Limit Pricing and the (In)Effectiveness of the Carbon Tax*

by

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Short abstract

Demand for oil is very price inelastic. Facing such demand, an extractive cartel induces the highest price that does not destroy its demand, unlike the conventional Hotelling analysis: the cartel tolerates ordinary substitutes but deters high-potential substitution possibilities. Limit-pricing equilibria of non-renewable resource markets sharply differ from usual Hotelling outcomes. Oil taxes have no effect on current extraction; extraction may only be reduced by supporting existing (ordinary) substitutes. Since the carbon tax applies to oil and to its existing carbon substitutes, it induces the cartel to increase its current oil production. The carbon tax further affects ultimately-abandoned oil reserves ambiguously.

JEL classification: Q30; L12; H21
Keywords: Carbon tax; Limit pricing; Non-renewable resource; Monopoly; Demand elasticity; Substitutes subsidies.

Long abstract

This paper argues that the effectiveness of a carbon tax is very limited when limit pricing arises on the oil market; a possibility that all existing studies on the design of the optimal carbon tax assumed away.

Demand for energy, for fossil fuels like oil in particular, is notoriously very price inelastic, even in the long run. Facing such demand, an extractive cartel increases its profits with higher prices, as long as those prices do not destroy its demand.

The academic literature inspired by Hotelling has examined how market power on non-renewable resource markets is limited by the intertemporal constraint that reserves are exhaustible (e.g. Stiglitz, 1976). Allowing low demand-elasticity levels highlights the static constraint that substitution possibilities may destroy profits.

The demand for oil features kinks, each corresponding to the entry price of one competing substitute. Some substitutes may be tolerated by an oil-extracting cartel (e.g. other fuels, including existing biofuels, solar and wind sources of energy...). However, when a substitution possibility has the potential to drastically deteriorate its market share, the cartel maximizes its profits by inducing the "limit price" that deters its entry. Limit-pricing equilibria of non-renewable resource markets sharply differ from the conventional Hotelling outcome; for instance, taxes on the cartel's resource become neutral on current extraction regardless of their dynamics.

Environmental policies may still reduce current extraction quantities when limit pricing occurs. For that, policies must support the production of existing substitutes, i.e. those not deterred by the cartel's pricing. On the contrary, a carbon tax increases current oil extraction: while its direct application to the oil (carbon) resource is neutral, its application to oil's (carbon) existing substitutes induces higher oil production. The carbon tax further affects abandoned oil reserves, yet ambiguously: it shortens the oil extraction period, which may not compensate higher extraction levels during this period.

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I. Introduction

There are three basic facts about the market for oil and its energy substitutes. First, the demand for energy is very price inelastic; in particular, the long-run price elasticity of the demand for oil is commonly estimated to be lower than one.[1] Second, oil reserves are highly concentrated; the OPEC cartel controls most of them.[2] Third, although the oil resource serves the largest share of the demand for energy, several other energy goods exist that compete with it, as for instance other fuels, various biofuels and flows of renewable energy from alternative sources.

Under standard cost conditions, a monopoly facing a relatively inelastic demand may increase its profits by charging higher prices (reducing quantities supplied). Yet, there is a limit up to which this monopoly can do so: high enough prices warrant the profitability of substitutes that would destroy the monopoly's demand. When substitution possibilities are represented by a perfect substitute that is producible without limit under constant returns ("backstop technology" as coined by Nordhaus, 1973), the monopoly maximizes its profits by inducing the limit price which deters substitution: below, higher prices increase profits; above, profits vanish.

This static limit-pricing theory carries over to the case of an extractive monopoly that exploits a finite stock of resource over time: as long as there is some resource to be exploited, the monopoly's profits are maximum when the limit price is induced at each date. The monopolistically-supplied resource may be oil, and its backstop substitute may be some high-potential future-generation biofuel. Under stationary market conditions,

[1] Krichene's (2005) estimate of the long-run price elasticity of the demand for crude oil is (absolute value) 0.26 for 1974-2004; a level that coincides with the elasticity used in Hamilton (2009b). According to Hamilton (2009a, Pages 217-218), since crude oil only represents about half the retail cost of final oil-based products like gasoline, the demand elasticity of the former is typically much lower than that of the latter (e.g. Hausman and Newey, 1995; Kilian and Murphy, 2014; references in Krichene, 2005, and in Hamilton, 2009a). See Hamilton (2009b, Page 192) on why the price elasticity of the crude oil demand should be expected to be even smaller now than over the last decades.

[2] According to the US Energy Information Agency (EIA), "OPEC member countries produce about 40 percent of the world's crude oil. [...] OPEC's oil exports represent about 60 percent of the total petroleum traded internationally". Available at http://www.eia.gov/finance/markets/supply-opec.cfm. More importantly, still according to the EIA, 72 percent of proved oil reserves were controlled by OPEC members in 2011 (http://www.eia.gov/).

limit pricing means a constant extraction path, together with a constant price path, until the resource is entirely depleted. The limit-pricing outcome of non-renewable-resource markets resulting from low demand elasticity has been first noticed by Hoel (1978) and Salant (1979).[3]

There are two basic limitations to the exercise of market power by an oil cartel like the OPEC. The academic literature inspired by Hotelling (1931) has extensively examined the intertemporal constraint that stocks to be exploited are exhaustible.[4] In contrast, the instantaneous constraint that high prices may trigger the entry of some oil substitutes has remained a recurrent business view.[5]

Besides its empirical foundations, the appeal of this limit-pricing theory further relies on its explanatory advantages. First, the limit-pricing type of equilibria immediately accounts for the long-run stationarity of oil prices and quantities (see Gaudet, 2007).[6] Second, unlike conventional models à la Hotelling (1931), these equilibria are compatible with less-than-one demand-elasticity estimates.[7] Last but not least, the relevance of these equilibria can also be substantiated on the ground of various revealing accounts by OPEC-

[3]See also Dasgupta and Heal (1979, Page 343) and Newbery (1981). Hoel and Salant's papers dealt with the limit-pricing phase that may follow the ordinary non-renewable-resource monopoly pricing stage of Stiglitz (1976). When the demand for the resource has a lower-than-one price elasticity, Salant and Hoel rightly anticipated that limit pricing may occur at all dates. On the limit-pricing-phase curiosity when demand is not so inelastic, see also the investigation on the effect of backstop subsidies by van der Ploeg and Withagen (2012).

[4]As Pindyck (1987) put it, "potential monopoly in extractive resource markets can be limited by the depletability of reserves".

[5]The influential energy industry analyst Stephen Schork reported to CNBC on August 16, 2010: "OPEC is more concerned about long-term market share than they are about short-term price gains. (...). I speak with OPEC regularly, and [raising the entry barrier for alternative fuels] is consistently their main concern (...). The cheaper you make OPEC oil, the harder you make it to bring alternative fuels to bring on." (http://www.theatlantic.com/business/archive/2010/08/why-opec-doesnt-mind-low-oil-prices/61557/).

[6]The constant-price and constant-quantity outcome of limit pricing sharply contrasts with the conventional Hotelling-type interior equilibrium where the monopoly's marginal revenue rises at the profit-discounting rate (Stiglitz, 1976); this is so despite identical stationary conditions.

[7]In Hotelling models, as Stiglitz (1976) put it, this would imply that "one can obtain larger profits by reducing [the quantity]"; as is well known, a monopoly never operates in regions of the demand curve where the price elasticity is less than unity. To guarantee that there exists a solution to the extractive monopoly's problem in absence of backstop substitute, Stiglitz (1976) and many others assumed away so low elasticity levels. This restriction may also be embedded in the form of the monopoly's gross revenue function; for instance, Lewis, Matthews and Burness (1979) assumed it to be decreasing with price everywhere.

related personalities and commentators.[8] As Cairns and Calfucura (2012) concluded from their recent analysis of the opaque OPEC behavior, Saudi Arabia's (and OPEC's) dominant strategy is indeed to "restrain the price to conserve its market in the long-run."

Limit pricing on non-renewable-resource markets has recently gained renewed attention (e.g. the application by van der Ploeg and Withagen, 2012, Page 353). A closely related line of research was also initiated by Gerlagh and Liski (2011, 2012) and followed by Jaakkola (2012). Their models provide the dynamic counterparts in resource markets of strategic entry-prevention equilibria in the spirit of Bain (1956) and Modigliani (1958). Oil-exporting countries strategically interact with oil-consuming nations which may costly switch to alternative sources of energy; exporters maintain low enough prices for such investment strategy to remain dominated. In contrast with that research, when account is taken of the inelasticity of demand, limit pricing arises regardless of strategic interactions; market power by a coordinated demand side is not required for that.[9]

This paper examines the effects of taxes – like the carbon tax – on a non-renewable resource – like oil – when limit pricing arises from the low elasticity of resource demand. The taxation of non-renewable resources is revisited in that context. Much research efforts currently revolve around the effects of carbon taxation and the design of the optimal carbon tax: see the influential works by Metcalf (2008), Sinn (2008), Golosov, Hassler, Krusell and Tsyvinski (2014), van der Ploeg and Withagen (2014), among many others. It is hoped that both the taxation of carbon resources like oil and the support to non-carbon substitutes are effective instruments to curb carbon emissions that are responsible for global warming. Moreover, relatively high tax rates are already applied to oil products in

[8]For instance in a famous 1974 interview, Jamshid Amuzegar, then Iran's Minister of the Interior and the Shah's right-hand oil expert, when explaining that OPEC's strategy is to have the oil price following the industrialized countries' inflation, had these illuminating words: "The first of our (...) principles is that the price of oil should be equivalent to the cost of alternative sources of energy." (Time Magazine, October 14, 1974, Page 36.). More recently, OPEC Secretary General Abdullah al-Badri commented on oil prices being around US$130: "We are not happy with prices at this level because there will be destruction as far as demand is concerned". He later identified US$100, as being a "comfortable" price (http://www.reuters.com/article/2012/05/03/us-opec-supply-idUSBRE8420UY20120503).

[9]The limit-pricing equilibria considered here may nevertheless be interpreted as Bain-Modigliani or Gerlagh-Liski strategic equilibria once the limit price is appropriately defined as a best response of a Nash game where players' strategies are considered given.

most countries. From existing governmental commitments and in light of current national and international policy discussions on climate change mitigation, it is to be anticipated that tax rates on carbon energies may further increase and that a more favorable fiscal treatment will be given to their non-carbon substitutes.

Yet, there exists no study of taxation-induced changes in non-renewable-resource equilibrium quantities that consider limit-pricing situations, whether in the literature on non-renewable-resource taxation (e.g. Gaudet and Lasserre, 2013) or in the literature about market power on resource markets. Studies on the specific effect of taxes on resource monopolies are entirely based on Stiglitz's (1976) Hotelling-type interior equilibria; e.g. Bergstrom, Cross and Porter (1981) or Karp and Livernois (1992). As we will see, exclusively relying on this conventional treatment of monopoly power on non-renewable resource markets may lead to wrongly assess the effects of large-scale environmental taxation policies.

We start with a standard setting, similar to Hoel (1978), Salant (1979): a finite stock of homogenous resource is depleted by a monopoly that faces a relatively price-inelastic demand; substitution opportunities are summarized by the availability of a backstop technology. In that setting, we introduce a specific tax applied to the extracted flow of resource and we examine its effect in the spirit of Gaudet and Lasserre (2013). Unlike Hotelling models where only constant-present-value taxes are neutral (Dasgupta, Heal and Stiglitz, 1981), we show that resource taxes have in general no effect in presence of limit pricing: as long as extraction remains attractive, a rise in the resource tax does not affect current equilibrium quantities. Hence, the goal of reducing the consumption flow of the oil resource can hardly be achieved by directly penalizing extraction. Additionally, subsidies to the backstop substitute result in more resource being extracted at each date. This is the object of Section 2.

A backstop technology represents the possibility that the oil resource be completely replaced in the long run, by a virtually-infinite resource base capable of meeting all demand requirements. Following Nordhaus' example, nuclear fusion would provide such energy abundance that oil would no longer be economically scarce. In contrast, current oil substitutes only offer limited substitution possibilities: the production of existing energy goods usually exhibits decreasing returns to scale because it relies on some scarce primary factors.[10] On these grounds, Section 3 further considers ordinary substitutes to the resource that have imperfectly-elastic supplies, unlike the backstop. Each substitute is characterized by its entry price and has a rising marginal cost function.

Current substitution possibilities leave a (residual) demand for the resource, whose curve progressively reflects the multiplicity of substitutes, with kinks and increasing demand elasticity at those kinks. On the one hand, the backstop technology has the potential to destroy the entire resource demand. Profit maximization thus requires that it be deterred as in Section 2. On the other hand, ordinary substitutes are not sufficient threats to the resource market share to deserve deterrence. Their entry does not cause the resource demand to become highly elastic, because their supply is relatively inelastic. Resource profits may increase with higher prices despite the fact that ordinary substitutes become economical, unlike the backstop. Limit pricing is compatible with ordinary substitutes being produced. Resource taxes remain neutral in that context. However, subsidies to ordinary (current) substitutes do induce a reduction of the extraction flow, unlike backstop subsidies.

The setup of Section 3 allows to examine the carbon tax. The carbon tax is applied to the carbon content of the oil resource; according to the above results, like a regular resource tax, the carbon tax has no effect on the equilibrium resource quantity. Yet other

[10]For non-renewable substitutes to oil (other carbon fuels, uranium), scarcity arises from the finiteness of total exploration prospects and/or from the fact that low-cost reserves specifically are limited. Similarly for standard biofuels, as well as for solar and wind energy production, scarcity arises from land limitations. For instance, at the microeconomic level of a wind turbine, returns to scale should be increasing because the turbine involves a fixed set-up cost and almost-constant marginal costs of maintenance; at the macroeconomic level however, the unit cost of wind energy output must be increasing both because of land supply limitations and because the marginal land is of worse quality as far as wind is concerned. See for instance Chakravorty, Magné and Moreaux (2008) and Heal (2009) on land requirements and large-scale substitution of fuel products. Land availability is considered an issue as soon as further use of land causes rents to rise. The same is true for hydropower exploitation: for example in Switzerland, the 25 projects of new hydroelectric power plants will exhibit an expected average unit cost that is twice as large as that of the existing plants (Swiss Federal Office of the Energy, 2013, Page 7).

energy goods contain carbon, that are substitutes to oil. Those carbon substitutes are currently produced and so are ordinary substitutes in our analysis. Because the carbon tax is also applied to these substitutes, their quantity is reduced; yet this reduction is exactly compensated by greater resource extraction.

In Section 4, we consider a Ricardian resource that is incompletely depleted: extraction may become uneconomical before exploitable reserves are exhausted. All along the limit-pricing exploitation period, taxation policies retain their effects on current extraction, but may further affect ultimately extracted quantities. The carbon tax increases resource extraction, but shortens the resource exploitation period; its effect on the ultimately extracted quantity is thus ambiguous.

Finally in Section 5, with further details in the Appendix, we discuss limit-pricing equilibria in less parsimonious models integrating various aspects of the oil market. First and foremost, we show that the models of Sections 3 and 4 are isomorphic to one with a competitive fringe, once an ordinary substitute is interpreted as the resource itself; we discuss the empirical relevance of limit pricing in that case. We also discuss exploration and reserve development, as well as the multiplicity of demand segments.

II. A simple limit-pricing model and the effects of taxation policies

This section follows the limit-pricing model of Hoel (1978), Salant (1979), Dasgupta and Heal (1979) and Newberry (1981), that assumes a backstop substitute. We study the effects of taxes on a non-renewable resource and of subsidies to the backstop technology.

A. Static limit pricing

At any single date t, a monopoly produces some energy resource flow q at a constant marginal cost $c_t > 0$.

The total energy demand is given by the function $\overline{D}_t(p)$ of its price p; it is continuously differentiable and strictly decreasing. We assume that the price elasticity of the energy demand is lower than unity all along the demand curve: $\xi_{\overline{D}t}(p) \equiv -\overline{D}_t'(p)p/\overline{D}_t(p) < 1$.

There is a backstop technology by which a competitive sector can produce a perfect substitute to the resource at a constant positive marginal cost $b_t > c_t$. The demand notion that is relevant to the monopoly is the residual demand it faces.[11] Let us denote it with $D_t(p) \leq \overline{D}_t(p)$. When $p < p_t^b$, the production of the substitute is not profitable and thus the residual demand for the resource is the entire energy demand $D_t(p) = \overline{D}_t(p)$. When $p > p_t^b$, the substitute becomes profitable and more attractive than the resource, whose demand is thus destroyed: $D_t(p) = 0$. For notational simplicity and without any consequence on our message, we assume, as is standard, that if $p = p_t^b$ consumers give priority to the resource: at this price, the monopoly may serve the entire demand $D_t(p_t^b) = \overline{D}_t(p_t^b)$, assumed to be strictly positive.

To sum up, we make the following assumption.

Assumption 1 (Low price elasticity of the resource demand)
At any date t, for all prices $p \leq p_t^b$, the residual demand $D_t(p)$ for the monopoly's resource is strictly positive and exhibits a low elasticity

$$\xi_{Dt}(p) \equiv -D_t'(p)p/D_t(p) < 1; \tag{1}$$

for prices $p > p_t^b$, this demand vanishes.

Figure 1 illustrates the residual demand schedule and its kink at price $p = p_t^b$.

Which production level maximizes the monopoly's profits in that context? If the monopoly supplies an amount q that is lower than the threshold quantity $\overline{D}_t(p_t^b) > 0$, it induces the limit price p_t^b and its spot profit is $(p_t^b - c_t)q$, which is strictly increasing in q until $\overline{D}_t(p_t^b)$. With a higher supply $q > \overline{D}_t(p_t^b)$, the monopoly depresses the price below p_t^b; then its spot profit as function of the resource quantity becomes $\left(\overline{D}_t^{-1}(q) - c_t\right) q$, which is strictly decreasing in q because demand is sufficiently inelastic. Indeed, marginal profit

[11] The presence of a competitive fringe producing an identical resource amounts to interpreting the residual demand for each price as being net of the fringe's supply for that price (e.g. Salant, 1976). More on that further below, in Sections 3 and 5.

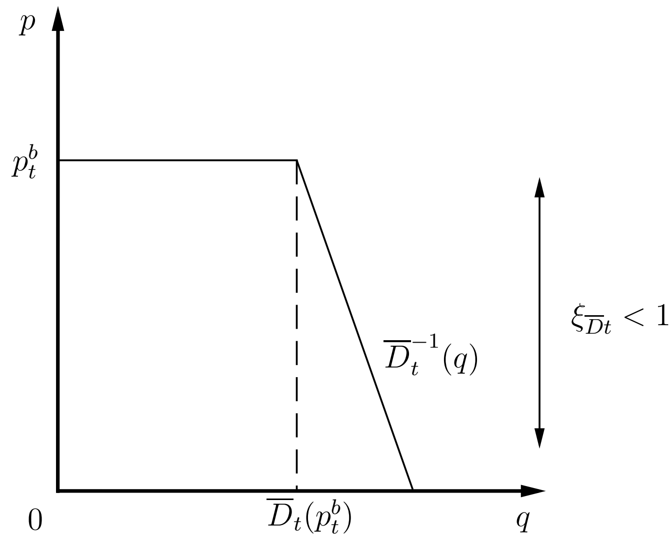

Figure 1: Residual demand for the resource in the presence of a backstop technology

may be written $p\,(1 - 1/\xi_{\overline{D}t}(p)) - c_t$, where $\xi_{\overline{D}_t}(p) < 1$ implies the term into parentheses to be positive. To sum up, the instantaneous profit is

$$\pi_t(q) = \begin{cases} (p_t^b - c_t)q, \ \text{increasing}, \ \text{for } q \leq \overline{D}_t(p_t^b) \\ \big(\overline{D}_t^{-1}(q) - c_t\big)q, \ \text{decreasing}, \ \text{for } q > \overline{D}_t(p_t^b) \end{cases}, \tag{2}$$

which is maximized by the supply level $q_t^m = \overline{D}_t(p_t^b)$ that induces the limit price $p_t = p_t^b$, the maximum price that deters the entry of the backstop.

B. Intertemporal limit pricing of extraction

Consider now that the resource is non-renewable; it is available in a finite quantity $Q_0 > 0$, that is to be extracted over the continuum set of dates $t \in [0, +\infty)$.

In that case, the monopoly's problem becomes intertemporal. Assuming a discount rate $r > 0$, the stream of discounted profits amounts to

$$\int_0^T \pi_t(q_t)e^{-rt} \, dt, \tag{3}$$

where the function $\pi_t(q_t)$ is given by the function (2) and where the terminal date T is endogenous. The monopoly chooses the extraction path $(q_t)_{t\geq 0}$ in such a way as to maximize (3) under the exhaustibility constraint

$$\dot{Q}_t = -q_t, \text{ where } Q_T \geq 0, \tag{4}$$

where Q_t denotes the remaining stock at date t, and $Q_0 > 0$ is given.

In such dynamic problems, the relevant instantaneous objective is the Hamiltonian function. The Hamiltonian at some date $t \geq 0$ does not only consist of the present-value static profit objective $\pi_t(q_t)$; it is corrected by a linear term that reflects the opportunity cost of extracting the scarce resource. For the problem of maximizing (3) under (4), the Hamiltonian writes

$$\mathcal{H}(q_t, Q_t, \lambda_t, t) \equiv \pi_t(q_t)e^{-rt} - \lambda_t q_t, \tag{5}$$

where $\lambda_t \geq 0$ is the multiplier associated with constraint (4). λ_t must be interpreted as the discounted scarcity value of the resource. By the Maximum Principle, it is constant over time at the producer's optimum: $\lambda_t = \lambda$.[12]

The optimal choice of extraction q_t must maximize the Hamiltonian (5) at all dates of the extraction period. Since both $\pi_t(q)$ as per (2) and λq are linear in q, the Hamiltonian is maximized by the same supply level $q_t^m = \overline{D}_t(p_t^b)$ as the instantaneous revenue $\pi_t(q)$ in (2), as long as the discounted marginal revenue $(p_t^b - c_t)e^{-rt}$ remains greater than the scarcity value λ (See Figure 2).

In the stationary model of Hoel (1978), Salant (1979), Dasgupta and Heal (1979) and Newberry (1981), p^b and c are constant with $p^b > c$, so that the discounted marginal revenue $(p^b - c)e^{-rt}$ is strictly decreasing because of discounting. In the non-stationary model used here, it need not be so. For simplicity, we make the following assumption that

[12] The time independence of λ along the optimal producer path is standard in models of Hotellian resources. It arises from the fact that the Hamiltonian does not depend on Q_t because the resource is homogenous. In Section 5, we examine the case of heterogenous resources.

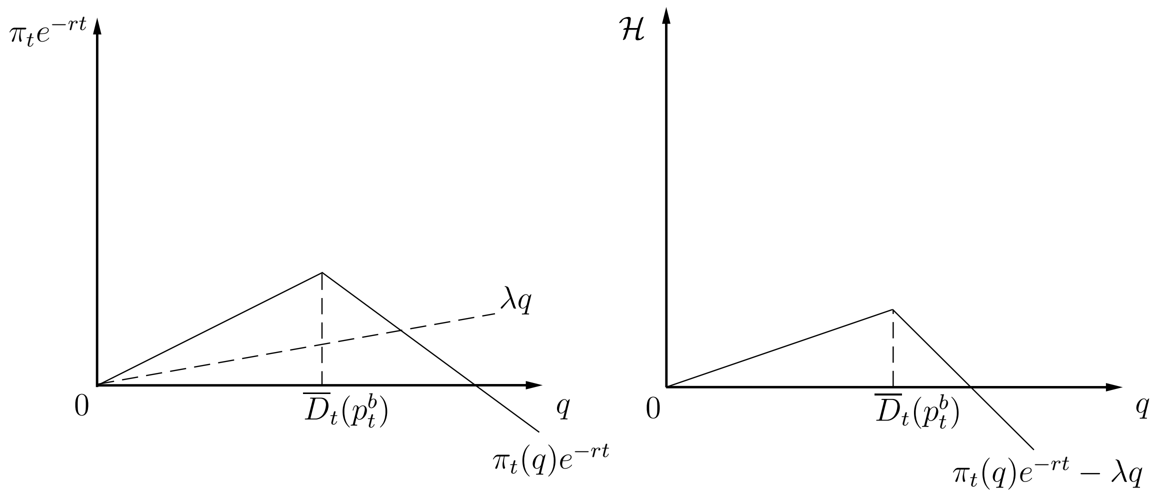

Figure 2: Instantaneous profit and Hamiltonian value

excludes supply interruptions during the resource exploitation phase;[13] an assumption that will be maintained until Section 4.

Assumption 2 (Complete and uninterrupted extraction)
For all $t \geq 0$, the limit-pricing marginal revenue is strictly positive and strictly decreasing in present-value terms.

Absent any policy, the limit-pricing marginal revenue is $p_t^b - c_t$. By Assumption 2, for all $t \geq 0$, $p_t^b > c_t$ and $(p_t^b - c_t)e^{-rt}$ is strictly decreasing, as in the standard stationary treatment.

Assume, as a statement to be contradicted, that λ is nil. Since the present-value marginal revenue $(p_t^b - c_t)e^{-rt}$ is always strictly positive by Assumption 2, extraction must be $q_t^m = \overline{D}_t(p_t^b) > 0$ at all dates. Clearly, this would violate the exhaustibility constraint (4) with $Q_t \geq 0$ in finite time.

Therefore $\lambda > 0$. Now contradict that $p_0^b - c_0 < \lambda$: in that case, also by Assumption 2, $(p_t^b - c_t)e^{-rt}$ would fall short of λ for all $t \geq 0$ and no extraction at all would be optimal; since $p_t^b > c_t$ for all $t \geq 0$, this would be strictly dominated by some positive extraction.

[13] The analysis can easily accommodate supply interruptions, as when the limit price p_t^b falls short of c_t for some dates of the exploitation period. This would not modify the analysis in any insightful manner. Section 4 considers the alternative possibility that limit-pricing extraction become uneconomical after some date.

Thus it must be the case that the marginal profit $(p_t^b - c_t)e^{-rt}$ is greater than or equal to λ, initially and until the terminal date T^m, such that $(p_{T^m}^b - c_{T^m})e^{-rT^m} = \lambda > 0$. Over the exploitation period $[0, T^m]$, extraction must be $q_t^m = \overline{D}_t(p_t^b) > 0$. Since $\lambda > 0$, T^m must also be the exhaustion date; it is defined by $\int_0^{T^m} q_t^m \, dt = \int_0^{T^m} \overline{D}_t(p_t^b) \, dt = Q_0$. Combining the last two conditions characterizes λ.

In the standard stationary model, the limit-pricing quantity $q^m = \overline{D}(p^b)$ is constant, that induces the limit price $p^m = p^b$. The terminal date T^m is defined by $T^m = Q_0/\overline{D}(p^b)$, which determines $\lambda = (p^b - c)e^{-rT^m}$.

When Assumptions 1 and 2 are verified, the general properties of the limit-pricing equilibrium in absence of taxation policies are summarized in the following proposition.

Proposition 1 (Limit-pricing equilibrium)

1. *The monopoly supplies $q_t^m = \overline{D}_t(p_t^b) > 0$, and so induces the limit price $p_t^m = p_t^b$ that deters the backstop-substitute production, at all dates t of the extraction period $[0, T^m]$;*

2. *The limit-pricing equilibrium leads to the complete exhaustion of the resource at the date T^m such that $\int_0^{T^m} \overline{D}_t(p_t^b) \, dt = Q_0$;*

It can easily be verified that deviations from this extraction path would decrease the sum of the monopoly's discounted profits. Two types of deviations are possible. First, consider reallocations of an infinitesimal quantity $\Delta > 0$ of resource from any date t to any date $t' \neq t$ such that $t, t' < T^m$. Reducing extraction by Δ at date t decreases present-value profits by $(p_t^b - c_t)\Delta e^{-rt}$ while increasing extraction at date t' decreases profits as well, since profits are decreasing for quantities exceeding the limit-pricing extraction q_t^m. Second, consider reallocations of an infinitesimal quantity $\Delta > 0$ of resource from any date $t \leq T^m$ to any date $t' > T^m$. Again, reducing extraction by Δ at date t decreases present-value profits by $(p_t^b - c_t)\Delta e^{-rt}$. On the other hand, increasing extraction at date t', from zero, by Δ, increases present-value profits by $(p_{t'}^b - c_{t'})\Delta e^{-rt'}$. However by Assumption 2

$(p^b_{t'} - c_{t'})e^{-rt'} < (p^b_t - c_t)e^{-rt}$, so that the overall effect on the discounted stream of profits remains negative.

To sum up in the context of this section, facing a relatively inelastic resource demand, the monopoly finds it optimal to choose the extraction path of level $q^m_t = \overline{D}_t(p^b_t)$ that induces the highest price $p^m_t = p^b_t$ which prevents the backstop's production from taking the entire demand. There are two basic differences between the limit-pricing equilibrium arising here and conventional Hotelling equilibria. First, along the extraction period, the equilibrium present-value marginal revenue $(p^b_t - c_t)e^{-rt}$ of the monopoly is decreasing, unlike in Hotelling equilibria where it is equalized with the constant scarcity component λ. Second, the stylized fact that the oil demand has a lower-than-unity price elasticity at equilibrium is observed, while it is incompatible with conventional treatments of monopoly power on resource markets.

C. Taxes on the non-renewable resource

Let θ_t be a specific resource tax (or subsidy if negative) applied to the producer resource price p_t at each date $t \geq 0$ to determine the consumer price $p_t + \theta_t$.[14]

The consumer price at which the substitute becomes profitable is p^b_t, irrespective of the resource tax. Thus the tax does not affect neither the resource quantity $q_t = \overline{D}_t(p^b_t)$ below which the backstop enters, nor the consumer price p^b_t that the market establishes in this case, but only the producer price, that becomes $p^b_t - \theta_t$ in the limit-pricing equilibrium.

Also, when $q_t \geq \overline{D}_t(p^b_t)$ so that only the resource may be produced, the tax-inclusive consumer price is given by the inverse demand $\overline{D}_t^{-1}(q_t)$, and the price accruing to the producer becomes $\overline{D}_t^{-1}(q_t) - \theta_t$.

It turns out that the problem of the previous section is only modified to the extent

[14] This is a consumer tax. As shown for instance by Bergstrom et al. (1981), its effect is formally equivalent to that of a tax falling on the producer.

that the instantaneous profit becomes

$$\pi_t(q) = \begin{cases} (p_t^b - \theta_t - c_t)q, \text{ increasing, for } q \leq \overline{D}_t(p_t^b) \\ \left(\overline{D}_t^{-1}(q) - \theta_t - c_t\right) q, \text{ decreasing, for } q > \overline{D}_t(p_t^b) \end{cases}. \tag{6}$$

The modification amounts to integrating the tax θ_t to the marginal cost c_t.

Let Assumption 2 apply in this context, where the cost c_t in the absence of policies is replaced here by $c_t + \theta_t$.[15] The assumption amounts to focusing on taxes that leave extraction attractive along the exploitation period. First, the property that the limit-pricing marginal revenue $p_t^b - c_t - \theta_t$ remains positive for all $t \geq 0$ excludes so high taxes that would leave no extraction profits at all. Second, the property that $p_t^b - c_t - \theta_t$ is decreasing in present value excludes taxes (subsidies) that are falling (rising) too rapidly. The two conditions rule out the possibility that depletion be interrupted during the exploitation phase.[16]

Once Assumption 2 is adjusted that way, the analysis of the previous subsection carries over, unchanged, and the same limit-pricing equilibrium described in Proposition 1 is realized. Indeed the quantity that the monopoly needs to supply so as to deter the backstop production remains, at each date $t \leq T^m$ of the exploitation period, $q_t^m = \overline{D}_t(p_t^b)$, regardless of whether the resource is taxed or not; in the limit-pricing equilibrium, the path of resource taxes is completely neutral to the monopolist's extraction. Meanwhile, its revenues are reduced by the tax burden $\theta_t \overline{D}_t(p_t^b)$ at all dates of the extraction phase.

Pathological resource taxes that violate Assumption 2 would cause resource supply interruption during the exploitation phase. First, too high taxes $\theta_t \geq p_t^b - c_t$ for some

[15] This is for simplicity. Assumption 2 is a sufficient condition for no supply interruption, that is not necessary. The analysis would easily extend to all cases of no supply interruption, but for no further insight.

[16] In the stationary model, the assumption holds in particular for all constant taxes (and subsidies) $\theta < p^b - c$, as discounting implies the present-value marginal revenue $(p^b - c - \theta)e^{-rt}$ to decrease. It also holds for all rising taxes (falling subsidies), as well as for those taxes (subsidies) that are not too decreasing (increasing) over time. For example let a tax θ_t have an initial level $\theta > 0$ and be rising at a negative rate $\alpha < 0$: $\theta_t = \theta e^{\alpha t}$. It can easily be shown that Assumption 2 applies as long as $\alpha > 1 - (p^b - c)/\theta$, with $p^b - c > \theta$. In the time-dependent model where $p_t^b - c_t$ is decreasing, the set of admissible taxes is broader.

$t \leq T^m$ would expropriate the entire profit at the monopolist's optimum; the monopolist in that case is better-off with no extraction. Second, with taxes that are falling so rapidly that discounted marginal revenue is greater at distant dates $t > T^m$ than during the exploitation period would lead the monopolist to completely shift extraction away from the exploitation phase.

The following proposition summarizes the effect of resource taxes for which Assumption 2 remains valid.

Proposition 2 (Effect of resource taxes)

Resource taxes leave resource extraction unchanged.

Neutral resource taxes exist in standard Hotelling models. Dasgupta et al. (1981) showed that specific resource taxes that grow at the rate at which profits are discounted are neutral to the extraction of a competitive sector; such taxes leave unaffected the intertemporal no-arbitrage condition that prevailed in any Hotelling competitive equilibrium. Karp and Livernois (1992) showed that this neutrality result also applies when extraction is monopolistic.[17] Under competition as well as in a monopoly, extreme taxes eat the entire Hotelling rent and do not warrant any extraction.

The neutrality result of Proposition 2 is reminiscent of the result that resource taxes may be neutral in Hotelling equilibria when they grow at the rate of discount. The novelty lies in the fact that resource taxation neutrality in limit-pricing equilibria is of a strong form in the sense that it does not require taxes to obey any particular dynamics.

D. Subsidies to the backstop substitute

Alternatively, let γ_t^b be a specific subsidy to the backstop substitute, applied to the backstop's producer price, which is also its marginal cost p_t^b. Thus, the problem in absence of taxation is only modified to the extent that the price of the backstop substitute p_t^b

[17]In Hotelling equilibria, whether under competition or monopoly, there exists a family of optimal resource tax/subsidy paths. This family is indexed by a tax component Ke^{rt}, where K is some scalar, that is constant in present value. As Karp and Livernois (1992, Page 23) put it: "If the amount Ke^{rt} is added to [the optimal unit tax], the monopolist will still want to extract at the efficient rate, provided that the dynamics rationality constraint is satisfied (...)."

should be replaced by the consumer net-of-subsidy price $p_t^b - \gamma_t^b$. Unlike a resource tax, a backstop subsidy γ_t^b always affects the limit-pricing equilibrium.

When the substitute price is reduced to $p_t^b - \gamma_t^b$, the resource supply that deters its production rises to $\overline{D}_t(p_t^b - \gamma_t^b) > \overline{D}_t(p_t^b)$; with a substitute subsidy, the monopoly must supply more so as to deter its entry.

Also, low resource quantities $q_t < \overline{D}_t(p_t^b - \gamma_t^b)$ that warrant the production of the substitute, no longer induce the market price p_t^b, but the lower price $p_t^b - \gamma_t^b$. Thus, for $q_t < \overline{D}_t(p_t^b - \gamma_t^b)$, the marginal extraction profit of the monopolist becomes $p_t^b - \gamma_t^b - c_t$.

In the sequel, we only consider subsidies such that Assumption 2 holds, so that resource supply is continuously warranted during the resource exploitation. First, $p_t^b - \gamma_t^b - c_t > 0$, for all $t \geq 0$; the condition assumes away subsidies that would destroy extraction profits because the substitute would be available to consumers for a price $p_t^b - \gamma_t^b$ lower than the resource extraction cost c_t. Second, $p_t^b - \gamma_t^b - c_t$ is decreasing in present value for all $t \geq 0$; the condition rules out backstop subsidies that are so decreasing over time that they would make extraction more attractive at distant dates rather than during the exploitation period.

Assumption 2 being adjusted that way, the instantaneous extraction profit with backstop subsidies becomes

$$\pi_t(q) = \begin{cases} (p_t^b - \gamma_t^b - c_t)q, \text{ increasing, for } q \leq \overline{D}_t(p_t^b - \gamma_t^b) \\ \left(\overline{D}_t^{-1}(q) - c_t\right) q, \text{ decreasing, for } q > \overline{D}_t(p_t^b - \gamma_t^b) \end{cases}, \tag{7}$$

and the same dynamic analysis applies as in absence of subsidies: at each date of the resource exploitation phase, the monopoly chooses the limit-pricing supply $q_t = \overline{D}_t(p_t^b - \gamma_t^b)$ that deters the backstop production. This modification of the limit-pricing equilibrium is illustrated in Figure 3.

In this context, the following proposition summarizes the effect of subsidies to a backstop substitute.

Proposition 3 (Effect of subsidies to the backstop substitute)

Subsidies to the backstop substitute increase the resource current extraction.

Extreme subsidies that make the extraction profit vanish, or make extraction no longer attractive during the exploitation period, cause resource supply interruptions.

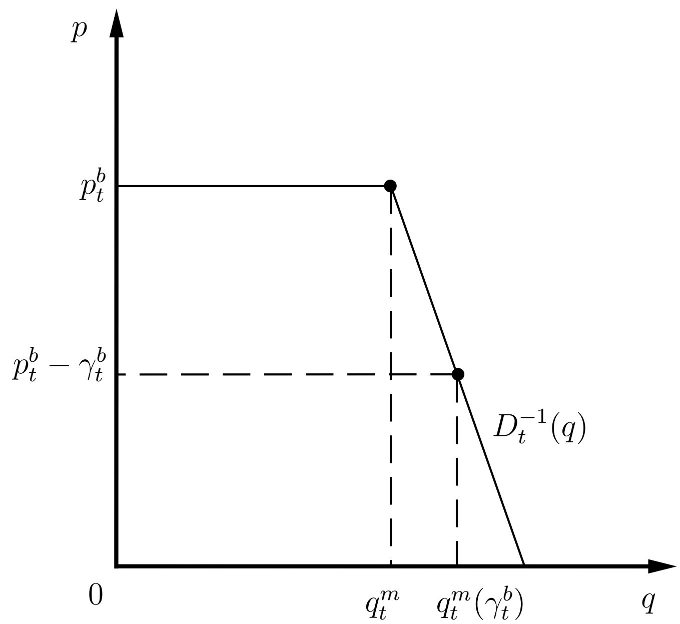

Figure 3: Limit-pricing equilibrium and the effect of a backstop subsidy

If taxation policies aim at reducing the current oil extraction quantity, the model of this section yields a quite pessimistic message. Leave aside extreme policies that would cause supply disruption: not only are resource taxes strongly neutral, but subsidizing the backstop substitute induces the monopoly to increase its supply.

III. Ordinary substitutes

A backstop technology is a meaningful and standard device. It represents the possibility that the resource be completely replaced, as a result of a virtually-infinite resource base. Whether in conventional Hotelling-type equilibria or in the limit-pricing equilibrium of Section 2, such backstop technology is never used before the exhaustion date, after which it becomes the exclusive source of energy.

In contrast, empirical evidence shows that ordinary substitutes to oil are currently traded and consumed on energy markets, such as other regular fuels, biofuels, and alternative energies. Yet, each substitute remains far from meeting a large fraction of the energy demand.

In this section, we do away with the single-backstop-substitute assumption and allow for the possibility that some ordinary substitutes may be used along the resource extraction phase. As a matter of fact, the existing substitutes to oil may differ according to the substitution opportunities they offer. Limit pricing to deter the backstop substitute is not incompatible with ordinary substitutes being produced during the resource exploitation phase.

A. The model

The elasticity of the residual demand is often interpreted as the extent of substitution opportunities (e.g. Lewis et al., 1979). Marshall (1920) argued that, ordinarily, demand curves should be expected to have the property that the price elasticity is increasing with price. In this section, there are several substitutes whose entries sequentially kink the resource demand and increase its elasticity.

The backstop substitute retains the same role as in Section 2; for prices greater than its entry price $p > p_t^b$, the backstop substitute offers an unlimited substitution opportunity that will induce the resource monopoly to deter its production.

We further consider ordinary substitutes. Like the backstop, ordinary substitutes are perfect ones and are produced competitively. However, their production exhibits decreasing returns to scale: they only offer relatively limited substitution possibilities.[18] In fact, we assume that ordinary substitutes offer so low substitution possibilities, that the resource monopoly does not find optimal to deter it. In brief, we define them in the

[18]Similarly one may consider substitutability to be partial because ordinary substitutes only replace oil for some uses (Hoel, 1984); the case of various uses with use-specific imperfect substitutes is discussed in Section 5.

following way, that will be given more precise grounds shortly below.

Definition 1 (Ordinary substitute)

With an ordinary substitute, at each date t, Assumption 1 remains satisfied.

As already argued in the Introduction, the supply of existing energy goods is subject to limitations. These limitations may arise because of the scarcity of some factors.[19] Whether this scarcity is static (e.g. land, as in the case of biofuels, and wind and solar energies) or dynamic (e.g. finite exploitable reserves, as in the case of other fossil fuels), higher instantaneous prices always warrant a higher instantaneous supply, yet at some greater marginal costs.[20] Thus for simplicity, we assume that the production of substitutes is static and the only good we explicitly treat as non renewable is the resource supplied by the monopoly.

We consider for brevity a single ordinary substitute. As will be clear shortly, the analysis immediately accommodates more than one such substitutes. The ordinary substitute is produced for all prices strictly greater than $p_t^o > 0$; we further assume

$$c_t < p_t^o < p_t^b, \text{ for all } t \geq 0, \tag{8}$$

so as to exclude the uninteresting case where the ordinary substitute is deterred at the same time as the backstop.[21] Thus the ordinary substitute will be produced along the resource exploitation limit-pricing phase. We now examine the 3 sections of the residual resource demand curve, which is represented in Figure 4.

$\imath$) For all prices $p \leq p_t^o$, no substitute is competing with the resource at all.[22] The residual demand the monopoly is facing is the entire demand $D_t(p) = \overline{D}_t(p)$. Since the residual

[19] See especially Footnote 10.

[20] In the case of a non-renewable substitute, supply is still characterized by the equalization of price with marginal costs, while marginal costs are adjusted to comprise the opportunity costs of extraction. See Sweeney (1993, Pages 775-776) for the interpretation of the instantaneous supply of a non-renewable resource.

[21] In principle, there may be substitutes, backstop or ordinary, with entry prices exceeding the equilibrium limit price, that are not produced over the limit-pricing extraction phase.

[22] In this section as in Section 2, the assumption that substitutes' production is nil at their entry price is made for notational simplicity.

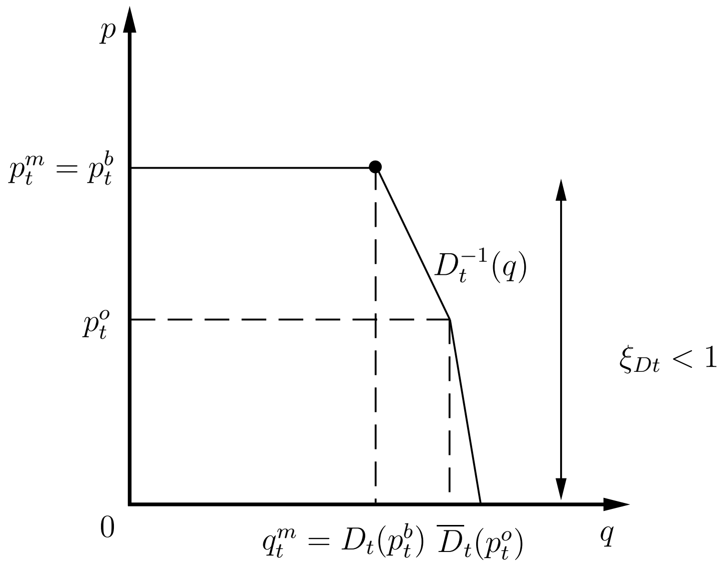

Figure 4: Residual demand and limit-pricing equilibrium with backstop and ordinary substitutes

demand $D_t(p)$ will turn out to be monotonic, the range of prices $p \leq p_t^o$ that deter both substitutes is induced by sufficiently high monopoly extraction

$$q \geq \overline{D}_t(p_t^o) \tag{9}$$

over which

$$\pi_t(q) = \left(\overline{D}^{-1}(q) - c_t\right) q \text{ is decreasing} \tag{10}$$

by (1).

ıı) For prices $p_t^o < p \leq p_t^b$, only the ordinary substitute is competing with the resource, as the price exceeds its entry price p_t^o, which is its marginal cost at the origin: $p_t^o \equiv C_t^{o\prime}(0) > 0$. Unlike the backstop of Section 2, the ordinary substitute is unable to meet a large fraction of the resource demand without exhibiting substantial cost increase. Thus the marginal cost $C_t^{o\prime}(x)$ of producing a quantity x of ordinary substitute is differentiable, strictly increasing and the ordinary-substitute supply function $S_t^o(p) \equiv C_t^{o\prime-1}(p)$ is continuous, with $S_t^o(p) > 0$ if and only if $p > p_t^o$.

Yet the price elasticity of the ordinary substitute's supply $\xi_{S^o t}(x) = C_t^{o\prime}(x)/\left(C_t^{o\prime\prime}(x)x\right)$ must be low in the sense that the elasticity $\xi_{Dt}(q)$ of the residual demand $D_t(p) = \overline{D}_t(p) - S_t^o(p)$ satisfies the inequality

$$\xi_{Dt}(q) = \frac{e}{q}\xi_{\overline{D}t}(e) + \frac{x}{q}\xi_{S^o t}(x) < 1, \tag{11}$$

where $e = q + x$ is the total energy supply. This way, Assumption 1 is verified, as per Definition 1.

The range of prices $p_t^o < p \leq p_t^b$ over which only the ordinary substitute is produced is induced by monopoly's supply

$$D_t(p_t^b) \leq q < \overline{D}_t(p_t^o), \tag{12}$$

with[23]

$$D_t(p_t^b) = \overline{D}(p_t^b) - S_t^o(p_t^b), \text{ assumed strictly positive.} \tag{13}$$

Over this range, it follows from (11) that

$$\pi_t(q) = \left(D_t^{-1}(q) - c_t\right) q \text{ is decreasing.} \tag{14}$$

iii) For all prices $p > p_t^b$, the backstop has the capacity of meeting the entire demand while remaining more attractive than both the ordinary substitute and the resource.[24]

Since the backstop is supplied competitively, any monopoly's supply as low as

$$q < D_t(p_t^b) = \overline{D}_t(p_t^b) - S_t^o(p_t^b) \tag{15}$$

[23]The assumption that $D_t(p_t^b) > 0$ despite the ordinary substitute is the counterpart of $\overline{D}_t(p_t^b) > 0$ in Section 2. This way, Assumption 1 is satisfied, which avoids the uninteresting case where the backstop supply and the residual resource demand do not intersect at all.

[24]Instead of a backstop, limit pricing may seek to deter a substitute with non-constant returns. Assume a substitute with a sufficiently high, although not infinite, supply elasticity; beyond its entry price, it may cause the residual demand to be sufficiently elastic for the monopoly's profit to be increasing. The analysis easily extends to that case, for no additional insight.

induces the resource price $p = p_t^b$, so that

$$\pi_t(q) = \left(p_t^b - c_t\right) q, \text{ which is increasing} \tag{16}$$

by Assumption 1.

To sum up, the instantaneous profit is continuous and such that

$$\pi_t(q) = \begin{cases} \left(p_t^b - c_t\right) q, \text{ increasing, for } q < D_t(p_t^b) \\ \left(D_t^{-1}(q) - c_t\right) q, \text{ decreasing, for } D_t(p_t^b) \leq q < \overline{D}_t(p_t^o) \\ \left(\overline{D}_t^{-1}(q) - c_t\right) q, \text{ decreasing, for } q \geq \overline{D}_t(p_t^o) \end{cases}, \tag{17}$$

and is thus maximized by the supply level

$$q_t^m = D_t(p_t^b) = \overline{D}_t(p_t^b) - S_t^o(p_t^b). \tag{18}$$

Thus, once q_t^m is given by (18), the dynamic analysis of Section 2 applies as before under Assumption 1. The following proposition summarizes the properties of the limit-pricing equilibrium in the context of this section.

Proposition 4 (Limit-pricing equilibrium with an ordinary substitute)
In presence of an ordinary substitute,

1. *The monopoly supplies $q_t^m = D_t(p_t^b) = \overline{D}_t(p_t^b) - S_t^o(p_t^b) > 0$ as per (18), and so induces the limit price $p_t^m = p_t^b$ that deters the backstop substitute's production, at all dates t of the extraction period $[0, T^m]$;*

2. *The limit-pricing equilibrium leads to the complete exhaustion of the resource at the date T^m such that $\int_0^{T^m} D_t(p_t^b)\, dt = Q_0$;*

3. *All along the extraction period $[0, T^m]$, the ordinary substitute is produced in quantity $S_t^o(p_t^b) > 0$.*

In the stationary model, the limit-pricing quantity $q^m = D(p^b) = \overline{D}(p^b) - S^o(b) > 0$ is constant, so that the exhaustion date is $T^m = Q_0 / \left(\overline{D}(p^b) - S^o(p^b)\right)$.

In absence of taxation policies, the limit-pricing equilibrium at any date t of the exploitation phase is depicted in Figure 4. As far as taxation policies are concerned, the distinction between the deterred backstop and the on-use ordinary substitute, will turn out to be fundamental.

B. *Taxes on the non-renewable resource*

The same way as in Section 2, a unit consumer tax θ_t leaves unchanged the consumer price p_t^b at which the drastic substitute enters, and thus the limit extraction quantity $D_t(p_t^b)$, given by (15), that deters its entry. It also leaves the entry price p_t^o unchanged. Thus the tax does only modify (17) to the extent that, for any extraction quantity q, the price accruing to the producer is the inverse demand $D_t^{-1}(q)$, reduced by the tax θ_t; as if the cost c_t was augmented by the levy θ_t.

Once Assumption 2 is adjusted to the augmented cost $c_t + \theta_t$, the instantaneous profit function becomes

$$\pi_t(q) = \begin{cases} \left(p_t^b - \theta_t - c_t\right) q, \text{ increasing, for } q < D_t(p_t^b) \\ \left(D_t^{-1}(q) - \theta_t - c_t\right) q, \text{ decreasing, for } D_t(p_t^b) \leq q < \overline{D}_t(p_t^o) \\ \left(\overline{D}_t^{-1}(q) - \theta_t - c_t\right) q, \text{ decreasing, for } q \geq \overline{D}_t(p_t^o) \end{cases} . \tag{19}$$

Thus to the extent that the tax does not violate Assumption 2 – it warrants no interruption of the resource exploitation –, it will not affect the monopoly's limit-pricing path described in Proposition 4: the strong neutrality result of resource taxes and subsidies holds as per Proposition 2 in presence of an ordinary substitute.

C. *Subsidies to the backstop substitute*

Subsidies to the backstop substitute have the same effect as in Section 2, regardless of whether there is an ordinary substitute.

Consider a subsidy γ_t^b to the backstop substitute. Its price is reduced to $p_t^b - \gamma_t^b$, which is also the resource price whenever the backstop is profitable. The extraction amount that deters the entry of the backstop substitute is thus increased to

$$D_t(p_t^b - \gamma_t^b) = \overline{D}_t(p_t^b - \gamma_t^b) - S_t^o(p_t^b - \gamma_t^b), \tag{20}$$

instead of $D_t(p_t^b)$ as in (15).

As long as backstop subsidies leave a strictly positive limit-pricing revenue to the monopoly, as per Assumption 2, its revenue is only modified in these respects. It rewrites:

$$\pi_t(q) = \begin{cases} \left(p_t^b - \gamma_t^b - c_t\right) q, \text{ increasing, for } q < D_t(p_t^b - \gamma_t^b) \\ \left(D_t^{-1}(q) - c_t\right) q, \text{ decreasing, for } D_t(p_t^b - \gamma_t^b) \leq q < \overline{D}_t(p_t^o) \\ \left(\overline{D}_t^{-1}(q) - c_t\right) q, \text{ decreasing, for } q \geq \overline{D}_t(p_t^o) \end{cases}, \tag{21}$$

with the exact same consequence as in Section 2 for the effect of γ_t^b: the equilibrium limit-pricing extraction q_t^m is increased as per (20).

D. *Subsidies to ordinary substitutes*

In the limit-pricing equilibrium of Proposition 4, the production of the backstop substitute is deterred by the monopoly. Currently used substitutes must all be ordinary substitutes as per Definition 1. As this section shows, in a limit-pricing context, the effect of subsidies to existing substitutes greatly differ from the effects earlier identified of subsidies to the backstop.

With a subsidy γ_t^o to the consumption of the ordinary substitute, the resource price at which its production is profitable becomes $p_t^o - \gamma_t^o$. Thus the extraction level below which the substitute enters is reduced to $\overline{D}_t(p_t^o - \gamma_t^o)$ instead of $\overline{D}_t(p_t^o)$ in (9).

For all resource prices $p > p_t^o - \gamma_t^o$ – equivalently all extraction levels $q < \overline{D}_t(p_t^o - \gamma_t^o)$ – that warrant the production of the ordinary substitute, its supply expressed as a function of the resource price is augmented to $S_t^o(p + \gamma_t^o)$. Accordingly, the residual demand for the resource is reduced to $D_t(p) = \overline{D}_t(p) - S_t^o(p + \gamma_t^o)$ by the subsidy.

Hence at the entry price p_t^b of the backstop substitute, the subsidy γ_t^o increases the ordinary substitute's production to $S_t^o(p_t^b + \gamma_t^o)$ and reduces the residual demand faced by the monopoly by the same quantity. Thus the extraction to be supplied so as to deter the backstop's production is, instead of (15),

$$D_t(p_t^b) = \overline{D}_t(p_t^b) - S_t^o(p_t^b + \gamma_t^o), \tag{22}$$

lower than in absence of subsidy.

Definition 1 and Assumption 1 assume away the case where the ordinary substitute would completely destroy the resource demand for prices lower than the backstop price p_t^b. Thus by assumption, the residual resource demand at the limit price $D_t(p_t^b) = \overline{D}_t(p_t^b) - S_t^o(p_t^b + \gamma_t^o)$ is strictly positive. Sufficiently high subsidies γ_t^o would make the ordinary substitute meet the entire energy demand, i.e. $S_t^o(p_t^b + \gamma_t^o) > \overline{D}_t(p_t^b)$, and would thus cause a disruption of resource supply. Such extreme subsidies are ruled out by our analysis.

Thus (17) rewrites

$$\pi_t(q) = \begin{cases} \left(p_t^b - c_t\right) q, \text{ increasing, for } q < \overline{D}_t(p_t^b) - S_t^o(p_t^b + \gamma_t^o) \\ \left(D_t^{-1}(q) - c_t\right) q, \text{ decreasing, for } \overline{D}_t(p_t^b) - S_t^o(p_t^b + \gamma_t^o) \leq q < \overline{D}_t(p_t^o - \gamma_t^o) \\ \left(\overline{D}_t^{-1}(q) - c_t\right) q, \text{ decreasing, for } q \geq \overline{D}_t(p_t^o - \gamma_t^o) \end{cases}, \tag{23}$$

where threshold quantities $\overline{D}_t(p_t^o - \gamma_t^o)$ and $\overline{D}_t(p_t^b) - S_t^o(p_t^b + \gamma_t^o)$ are lowered by the subsidy.

Thus the dynamic analysis of Section 2 applies, and a limit-pricing equilibrium realizes, in which the monopoly supplies less, so as to induce the unchanged limit price p_t^b: $q_t^m = \overline{D}_t(p_t^b) - S_t^o(p_t^b + \gamma_t^o)$, decreasing with γ_t^o. Figure 5 depicts the change in the residual demand faced by the monopoly as a consequence of the subsidy to the ordinary substitute, and the resulting reduction in the limit-pricing resource quantity.

The message of the following proposition sharply contrasts with that of Proposition 3.

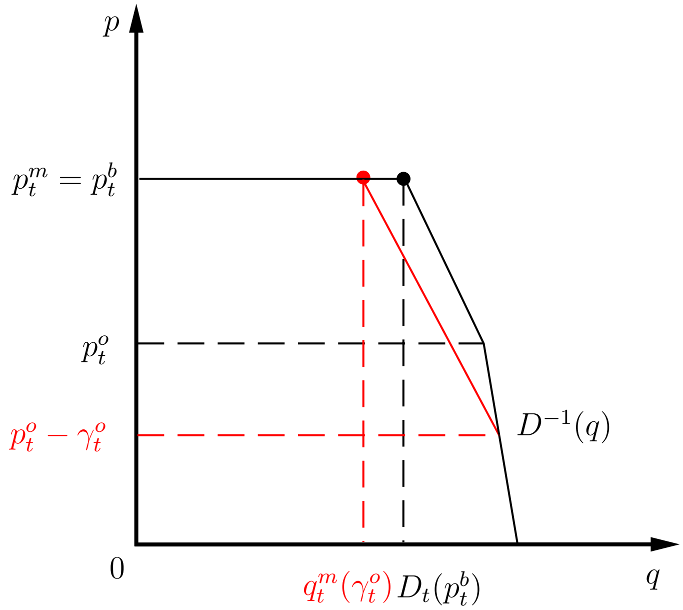

Figure 5: Limit-pricing equilibrium and the effect of a subsidy to the ordinary substitute

Proposition 5 *Subsidies to an ordinary substitute,*

1. *Increase the substitute current production;*
2. *Reduce the resource current extraction in the same quantity.*

E. The carbon tax

The carbon tax is applied to the carbon content of energy goods. Thus the carbon tax is formally equivalent to several taxes, each applied to a carbon-energy good, to an extent that reflects its unit carbon content.

In particular, the carbon tax comprises a tax on the oil resource as earlier examined. Under our assumptions, the result of Proposition 2 is valid in the context of this section; it indicates that such tax has no direct effect on resource supply because it modifies neither the entry price of the backstop substitute nor the extraction supplied by the monopoly so as to induce a lower price.

Energy goods that are substitutes to oil also contain carbon (e.g. gas, coal). Those carbon substitutes are currently produced and are ordinary substitutes in our analysis.

Thus the carbon tax simultaneously act as a tax on the ordinary substitute. The analysis of this section establishes that such tax (a negative subsidy) reduces the supply of the substitute and increases the supply of the resource by the same amount. Indeed, with a lower supply of ordinary substitute, the monopoly is supplying more resource so as to induce a price lower than the backstop price.

Since the carbon tax combines a resource tax with a tax on the ordinary substitute, its effect immediately results from Propositions 2 and 5, as summarized in the following corollary.

Corollary 1 *The combination of a resource tax, with a tax on the ordinary substitute,*

1. *Decreases the substitute current production;*

2. *Increases the resource current extraction by the same amount.*

IV. Resource heterogeneity and exploitation duration

In the standard limit-pricing model of Hoel (1978) and Salant (1989), as in the models of Section 2 and 3, the resource reserves are completely depleted. In such context, our analysis showed that resource taxes like the carbon tax are very limited instruments to curb resource consumption and carbon emissions; they have no effect on current quantities at each date of the exploitation period.

As a matter of fact, reserves of oil are heterogenous. One standard way to take resource heterogeneity into account is to assume that marginal extraction costs increase as less reserves are to be extracted, as when the resource is Ricardian and its units are exploited in order of their respective costs. This approach has been recently used for instance by van der Ploeg and Withagen (2012, 2014) in works on the carbon tax.[25]

Stock effects notoriously introduce incentives to extract the resource less rapidly (Dasgupta and Heal, 1979). This section extends the limit-pricing model of Sections 2 and

[25] The view that exploited reserves contribute to increasing extraction costs has been initiated by Hotelling (1931), and consolidated by Gordon (1967).

3 to the Hotelling-Gordon cost representation just described. This extension makes the limit-pricing model comparable with the conventional non-renewable-resource monopoly models of Karp and Livernois (1992); it turns out that the limit-pricing outcome survives the introduction of stock effects.

Also with stock effects, the ultimately extracted quantity becomes endogenous because extraction can stop before the complete depletion of available reserves: the benefit derived from the last units to be extracted may fall short of too high extraction costs. Thus in principle, more reserves may become economical or uneconomical as a result of a policy. Although the possibility was assumed away by classical papers on the taxation of resource monopolies like Bergstrom et al. (1981) and Karp and Livernois (1992),[26] it is considered an important aspect of climate policy.

A. The model

Assume now that at each date $t \geq 0$ the marginal extraction cost c_t is given by the decreasing function

$$c_t \equiv C_t(Q_t) > 0 \tag{24}$$

of remaining reserves $Q_t \geq 0$. The function C_t is assumed differentiable everywhere.

To consider the possibility that extraction be incomplete, we do away in this section with Assumption 2 that the cost of extraction is always covered by extraction benefits. Absent any taxation policy, the discounted marginal limit-pricing revenue is $(p_t^b - c_t)e^{-rt}$ with $c_t = C_t(Q_t)$, and it may now be negative.

In this context, at any date t when remaining reserves are Q_t, the instantaneous monopoly revenue (17) writes as in Section 3:

$$\pi_t(q, Q_t) = \begin{cases} \left(p_t^b - C_t(Q_t)\right) q, \text{ increasing or decreasing, for } q < D_t(p_t^b) \\ \left(D_t^{-1}(q) - C_t(Q_t)\right) q, \text{ decreasing, for } D_t(p_t^b) \leq q < \overline{D}_t(p_t^o) \\ \left(\overline{D}_t^{-1}(q) - C_t(Q_t)\right) q, \text{ decreasing, for } q \geq \overline{D}_t(p_t^o) \end{cases} . \tag{25}$$

[26] Karp and Livernois (1992) specifically considered the full extraction of reserves, with stock effects: they assumed that all units remain economical despite those effects and despite taxation.

For large supplies that deter the backstop, it remains decreasing by Assumption 1 and Definition 1. However, $\pi_t(q, Q_t)$ may not always be increasing for low supplies $q > D_t(p_t^b)$ that warrant the backstop production. It retains the same form as before, and exhibits the same limit-pricing maximum $D_t(p_t^b) > 0$, only when the limit-pricing marginal revenue $p_t^b - C_t(Q_t)$ positive. Otherwise, extraction is not economical for the monopoly; zero extraction is optimal.

As previously, the monopoly seeks to maximize its intertemporal stream of discounted profits (3) over the free extraction period $[0, T]$ under the exhaustibility constraint (4). At any date $t \geq 0$, its relevant instantaneous objective for the optimal choice of extraction q_t, is the Hamiltonian

$$\mathcal{H}(q_t, Q_t, \lambda_t, t) \equiv \pi_t(q_t, Q_t)e^{-rt} - \lambda_t q_t, \tag{26}$$

where $\lambda_t \geq 0$ denotes the multiplier associated with (4).

As described in Section 2 (see Figure 2), the Hamiltonian admits the same maximum as the instantaneous revenue (25) whenever the discounted marginal profit $\left(p_t^b - C_t(Q_t)\right) e^{-rt}$ is greater than the extraction opportunity cost $\lambda_t \geq 0$. In that case, $\left(p_t^b - C_t(Q_t)\right) e^{-rt} > 0$, so that the optimal extraction is the limit-pricing supply $q_t^m = D_t(p_t^b)$.

In the spirit of Assumption 2, its following alternative assumes that limit-pricing marginal revenue decreases in present value; this is made for simplicity to exclude supply disruption along the exploitation path. Unlike Assumption 2 however, the alternative Assumption 3 considers that extraction may become uneconomical.

Assumption 3 (Uninterrupted incomplete extraction)

The marginal limit-pricing revenue is strictly positive at date 0 *for initial reserves* $Q_0 > 0$*; for all* $t \geq 0$ *and any reserves* $Q_t \geq 0$*, it is continuously decreasing in present-value terms as long as it is positive.*

Thus with no taxation policies, the marginal limit-pricing revenue $\left(p_t^b - C_t(Q_t)\right) e^{-rt}$

is positive at early dates, and decreases continuously with time for two reasons: for unchanged reserves by Assumption 3, and because diminishing reserves as per (4) increase C_t by (24). Yet, unlike Sections 2 and 3, the value λ_t of the scarce resource underground is also decreasing in this context, to reflect that reserves exploited later are more costly: by the maximum principle, $\dot{\lambda}_t = C_t'(Q_t)q_t e^{-rt} < 0$ at each date t when $q_t > 0$ is extracted. Appendix B shows that the marginal limit-pricing revenue $\left(p_t^b - C_t(Q_t)\right) e^{-rt}$ always decreases more rapidly than the opportunity cost λ_t.

As shown in Appendix B, the marginal revenue $p_0^b - C_0(Q_0))$ must initially exceed λ_0. Thus the discounted marginal extraction revenue covers the scarcity value initially and until extraction stops at date T:

$$\left(p_t^b - C_t(Q_t)\right) e^{-rt} \geq \lambda_t, \ \forall t \in [0, T]. \tag{27}$$

All along the exploitation phase $[0, T]$, optimal extraction is thus the limit-pricing extraction $q_t^m = D_t(p_t^b)$ that induces the limit price $p_t^m = p_t^b$.

As far as the optimal terminal date T^m and abandoned reserves Q_{T^m} are concerned, there are two possibilities, as detailed in Appendix B. Consider first that $Q_{T^m} = 0$. In that case, the limit-pricing extraction lasts until reserves are exhausted: T^m is such that

$$\int_0^{T^m} D_t(p_t^b)\, dt = Q_0, \tag{28}$$

as in Section 3. Full exhaustion may only be optimal if the marginal limit-pricing revenue is not becoming negative before the exhaustion date T^m, determined by (28).

Otherwise, the terminal date is such that

$$\left(p_{T^m}^b - C_{T^m}(Q_{T^m})\right) e^{-rT^m} = 0, \tag{29}$$

with

$$Q_{T^m} = Q_0 - \int_0^{T^m} D_t(p_t^b)\, dt. \tag{30}$$

The system jointly determines the date T^m when extraction stops, and abandoned reserves Q_{T^m} at that date, as detailed in Appendix B.

We have the following proposition that summarizes the properties of the limit-pricing equilibrium in the context of this section.

Proposition 6 (Limit-pricing equilibrium with incomplete extraction) *Under the assumptions of this section,*

1. *The monopoly supplies $q_t^m = D_t(p_t^b) > 0$, and so induces the limit price p_t^b that deters the backstop substitute's production, at all dates of the exploitation period $[0, T^m]$;*

2. *Extraction is complete if there exists no date $T > 0$ such that the marginal revenue $p_T^b - C_T(Q_T)$ is nil with $Q_T = Q_0 - \int_0^T D_t(p_t^b)\, dt > 0$: then $Q_{T^m} = 0$ and T^m is given by (28);*

3. *Otherwise, extraction is incomplete: the terminal date T^m and abandoned reserves $Q_{T^m} > 0$ are determined by (29).*

B. Taxation policies

Assume at each date $t \geq 0$, a resource tax $\theta_t > 0$, a backstop subsidy $\gamma_t^b > 0$ and a subsidy (tax) to the ordinary substitute $\gamma_t^o > 0 (< 0)$. In light of the analysis of Section 3, the monopoly's profit at date $t \geq 0$, with reserves $Q_t \geq 0$, writes in that context

$$\pi_t(q, Q_t) = \begin{cases} \left(p_t^b - \gamma_t^b - \theta_t - C_t(Q_t)\right) q, \text{ for } q < \overline{D}_t(p_t^b - \gamma_t^b) - S_t^o(p_t^b - \gamma_t^b + \gamma_t^o) \\ \left(D_t^{-1}(q) - \theta_t - C_t(Q_t)\right) q, \text{ for } \overline{D}_t(p_t^b) - S_t^o(p_t^b + \gamma_t^o) \leq q < \overline{D}_t(p_t^o - \gamma_t^o) \\ \left(\overline{D}_t^{-1}(q) - \theta_t - C_t(Q_t)\right) q, \text{ for } q \geq \overline{D}_t(p_t^o - \gamma_t^o) \end{cases}, \tag{31}$$

which has the same pattern as in (25). By Assumption 1 and Definition 1, the revenue (31) is decreasing for all quantities $q < \overline{D}_t(p_t^o - \gamma_t^o)$ that do not warrant the backstop substitute's production. By Assumption 3, it is increasing for all $q < \overline{D}_t(p_t^b - \gamma_t^b) -$

$S^o_t(p^b_t - \gamma^b_t + \gamma^o_t)$, as long as the marginal revenue $p^b_t - \gamma^b_t - \theta_t - C_t(Q_t) > 0$.[27]

Thus for policies that satisfy Assumption 3 and Definition 1, the same analysis as in absence of policies applies so that the limit-pricing equilibrium realizes as follows. At each date t of the exploitation period $[0, T^m]$, resource extraction becomes

$$q^m_t = \overline{D}_t(p^b_t - \gamma^b_t) - S^o_t(p^b_t - \gamma^b_t + \gamma^o_t), \tag{32}$$

that induces the limit-price $p^m_t = p^b_t - \gamma^b_t$. All along this period, it can easily be verified that the effects of θ_t, γ^b_t and γ^o_t on current extraction q^m_t remain those identified earlier in Propositions 2, 3 and 5.

When the resource is fully exploited, the date at which exploitation ends is such that

$$\int_0^{T^m} \left(\overline{D}_t(p^b_t - \gamma^b_t) - S^o_t(p^b_t - \gamma^b_t + \gamma^o_t)\right) dt = Q_0. \tag{33}$$

Backstop subsidies bring the terminal date forward because they increase current extraction during the exploitation period. In contrast, subsidies to ordinary substitutes reduce current extraction, and so induce a longer depletion.

When the marginal revenue $\left(p^b_T - \gamma^b_T - \theta_T - C_T(Q_T)\right) e^{-rT}$ becomes negative for $Q_T = Q_0 - \int_0^T q^m_t \, dt > 0$, extraction stops at the following terminal date:

$$\left(p^b_{T^m} - \gamma^b_{T^m} - \theta_{T^m} - C_{T^m}(Q_{T^m})\right) e^{-rT^m} = 0 \tag{34}$$

with

$$Q_{T^m} = Q_0 - \int_0^{T^m} \left(\overline{D}_t(p^b_t - \gamma^b_t) - S^o_t(p^b_t - \gamma^b_t + \gamma^o_t)\right) dt. \tag{35}$$

The marginal revenue in (34) is decreasing in the terminal date T^m and increasing in

[27] As for previous sections, Assumption 3 and Definition 1 amount to the following restrictions on the tax instruments under study. The resource tax and the backstop subsidy are not sufficiently high to make extraction uneconomical at early dates, and are not decreasing rapidly enough to make discounted marginal revenue increase. The subsidy to the ordinary substitute is not high enough to destroy the (residual) resource demand.

remaining reserves at that date Q_{T^m}. The remaining reserves in (35) are diminishing with the length of extraction T^m. Other things given, Appendix B shows that the two formulas systematically characterize the terminal date T^m and remaining reserves Q_{T^m}, and can be used to examine the effects of any particular trajectory of tax instruments. It brings up the following general insights about the qualitative effects of policies with limit pricing.

In general, taxation policies may affect the marginal extraction revenue, thus the terminal date and abandoned reserves at that date, in two basic ways. On the one hand, for unchanged remaining reserves Q_{T^m}, policies may deteriorate the marginal extraction revenue in (34) directly. On the other hand, policies that reduce (increase) current extraction q_t^m via (32), increases (decreases) future reserves Q_{T^m} of (35) to be eventually extracted, and so improve (deteriorate) the marginal revenue in (34).

For instance, since resource taxes do not affect current extraction (32) over the exploitation phase, they only bring the terminal date backward because they make extraction less profitable as per (34). Resource taxes unambiguously reduce ultimately extracted reserves in that context.

In contrast, for unchanged reserves, subsidies to ordinary substitutes do not affect directly the profitability of extraction in (34). As they reduce current extraction (32) along the exploitation phase, it takes longer to reach remaining reserves (35) that make extraction uneconomical as per (34). Yet since extraction is less profitable over time, a later terminal date implies larger uneconomical (abandoned) reserves.

Backstop subsidies induce extraction (32) to increase along the exploitation phase, and thus contribute to greater extraction costs. Simultaneously, for unchanged reserves, they make extraction less profitable in (34). For these two reasons, backstop subsidies bring the terminal date backward. Yet they imply a lower extraction over a shorter period and thus have an ambiguous effect on ultimately extracted quantities.

We thus have the following results when extraction is incomplete.

Proposition 7 (Effect of policies with incomplete extraction)

When extraction is incomplete,

1. *Resource taxes shorten the extraction period and reduce the ultimately extracted quantity;*

2. *Subsidies to the backstop substitute shorten the extraction period but have an ambiguous effect on the ultimately extracted quantity;*

3. *Subsidies to the ordinary substitute extend the extraction period, but reduce the ultimately extracted quantity;*

As a result, the carbon tax has the following effect.

Corollary 2 *The combination of a resource tax, with a tax on the ordinary substitute,*

1. *Shortens the extraction period;*

2. *Affects the ultimately extracted quantity ambiguously.*

Indeed in light of Proposition 6, a resource tax and a tax on the ordinary substitute both contribute to shorten the extraction period. A resource tax alone thus reduces the cumulative extraction; yet an ordinary-substitute tax tends to increase resource extraction at each date of the shorter extraction period.

V. Discussion: market structure, reserves' production, demand segmentation...

This paper points at the empirical relevance of limit-pricing equilibria for the oil market and shows that the effects of environmental taxation instruments in such context differ from most conventional studies. In particular, taxes applied to flows of resources, when they warrant no supply disruption, are ineffective regardless of their time dynamics. As far as subsidies to oil substitutes are concerned, it is fundamental to make a distinction between two sorts of substitutes. On the one hand, limit pricing deters the entry of drastic substitution possibilities. Subsidies to a backstop substitute induce equilibrium extraction quantities to increase. On the other hand, currently used substitutes to oil – we called them ordinary – offer less drastic substitution possibilities that are compatible with limit pricing. Unlike the backstop, subsidies to any currently in-use substitutes do reduce current extraction quantities by an amount that depends on their respective elasticity of supply.

While we have restricted attention to a single ordinary substitute for simplicity, extension to several such substitutes is immediate. Since the effect of subsidies depends on the supply elasticity of the substitute, the objective of reducing carbon-resource extraction quantities in a cost-efficient manner may imply selecting non-carbon substitutes on the grounds of their supply elasticity; an issue that is beyond the scope of the present work.

The existing literature has mentioned limit-pricing equilibria of non-renewable-resource monopolies in the simple model of Section 2: substitution possibilities are summarized with a backstop technology and the resource is entirely exhausted. Section 3 refined the description of substitution possibilities, while Section 4 considered incomplete resource exhaustion. Those extensions proved to deliver a sharply different message on the incidence of taxation policies. Yet, our results have been obtained in a relatively parsimonious model; one may question whether limit-pricing equilibria survive more complex setups. In the sequel, we discuss various aspects of the oil market.

A. Competitive fringe

The actual industrial structure of the oil market differs from the frequently-used monopoly model. The OPEC cartel controls the vast majority of oil reserves; yet non-OPEC reserves yield a substantial fraction of current oil production.[28] Thus a better representation of the market power exerted in the oil production sector must assume that a competitive fringe limits the power of the dominant extractor as in the model initiated by Salant (1976).[29]

The resource produced by a competitive fringe is analogous to a competitively-supplied

[28] See Footnote 2 for more details.

[29] Issues about the coordination within the OPEC cartel are out of the scope of this discussion. See for instance Griffin (1985).

perfect substitute to the monopoly of Section 3. The residual demand that the monopoly is facing is that fraction of the total oil demand that exceeds the fringe's production. Because of reserve limitations, the supply of non-OPEC oil cannot be so elastic. As will be shortly argued, it is sensible to consider that Definition 1 of ordinary substitutes applies to the fringe's production – thus Assumption 1 is satisfied –, so that the limit-pricing analysis of Sections 3 and 4 carries over unchanged: our results become relevant to the current structure of the oil market.

Has the residual demand the OPEC cartel is facing a lower than one price elasticity, as per (11)? When the substitute to the cartel's resource is the fringe's oil, formula (11) applies where x is the fringe's extraction and $e = q + x$ is the total oil production:

$$\xi_{Dt}(q) = \frac{\xi_{\overline{D}t}(e)}{q/e} + \frac{x/e}{q/e}\xi_{S^o t}(x) < 1 \tag{36}$$

gives the residual oil demand elasticity, as the weighted sum between the elasticity of the total oil demand $\xi_{\overline{D}t}(e)$ and that of the fringe's supply $\xi_{S^o t}(x)$; q/e and x/e are respectively the market shares of the cartel and the fringe.

Market shares are currently $q/e = 0.4$ and $x/e = 0.6$. For the price elasticity of the total oil demand, the value used in Hamilton (2009b) is 0.25, in line with Krichene's (2005) long-run estimate for the period 1974-2004. Hamilton (2009b, Page 192) argues that this elasticity should be expected to be even smaller. Taking these values, (36) holds for any elasticity of the fringe's supply $\xi_{S^o t}(x)$ lower than 0.25. For instance, Lin's (2014) recent estimate (0.24) of the non-OPEC supply elasticity is compatible with that condition.[30] Yet testing Assumption 1 for OPEC requires that the estimate be based on a limit-pricing model; this calls for further empirical research.

[30]Taking her own estimate of the elasticity of the total demand for oil (0.005), Condition (36) would hold for any elasticity of the fringe's supply lower than 0.66.

B. *Reserves' production*

Section 4 assumes heterogenous reserves whose extraction cost rises as extraction goes. In that context, extraction may become uneconomical before reserves are completely depleted, so that in general taxation policies affect the exploitation duration, and the ultimately extracted quantity.

Another reason why policies may affect the ultimately exploited resource is that they discourage exploration and development efforts by which reserves become exploitable. In Appendix C, we borrow the approach of Gaudet and Lasserre (1988), also used for instance in Fischer and Laxminarayan (2005) or Daubanes and Lasserre (2012). In these models, the marginal cost of developing an amount of exploitable reserves is rising, as when resource units are developed in order of their respective development costs; reserves are established so as to equate the marginal development cost to the implicit value of marginal reserves. This extension does not modify the limit-pricing outcome and the policies' effect on ultimately developed and exploited quantities mentioned above.

C. *Multiple demand segments with various degrees of substitutability*

It is standard to rely on a unique continuous function to describe the heterogeneity of the aggregate demand. Yet in reality, the oil demand is segmented. Segments mainly correspond to different uses of the resource (e.g. Hoel, 1984), and to different regions.

One particular resource use in one particular region can be represented by a particular demand function of a form similar to the demand of Section 3. Resource uses and regions may differ by their accessible possibility of substitution as well as by their regulation.

One can also consider substitutes to vary by their degree of substitutability with the resource. On the one hand, as imperfect substitutes only become profitable beyond a certain resource price, they introduce kinks to the oil demand as in Sections 3 and 4. On the other hand, imperfect substitutability amounts to a broader interpretation of the demand elasticity. On each segment, the sensitiveness of the resource demand at some resource price jointly reflects the elasticity of supply and the degree of substitutability of resource substitutes that are profitable at that price.

Limit pricing in that context intuitively arises from the entry threat of sufficiently substitutable alternative sources, on large enough demand segments. For instance, in the interview mentioned in Footnote 5, the energy industry analyst Stephen Schork later clarified OPEC's "main concern" (CNBC on August 16, 2010): the "shift of the sentiment in the U.S. *especially* towards alternative fuels." [our italics].

D. Interpretation of the limit price

The limit price may also be interpreted more broadly than the entry price of a (backstop) substitute that offers drastic substitution possibilities. In Gerlagh and Liski (2011), the backstop substitute needs to be developed: the falling limit price induced by the strategic oil producer is the price beyond which the costly development of the backstop substitute is irreversibly triggered, which destroys the oil demand after some lag.

Gerlagh-Liski equilibrium results from strategic interactions which are absent here. But one may borrow from their analysis a reinterpretation of the limit price as the price level beyond which a sufficiently drastic threat to the monopoly's profits would be carried out.

A Appendix to Sections 2 and 3: The Simple Stationary Case

This appendix makes the analysis of Section 2 in the stationary model of Hoel (1978), Salant (1979), Dasgupta and Heal (1979) and Newberry (1981).

Assume that the resource marginal extraction cost c and the backstop marginal production cost p^b are constant with $p^b > c$. The total energy demand $\overline{D}(p)$ is stationary, and satisfies Assumption 1.

At each date t when there is some resource left to be exploited, the monopoly's instantaneous profit writes

$$\pi(q) = \begin{cases} (p^b - c)q, \text{ increasing, for } q \leq \overline{D}(p^b) \\ \big(\overline{D}^{-1}(q) - c\big)q, \text{ decreasing, for } q > \overline{D}(p^b) \end{cases}, \tag{37}$$

and is maximized by the supply $\overline{D}(p^b)$ which induces the limit price p^b that deters the backstop.

The intertemporal problem of maximizing the discounted stream of profits (3) under the exhaustibility constraint (4) implies the Hamiltonian function (5), where the scarcity value λ is constant. All along the extraction period $[0, T]$, the Hamiltonian is maximized by the same supply level $q^m = \overline{D}(p^b)$ that maximizes the instantaneous profit.

Thus the maximized Hamiltonian

$$\mathcal{H}(q^m, Q_t, \lambda, t) \equiv (p^b - c)q^m e^{-rt} - \lambda q^m \tag{38}$$

is decreasing because profits are discounted at rate $r > 0$; in the stationary case, Assumption 2 is not required. It can easily be verified that the maximized Hamiltonian is initially positive because $p^b > c$ so that extraction is warranted. Also, one can verify that λ is strictly positive so that the exhaustibility constraint is not violated. Thus the resource is completely exhausted. At each date of the extraction period $[0, T^m]$, extraction is q^m, so that exhaustion occurs at the terminal date $T^m = Q_0/q^m$.

Since the duration of the exploitation period is free, the Hamiltonian should become zero at date T^m. This characterizes the scarcity value λ under limit pricing: $\lambda = (p^b - c)e^{-r(Q_0/q^m)}$, with $q^m = \overline{D}(p^b)$.

Effect of a constant resource tax

Assume a constant tax on the resource $\theta > 0$ that warrants positive extraction profits: $\theta < p^b - c$. The producer price of the resource is reduced by θ, regardless of whether consumers are ready to pay $\overline{D}^{-1}(q)$ or p^b, as when the backstop is profitable.

Thus the instantaneous monopoly's profit becomes

$$\pi(q) = \begin{cases} (p^b - \theta - c)q, \text{ increasing, for } q \leq \overline{D}(p^b) \\ \big(\overline{D}^{-1}(q) - \theta - c\big)q, \text{ decreasing, for } q > \overline{D}(p^b) \end{cases}. \tag{39}$$

The same analysis as in absence applies, to the extent that c is replaced by $c+\theta$. The limit-pricing equilibrium is not modified: it implies an unchanged extraction level $q^m = \overline{D}(p^b)$ at each date preceding $T^m = Q_0/q^m$.

Effect of a constant backstop subsidy

Assume a constant subsidy to the backstop $\gamma^b > 0$. The price at which the backstop is profitable becomes $p^b - \gamma^b$ instead of p^b. Further assume that the backstop subsidy warrants positive extraction profit: $p^b - \gamma^b > c$. Then, the instantaneous profit of the monopoly writes

$$\pi(q) = \begin{cases} (p^b - \gamma^b - c)q, \text{ increasing, for } q \leq \overline{D}(p^b - \gamma^b) \\ \big(\overline{D}^{-1}(q) - c\big)q, \text{ decreasing, for } q > \overline{D}(p^b - \gamma^b) \end{cases}, \tag{40}$$

and the same analysis as in absence of policies applies with $p^b - \gamma^b$. The limit-pricing equilibrium is thus modified. All along the extraction period, the monopoly's extraction is $q^m = \overline{D}(p^b - \gamma^b)$, which is greater than $\overline{D}(p^b)$ in absence of subsidies. The resource is exhausted earlier, at the terminal date $T^m = Q_0/\overline{D}(p^b - \gamma^b)$.

Ordinary substitute

Assume that the demand the monopoly is facing is reduced by a constant amount S^o, exogenous, of a perfect substitute to the resource. unlike the backstop, assume that this amount is limited so that it falls short of the monopoly's total demand: $S^o < \overline{D}(p^b)$. In that case, the limit-pricing extraction is modified as follows.

For any monopoly's supply q that deters the backstop, the resource price p is established in such a way that $q = \overline{D}(p) - S^o$. Therefore, the supply that induces the limit price p^b is reduced to $\overline{D}(p^b) - S^o$ instead of $\overline{D}(p^b)$. Also, the inverse demand for the resource is reduced to $\overline{D}^{-1}(q - S^o)$.

Thus the monopoly's instantaneous profit becomes:

$$\pi(q) = \begin{cases} (p^b - c)q, \text{ increasing, for } q \leq \overline{D}(p^b) - S^o \\ \big(\overline{D}^{-1}(q - S^o) - c\big)q, \text{ decreasing, for } q > \overline{D}(p^b) - S^o \end{cases}, \tag{41}$$

which leads to the same dynamic analysis as before. The limit-pricing equilibrium realizes, with constant extraction $q^m = \overline{D}(p^b) - S^o$ until the exhaustion date $T^m = Q_0/\left(\overline{D}(p^b) - S^o\right)$.

B Appendix to Section 4: Elements of Proofs

The results of Section 4 are mostly shown in the main text. The main text also refers to the following elements.

Limit-pricing marginal revenue and scarcity value

The limit-pricing marginal revenue, in present value terms, decreases more rapidly than the multiplier λ_t; this can be shown as follows.

At any date t, when remaining reserves are Q_t and extraction is $q_t \geq 0$, the derivative of $\left(p_t^b - C_t(Q_t)\right)\right) e^{-rt}$ with respect to time yields

$$\frac{d\left(\left(p_t^b - C_t(Q_t)\right) e^{-rt}\right)}{dt} = \left[\frac{d\left(p_t^b - C_t(Q_t)\right)}{dt} - r\left(p_t^b - C_t(Q_t)\right)\right] e^{-rt} + C_t'(Q_t) q_t e^{-rt} \leq 0,$$

where the first term between brackets is the increase in the discounted marginal revenue for given reserves. By Assumption 3, it is negative or zero. The second term $C_t'(Q_t)q_t e^{-rt}$ corresponds to the decrease in the marginal revenue that arises because reserves diminish. It is strictly negative when extraction is non zero, and zero otherwise.

By the maximum principle, the latter term is also the time derivative of λ_t:

$$\dot{\lambda}_t = -\frac{\partial \mathcal{H}(q_t, Q_t, \lambda_t, t)}{\partial Q_t} = C_t'(Q_t) q_t e^{-rt} \leq 0.$$

It follows that

$$\frac{d\left(\left(p_t^b - C_t(Q_t)\right) e^{-rt}\right)}{dt} \leq \dot{\lambda}_t \leq 0.$$

Extraction at date 0

Consider, as a statement to be contradicted, that $\lambda_0 < p_0^b - C_0(Q_0))$. Since the marginal revenue is decreasing more rapidly than $\lambda_t \geq 0$, then $\left(p_t^b - C_t(Q_t)\right) e^{-rt} \leq \lambda_t$, for all $t \geq 0$, where the equality may only hold as $\left(p_t^b - C_t(Q_t)\right) e^{-rt} = \lambda_t = 0$; some extraction may be optimal in that case, but for no profit at all. Clearly, this is dominated by some extraction at initial dates since by Assumption 3, $p_0^b - C_0(Q_0)) > 0$.

Terminal date and ultimately unexploited reserves

Since the terminal date T when extraction stops is free, the Hamiltonian (26), the relevant flow of extraction benefits, must be zero at that date. The standard transversality condition

$$\left(p_T^b - C_T(Q_T)\right) e^{-rT} = \lambda_T \tag{42}$$

applies.

Also at the terminal date T, reserves left unexploited must be non-negative by constraint (4):

$$Q_T \geq 0. \tag{43}$$

Therefore, another standard transversality condition must be satisfied, by which

$$\lambda_T Q_T = 0. \tag{44}$$

Hence two possibilities. Consider first that $Q_{T^m} = 0$. In that case, the limit-pricing extraction lasts until reserves are exhausted, so that T^m is characterized by (28).

Second, consider that $Q_{T^m} > 0$ because the extraction of the last units is uneconomical. By (44), this can only be compatible with reserves having no more value at the terminal date T^m: $\lambda_{T^m} = 0$. In this case, the terminal date T^m must satisfy

$$\left(p_T^b - C_T(Q_T)\right) e^{-rT} = 0, \tag{45}$$

with

$$Q_T = Q_0 - \int_0^T D_t(p_t^b)\, dt; \tag{46}$$

a system that will turn out to uniquely characterize the terminal date T^m and abandoned reserves Q_{T^m}: hence (29) and (30).

We analyze this system now. By Assumption 3, the marginal revenue in (45) is initially positive for low T when Q_T is close to Q_0 by (46). If T does not exist such that, together with Q_T in (46), it implies the marginal revenue in (45) to take a zero value, then extraction continues until $Q_T = 0$. In that case, $Q_{T^m} = 0$ is solution as in the first possibility; T^m is given by (28), and the analysis is similar to that of Section 3 with complete exhaustion.

Thus the analysis of Section 4 is most interesting in the second possibility, when T exists such that $Q_T > 0$ in (46) and T jointly satisfy (45). In this case, the solution is obviously unique since the marginal revenue in the left-hand side of (45) is strictly decreasing with T and Q_T. Precisely, it is decreasing in T for a given Q_T, and strictly decreasing when it is taken into account that an increase in T goes hand in hand with a decrease in Q_T as per (46).

Focus now on that unique interior solution when it exists. For that, it will be useful to consider T and Q_T as two variables that separately affect (45); the effect of T and Q_T being encompassed in (46). In (45), the discounted marginal revenue in the left-hand side is decreasing in T and increasing with Q_T. Thus the equation defines a positive relationship between T and Q_T, that we denote with the following function:

$$T = T_1(Q_T), \text{ increasing.} \tag{47}$$

According to (46), a greater Q_T is associated with a shorter extraction period that lasts until a lower T. This defines a negative relationship between, represented by the function

$$T = T_2(Q_T), \text{ decreasing.} \tag{48}$$

The intersection of the T_1 and T_2 relations defines either the unique interior solution (Q_{T^m}, T^m) given by (29) and (30) when they cross at the right of the $Q_T = 0$ vertical axis

($Q_{T^m} > 0$), or the complete-exhaustion solution $Q_{T^m} = 0$ earlier mentioned otherwise. The graphical representation of Figure 6 is particularly useful to identify how this solution modifies with parametric policy changes.

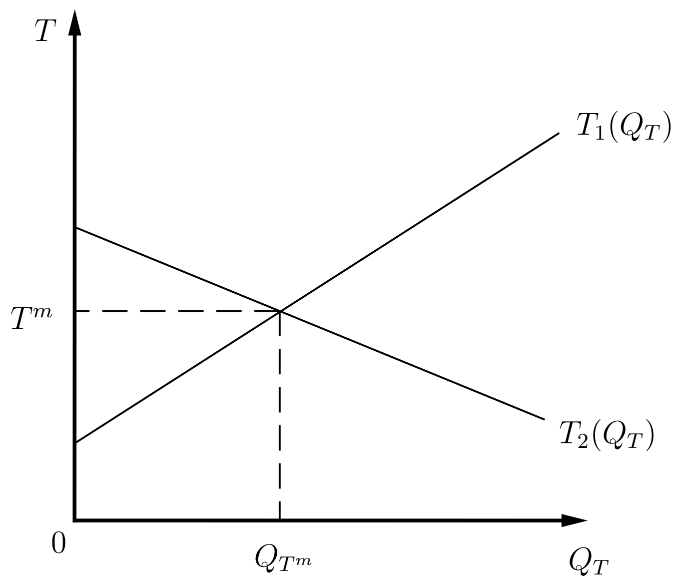

Figure 6: Graphical characterization of T^m and Q_{T^m}

Effects of policies with incomplete extraction

The taxation policies in Section 4 are considered to satisfy Assumptions 1 and 3. In that context, the terminal date T^m and the ultimately abandoned reserves Q_{T^m} are characterized by (34) and (35), instead of (29) and (30). Under the same assumptions, the same analysis applies as in absence of policies: (34) and (35) can be represented with the T_1 and T_2 functions of (47) and (48), except that these functions now depend on policy parameters that enter (34) and (35).

We focus on the effects of taxation policies on the interior solution depicted in Figure 6. When the solution implies complete exhaustion, the analysis is the same as in Section 3 and is only concerned with the effects on current extraction levels over the exploitation period; effects on the length of this period are obvious. In what follows we derive results exposed in Section 4 by shifting the T_1 and T_2 curves of Figure 6 whose intersection characterizes Q_{T^m} and T^m in the limit-pricing equilibrium.

A tax $\theta_t > 0$, $\forall t \geq 0$, only affects (34). For given reserves Q_T, it brings backward the date T when the (tax-inclusive) marginal revenue becomes zero. Thus a rise in the tax amounts to shifting down the T_1 curve: it implies extraction until a lower T^m, and greater abandoned reserves Q_{T^m}.

A subsidy to the ordinary substitute $\gamma_t^o > 0$, $\forall t \geq 0$, only affects (35). For given terminal reserves Q_T, it brings forward the terminal date T at which those reserves will be left. Thus a rise in the subsidy amounts to shifting up the T_2 curve: it implies extraction until a later T^m, and greater abandoned reserves Q_{T^m}. The opposite result is obviously obtained for a tax $\gamma_t^o < 0$, $\forall t \geq 0$.

A subsidy to the backstop substitute $\gamma_t^b > 0$, $\forall t \geq 0$, enters both (34) and (35). On the one hand, for given reserves Q_T, the subsidy brings backward the date T when the marginal revenue in (34) becomes zero; a subsidy rise amounts to shifting down the T_1 curve. On the other hand, for given abandoned reserves Q_T, the subsidy reduces the date T when those reserves will be reached in (35); a subsidy rise amounts to shifting down the T_2 curve. Those two changes in Figure 6 implies that subsidies to the backstop substitute implies a shorter extraction period, i.e. until a lower T^m. Yet they have an ambiguous effect on the ultimately extracted quantity over that period, and thus on abandoned reserves Q_{T^m}.

These results are summarized in Proposition 7, which also yields Corollary 2.

C Appendix to Section 4: Costly Exploration and Development Efforts

In the context of Section 4, consider that reserves $Q_0 - Q_{T^m}$ to be exploited arise from costly exploration and development efforts. Following Gaudet and Lasserre (1988), assume that the production of those reserves occurs at date 0 and is subject to decreasing returns because, as exploration prospects are finite, it must be more and more difficult to produce new reserves. When reserves' production is costly, it cannot be optimum to produce more than what is to be exploited. Formally, the cost of producing $Q_0 - Q_{T^m}$ is given by the increasing and strictly convex function $E(Q_0 - Q_{T^m})$. Let us further assume that $E'(0) = 0$ so as to avoid the uninteresting situation where those costs induce the monopoly to produce no reserves at all.

The objective (3) of the monopoly now incorporates the reserve development function E. Thus the monopoly's problem is

$$\max_{(Q_0 - Q_T),(q_t)_{t\geq 0}} \int_0^T \pi_t(q_t, Q_t)e^{-rt}\, dt - E(Q_0 - Q_T), \tag{49}$$

subject to (4), where T is a free variable.

Despite this modification of the objective, the Hamiltonian associated with the above problem is the same as in Section 4, given by (26). The integration of reserves production into the monopoly's problem affects neither the analysis of the limit-pricing exploitation phase, nor the transversality condition (42), but the transversality condition associated with the non-negativity constraint (43).

Specifically, condition (44) is modified as follows. Q_0 may be entirely developed and completely exhausted as before and $Q_T = 0$ if development and extraction costs make it profitable. Such is compatible with the marginal reserve production cost being lower than the implicit value of marginal reserves: $E'(Q_0) \leq \lambda_T$. Yet when reserves are not completely developed and extracted, Q_T is strictly positive, and the implicit value of marginal reserves λ_T, instead of being equalized to zero as in absence of reserve production cost, is equalized to the the marginal cost $E'(Q_0 - Q_T)$. The transversality condition associated with the non-negativity constraint (43) becomes

$$Q_T\left(\lambda_T - E'(Q_0 - Q_T)\right) = 0. \tag{50}$$

When $Q_T = 0$, things go as in absence of reserve development efforts; no adjustment to Section 4 is needed. When $Q_T > 0$, the condition tells that instead of a zero value as in Section 4, λ_T equals the positive marginal cost of reserve production:

$$\lambda_T = E'(Q_0 - Q_T).$$

Thus condition (42) yields, instead of (29),

$$\left(p^b_{T^m} - C_{T^m}(Q_{T^m})\right) e^{-rT^m} - E'(Q_0 - Q_{T^m}) = 0, \tag{51}$$

where Q_{T^m} is still given by (30).

In that case, (51) and (30) form the system that uniquely characterizes the terminal date T^m and abandoned reserves Q_{T^m}. Since the left-hand side of (51) is increasing with Q_{T^m} as in (29), the new system retains the same properties as in the analysis of Section 4. Also, the system (51)-(30) only differ from (29)-(30) by the marginal development cost term $E'(Q_0 - Q_T)$. Since this term is not directly affected by the taxation policies considered in this paper, the interested reader can easily verify that the policies' effects established in Section 4 carry over to the case of this appendix.

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