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Limit pricing, climate policies, and imperfect substitution

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Abstract

The effects of climate policies are often studied under perfect competition and constant marginal extraction costs. In this paper, we allow for monopolistic fossil fuel supply and more general cost functions, which, in the presence of perfectly substitutable renewables, gives rise to limit-pricing behavior. Four phases of supply may exist in equilibrium: sole supply of fossil fuels below the limit price, sole supply of fossil fuels at the limit price, simultaneous supply of fossil fuels and renewables at the limit price, and sole supply of renewables at the limit price. The consequences of climate policies for initial extraction depend on the initial phase: in case of sole supply of fossil fuels at the limit price, a renewables subsidy increases initial extraction, whereas a carbon tax leaves initial extraction unaffected. With simultaneous supply at the limit price or with sole supply of fossil fuels below the limit price, a renewables subsidy and a carbon tax *lower* initial extraction. Both policy instruments decrease cumulative extraction. If fossil fuels and renewables are imperfect but good substitutes, the monopolist will exhibit 'limit-pricing resembling' behavior, by keeping the effective price of fossil close to that of renewables for considerable time.
JEL codes: Q31, Q42, Q54, Q58
Keywords: limit pricing, non-renewable resource, monopoly, climate policies

1 Introduction

It is well known from the Green Paradox literature (cf. Sinn, 2008, 2012; Van der Ploeg and Withagen, 2015) that climate policies such as subsidies on renewables or rapidly increasing carbon taxes may turn out to be counterproductive in a competitive but otherwise second-best world. When fossil fuels are traded competitively, upon the introduction of these climate policies owners of fossil fuel resources will supply more fossil fuel at the outset (Weak Green Paradox) and may extract faster over time so that also accumulation of carbon in the atmosphere is accelerated, and damages caused by climate change are increased (Strong Green Paradox). Since the market for oil, an important type of fossil fuel, can hardly be characterized as competitive, the question arises whether this pessimistic outcome will also be obtained under alternative market structures. This is the issue we address in this paper.

In order to investigate the impact of policy instruments, we first have to derive the equilibrium on the energy market. In the seventies of the previous century the equilibrium has been characterized for several specific market structures. See Stiglitz and Dasgupta (1982) for a survey. We restrict ourselves here to a monopolist that owns a non-renewable resource, and is facing a competitive fringe of suppliers of a renewable resource. Renewables can be produced at constant marginal cost, which puts an upper limit on the price the monopolist can charge its customers. This gives rise to the possibility of a limit-pricing strategy by the monopolist, which consists of setting the price equal to (or marginally below) the marginal cost of producing the backstop.

Hoel (1978a,b) was the first to show that limit pricing may prevail in equilibrium, in case of constant marginal extraction costs. He also shows that with iso-elastic demand and zero extraction costs the existence of a perfect substitute implies that the initial price set by the monopolist is higher than it would be without the substitute. Moreover, the lower the price of the substitute, the lower initial extraction, at least if the initial price set by the monopolist is below the substitute's price, i.e., if there is no limit pricing from the start. The same case is treated by Stiglitz and Dasgupta (1982, pp. 145-146). The phenomenon of limit pricing was also found by Salant (1979), who considered extraction costs that are strictly convex in the rate of extraction.

Gilbert and Goldman (1978) and Hoel (1983) show that any threat of entry encourages the monopolist to charge a higher initial price than without the threat. More recently, Andrade de Sá and Daubanes (2016) have argued that, with constant marginal extraction costs, limit pricing will occur throughout if demand for energy is inelastic. Finally, Wang and Zhao (2013, 2015) pay attention to a monopolist facing two competitive backstops. One, e.g., biofuel, has a capacity constraint in such a way that it cannot meet by itself total demand at the backstop price. The other, e.g., solar, has no capacity constraint, but is more expensive to produce. All marginal costs are constant. Wang and Zhao (2015) perform a comparative statics analysis with regard to policy instruments, such as a subsidy on biofuel.

The objective of the present paper is threefold. Firstly, we consider the limit-pricing problem allowing simultaneously for stock-dependent and convex extraction costs.[1] Furthermore, we allow both for elastic and inelastic energy demand. We are able to show that there still is a final period of time with limit pricing and that part of this limit-pricing phase may be characterized by simultaneous supply of fossil fuels and renewables. Moreover, we identify the conditions under which there is limit pricing throughout. Secondly, we relax the unrealistic assumption made in the previous literature of perfect substitutability of fossil fuels and renewables (cf. Papageorgiou et al., 2017). We show that for large enough elasticities of substitution the price path comes close to the path for perfect substitutability. Moreover, with imperfect substitution a distinction needs to be made between the price elasticity of energy demand and that of fossil fuel demand. Actually, the monopolist will always supply fossil fuel at a point of elastic demand for fossil. Hence, the issue of inelastic demand in reality should be seen from a modified perspective. Thirdly, we are particularly interested in the effect of policy measures such as a carbon tax or a renewables subsidy. We find that such effects crucially depend on whether or not there is limit pricing with or without simultaneous use from the start.

Our analysis has some limitations. We do not consider strategic interaction, such as a strategic game between a monopolistic supplier and a monopsonistic group of demanders (cf. Liski and Tahvonen, 2004; Kagan et al., 2015), or a differential game between a resource monopolist and a producer of a backstop that becomes cheaper

[1]Hart (2016) argues that extraction costs of petroleum are increasing in cumulative extraction. Anderson et al. (2018) refer to Hyne (2012) to justify their assumption that the unit costs of drilling additional wells is increasing in the industry-wide drilling rate.

over time due to investments (cf. Jaakkola, 2019). We also do not study the more realistic setting in which part of the global resource stock is owned by a competitive fringe. See Groot et al. (1992) for the case without and Benchekroun et al. (2017) for the case with a backstop technology. Following Fischer and Salant (2017), we furthermore abstract from dirty backstops (cf. Michielsen, 2014) and interpret the backstop technology as being able to produce biofuels or to enable the electrification of transport in combination with technologies that generate clean electricity, such as wind and solar. Moreover, we do not allow for heterogeneity of climate change policies across fossil fuel consuming countries. Hence, here we do not address issues like spatial carbon leakage under monopoly. This is considered in Van der Meijden et al. (2018). Finally, we do not perform a welfare analysis of policy interventions (cf. Dasgupta and Heal, 1979; Van der Ploeg and Withagen, 2015).

In the next section, we introduce the model, derive the main results and compare them to what others have found. We give a full characterization of the optimum for the monopolist and perform a policy analysis. Section 3 extends the model with imperfect substitutability. Section 4 concludes.

2 The model

We consider a two-country model. One country derives welfare from the use of energy. Energy comes from fossil fuel, that is supplied by a monopolist located in the other country, or from a renewable resource that is supplied competitively. Production of renewable energy has constant marginal costs. We abstract from set up costs and capacity constraints in renewables production. For the time being, we assume fossil fuel and renewables to be perfect substitutes. This assumption will be relaxed in Section 3. The importing country's government imposes a constant carbon tax on the domestic consumption of fossil fuel. This can be justified by linear climate damages. We also assume a constant unit subsidy on renewables—as we often observe second-best climate policies such as subsidies on solar or wind energy in practice—and that the consumer country's government can commit itself to this constant subsidy from the beginning.

2.1 Energy demand and supply

The inverse demand function for energy is $p^e(q(t)+x(t))$, where $p^e(t)$ denotes the consumer price of energy, and $q(t)$ and $x(t)$ denote demand for fossil fuel and for renewables, respectively, at instant of time t. The producer price of fossil fuel is denoted by $p(t)$. The tax per unit of fossil fuel use is τ, the cost of producing energy from renewables is b, and the subsidy per unit of the renewable resource is σ. In equilibrium, both supply of fossil fuel and of renewables is equal to demand. Hence, we denote fossil fuel and renewables supply again by $q(t)$ and $x(t)$, respectively. Supply of and demand for renewables is zero if the consumer price of fossil fuel $p^c(t) \equiv p(t) + \tau$ is below the consumer price of renewables, i.e., if $p^c(t) < b - \sigma$ or $p(t) < b - \sigma - \tau \equiv \hat{b}$. If the producer price $p(t)$ equals $\hat{b}$, we get $p^c(t) = b - \sigma$, implying that the consumer is indifferent between the two sources of energy. The monopolist sets the price as well as its own supply, thereby leaving residual demand to the competitive suppliers of renewables. Energy demand at producer price $\hat{b}$ is denoted by $\hat{q}$. With $S(t)$ being the fossil fuel stock at instant of time t, net instantaneous profits of the monopolist are[2]

$$\Pi(q(t), x(t), S(t)) = p(q(t) + x(t))q(t) - C(q(t), S(t)),$$

where C is the extraction cost function. We assume $C_q(q,S) \geq 0$, $C_S(q,S) \leq 0$, $C_{SS}(q,S) \geq 0$, $C_{qS}(q,S) \leq 0$, meaning that extraction costs weakly increase in the extraction rate, weakly decrease in the stock size, and that for a given extraction rate (resource stock) the marginal costs weakly increase (decrease) if the remaining resource stock becomes smaller. The initial stock is denoted by S_0. We assume Π is well-defined, strictly concave in q and continuously differentiable for $q \geq \hat{q}$. In addition, to have an interesting problem we only consider initial stocks such that there exists a price not larger than $\hat{b}$ and an extraction rate such that profits are positive.

It will be shown in the sequel that the equilibrium typically consists of three phases. Initially, from time 0 until time T_1, the monopolist supplies at a consumer price below the net renewables price $b-\sigma$, so that $p(t)+\tau < b-\sigma$ (or $p(t) < \hat{b}$); then, from T_1 on the producer price is set equal to $\hat{b}$, whereas $q(t) > 0$ for some interval of time $[T_1, T_3)$ with $T_3 > T_1$. The limit-pricing phase consists of two sub-phases. One phase, from T_1 until

[2]Note that the producer price p is also dependent on the tax rate τ, as $p(q+x,\tau) = p^e(q+x) - \tau$. However, for notational brevity we write $p(q+x)$ instead of $p(q+x,\tau)$.

T_2, where the extraction rate is equal to $\hat{q}$ such that the monopolist captures the entire market. And a final phase, from T_2 until T_3 where the monopolist allows renewables on the market, implying simultaneous supply of fossil fuel and renewables at the limit price. Hence, in contrast to the case of extraction costs that are linear in the extraction rate, a limit-pricing strategy is not necessarily meant to keep renewables producers at bay. All phases can be degenerate, but the optimum always features at least one of the two limit-pricing sub-phases. We use T_3 generically as the final instant of time where there is fossil fuel supply. After T_3 only renewables are produced and supplied.

2.2 The monopolist's problem

The monopolist needs to take into account that the price it sets should not exceed $\hat{b}$, because otherwise all demand is met by renewables. It should also take into account that total demand is to met by fossil fuel and renewables. Hence, the monopolist's problem is to find a path of extraction rates, supply of renewables and a final time of fossil fuel supply, T_3, such that its profits are maximized. Hence

$$\max_{T_3,\, q(t),\, x(t)} \int_0^{T_3} e^{-rt}(p(q(t)+x(t))q(t) - C(q(t), S(t)))dt, \tag{1}$$

subject to the resource constraint

$$\dot{S}(t) = -q(t),\ S(t) \geq 0,\ S(0) = S_0, q(t) \geq 0, \tag{2a}$$

the condition that the producer price does not exceed the limit price

$$p(q(t)+x(t)) \leq \hat{b}, \tag{2b}$$

and the nonnegativity of renewables supply

$$x(t) \geq 0. \tag{2c}$$

Here, r is the constant rate of interest. Note that we can do as if the monopolist also decides on the supply of renewables. From here on we omit the time argument when there is no danger of confusion.

The Hamiltonian $\mathcal{H}$ and the Lagrangian $\mathcal{L}$ of the problem read

$$\mathcal{H}(q,x,S,\lambda,t) = e^{-rt}(p(q+x)q - C(q,S)) + \lambda[-q],$$
$$\mathcal{L}(q,x,S,\lambda,\mu,t) = e^{-rt}(p(q+x)q - C(q,S)) + \lambda[-q] + \mu[\hat{b} - p(q+x)] + \nu x.$$

According to the Maximum Principle, the Lagrangian is maximized with respect to q and x, implying

$$e^{-rt}(p'(q+x)q + p(q+x) - C_q(S,q)) = \lambda + \mu p'(q+x) \quad \text{if } q > 0, \tag{3a}$$
$$e^{-rt}p'(q+x)q = \mu p'(q+x) - \nu, \tag{3b}$$

and, along the optimal path, the evolution of the shadow price satisfies

$$-\dot{\lambda} = -e^{-rt}C_S(q,S). \tag{3c}$$

At T_3, the time at which extraction stops, the transversality conditions read

$$\begin{aligned}\mathcal{H}(q(T_3),x(T_3),S(T_3),\lambda(T_3),T_3) = e^{-rT_3}&(p(q(T_3)+x(T_3))q(T_3) - C(q(T_3),S(T_3)))\\ &- \lambda(T_3)q(T_3) = 0,\end{aligned} \tag{4a}$$
$$\lambda(T_3)S(T_3) = 0. \tag{4b}$$

Finally, the complementary slackness conditions are

$$\mu[\hat{b} - p(q+x)] = 0,\ \mu \geq 0,\ \hat{b} \geq p(q+x), \tag{5a}$$
$$\nu x = 0,\ \nu \geq 0,\ x \geq 0. \tag{5b}$$

We first show that there is always a final interval of time with limit pricing, i.e., with $p = \hat{b}$. Actually there might be limit pricing throughout. To give an example, let us define the consumer price elasticity of demand as

$$\varepsilon^c(q+x) \equiv -\left(\frac{d[p(q+x)+\tau]}{dq}\frac{q}{p(q+x)+\tau}\right)^{-1},$$

and the producer price elasticity of demand as

$$\varepsilon^p(q+x) \equiv -\left(\frac{dp(q+x)}{dq}\frac{q}{p(q+x)}\right)^{-1} = \varepsilon^c(q+x)\frac{p(q+x)}{p(q+x)+\tau}.$$

The difference is in the carbon tax to be paid by the consumer. We can then rewrite (3a) as

$$e^{-rt}\left[\left(1-\frac{1}{\varepsilon^p(q+x)}\right)p(q+x) - G_q(S,q)\right] = \lambda + \mu p'(q+x).$$

With inelastic demand (i.e., $\varepsilon^c(q) < 1$ and thus $\varepsilon^p(q) < 1$, for all $q \geq \hat{q}$) the term between brackets is negative and there is limit pricing throughout, because μ is necessarily strictly positive then. Intuitively, if demand is inelastic the profit maximizing monopolist optimally chooses the highest possible price at any point in time. For the case of a non-renewable resource monopoly with inelastic demand, this result was derived by Andrade de Sá and Daubanes (2016). Proposition 1 describes the outcome for the more general case we investigate here.

Proposition 1 (Limit pricing) *There always exists a final limit-pricing phase.*

Proof. We will show that there exist T_1 and T_3 with $T_3 > T_1 \geq 0$ such that $p(t) = \hat{b}$ for all $T_3 \geq t \geq T_1$ and $q(t) = 0$ for all $t > T_3$. Suppose $p(t) < \hat{b}$ for all $t < T_3$. We first show that $p(T_3) = \hat{b}$. If $p(T_3) < \hat{b}$ then $q(T_3) > \hat{q} > 0$ and $x(T_3) = 0$. Hence, from (3a),

$$e^{-rT_3}(p'(q(T_3))q(T_3) + p(q(T_3)) - C_q(S(T_3), q(T_3))) = \lambda(T_3), \tag{6a}$$

and from (4a)

$$e^{-rT_3}(p(q(T_3)) - C(S(T_3), q(T_3))/q(T_3)) = \lambda(T_3). \tag{6b}$$

But this violates the strict concavity of the instantaneous profit function in q.

The Hamiltonian evaluated at the optimum is continuous. Since the Hamiltonian equals zero at T_3 it must approach zero as t approaches T_3. Suppose $p(t) < \hat{b}$ for interval (T_1, T_3). We have $p(t) \to \hat{b},\ q(t) \to \hat{q}$ as $t \to T_3$ so that

$$\lambda(t) \to e^{-rT_3}(p'(\hat{q}))\hat{q} + \hat{b} - C_q(S(T_3), \hat{q})) \text{ as } t \to T_3.$$

But from (4a)

$$e^{-rT_3}(\hat{b} - C(S(T_3), \hat{q})/\hat{q} = \lambda(T_3). \tag{7}$$

So that we have a contradiction with strict concavity in q again, implying that there must be a final interval with $p = \hat{b}$. □

Hoel (1978a,b) shows the occurrence of limit pricing with constant marginal extraction cost. This result was also obtained by Salant (1979) for cost functions that are linear or strictly convex in the rate of extraction, but stock-independent. Andrade de Sá and Daubanes (2016) assume $C(q, S) = c(S)q$. Hence, the novelty of our finding lies in a generalization with respect to the cost function.

Intuitively, without a regime of limit pricing, marginal profits of the last resource unit sold just before depletion of the stock at instant of time T_3 would be smaller than the price of renewable energy, which is the price the monopolist could get when selling this last unit directly after T_3 instead. Therefore, the monopolist always prefers a final regime with the price equal to the unit cost of renewables.

Another general result is that a final phase with simultaneous use exists in case the cost function is strictly convex in extraction.[3]

Proposition 2 (Simultaneous use) *A final limit-pricing phase with simultaneous use of the resource and renewable energy exists if and only if $C(S, q)$ is strictly convex in q.*

Proof. We will first show that $q(T_3) = 0$. Suppose $q(T_3) > 0$. Then it follows from (4a) that

$$\lambda(T_3) = e^{-rT_3}\left(\hat{b} - C(S(T_3), q(T_3))/q(T_3)\right).$$

It follows from (3a) and (3b) that

$$\lambda(T_3) = e^{-rT_3}(\hat{b} - C_q(S(T_3), q(T_3))) - \nu(T_3).$$

[3] Due to the presumed linearity of their cost function, Hoel (1978a,b) and Andrade de Sá and Daubanes (2016) do not get simultaneous use, contrary to Salant (1979) who works with a cost function that is strictly convex in extraction.

Hence

$$e^{-rT_3}\left(\frac{C(S(T_3),q(T_3))}{q(T_3)} - C_q(S(T_3),q(T_3))\right) = \nu \geq 0. \tag{8}$$

But if the cost function is strictly convex in the extraction rate, this is ruled out. Therefore, $q(T_3) = 0$, which by continuity implies that a final regime with simultaneous use exists, except at $t = T_3$. Finally, if there is simultaneous supply the cost function cannot be linear in the extraction rate. □

Intuitively, if the monopolist would extract a strictly positive amount and sell it at the limit price just before depletion at instant of time T_3, profits could be increased by conserving a marginal unit and extract it at lower marginal costs directly after T_3. In other words, due to strict convex extraction costs it becomes profitable to smooth out extraction over time. Hence, in the case at hand 'limit pricing' should no longer be interpreted as serving the goal of preventing the renewable substitute from entering the market altogether.

The next proposition deals with the possibility of stranded assets.

Proposition 3 (Stranded assets) *If the condition $\hat{b} - C_q(S(T_3),0) = 0$ has a solution with $S(T_3) > 0$, this amount remains unexploited.*

Proof. If $S(T_3) > 0$ then $\lambda(T_3) = 0$ from (4b). It follows from (4a) that

$$\hat{b}q(T_3) = C(q(T_3),S(T_3)).$$

Hence, profits are zero and zero extraction is optimal, meaning zero extraction is as good as any positive rate of extraction, implying $\nu(T_3) = 0$. We then have from the optimality conditions (3a) and (3b) that

$$\hat{b} - C_q(S(T_3),0) = 0.$$

Given our concavity assumptions, it also holds that if this equation has a positive solution with $S(T_3) > 0$, this amount remains unexploited. □

Intuitively, if marginal extraction costs reach the unit price of renewable energy once the remaining stock reaches the threshold value $S(T_3)$, the remaining reserves are too expensive to exploit profitably, implying that they will remain untapped.

Andrade de Sá and Daubanes (2016, appendix) allow for stock-dependent extraction costs that are linear in extraction. They examine, with their assumption of inelastic demand, the effect of climate policies and show that there still will be limit pricing throughout. We have more general extraction cost and demand functions and we get more results for our specific example in Case 3 later in this section.

We illustrate the outcomes for several cost specifications and provide additional insights by means of three special cases.

Case 1: Linear stock-independent extraction costs. Suppose $C(q, S) = kq$ with $0 \leq k < \hat{b}$. Hence extraction costs are linear in the extraction rate and stock-independent. This is a special case of the model in Van der Meijden et al. (2018). Along an optimal path the resource will be completely depleted. Moreover, along the final phase of limit pricing the extraction rate is $\hat{q}$, because discounting induces the monopolist to extract as fast as possible, given that it is constrained by the price $\hat{b}$. This, together with the constancy of the shadow price λ, implies from (4a) that

$$\lambda = e^{-rT_3}(\hat{b} - k).$$

Now suppose that limit pricing starts at $T_1 > 0$, so that there is an initial phase with the price below $\hat{b}$. Then it follows from (3a) with $\mu(T_1) = 0$ that

$$\lambda = e^{-rT_1}(p'(\hat{q})\hat{q} + \hat{b} - k).$$

Hence,

$$\frac{\hat{b} - k}{p'(\hat{q})\hat{q} + \hat{b} - k} = e^{rT_3 - rT_1}. \tag{9}$$

Provided that $p'(\hat{q})\hat{q} + \hat{b} - k > 0$, this yields the length of the limit-pricing phase. In order to determine the optimum, the initial stock has to be taken into account. Let us define the critical stock $\hat{S} = (T_3 - T_1)\hat{q}$. If the initial stock is smaller than $\hat{S}$ the equilibrium is one with limit pricing from the start. If the initial stock is larger than $\hat{S}$ then there will be an initial phase with the price below the limit price $\hat{b}$. However, if $p'(\hat{q})\hat{q} + \hat{b} - k \leq 0$ (which holds, e.g., for inelastic demand) it is optimal to have limit pricing from the start, irrespective of the initial stock size.

Case 2: Strictly convex stock-independent extraction costs. Next we consider the case of extraction costs that are still stock-independent, but strictly convex in the extraction rate: $C(S, q) = c(q)$ with $c_{qq}(q) > 0$. We assume that $\hat{b} > c_q(0)$. This is the case studied by Salant (1979). We will show that the optimum typically consists of three phases. Phase 1 runs from time zero until time T_1 and has a price smaller than $\hat{b}$. Then follows an interval of time from T_1 until T_2 with limit pricing and the monopolist serving the entire market. Finally there is a phase, from T_2 until T_3 with simultaneous supply of fossil and renewables at the limit price, where the extraction rate is declining to zero over time. We will show this by constructing the path and prove that it satisfies all the necessary conditions and is therefore optimal in view of our concavity assumptions.

In the proposed optimum along (T_2, T_3) we have $p(t) = \hat{b},\ \dot{q}(t) < 0$ and, hence, $\dot{x}(t) > 0$. Moreover, $q(T_2) = \hat{q}$ and $q(T_3) = 0$. Therefore (3a)-(3b) imply

$$\lambda = e^{-rT_3}(\hat{b} - c_q(0)), \tag{10a}$$

$$\lambda = e^{-rT_2}(\hat{b} - c_q(\hat{q})), \tag{10b}$$

which gives the length of the final limit-pricing phase. We can then determine total extraction along the interval by putting $T_2 = 0$. If the actual initial stock is smaller than this level, it is optimal to start with limit pricing, with a smaller initial extraction rate than $\hat{q}$. If the actual stock is larger, then there is room for a first limit-pricing phase along which $q(t) = \hat{q}$. The critical initial resource stock for having an initial phase where the price is below the limit price is determined as follows. At T_1 it holds by continuity from (3a) that:

$$\lambda = e^{-rT_1}(p'(\hat{q})\hat{q} + \hat{b} - c_q(\hat{q})). \tag{10c}$$

Hence, provided that $p'(\hat{q})\hat{q} + \hat{b} - c_q(\hat{q}) > 0$, the duration of the first limit-pricing phase is given by

$$e^{rT_2 - rT_1} = \frac{\hat{b} - c_q(\hat{q})}{p'(\hat{q})\hat{q} + \hat{b} - c_q(\hat{q})}.$$

Since we already know how much is needed in the second limit-pricing phase we can now determine the critical stock needed to have $T_1 > 0$. If the actual stock is larger than this stock then indeed $T_1 > 0$.

We further illustrate this case by considering an example with quadratic extraction costs and linear demand, $C(q, S) = c(q) = kq + \frac{1}{2}\psi q^2$ and $p(q + x) = \alpha - \tau - \beta(q + x)$, respectively. By using (10a)-(10c) we obtain

$$e^{-rT_3}(\hat{b} - k) = \lambda, \tag{11a}$$

$$e^{-rT_2}[\hat{b} - (k + \psi\hat{q})] = \lambda, \tag{11b}$$

$$e^{-rT_1}[-\beta\hat{q} + \hat{b} - (k + \psi\hat{q})] = \lambda. \tag{11c}$$

The duration of the two limit-pricing phases crucially depends on the convexity of the extraction cost function, which is governed by ψ. Let us define $\tilde{\psi}$ by $\hat{b} - k - \tilde{\psi}\hat{q} - \beta\hat{q} = 0$ and $\hat{\psi}$ by $\hat{b} - k - \hat{\psi}\hat{q} = 0$. Hence, $\tilde{\psi}$ is the value of ψ for which the marginal profit equals zero if the monopolist would serve the entire market at the limit price. It is clear from (11c) that $T_1 \to 0$ if $\psi \to \tilde{\psi}$, because the monopolist will perform a limit-pricing strategy throughout. Condition (11b) implies that $T_2 \to 0$ if $\psi \to \hat{\psi}$, meaning that the limit-pricing phase without renewables production vanishes: due to highly convex extraction costs it is too expensive for the monopolist to serve the entire market at the limit price. Furthermore, note from (11a)-(11b) that $T_3 \to T_2$ if $\psi \to 0$: the limit-pricing phase with simultaneous use vanishes if extraction costs become linear, as in Case 1.

To illustrate the effect of convex extraction costs and the interest rate on the resource extraction path, and in particular on the duration of the different phases of extraction, we conduct a simulation analysis.[4] We choose the parameters of our model such that the benchmark equilibrium results in initial extraction of 32 billion barrels of oil and an initial oil price of 82 dollars per barrel, in line with the average crude oil consumption

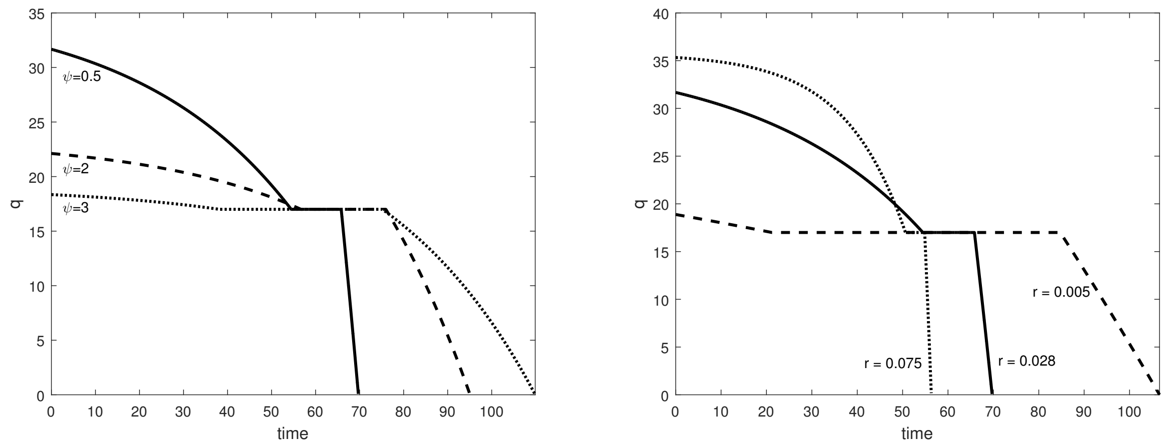
[4]The derivation of the resource constraint that, together with (11a)-(11c), can be used to solve for the equilibrium is shown in Appendix A.1.

and crude oil price over the last decade (EIA, 2017)). The benchmark parameter values are: $\alpha = 120$, $\beta = 1.2$, $b = 100$, $k = 18$, $\psi = 0.5$, $\sigma = \tau = 0$ (all in terms of US \$ per barrel of oil), $r = 0.028$, and $S_0 = 1650$ (billion barrels of oil).

Figure 1: Resource extraction paths

Panel (a) - Effect of cost convexity

Panel (b) - Effect of the interest rate



Notes: Panel (a) shows the effect of changes in the extraction cost convexity parameter, ψ. The solid, dashed and dotted curves are the equilibrium time paths for $\psi = 0.5$, $\psi = 2$, and $\psi = 3$, respectively. Panel (b) shows the effect of the interest rate, r. The solid, dashed and dotted curves are the equilibrium time paths for $r = 0.028$, $r = 0.005$, and $r = 0.075$, respectively.

Figure 1 shows the extraction time profile for different values of the extraction cost convexity parameter, ψ, (panel (a)) and of the interest rate, r, (panel (b)). In all scenarios shown in the figure, the equilibrium starts with sole supply of fossil fuel at a price below the limit price, with extraction declining over time. Subsequently, there is a limit-pricing phase with sole supply of fossil and constant extraction over time. The final phase is characterized by simultaneous supply of fossil and renewables at the limit price, and declining extraction over time. In panel (a) the solid curve corresponds to the 'weakly convex' benchmark scenario with $\psi = 0.5$. The dashed and dotted curves represent the 'medium convex' and the 'highly convex' scenario with $\psi = 2$ and $\psi = 3$, respectively. The curves clearly show that the duration of the second limit-pricing phase (featuring simultaneous use of the resource and renewables) increases with the convexity of extraction costs. In panel (b), the solid curve represents the benchmark scenario with $r = 0.028$. The dashed (dotted) curve corresponds to a scenario with a relatively low (high) interest rate of $r = 0.005$ ($r = 0.075$). The figure makes clear that the duration of the limit-pricing phase with simultaneous use depends negatively on the interest rate, because smoothing out extraction over time (induced by convex extraction costs) implies postponing revenues, which becomes more costly if the interest rate is high. Similarly, an increase in the interest rate lowers the duration of the limit-pricing phase during which the monopolist serves the entire market. The reason is that postponing extraction from the beginning until the end of the limit-pricing phase is more costly if the interest rate is higher.

Case 3: Stock-dependent extraction costs. Finally, we consider the case of stock-dependent extraction costs. To give an example, let us generalize the quadratic extraction cost function to

$$C(S,q) = \frac{kq + \frac{1}{2}\psi q^2}{S}. \tag{12}$$

As demonstrated in Proposition 2 whether or not some of the resource is left unexploited depends on the solution of the following equation:

$$C_q(S,0) = \frac{k}{S} = \hat{b}. \tag{13}$$

If $k > 0$, (13) has a positive solution for S, so that this amount is left unexploited. Clearly, if the actual initial stock is smaller then nothing will be exploited. If, however, $k = 0$ then nothing is left in the ground.

Appendix A.2 shows how to find the initial stock such that it is optimal to start with an extraction rate $\hat{q}$ and let extraction decrease over time, and the largest initial stock such that the equilibrium starts with limit pricing.

2.3 Policy analysis

The existing literature on monopoly and limit pricing is scarce and mainly addresses the effect of changes in the renewables price on limit pricing in special cases. Only a few papers pay attention to the effect of policy instruments under monopolistic resource extraction: Andrade de Sá and Daubanes (2016) consider the case with inelastic fossil fuel demand and Van der Meijden et al. (2018) impose linear, stock-independent extraction costs. Policy analysis is relevant in view of the Green Paradox. This branch of the literature (cf. Sinn, 2008, 2012; Van der Ploeg and Withagen, 2015) is concerned with the problem that climate policy instruments may be counterproductive. For example, it could be that a subsidy on renewables leads the owners of fossil fuel reserves to extract faster initially and deplete fossil fuels sooner, thereby aggravating the climate problem. This result is obtained in many models with perfect competition on the energy market. Here we address the question how the effectiveness of climate policies works out in the case of a monopoly.

In the Green Paradox literature a distinction is made between the *Weak* Green Paradox, which occurs if initial extraction goes up, and the *Strong* Green Paradox, which is said to occur if total climate damages go up (cf. Gerlagh, 2011). For completeness we also study the effect of (exogenous) technological change that leads to a lower cost of producing the backstop technology b. This is different from assuming a gradual decline in the backstop cost as examined by Fischer and Salant (2017). We will consider marginal changes in parameters. With non-marginal changes different results can be obtained. For example, the subsidy on renewables can be set such that renewables become cheaper than fossil fuel.

The next proposition considers the effect of climate policies on initial extraction for the three possible cases in which the optimum starts with (i) a limit-pricing phase featuring simultaneous supply of fossil and renewables, (ii) a limit-pricing phase in which the monopolist serves the entire market, and (iii) the phase in which the resource price is strictly below the price of renewables, respectively.[5]

Proposition 4 (Climate policies and initial extraction)

(i) Suppose the monopolist initially sets the limit price, but does not serve the entire market, i.e., $q(0) < \hat{q}$, $T_1 = T_2 = 0$, $T_3 > 0$. *Then*

(a) the initial extraction rate decreases if b *marginally decreases or if* σ *marginally increases.*

(b) the initial extraction rate decreases if τ *marginally increases.*

(ii) Suppose the monopolist initially sets the limit price and serves the entire market, i.e., $q(0) = \hat{q}$, $T_1 = 0$, $T_2 > 0$, $T_3 > 0$. *Then*

[5] Part (ii) of Proposition 4 resembles results obtained by Andrade de Sá and Daubanes (2016), for the case of linear extraction costs and a price elasticity of demand below unity. We show that the result holds in any limit pricing phase, under more general assumptions.

(a) *the initial extraction rate increases if b marginally decreases or if σ marginally increases.*

(b) *the initial extraction rate is unaffected by a marginal change in τ.*

(iii) *Suppose the monopolist initially sets a price strictly below the unit cost of renewables (and thus initially serves the entire market), i.e., $q(0) > \hat{q}$, $T_1 > 0$, $T_2 > 0$, $T_3 > 0$. Then*

(a) *the initial extraction rate decreases if b marginally decreases or if σ marginally increases.*

(b) *the initial extraction rate decreases if τ marginally increases.*

Proof. Part (i): Note that generally

$$\dot{\mathcal{H}} = \frac{\partial \mathcal{H}}{\partial t}.$$

Hence

$$\Lambda(S_0, b, \sigma, \tau) \equiv \int_0^{T_3} e^{-rt}\Pi(q(t), S(t))dt = \frac{\mathcal{H}(0) - \mathcal{H}(T_3)}{r} = \frac{\mathcal{H}(0)}{r},$$

since $\mathcal{H}(T_3) = 0$ in an optimum. In the case at hand we have $\nu(0) = 0$, because $x(0) > 0$ by assumption, so that

$$p'(q(0) + x(0))q(0) = \mu p'(q(0) + x(0)).$$

Hence, we can write the Hamiltonian in shorthand as

$$\mathcal{H}(0) = C_q(q(0), S_0)q(0) - C(q(0), S_0).$$

Due to the strict convexity of C in q, implied by the proposed equilibrium, $\mathcal{H}(0)$ is increasing in $q(0)$. A decrease in b reduces the profitability of the monopolist. Hence $d\Lambda(S_0, b, \sigma, \tau)/db > 0$, implying $d\mathcal{H}(0)/db > 0$. Therefore, $dq(0)/db > 0$. The same type of argument applies to changes in the tax rate.

Part (ii): $\hat{q}$ is total energy demand at a consumer price is $p(t) + \tau = b - \sigma$. In the case at hand $q(0) = \hat{q}$. A decrease in b or an increase in σ stimulate demand. An increase in

τ leaves fossil fuel demand unaffected.

Part (iii): As in part (i) we have

$$\Lambda(S_0, b, \sigma, \tau) \equiv \int_0^{T_3} e^{-rt}\Pi(q(t), S(t))dt = \frac{\mathcal{H}(0) - \mathcal{H}(T_3)}{r} = \frac{\mathcal{H}(0)}{r}.$$

We now have $\mu(0) = 0$, because $p(0) < \hat{b}$ by assumption. Now we use the concavity of the (entire) profit function to get the result. □

This proposition demonstrates that only in case of limit pricing with the monopolist supplying the entire market from the beginning (part (ii)), we obtain a Weak Green Paradox upon a decrease in $b - \sigma$. In the two other cases (part (i) and part (iii)), the opposite of the Weak Green Paradox occurs: a decrease in $b-\sigma$ *lowers* initial extraction.

In part (i), where the monopolist sets the limit price but does not supply the entire market, the reason for the reversal of the Weak Green Paradox is that the climate policies lower marginal profits of the monopolist, who responds by smoothing out extraction over time to lower extraction costs.

In part (iii), where the optimum starts with a phase during which the monopolist sets a price strictly below the price of renewables, we also obtain a decrease in extraction upon more stringent climate policies. The intuition for the case of the decline in b or an increase in σ, which affect future profits of the monopolist, is as follows. Suppose that, upon a decrease in $\hat{b}$, the monopolist keeps the price path until the moment at which the price reaches the new, reduced, $\hat{b}$ unchanged. Then, cumulative extraction and discounted profits until this moment remain unchanged as well. However, discounted profits after this moment go down, due to the lower $\hat{b}$.[6] Therefore, the monopolist optimally responds by smoothing out cumulative extraction until this moment over a longer time horizon. This implies that the initial price rises and initial extraction falls. In so doing, the monopolist postpones the start of the era with reduced discounted profits.

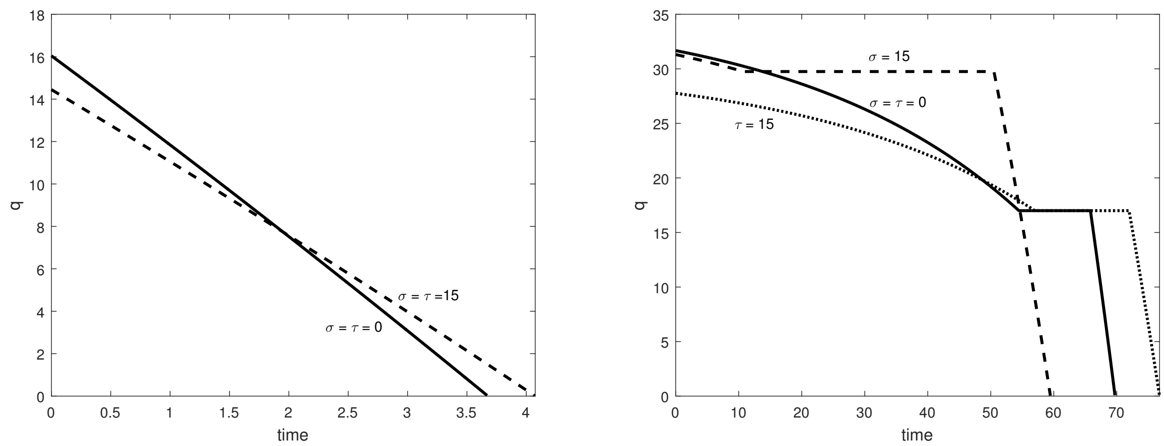
Figure 2 shows the effect of a carbon tax and a renewables subsidy in these latter two scenarios on the entire extraction path, for the quadratic extraction cost setting discussed in Case 2. Panel (a) shows the scenario in which the optimum starts with

[6]Technically, this would imply a downward jump in the Hamiltonian at the instant of time at which $p(t) = \hat{b}$.

simultaneous supply of fossil fuel and renewables at the limit price. In panel (b), the monopolist initially sets a price strictly lower than the per unit price of renewables.

Figure 2: Effect of climate policies

Panel (a) - Start with $p(0) = \hat{b}, q(0) < \hat{q}$ Panel (b) - Start with $p(0) < \hat{b}, q(0) > \hat{q}$



Notes: Panel (a) shows the case with an initial limit-pricing phase in which there is simultaneous supply of fossil fuel and renewables at the limit price. The dashed line shows the effect of a carbon tax (or renewables subsidy, which is similar). Panel (b) shows the case in which only fossil is supplied initially at a price strictly below the price of renewables. The dashed (dotted) line shows the effect of a carbon tax (renewables subsidy). Parameters are set at their benchmark values (see Section 2.2), except for the initial resource stock in panel (a), which is reduced to 30 in order to get $T_1 = T_2 = 0$.

The figure clearly shows that in both scenarios, extraction goes down upon the strenghtening of climate policies. In panel (a), both the carbon tax and the renewables subsidy increase the time at which the stock is depleted. In panel (b), however, a renewables subsidy speeds up, whereas a carbon tax slows down, depletion. Furthermore, panel (b) shows that when the optimum starts with an initial phase in which fossil fuel is cheaper than renewable energy, a renewables subsidy substantially increases intermediate extraction, after the initial fall. The reason is that the limit-pricing phase in which the monopolist serves the entire market starts earlier and is characterized by a higher extraction rate.

The next proposition examines the effect of climate policies on stranded assets.

Proposition 5 (Climate policies and stranded assets) *If $\hat{b} - C_q(S(T_3), 0) = 0$ has a solution with $S(T_3) > 0$, a lower renewables cost, a higher renewables subsidy or a higher tax all induce the monopolist to leave more fossil fuel untapped.*

Proof. If the condition $\hat{b} - C_q(S(T_3), 0) = 0$ has a solution with $S(T_3) > 0$, part of the stock will remain untapped, by Proposition 3. Since $C_{qS} < 0$ we obtain an increase in $S(T_3)$ if b falls, if σ increases, or if τ increases. $\square$

Hence, technological change and climate policies will lower the cumulative amount of carbon emissions, by inducing the monopolist to leave a larger share of its reserves unexploited.

3 Imperfect substitution

Andrade de Sá and Daubanes (2016) argue that demand for energy is price inelastic and conclude for a model with linear extraction costs that in the equilibrium only limit pricing occurs. Contrary to their assumption and our assumption thus far (in line with most of the literature about the transition from fossil fuels to renewables), in reality fossil fuels and renewables are not perfect substitutes. Papageorgiou et al. (2017) present evidence that the elasticity of substitution between clean and dirty energy inputs significantly exceeds unity, but is far from infinitely large (around 2 for the electricity-generating sector and close to 3 for the non-energy industries). This has major implications for the equilibrium. To illustrate the consequences of imperfect substitutability, we consider an example in which utility (or, alternatively, production) from energy is given by the following CES specification:

$$U(E) = \frac{E^{1-\frac{1}{\gamma}} - 1}{1 - \frac{1}{\gamma}},$$

where energy (E) is a CES aggregate of fossil fuel q and renewables x:

$$E(q, x) = \left(\delta q^{\frac{\varepsilon-1}{\varepsilon}} + (1-\delta) x^{\frac{\varepsilon-1}{\varepsilon}}\right)^{\frac{\varepsilon}{\varepsilon-1}}. \tag{14}$$

The elasticity of substitution between fossil fuels and renewables is equal to ε. Assuming quasilinear utility and denoting the composite energy price by p_E, consumers maximize $U(E) - p_E E$, implying that energy demand is given by

$$E = p_E^{-\gamma}, \tag{15}$$

from which it can be seen that the (positively defined) price elasticity of energy demand equals γ. The first-order conditions for fossil and renewables use read

$$p_E \frac{\partial E(q,x)}{\partial q} \leq p + \tau, \tag{16a}$$

$$p_E \frac{\partial E(q,x)}{\partial x} \leq b - \sigma, \tag{16b}$$

with equalities holding if $q > 0$ and $x > 0$, respectively. If there is positive demand for both energy sources, fossil fuel demand can be solved from (14)-(16a), yielding

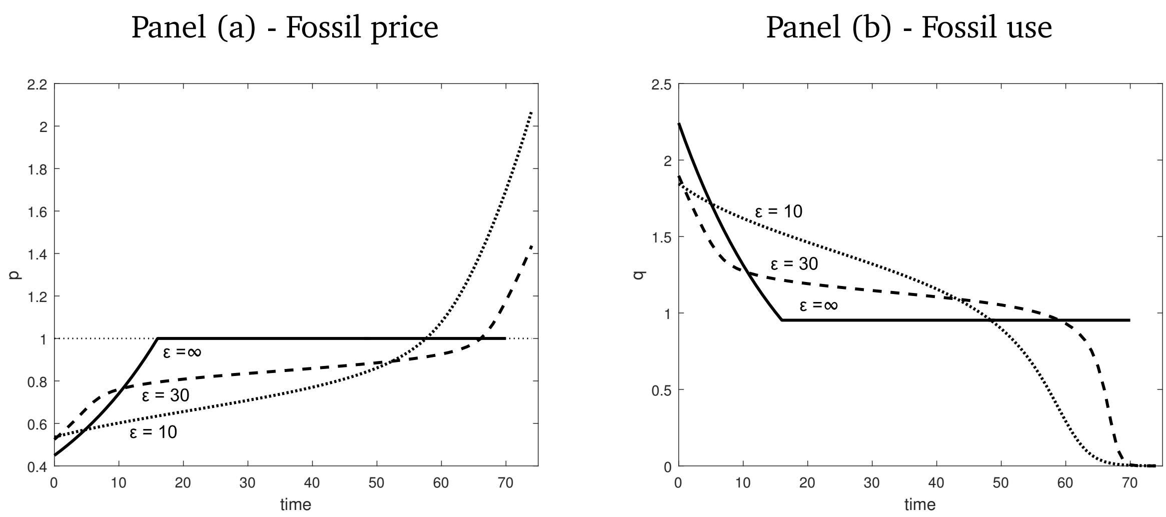
$$q(p) = \left(\frac{p+\tau}{\delta}\right)^{-\gamma} \left(\delta + (1-\delta)\left(\frac{(p+\tau)/\delta}{(b-\sigma)/(1-\delta)}\right)^{\varepsilon-1}\right)^{\frac{\gamma-\varepsilon}{1-\varepsilon}}. \tag{17}$$

With constant marginal extraction costs k, the problem of the monopolist is to

$$\max_{q(t)} \int_0^\infty e^{-rt}(p(q(t)) - k)q(t)dt \text{ subject to } \dot{S}(t) = -q(t),\ S(t) \geq 0,\ S(0) = S_0, \tag{18}$$

where $p(q)$ is the inverse function of (17). The necessary conditions for the solution to the monopolist's problem are provided in Appendix A.3.

Figure 3: Time profiles: the role of the elasticity of substitution



Notes: The solid, dashed and dotted line correspond to the scenarios with $\varepsilon = \infty$, $\varepsilon = 30$, and $\varepsilon = 10$, respectively. We have used $\gamma = 1.07$, $\sigma = 0$, $\tau = 0$, $b = 1$, $k = 0$, $r = 0.05$, and $S_0 = 76.5$.

In order to show the effects of imperfect substitutability, we simulate the model for different values of the elasticity of substitution between fossil fuels and renewables. Figure 3 shows the time profile of the fossil fuel price in panel (a) and of fossil fuel use in panel (b). The solid curves represent the case in which fossil fuels and renewables are perfect substitutes (i.e., $\varepsilon = \infty$). For the dashed curves, we have used $\varepsilon = 30$ and for the dotted curves $\varepsilon = 10$. The figure shows that the time profiles of the price and use of fossil fuels converge to those under perfect substitutability if the elasticity of substitution between fossil and renewables is increased. This illustrates the robustness of our earlier results in which we have assumed perfect substitutability.

As noted by Andrade de Sá and Daubanes (2016) and in Section 2.2 of this paper, if fossil and renewable energy are perfect substitutes, and extraction costs are linear and stock-independent, there is a crucial role for the price elasticity of energy demand. If demand is inelastic, the monopolist will optimally choose a strategy of limit pricing throughout, which effectively implies choosing the point on the demand curve where the price elasticity of demand for fossil is infinitely large. In case of a constant elastic energy demand such as in (15) with $\gamma > 1$, the price elasticity of demand for fossil fuels is constant and equal to the price elasticity of energy demand until the limit-pricing phase starts, when it jumps to infinity. With imperfect substitutability, however, the elasticity $\Phi(p) \equiv -(dq/dp)(p+\tau)/q$ gradually changes over time. By using (17) we find

$$\Phi(p) = \frac{\Omega(p)}{1+\Omega(p)}\gamma + \frac{1}{1+\Omega(p)}\varepsilon, \text{ with } \Omega(p) = \frac{\delta}{1-\delta}\left(\frac{(p+\tau)/\delta}{(b-\sigma)/(1-\delta)}\right)^{1-\varepsilon}. \quad (19)$$

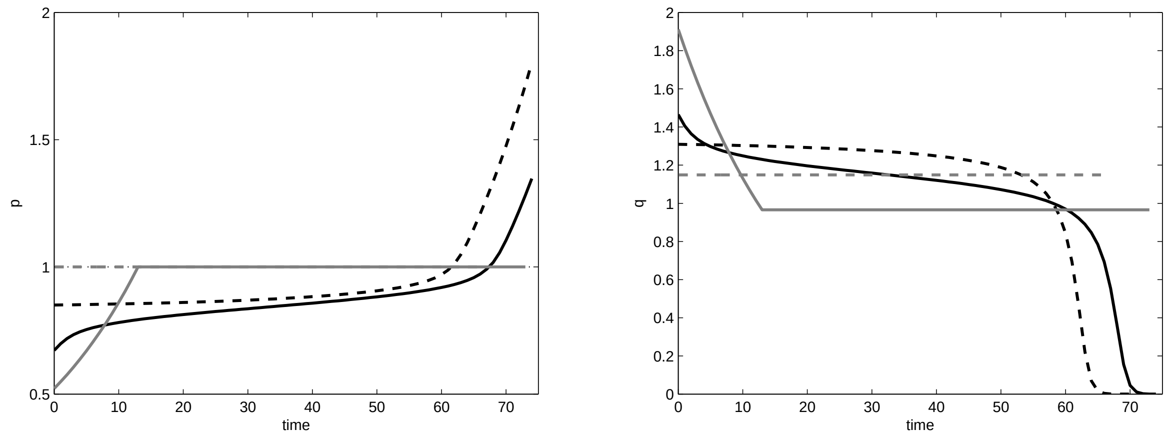
Hence, the price elasticity of fossil demand can be written as a weighted average of the price elasticity of energy demand, γ, and the elasticity of substitution between fossil fuels and renewables, ε. Moreover, if fossil and renewable energy are close substitutes, which we assume to be the case, the relative weight of the elasticity of substitution increases over time as the fossil price rises. To see this, note that by imposing a finite $\varepsilon > 1$, we ensure that fossil fuels and renewables are good, but imperfect substitutes. As a result, $\Omega(p)$ tends to zero if p becomes infinitely large. Therefore, (19) implies that the elasticity of fossil demand tends to ε.

Note that, irrespective of the price elasticity of energy demand (which may well be chosen smaller than unity on empirical grounds), the monopolist always chooses extraction such that the price elasticity of fossil demand exceeds one. As a result,

Figure 4: Time profiles: the role of the energy demand elasticity

Panel (a) - Fossil price

Panel (b) - Fossil use



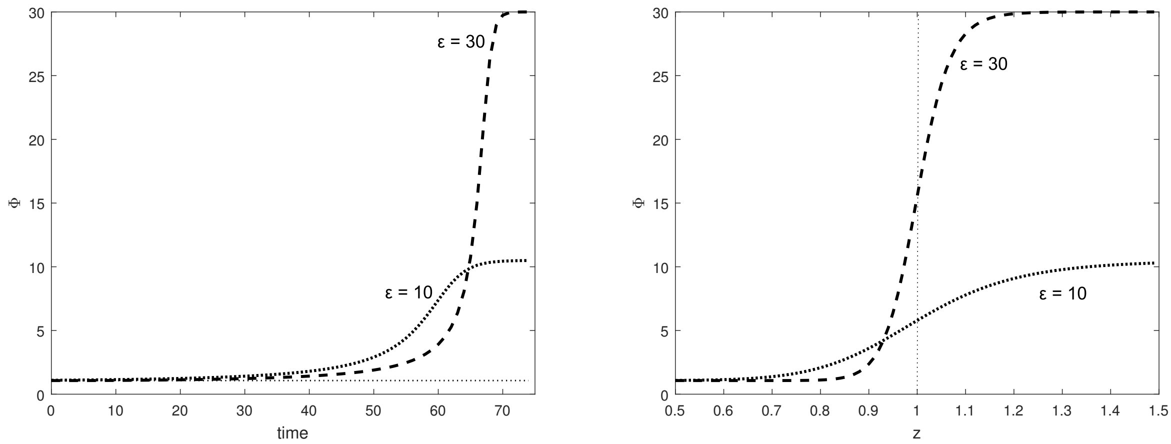
Notes: The solid and dashed lines correspond to the scenarios with $\gamma = 1.05$ and $\gamma = 0.8$, respectively. The black lines represent the case with good, but imperfect substitution ($\varepsilon = 30$). The gray lines represent the case with perfect substitution ($\varepsilon = \infty$). We have used $\sigma = 0$, $\tau = 0$, $b = 1$, $k = 0$, $r = 0.05$, and $S_0 = 76.5$.

the difference between the case with inelastic and elastic energy demand is less sharp than it is under perfect substitutability. Figure 4 shows that by moving from elastic demand (solid gray lines, $\gamma = 1.05$) to inelastic energy demand (dashed gray lines, $\gamma = 0.8$) under perfect substitutability, the price and extraction paths in panel (a) and (b), respectively, change considerably, because in the case with $\gamma = 0.8$ there will be limit pricing throughout. Under imperfect substitution, however, the solid black lines ($\gamma = 1.05$) do not differ drastically from the dashed black lines ($\gamma = 0.8$).

Hence, when allowing for imperfect substitution between fossil fuels and renewables, the empirical question whether energy demand is elastic or inelastic becomes less important than in the case of perfect substitution studied by Andrade de Sá and Daubanes (2016). Still, the case with monopolistic supply differs considerably from the case with competitive resource supply. If fossil fuels and renewables are close substitutes, i.e., if ε is large, $\Phi(p)$ will rapidly change with p if the relative effective price of these energy sources, $z \equiv [\delta/(1-\delta)](p+\tau)/(b-\sigma)$, is close to unity. This gives rise to 'limit-pricing resembling' behavior by the monopolistic fossil fuel supplier: if z comes close to unity, marginal profits will rapidly rise with increases in p. Therefore, once z comes close to unity, it is profitable for the supplier to keep it close to unity until

Figure 5: Price elasticity of fossil demand

Panel (a) - Time profile | Panel (b) - Elasticity versus price



Notes: The solid, dashed and dotted line correspond to the scenarios with $\varepsilon = \infty$, $\varepsilon = 30$, and $\varepsilon = 10$, respectively. We have used $\gamma = 1.07$, $\sigma = 0$, $\tau = 0$, $b = 1$, $k = 0$, $r = 0.05$, and $S_0 = 76.5$.

most of the stock is exhausted. Afterwards, the price will increase, fossil demand will tend to zero, the elasticity of fossil demand will rapidly increase and marginal profits will converge to average profits, as in the extreme case of perfect substitutability.

Figure 5 illustrates the development of the price elasticity of fossil demand over time in panel (a) and its dependence on the effective relative price z in panel (b), for two different values of the elasticity of substitution between fossil and renewable energy. The dashed line corresponds with $\varepsilon = 30$ and the dotted line with $\varepsilon = 10$. In both cases, the price elasticity of fossil demand starts out just above one (indicated by the flat dotted line in panel (a)) and tends towards ε in the long run.

4 Conclusion

In a general model of non-renewable resource supply by a monopolist (allowing for stock-dependent extraction costs that are convex in the extraction rate) we have shown that, if fossil fuels and renewables are perfect substitutes, the equilibrium necessarily contains a limit-pricing phase. Moreover, if extraction costs are strictly convex in the extraction rate, at least part of this limit-pricing phase is characterized by simultaneous supply of the non-renewable resource and the renewable substitute. Hence, a strategy of limit pricing is not necessarily meant to keep producers of renewable energy at bay.

It has been shown that the effects of environmental policies, such as a carbon tax or a renewables subsidy, can be the opposite of what they would be in the case of perfect competition. In particular, the initial use of fossil fuels can decrease instead of increase as a consequence of more stringent climate policies. This is not to say that such policies are less harmful from a social welfare perspective than in the case of perfect competition: whether or not this is the case depends on the acuteness of climate change damages.

We have demonstrated that our results are robust to introducing imperfect but good substitutability between fossil and renewable resources: the monopolist will choose a 'limit-pricing resembling' strategy by keeping the effective fossil price just below the effective renewables price for a considerable period of time. Nevertheless, abrupt regime shifts from 'Hotelling pricing' to 'limit pricing' disappear and the empirical question whether energy demand is elastic or inelastic has less drastic implications for the fossil price and extraction paths than under perfect substitutability.

In future research, a strategic game in which the fossil importing country sets a renewables subsidy and the fossil fuel exporter sets its price—both conditional on the remaining stock—could be introduced. Another promising way to proceed is by generalizing the analysis to the case of oligopolistic fossil supply. This is an interesting field of research because of the possibility of strategic interaction among supplying firms, which is absent in the cases of monopoly and perfect competition.

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Appendix

A.1 Resource constraint

In this Appendix, we derive the resource constraint that, together with (11a)-(11c) completes the description of the equilibrium in Case II of Section 2.2. By imposing $\mu = 0$ in (3a) we get

$$e^{-rt}[-\beta q(t) + \hat{b} - (k + \psi q(t))] = \lambda, \text{ if } 0 \leq t \leq T_1. \tag{A.1a}$$

Furthermore, by using $\nu = 0$ in (3a)-(3b) we obtain

$$e^{-rt}[\hat{b} - (k + \psi q(t))] = \lambda, \text{ if } T_2 \leq t \leq T_3. \tag{A.1b}$$

During the first limit-pricing phase from T_1 until T_2, when the monopolist serves the whole market, we have $q(t) = \hat{q}$. Using this equation and solving (A.1b) for q, we obtain the following critical stock levels

$$\hat{S}_0 = \int_{T_2}^{T_3} \frac{\hat{b} - k - \lambda e^{rt}}{\psi} dt = \frac{\hat{b} - k}{r\psi} \left[r(T_3 - T_2) - 1 + e^{-r(T_3 - T_2)} \right], \tag{A.2a}$$

$$\tilde{S}_0 = \hat{S}_0 + \int_{T_1}^{T_2} \hat{q} dt = \hat{S}_0 + (T_2 - T_1)\hat{q}. \tag{A.2b}$$

If $S_0 < \hat{S}_0$ we have $T_1 = T_2 = 0$ and the monopolist sets $p = \hat{b}$ from the beginning, but does not serve the entire market. If $\hat{S}_0 < S_0 < \tilde{S}_0$ we get $T_1 = 0$ and the monopolist also starts with limit pricing (i.e., $p = \hat{b}$) and initially serves the entire market. If $S_0 > \tilde{S}_0$ the initial producer price is below $\hat{b}$ and, by using (A.1a), the resource constraint requires

$$S_0 = \tilde{S}_0 + \int_0^{T_1} \frac{\alpha - \tau - k - \lambda e^{rt}}{2\beta + \psi} dt = \tilde{S}_0 + \frac{\alpha - \tau - k}{2\beta + \psi} + \frac{\hat{b} - k}{2\beta + \psi} \left(e^{rT_3} - e^{-r(T_3 - T_1)} \right). \tag{A.3}$$

Hence, if $S_0 > \tilde{S}_0$, the resource constraint and (11a)-(11c) can be used to solve for T_1, T_2, T_3, and λ, which fully describes the equilibrium.

A.2 Critical stock levels with stock-dependent extraction costs

In this Appendix, we show how to find the initial stock such that it is optimal to start with an extraction rate $\hat{q}$ and let extraction decrease over time, and the largest initial stock such that the equilibrium starts with limit pricing if extraction costs are given by (12).

Assume that (13) is satisfied. We will first determine the initial stock such that it is optimal to start with an extraction rate $\hat{q}$ and let extraction decrease over time. So, $T_2 = 0$. This is a bit more complicated than in Case 2 (where extraction costs were stock-independent) because the shadow price is no longer a constant. From the optimality conditions (3a)-(3c), with $x(t) > 0$, we have

$$e^{-rT_2}(\hat{b} - C_q(S(T_2), \hat{q})) = \lambda(T_2), \tag{A.4a}$$

$$\hat{b} - C_q(S(T_3), 0) = \lambda(T_3) = 0, \tag{A.4b}$$

$$e^{-rt}(\hat{b} - C_q(S(t), q(t)) = \lambda(t),\ T_2 < t < T_3, \tag{A.4c}$$

$$\dot{\lambda}(t) = e^{-rt} C_S(q(t), S(t)), T_2 < t < T_3, \tag{A.4d}$$

$$\dot{S}(t) = -q(t), T_2 < t < T_3. \tag{A.4e}$$

This yields a second-order differential equation in S. Under the conditions that we have imposed on the extraction cost function, there exists a unique initial S that satisfies the boundary conditions, which we denote by $S(T_2)$. Hence, if the initial resource stock equals $S(T_2)$ it is optimal to start with $q(T_2) = \hat{q}$, to have limit pricing, but allowing for a gradually increasing market share of renewables, to leave part of the resource stock in the ground and to let extraction go to zero. For a smaller stock there will still be limit pricing from the start, but initial extraction will be below $\hat{q}$. If the initial stock is smaller than the solution to (13) no extraction will take place at all. For a larger initial stock, there will be an initial phase with limit pricing, where the monopoly serves the entire market.

Finally, we derive the critical stock $S(T_1)$ for which this optimum prevails, meaning that for a higher stock than $S(T_1)$, the initial price is below the limit price. To find the threshold we have to consider the following system of equations:

$$e^{-rT_1}(p'(\hat{q})\hat{q} + \hat{b} - C_q(S(T_1), \hat{q})) = \lambda(T_1), \tag{A.5a}$$

$$\dot{\lambda}(t) = e^{-rt}C_S(S(t), \hat{q}), T_1 < t < T_2, \tag{A.5b}$$

$$\dot{S}(t) = -\hat{q}, T_1 < t < T_2. \tag{A.5c}$$

Condition (A.5a) says that with an initial stock larger than $S(T_1)$ there will be no limit pricing at T_1. Note that for a given $S(T_1)$ we know $\lambda(T_1)$ (since we can put $T_1 = 0$). We know $S(T_2)$ from (A.4a)-(A.4e). Under the conditions that we have imposed on the extraction cost function, there exists a unique initial $\lambda(T_2)e^{rT_2}$ that satisfies (A.5a)-(A.5c) for the given $S(T_1)$ and $S(T_2)$. So, we need to find the $S(T_1)$ that yields the $\lambda(T_2)e^{rT_2}$ obtained from (A.4a).

A.3 Imperfect substitution

The Hamiltonian $\mathcal{H}$ associated with the profit maximization problem of the monopolist reads

$$\mathcal{H}(q, \lambda, t) = e^{-rt}(p(q) - k)q + \lambda[-q],$$

As before, λ denotes the shadow price of unextracted fossil fuel. According to the Maximum Principle, the necessary condition reads

$$e^{-rt}\left(p(q) + p'(q)q - k\right) = \lambda(t). \tag{A.6}$$

Along the optimal path, the evolution of the shadow price satisfies

$$-\dot{\lambda}(t) = 0. \tag{A.7}$$

Furthermore, the transversality condition is given by

$$\lim_{t\to\infty} \lambda(t)S(t) = 0. \tag{A.8}$$