewable energy production and oil extraction

oil production shuts down. As long as oil is produced, the share of backstop energy from total production is small (see Figure 6). Maximal 33.4% (27.3%) of total energy production comes from renewable's in the R&D (backstop) scenario. Nonetheless, the time profile of oil extraction is affected by the presence of alternative energy technology from the beginning. The optimal level of extraction is raised during the first periods and lower in later time periods. Oil production ceases after 70 years in case of exogenous technical change and after 60 years in the presence of endogenous renewable energy R&D. In both cases, it is not optimal to drive oil reserves to zero (see Figure 3).

The impact of renewable energy technology on oil exploration is even larger than that on extraction. Since the availability of renewable energy reduces the scarcity rent of proven oil reserves and, thus, the benefits of enhancing the reserve base, the incentives to discover new oil fields decline.

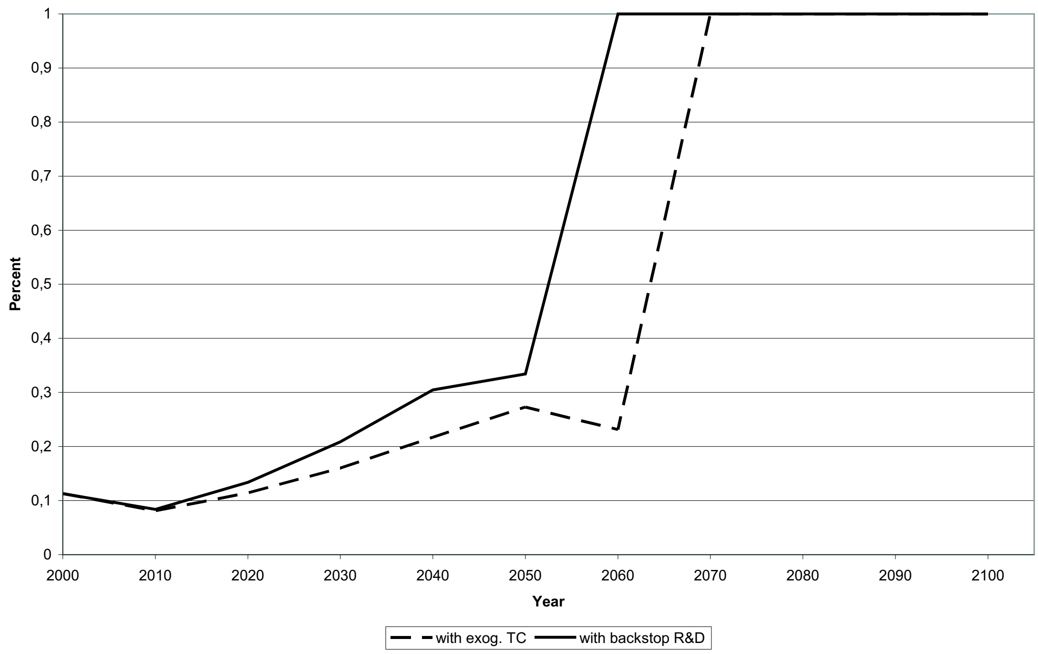

Figure 6: Share of renewable energy production

Figure 2 illustrates that the availability of a substitute for conventional energy decreases the optimal number of exploratory wells drilled in each period (except in 2000 where the number of new field wildcats is fixed) and, corresponding to extraction, shortens the period of time where exploration is undertaken.[23] The impact on drilling becomes stronger in later time periods when the share of renewable energy in consumption increases and oil production decreases. Figure 2 reveals that the backstop technology affects the shape of the optimal exploration path. In the presence of renewable energy R&D the optimal time path for exploration is similar to the path found by Pindyck (1978a) in case of small initial reserves. The difference here is that reserves are initially large and decline over time. The replacement ratio, i.e.,

[23]The shorter time horizon of exploration and discovery results from the numerical specification of the discovery function. Since the nonlinear programming solver requires a lower bound in the discovery function, $C_w^2(0)/F_w(0) > 0$ in T^* where oil production shuts down. According to the terminal conditions (see Section **??**) exploration ceases in this case before extraction stops.

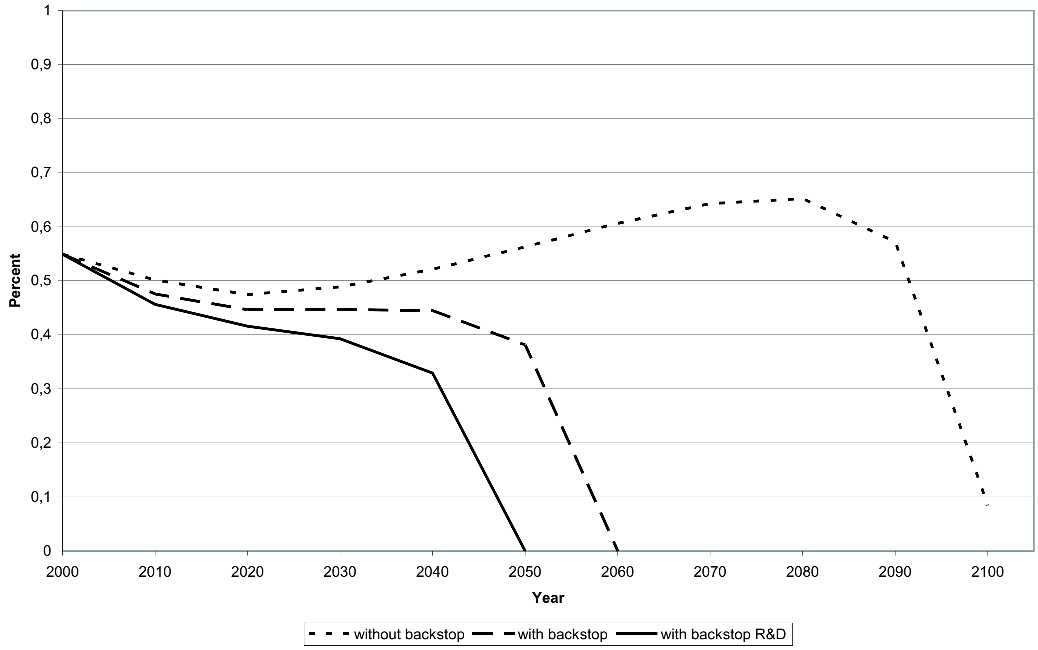

Figure 7: Oil replacement ratio

the ratio by which extracted oil is replaced by new field discoveries in each period, thus also declines over time in both backstop scenarios (see Figure 7). As a result, cumulative discoveries are considerably lowered: by 40% in the first backstop scenario and by additional 17% in the case of renewable energy R&D (cf. Figure 3).

The price of energy is always lower in the backstop scenarios due to the reduction of the scarcity rent and of marginal renewable energy cost. In addition, Figure 4 shows that the (average) slope of the price path is less steep when renewable energy is available and nearly flat in the presence of renewable energy R&D. This has important policy implications in view of currently high oil prices and reduced governmental spending on renewable energy R&D. In order to hold the price path almost constant over time, public and private research expenditures should grow in the near term, as the time profile for optimal R&D, which is depicted in Figure 8, suggests.

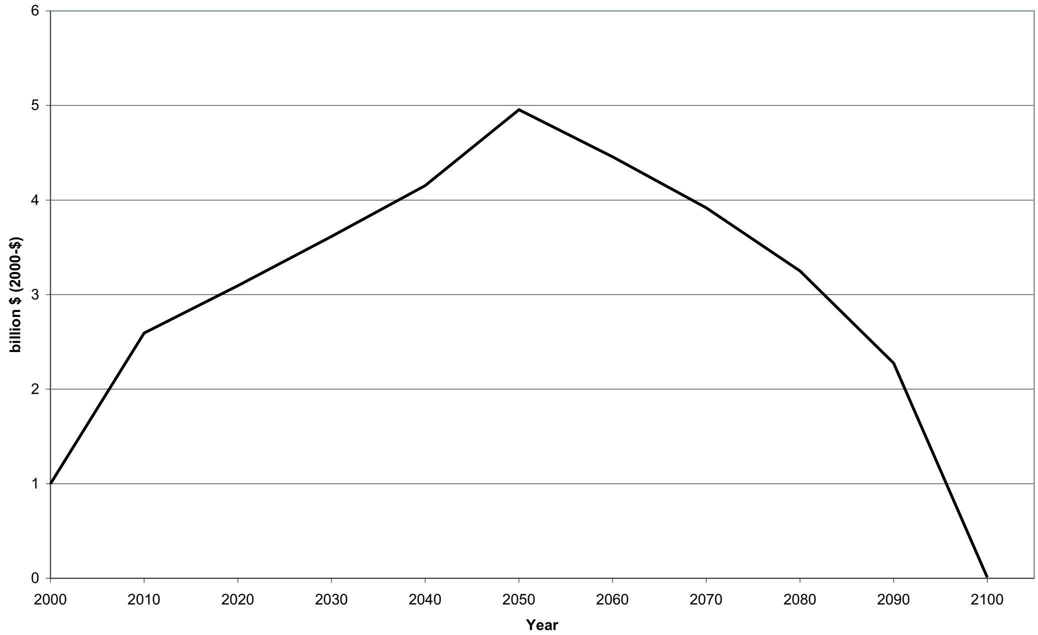

Figure 8: Optimal R&D (scenario (3))

The numerical results presented above reveal that renewable energy R&D strengthens the effects of the presence of a backstop technology on oil extraction and exploration. Since it takes time to accumulate knowledge, the impact of endogenous R&D is generally larger in later time periods than at the beginning of the planning horizon. This implies that the extent to which endogenous R&D influences cumulative model variables is smaller than that of 'simple' energy substitution, where the gains arise immediately. For example, discounted social net benefits from energy consumption increase in the second scenario by 4.5%, but only by additional 1.6% in the R&D scenario. On the other hand, the energy price in 2100 is reduced by only 15.6% in case of substitution but by additional 56.6% in case of endogenous R&D. This highlights again the importance of endogenizing technological change in environmental economic models.

3.3 Sensitivity analysis

In this section, I examine the sensitivity of the numerical findings presented above to changes in individual parameters. The results of the sensitivity analysis are summarized in Table 1. I tested six groups of parameter values by solving the R&D and the backstop version of the model for each variant, holding all other parameters unchanged. Then the percentage difference of selected simulation results are calculated, where the backstop scenario (2) is taken as the reference case. Results are reported for discounted social net benefits from energy consumption, cumulative discoveries, energy price and backstop consumption in the period 2100. The first row in Table 1 shows the percentage changes of the base case scenarios presented in the previous section.

Demand. One important variation concerning energy demand is to allow demand to grow over time. I tested this by assuming an exogenous growth rate of income (GWP) of 1.5% per annum. A growing energy demand implies that future energy prices and production levels are higher compared to the case with stationary demand. Higher future prices increase the incentives to invest in both oil exploration and renewable energy R&D. However, in the long run benefits can only be obtained from renewable energy R&D since oil reserves are exhaustible. Thus, the impact of endogenous technical change is larger in this variant compared to the base case scenario.

The role of endogenous technical progress increases also, when energy demand reacts less or more sensitive to price changes. As expected, the exceptions are changes in energy consumption (price) in 2100 when the price elasticity of demand decreases (increases).

Proven reserves. If the initial proven reserve base is smaller energy will become more scarce and the importance of renewable energy R&D will increase. Accordingly, larger initial oil reserves reduce the share of renewable energy over a longer period of time and, hence, the role of endogenous technical change. The greater reduction of cumulative discoveries in this case results primarily from the enlargement of proven reserves than from renewable energy R&D.

Table 1: Sensitivity analysis

Percentage changes R&D scenario (3) relative to backstop scenario (2)

	Parameter variation	Net benefits (discounted)	Cumulative discoveries 2000-2100	Energy price in 2100	Energy consumption in 2100
Base case	-	1.6	−16.7	−53.6	58.6
Demand	GWP growth, 1.5% p.a.	2.5	−32.9	−58.3	69.0
	$\beta_{D_2} = -0.3$	3.4	−38.5	−62.4	34.1
	$\beta_{D_2} = -0.9$	0.3	−26.1	−46.9	76.7
Reserves	$R_0 = 500$	2.1	−22.7	−54.2	59.7
	$R_0 = 2000$	0.8	−24.9	−26.3	131.3
Cost functions	$c_0^1 = 5$	1.6	−29.1	−53.4	58.0
	$c_0^1 = 15$	1.5	−28.3	−53.6	58.6
	$c_0^2 = 0.017$	1.2	−19.2	−52.6	56.6
	$c_0^2 = 0.068$	1.8	−32.2	−54.0	59.3
	$c_0^3 = 2$	2.1	−37.3	−53.8	58.8
	$c_0^3 = 8$	0.9	−20.8	−53.1	57.4
Exploration	$\alpha_F = 0.2$	2.3	−48.6	−54.8	61.1
	$\alpha_F = 0.9$	1.0	−20.2	−52.2	55.8
	$\beta_{F_2} = 0.00075$	1.0	−30.9	−52.4	56.2
	$\beta_{F_2} = 0.003$	2.0	−15.0	−54.1	59.5
Knowledge accum.	$\alpha_\Psi = 0.006$	0.7	−14.1	−34.6	29.1
	$\alpha_\Psi = 0.023$	3.2	−32.2	−72.6	117.6
	$\beta_{\Psi_2} = -0.0015$	1.2	−15.8	−42.8	39.9
	$\beta_{\Psi_2} = 1$	2.1	−18.5	−71.1	110.6
	$\alpha_H = 0\%$	1.5	−25.0	−58.9	70.4
	$\alpha_H = 1\%$ p.a.	1.5	−23.4	−48.8	49.3
Discounting	$\rho = 3\%$ p.a.	3.1	−32.8	−56.8	65.5
	$\rho = 7\%$ p.a.	0.7	−32.5	−51.0	53.4

Costs functions. Varying the parameters in the cost functions has only little impact on changes in energy price and consumption in 2100, where in both variants only renewable energy is consumed. Here, R&D has a greater impact on cumulative discoveries and social net benefits when initial marginal backstop production cost are smaller or unit exploration cost are higher.

Exploration. Lowering the productivity (α_F) of the discovery process increases the impact of backstop R&D, while a more productive discovery process generally lowers it. A modification of the depletion effect (β_{F_2}) implies that the shadow costs of cumulative discoveries are altered too. In general, a lower (higher) depletion effect enhances (reduces) exploratory activity. The reduction of cumulative discoveries due to renewable energy R&D is proportional to these effects, i.e, higher in the first case and lower in the second variant. Since exploratory activity always ceases before 2100, the long-run price and consumption changes are less affected by parameter variations in the discovery function.

Knowledge accumulation. Altering the knowledge accumulation process has the strongest influence on the role of endogenous technical change. As expected, when the knowledge accumulation process is less productive ($\alpha_\Psi = 0.006$) the impact of endogenous R&D is weakened. The reverse holds when the accumulation process is more productive or when there are constant returns to knowledge ($\beta_{\Psi_2} = 1$). Since the accumulation of oil discoveries is modeled as 'fishing-out' process I also tested this concept in the knowledge accumulation function ($\beta_{\Psi_2} = -0.0015$), which weakened the impact of endogenous R&D.

A variation of the rate of exogenous technical progress influences mainly the long-run impacts of endogenous technical change. If there is no autonomous technical progress, the changes of energy price and consumption in 2100 are greater, while a higher rate of exogenous technical progress steepens the slope of the price path.

Discounting. Finally, I tested a lower and a higher social rate of discount. A lower discount rate implies that society evaluates future benefits of endogenous R&D higher than in case of a high discount rate. Consequently, the impact of endogenous technical change increases (decreases) when the social rate of discount is lower (higher).

The sensitivity results presented above reveal that the findings concerning the effects of endogenous technical change in backstop technology are very robust against parameter variations. While in most variants the impact of renewable energy R&D on the long-run optimum changes only slightly in response to parameter variations, the pressure on oil exploration and discovery is typically enhanced. Since it is costly to accumulate knowledge through R&D, the welfare gains of renewable energy research are generally small.

4 Summary and conclusions

In this paper a variant of Pindyck's (1978a) well-known nonrenewable resource extraction and exploration model have been employed to study analytically and numerically the implications of endogenous technical change in renewable energy technology for oil exploration and extraction.

The analysis shows that incorporating a backstop technology in the model has similar impacts on the optimal extraction profile as is well-known from exhaustible resource models without exploration (see, e.g., Dasgupta and Heal, 1979): since the scarcity rent of oil resources is lower in all time periods when a substitute for oil is available, reserves are faster depleted than in case without renewable energy production. In the model variant used in this paper simultaneous backstop and oil production lead to a less steep slope of the consumer's price path. Endogenizing technical progress that reduces marginal cost of renewable energy production over time reinforces these effects. Oil extraction is shifted from the future towards the present, while the price path becomes more flat.

The impact of renewable energy production and R&D on oil exploration and discovery is of indirect nature. Since the availability of renewable energy reduces the scarcity rent of oil reserves *in situ*, the incentives to discover new oil fields are lower than without the substitute. The presence of renewable energy affects the shape of the optimal time path for exploratory effort as well as the level of exploration and discovery. Again, endogenous technical change magnifies these effects.

The sensitivity analysis establishes that the above findings are very robust against variations of the model parameters. The quantitative impact of endogenous technical progress on social welfare and cumulative discoveries, however, turned out to be small compared to the case of pure energy substitution. This is a well-known result in the literature on endogenous technical change (see, e.g., Popp, 2004; Nordhaus, 2002).

Although the model developed above is simplified in a number of manners the analysis has important implications for climate change modelling and environmental policy. First, since the combustion of fossil fuels is the main source of CO_2 emissions, the study suggests that incorporating both endogenous technical progress in renewable energy technology *and* resource exploration in climate-change models might lead to a lower (business-as-usual) path of CO_2 emissions than currently expected.[24] Second, increasing the at present low public research funds for renewable energy research seems to be a viable policy option to stabilize energy price in the medium and long term. It might also have the positive side effect of reducing CO_2 emissions. Certainly, to give a concrete policy recommendation would require a broader analysis than the one presented here.

The study abstracts from a number of issues. One important task for future research is to incorporate uncertainty in the discovery process and/or the process of knowledge accumulation. For example, Devarajan and Fisher (1982) and Pindyck (1980) have shown that under certain conditions uncertainty in the discovery process alters the time profile of exploratory activity. Similarly, uncertainty with respect to the outcome of research influences the optimal time path of renewable energy R&D (see, e.g., Hung and Quyen, 1993).

In addition, I have assumed that the world energy market is fully compet-

[24] See also Chakravorty et al. (1997).

itive. One useful extension of the model above would be to consider explicitly the OPEC cartel.[25] This would allow investigations of OPEC's behavior in response to improvements of renewable energy technology (and vice versa). A more 'realistic' model could also serve for evaluations of different policy targets, such as the plan of the European Union (EU) to double the share of renewable energy in the EU by 2010.

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[25] See also Berg et al. (2002).

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Appendix

Derivation of optimal time path for oil exploration

Differentiating the first order condition (6) with respect to time, t, yields:

$$-C^2_{ww}\dot{w} + (\lambda^1 + \lambda^2)(F_{ww}\dot{w} + F_{wX}\dot{X}) + (\dot{\lambda^1} + \dot{\lambda^2})F_w = 0 \ . \qquad \text{(A.1)}$$

Inserting the equations of motion (1)-(2) and (9)-(11) for $\dot{R}, \dot{X}, \dot{\lambda^1}, \dot{\lambda^2}$ gives (after rearranging):

$$\begin{aligned} &-C^2_{ww}\dot{w} + (\lambda^1 + \lambda^2)(F_{ww}\dot{w} + F_{wX}F) \\ &+((\rho - F_X)(\lambda^1 + \lambda^2) + C^1_R q^R)F_w = 0 \ . \end{aligned} \qquad \text{(A.2)}$$

Using the first order conditions to eliminate the costate variables and cancelling terms yields:

$$-C^2_{ww}\dot{w} + \frac{C^2_w}{F_w}(F_{ww}\dot{w} + F_{wX}F) + (\rho - F_X)C^2_w + C^1_R q^R F_w = 0. \text{(A.3)}$$

Solving for $\dot{w}$, one obtains the equation of motion given in the main text.