Helsinki Center of Economic Research

Discussion Papers

Strategic resource dependence

Reyer Gerlagh
University of Manchester

and

Matti Liski
Helsinki School of Economics, HECER and MIT-CEEPR

Discussion Paper No. 224
June 2008

ISSN 1795-0562

HECER – Helsinki Center of Economic Research, P.O. Box 17 (Arkadiankatu 7), FI-00014
University of Helsinki, FINLAND, Tel +358-9-191-28780, Fax +358-9-191-28781,
E-mail info-hecer@helsinki.fi, Internet www.hecer.fi

HECER
Discussion Paper No. 224

Strategic resource dependence*

Abstract

We consider a situation where an exhaustible-resource seller faces demand from a buyer who has a substitute but there is a time-to-build delay for the substitute. We find that in this simple framework the basic implications of the Hotelling model (1931) are reversed: over time the stock declines but supplies increase up to the point where the buyer decides to switch. Under such a threat of demand change, the supply does not reflect the current resource scarcity but it compensates the buyer for delaying the transition to the substitute. The analysis suggests a perspective on costs of oil dependence.

JEL Classification: D4; D9; O33; Q40

Keywords: dynamic bilateral monopoly, Markov-perfect equilibrium, depletable resources, energy, alternative fuels, oil dependence

Matti Liski

Department of Economics
Helsinki School of Economics
P.O. Box 1210
00101 Helsinki
FINLAND

e-mail: liski@hse.fi

Reyer Gerlagh

Department of Economics
School of Social Sciences
University of Manchester
Oxford Road, M13 9PL Manchester
UNITED KINGDOM

e-mail: reyer.gerlagh@manchester.ac.uk

* This paper is a simplified version of our working paper “Strategic oil dependence”. This research was initiated at the Center for Advanced Studies (CAS) in Oslo 2005-2006. We thank CAS for generous support and Michael Hoel in particular for indispensable insights to the problem. We also thank Brita Bye, Markus Haavio, Markus Herrmann, Juuso Välimäki, and seminar participants at U. of Birmingham, Catholic U. of Chile, NEMIEC-Island, HECER-Helsinki, U. of Manchester, U. of Toulouse, and U. of Stirling for valuable comments. Liski is grateful for funding from Academy of Finland and Nordic Energy Research.

1 Introduction

Policies such as fuel taxes, technology programs, or even international agreements on pollution emissions reductions are likely to entail a demand change in some important exhaustible-resource markets. When resource sellers are strategic, they have an incentive to distort these policies to their own advantage, potentially leading to an increased dependence on the resource. To understand the seller side effort to distort the adoption of demand-changing policies, we consider a simple framework where a monopolistic seller (or a group of sellers coordinating actions) of an exhaustible resource faces demand from a buyer (or a group of buyers coordinating actions) who has a substitute but there is a time-to-build delay for the substitute. We find that in this framework the basic implications of the Hotelling model (1931) are reversed: over time the resource stock declines but supplies increase, rather than decrease, up to the point where the buyer decides to initiate the transition to the substitute. Under such a threat of change in the demand infrastructure, the supply today does not reflect the true resource scarcity, but it seeks to postpone the buyer's decision by compensating for the future scarcity felt during the transition time to the substitute when the buyer is still dependent on the resource.

Our research builds on Hotelling's theory of exhaustible-resource consumption (1931), Nordhaus' (1973) concept of a backstop technology,[1] and the extensive literature on strategic equilibria in resource economics. Our main addition to the standard framework for analysis is the inclusion of a time-to-build delay for the backstop. Previous literature closest to our approach can be divided on the assumptions made for the strategic variable on the buyer side.[2] First, there is a large literature on optimal tariffs in depletable-resource markets showing how coordinated action on the buyer side can be

[1]Nordhaus (1973) was the first to define and analyze the concept of backstop technology in exhaustible-resource markets. He defined it as follows: "The concept that is relevant to this problem is the *backstop technology*, a set of processes that (1) is capable of meeting the demand requirements and (2) has a virtually infinite resource base" (Nordhaus, 1973, pp. 547-548).

[2]There is a large but less closely related literature focusing purely on seller power in the exhaustible-resource framework. Hotelling himself (1931) already analyzed the monopoly case. Salant (1976) considered an oligopolistic market structure with one dominant firm, and Lewis and Schmalensee (1980) analyzed an oligopoly where all firms have some market power. This literature has developed on two frontiers. First, it has focused on developing less restrictive production strategies: from path strategies as in Lewis and Schmalensee, Loury (1986) and Polansky (1992), to decision rule strategies as, for example, in Salo and Tahvonen (2001). Second, the literature has developed more natural cost concepts for extraction under which the resource is economically rather than physically depleted. See Salo and Tahvonen (2001) for a discussion and contribution on this.

used to decrease the seller's resource rent (e.g., Newbery, 1983, Maskin and Newbery, 1990; see Karp and Newbery 1993 for a review). Hörner and Kamien (2004) provide a general view on these models by showing that the problem faced by a monopsonistic exhaustible-resource buyer is formally equivalent to that faced by a Coasian durable-good monopoly. We depart from the Coasian framework because the buyer is not a pure monopsony and has a different strategic variable (the substitute). While import tariffs and fuel taxes are important, they are more flexible instruments as compared to the development or adoption of substitute technologies that have a permanent effect on the resource dependence. The latter thus creates potentially greater or at least very different strategic threats to the seller. To be effective, optimal tariffs have to be successful in changing the dynamic demand perceived by the seller. The degree of success obviously depends on the precise formulation of the game, but generally the seller's sales path still follows a Hotelling rule modified to take into account the buyers' tariff policy. This leads to supplies declining over time. We believe that the technology threat potentially is a more important determinant of how sellers perceive their future demand.

Second, there is a large but somewhat dated literature on the same bilateral monopoly situation where the buyers' strategic variable is to develop or adopt a substitute technology. Early papers such as Dasgupta *et al.* (1983), Gallini *et al.* (1983), and Hoel (1983) assume the buyer exploits a Stackelberg leadership and can commit to a deterministic R&D program for the development of the substitute. The results provide interesting insights into how the buyer side can extract the seller's rent by altering the timing of sales. Later developments analyzed the role of leadership and commitment (Lewis *et al.*, 1986) and, finally, probabilistic success in R&D and Markov-perfect strategies (Harris and Vickers, 1995). None of the above papers predict that the basic Hotelling implications are reversed, although Harris and Vickers (1995) obtain a result that sales path may be non-monotonic (but not generically increasing).[3]

The market structure we describe is such that not only sellers have market power but also buyers enjoy some power so that no party is in explicit leadership. The nature of the strategic interaction between buyers and sellers is preserved in the limiting case without discounting, which allows an essentially static analysis and it shows the way to analyze

[3]It should be clear that we are focusing on how strategic relationships in the resource market shape the supplies. There are also other ways to explain the failure of the standard Hotelling model (see Dasgupta and Heal (1974) for the standard model), or its extensions, to match reality (see Krautkramer (1999) for a review of the literature). And there are other ways to extend the traditional economic growth-resource depletion model such that supplies increase over time (cf. Tahvonen and Salo 2001).

the discounted case. Moreover, in addition to market structure assumptions, we depart from previous literature in that we abstract from the precise instrument implementing the structural change in demand: when action is taken, it changes the demand irreversibly after a time lag. This abstraction simplifies the strategic variable on the buyer side while keeping what seems essential in the relationship.

The structure of the paper is the following. In Section 2, we discuss some developments in the oil market that motivate our study. In Section 3, we introduce the basic resource allocation problem by considering the social optimum, consumers' optimum, and also by having a first look at the equilibrium. In Section 4, we introduce and analyze the game without discounting. In Section 5, we investigate the changes to equilibrium and robustness of overall findings under discounting. In Section 6, we conclude by discussing alternative approaches to the problem and potential implications for the oil market.

2 Motivating example: the market for cheap oil

Our contribution is to the basic exhaustible-resource theory but we are motivated by some recent developments affecting the oil market. First, while there is no single buyer in the oil market, policies aiming to reduce dependence on imported oil imply a collective action on the consumer side. Whatever the reason for policies – need to safeguard the economy against macroeconomic risks or perhaps global warming – they are likely to affect how oil producers perceive their future demand, influencing supplies today.[4] The results suggest that, under such a threat of structural change in oil demand, the true resource scarcity cannot be read from the current supply.

Second, while it is clear that the world will never run out of all fossil fuel sources, it is equally clear that we may run out of conventional, cheap oil. The ownership of the cheapest oil reserve is extremely concentrated by any measure and concentration is expected to increase in the near future.[5] The concentration of ownership implies that strategic management of the cheap oil stocks is likely even without a formal cartel among producers. Cheap oil producers understand their influence on market development and take an active role in "demand management"; they often communicate like central

[4]The Stern Review on the Economics of Climate Change (2006), while being a very comprehensive cost-benefit analysis, is also a political document illustrating the willingness to take actions changing the demand for fossil-fuels.

[5]See the "2007 Medium-Term Oil Market Report" published by the International Energy Agency for estimates of the Core OPEC reserves. The Saudi share of the Core OPEC stocks is expected to increase over time.

bankers with the market, emphasizing credibility and security of supply.[6] The resource that, for example, Saudi Arabia is controlling is unique in that it allows extraction of high quality output with relatively little capital investment. It also allows for rapid and large production rate changes. Reserves with such properties are at the heart of the economics of the oil dependence because, roughly put, the remainder of the fossil fuel supply is capital intensive and costly when used for the production of liquid fuels. In fact, what is essential for the strategic interaction that we consider is the existence of a low-cost but finite reserve with concentrated ownership and inelastic short-run demand; the rest of 'oil' production can be seen as part of substitute fuel production, including costly conventional oil sources, nonconventional oils, biofuels, and alternative energy sources.[7]

While the relationship between major oil importers and exporters is clearly not an open bargaining situation, as explicit contracts are not conceivable in the context, it has a flavor of bargaining taking place through markets where offers and responses are implicit. Sellers' focus on secure supply suggests a compensation to the importing party for continuing potentially costly dependence. On the buyer side, trust in the relationship is expressed by voluntary inaction, that is, postponement of actions changing the demand structure. Our timing assumptions for strategies are perhaps better suited for capturing what is material in this kind of relationship than those used in earlier literature.

3 The resource allocation problem

3.1 Socially optimal resource dependence

Before going to strategic interactions, we start the analysis by looking at socially optimal resource use. This way we will introduce the basic elements of the model and provide a benchmark so that distortions introduced by strategic interactions become clear. Throughout we assume that time is continuous.

Consider an economy starting at time $t = 0$ with a finite resource endowment s_0

[6] The following citation describes this: "We've got almost 30 percent of the world's oil. For us, the objective is to assure that oil remains an economically competitive source of energy. Oil prices that are too high reduce demand growth for oil and encourage the development of alternative energy sources" (Adel al-Jubeir, foreign policy adviser of crown prince Abdullah of Saudi Arabia, Herald Tribune, Jan 24, 2007).

[7] There are different definitions of conventional and nonconventional oils, and these also change over time; see the Hirsch Report (prepared for the U.S. Department of Energy, 2005). The report makes clear that the important scarcity is in the reserves of high-quality conventional oil.

that can be consumed at rate q_t yielding a strictly concave utility $\widetilde{u}(q_t)$. We assume no extraction costs. The resource has a substitute that provides the same service and ends the need to use the resource. The economy can choose to adopt the substitute by paying one-time cost $I > 0$ at any t, and then wait for interval of time k, so that the alternative supply infrastructure arrives at time $t + k$ and provides a surplus flow $\bar{u}$ to consumers thereafter. Thus, after the time-to-build delay, the substitute fully replaces the resource: by assumption, the resource is not needed after the change. We can relax this assumption, without changing the main result, by letting the resource compete with the substitute, or by making the change gradual and uncertain. We discuss these extensions after the main model, and ask now the following simple question: how much of the resource should be used before actions are taken, and how much should be left for the transition time interval towards the substitute?

To describe the social optimum, it is useful to treat the interval of time over which there is some resource consumption as an excursion from the long-run situation where the substitute is present and consumers enjoy surplus $\bar{u}$ per time unit. The consumer price is $p_t = \psi(q_t) = \widetilde{u}'(q_t)$, and demand is subsequently defined by $q_t = D(p_t) = \psi^{-1}(p_t)$. For interpretation, we can assume cost flow c for maintaining the alternative supply infrastructure and define the long-run surplus flow as

$$\bar{u} = \widetilde{u}(D(0)) - c,$$

but this interpretation is not necessary for the model, i.e., $\bar{u}$ need not be linked to the original utility formulation and then we can abstract from cost flow c. For future reference, we separate the consumers and producers overall surplus from resource consumption. Sellers' profit flow is $\pi(q_t) = \psi(q_t)q_t$ and assumed to be strictly concave. Consumers' surplus is $u(q_t) = \widetilde{u}(q_t) - \pi(q_t)$, and need not be concave.[8] We assume that surplus $u(q_t)$ is everywhere nonlinear,[9] differentiable, and bounded at some level above $\bar{u}$. The resource can thus provide surplus above long-run level $\bar{u}$. Throughout the paper we assume that stock s_0 is large enough, so that actions to end resource consumption are not taken immediately but at some $T > 0$.

We assume no discounting for now.[10] We denote the seller's stock-dependent payoff

[8] Consumer surplus will be a central determinant of the buyer's investment decision, but our results do not require a particular form for $u(q)$. For example, under linear demand, $u(q)$ is convex on $[0, D(0)]$ and constant thereafter. For constant elasticity of demand, $u(q)$ is concave for all values of the demand elasticity.

[9] That is, there is no non-empty interval (a, b), with $a < b$, such that $u(q)$ is linear over (a, b).

[10] In Section 5, we extend the model to positive discounting. It is not obvious that the undiscounted

by $V(s_t)$ and consumers' payoff by $W(s_t)$ if there has been no investment before t. Expression $V(s_t)$ measures cumulative (undiscounted) future profits while $W(s_t)$ measures cumulative surplus from the excursion above the long-run surplus from time t onwards:

$$V(s_t) = \int_t^{T+k} \pi(q_\tau) d\tau \tag{1}$$

$$W(s_t) = \int_t^{T+k} [u(q_\tau) - \overline{u}] d\tau \tag{2}$$

The social optimum depends on the time interval of resource use, $T + k$, and the supply path q_t, that maximizes total resource surplus

$$\mathcal{W}(s_t) = V(s_t) + W(s_t) = \int_t^{T+k} [\widetilde{u}(q_\tau) - \overline{u}] d\tau \tag{3}$$

Notice that we leave the investment costs out of the welfare function since, without discounting, the timing of investment has no bearing on the net present value of its costs.[11] The socially optimal supply solves a simple problem: Maximize (3) with respect to q_τ and T and subject to $\dot{s}_\tau = -q_\tau$. Let variable λ_τ measure the marginal value of the resource. The optimality conditions are: (i) marginal utility should equal the marginal value of the resource; $\widetilde{u}'(q_\tau) = \lambda_\tau$; (ii) marginal value of the resource at the end point T is equal to the extra utility it provides per extra unit of the resource, $\lambda_{T+k} = (\widetilde{u}(q_{T+k}) - \overline{u})/q_{T+k}$, and (iii) without discounting, the marginal value of the resource should be constant, $\lambda_\tau = \lambda$. From these three conditions, we can see that the resource surplus is linear, $\mathcal{W}(s_t) = \lambda s_t$, and the maximization is equivalent to maximizing the average excursion above the long-run payoff $\overline{u}$:

$$\lambda = \max_q [\widetilde{u}(q) - \overline{u}]/q.$$

It is instructive to see Figure 1, where we can find the social optimal supply level $q = q^{**}$ on the curve of utility $\widetilde{u}(q)$ such that the line through $(0, \overline{u})$ and $(q, \widetilde{u}(q))$ has the steepest slope.[12] Recall that utility $\widetilde{u}(q)$ is concave, and thus q^{**} must also satisfy

$$\widetilde{u}(q^{**}) = \overline{u} + q^{**}\widetilde{u}'(q^{**}).$$

case is the true discounted equilibrium limit (see Dutta 1991), but in our case it is, as we will verify.

[11] As we will see, in the case without discounting, the level of investment required does not affect supply levels in the equilibrium. In the discounting case, it does, see (22), as costs of investments enter negatively in the costs of waiting $e^{-rk}\bar{u} - rI$. For investments costs too large, $I > e^{-rk}\bar{u}/r$, no investment takes place.

[12] We use one asterisk for equilibrium constants, and two asterisks for social optimum constants.

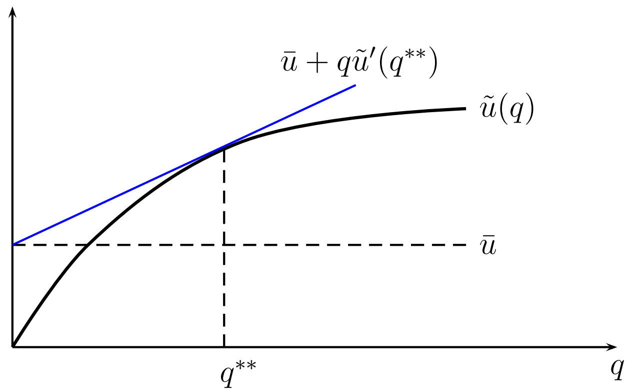

Figure 1: Determination of socially optimal supply

Since consumer surplus is $u(q) = \widetilde{u}(q) - q\widetilde{u}'(q)$, we must have

$$u(q^{**}) = \overline{u}. \tag{4}$$

Proposition 1 *In the social optimum, consumers receive reservation utility level $\overline{u}$ in all stages, while producers receive all the resource surplus. Consumers do not benefit from an increase in the resource stock, $W'(s_0) = 0$.*

Proof. The first part of the proposition states that along the social optimal path, the buyer side is indifferent between resource dependence and the substitute technology. This part follows immediately from (4). The last part of the proposition then follows from the definition of the buyer's payoff (2). ■

3.2 Buyers' first-best

Consider then what would be the first-best for the buyer side. This corresponds to a situation where producers are perfectly competitive and the time of investment is chosen to maximize $W(s_t)$ only. Competitive sellers rationally foresee when the buyer side is going to invest and based on this, they choose a constant supply path to equalize prices across times before and after the investment. We can copy the template from the social optimum to show that along consumers' first-best path, welfare $W(.)$ is linear, that is, $W(s) = \lambda s$ for some constant λ. In figure 1, we can maximize the buyer's value of the resource if we find the supply level q^* on the curve of utility surplus $u(q)$ where the line through $(0, \overline{u})$ and $(q, u(q))$ has the steepest slope. The solution either takes the maximum demand level, with optimal supply $q^* = D(0)$,[13] or otherwise, optimal supply q^* must satisfy

$$u(q^*) = \overline{u} + q^* u'(q^*). \tag{5}$$

We have a simple graphical determination of the consumers' optimum,[14] which is unique as $u(.)$ is nonlinear everywhere. In turn q^* determines the date of investment, by $T + k = s_0/q^*$. Relative to the social optimum, consumers can increase their payoff by forcing sellers to sell the resource faster:

Proposition 2 *The resource supply in the buyers' optimum exceeds resource supply in social optimum: $q^* > q^{**}$. The time interval of resource dependence is shortened.*

Proof. From (5) and $u' > 0$, it follows that $u(q^*) > \overline{u}$, and thus $q^* > q^{**}$. ■

The opposing interests are now clear: the seller side would like to delay investment as much as possible (to spread supplies thinly over time as profits are concave), the social optimum requires that consumers at least receive reservation utility, and the buyer side prefers even faster depletion.[15] It is obvious that in the equilibrium of the game supplies and investment time must lie between the extremes identified here.

For the equilibrium, an important feature is whether q^* is smaller than the maximal supply that the seller is willing to provide, $q^m = \arg\max\{\pi(q)\}$. Recall that a larger q^* follows from a greater long-run surplus $\bar{u}$: the buyer wants to consume the resource faster the better is the outside option. If q^* is larger than q^m, we call the substitute strong.

Definition 1 *The buyer has a weak substitute if $q^* < q^m$. Otherwise, the substitute is strong.*

Throughout this paper, we assume that the substitute is weak, unless explicitly otherwise stated.[16] Thus, we assume that the cost of the substitute is high enough such that

[13] This is, for example, the case with a convex surplus function $u(.)$.

[14] The graphical presentation of q^* is very similar to the presentation of q^{**} in Figure 1. The only difference is that $u(.)$ should substitute for $\tilde{u}(.)$, and that $u(.)$ need not be concave.

[15] These results are consistent with the common view that the seller's market power makes the resource-depletion path more conservative (see Hotelling 1931). Buyers' market power speeds up consumption both in the optimal tariff literature (see Karp-Newbery 1993) and strategic R&D and technology literature (see the papers cited in the introduction).

[16] For the analysis of the strong substitute cases that we do not consider in this paper, we refer to Gerlagh and Liski (2007).

$q^* < q^m$. The assumption ensures that the buyer's first-best is given by (5).[17] For future reference, we define the buyer's first-best marginal value of the resource as

$$\lambda^* = [u(q^*) - \overline{u}]/q^*.$$

In the buyers' optimum, the consumer share of total resource surplus $V(s) + W(s_0)$ is $\lambda^* s$; the seller receives the remainder.

3.3 First look at equilibrium: investment indifference

As we will show formally in Section 4, the key to the equilibrium is the seller's strategy to keep the buyer side indifferent between the following two actions: (i) invest today and consume the remaining stock during the transition time interval k, and (ii) postpone the decision by one marginal unit of time, maintaining the possibility for investing tomorrow. The seller side postpones investment as long as possible by sustaining the buyer's indifference. When the time interval is continuous, the indifference can be characterized, at each time t, by

$$u(q_t) = \bar{u} + q_t u'(s_t/k). \tag{6}$$

Under the postulated indifference, surplus $u(q_t)$ should cover *the cost from postponing* the long-run surplus flow $\bar{u}$ by marginal unit of time, and *the cost from depleting* the stock at rate q_t.[18] In view of Fig. 2, which depicts a concave surplus frontier and a line summing up the two cost terms for a given s_t, we see that the supply making the indifference to hold is uniquely defined by the intersection of the surplus curve (left-hand side of (6) as a function of q_t) and the cost curve (right-hand side for given s_t). As the resource is depleted, s_t/k declines, which for concave $u(.)$ causes the depletion cost to increase. That is, the slope of the cost curve (RHS) increases and, therefore, quantity q_t needed for the indifference must increase as well:[19]

$$\frac{dq_t}{ds_t} = \frac{q_t u''(s_t/k)}{k(u'(q_t) - u'(s_t/k))} < 0 \text{ for } q_t < s_t/k,$$

[17] Since $D(0) > q^m$, the assumption $q^m > q^*$ implies that q^* must be given by (5) and not by the corner $D(0)$.

[18] We immediately see that this condition closely resembles the buyer's optimum (5). There is one important distinction. Whereas the right-hand-side of the buyer's optimum indifference condition (5) takes the constant marginal value of the resource at the buyer's optimal path and so defines a constant q^*, the strategic buyer's indifference condition (10) is based on the marginal value of the current resource and so it defines a supply scheme q_t that is dependent on the current resource level s_t.

[19] The main model section will describe the general case of a not necessarily concave surplus.

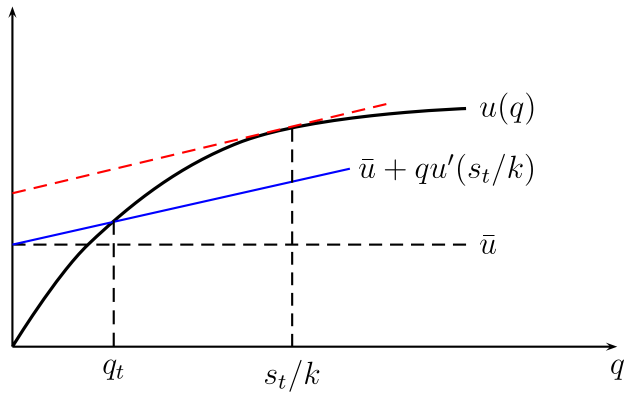

Figure 2: Determination of equilibrium q_t

as the numerator is negative while the denominator is positive. Thus, to postpone the investment, *supplies must increase when the remaining resource stock declines*, until the point where the buyers' optimum given by (5) and the indifference (6) coincide. That is, buyers will always invest when by doing so they can implement their first best. The resource level at which investment must take place s^*, is thus defined by buyers' first-best supply q^*,

$$s^* = kq^*.$$

It follows that at the time of investment, supplies under continuation and after investment coincide, at level q^*. The overall path of supplies is thus increasing up to the point of investment, after which it is constant. Later on, we will be more precise about the supply path.

4 Strategic resource dependence

There are three types of agents in the model. First, producers of the resource form a coherent cartel (from now on, the seller). Second, large number of competitive consumers derive utility from resource consumption or, if present, from consuming the substitute service provided by the substitute. Third, there is the consumers' agent who cares only about the consumer surplus. The buyers' agent can affect the surplus only by making the decision to end the relationship with the seller. The decision is about changing the demand infrastructure; we abstract from the precise policy instrument implementing the change. Since the only strategic actions are taken by the seller and the buyer's agent, from now on we use the words 'buyers' agent' and 'buyer' interchangeably. There is one single market: the spot market for the resource flow.

4.1 Timing and strategies

The economy has three stages, starting in initial stage before investment, $t < T$, labeled with superscript '0'. The next stage follows investment, $T \leq t < T + k$, also called the post-investment stage, and labeled with superscript '1'. The final stage starts at the arrival of the new substitute technology, $t \geq T + k$. During the pre-investment stage, buyer and seller interact strategically such that the seller chooses a supply level q_t^0, and the buyer decides whether or not to invest, $d_t \in \{0, 1\}$. Since the investment decision is irreversible, the game moves to the investment stage permanently once the buyer invests. During the post-investment stage, there are no strategic interactions. The seller can only sell the remaining stock in interval of time k (or the monopoly quantity q^m if the stock is too large to be sold in this time span), and the buyer side can only accept what is offered to the market. We denote the quantity sold at time t in the second stage by q_t^1. In the final stage, all resources remaining at time $T + k$ are left unused.

Time is continuous but it proves useful to define strategies over discrete time periods, and then let the time period converge to zero.[20] All strategic interaction thus takes place before investment; technically, we solve a stopping game. At any time t where decisions are taken, if the game is in the pre-investment stage, we denote the seller's supply by q_t^0 and assume that there are three sub-stages with the following timing:

1. Seller chooses a supply q_t^0;
2. Buyer chooses $d_t \in \{0, 1\}$;
3. If $d_t = 0$, market clears at q_t^0. If $d_t = 1$, the economy moves to post-investment stage.

The seller's initial resource stock s_0 is known by the buyer side with certainty, and we can condition strategies on the remaining stock s_t. We thus look for Markov-perfect strategies of the form $q_t^0 = \eta(s_t)$, and $d_t = \mu(s_t, q_t^0) \in \{0, 1\}$. Note that because of the timing assumption (the three substages above), the buyer's Markov strategy depends not only on the state but also on the seller's offer.[21]

[20]We follow this approach to make the extensive form of the game clear, and to be able to use differential methods to characterize the equilibrium.

[21]In this respect, a similar formulation is used in Felli and Harri (1996) and Bergemann and Välimäki

4.2 The buyer's problem

When buyers have taken the action to move to the substitute, the game is over: buyers have no more decisions to make and the seller can only sell the remaining stock during the transition time. When not yet used, the buyer's strategic investment option will affect the supply levels. To describe the buyer's payoff, we need to make it contingent on whether the strategic variable has been used or not. We define $W^I(s_t)$ as the value of the excursion above the long-run payoff, measured from current from time t onwards, immediately after investment when resource dependence still continues for k units of time. $W^I(s_t)$ is unambiguously determined by the seller's post-investment supply policy which is just $q_t^1 = \min\{q^m, s_t/k\}$ for the remaining sales window.[22] If the buyer's decision is made at some time T with $s_T > 0$, then

$$W^I(s_T) = \begin{cases} k(u(s_T/k) - \bar{u}) \text{ if } s_T < kq^m \\ k(u(q^m) - \bar{u}) \text{ otherwise,} \end{cases} \tag{7}$$

It follows that for $s_T < kq^m$ we have $W^{I\prime}(s_T) = u'(s_T/k)$, which measures the scarcity cost to the buyer from continued resource dependence.

The seller has a strategy $q_t^0 = \eta(s_t)$, and based on the seller's strategy we find the strategy for the buyer to invest. The buyer's best response to $\eta(s_t)$ is best understood when we consider supply constant over a small interval $[t, t+\varepsilon]$, and let ε converge to zero. Using the above expression for $W^I(s_t)$ and assuming the seller's strategy $q_t^0 = \eta(s_t)$, we can write the expression for the payoff before the investment, $W(s_t)$, when the buyer optimizes over a short interval with length ε:

$$W(s_t) = \max_{d_t \in \{0,1\}} \{[\varepsilon u(\eta(s_t)) - \varepsilon\bar{u} + W(s_t - \varepsilon\eta(s_t))](1-d_t) + W^I(s_t)d_t\}. \tag{8}$$

Term $\varepsilon\bar{u}$ is the direct cost from postponing the investment since the buyer side loses long-run surplus $\bar{u}$ for ε units of time by not investing today. As ε approaches zero, (8) can be approximated as follows:

$$W(s_t) = \max_{d_t \in \{0,1\}} \{[\varepsilon u_t^0 - \varepsilon\bar{u} - \varepsilon q_t^0 W'(s_t) + W(s_t)](1-d) + W^I(s_t)d\}, \tag{9}$$

where we use shorthands $u_t^0 = u(\eta(s_t))$ and $q_t^0 = \eta(s_t)$. Thus, if choosing $d = 0$ is optimal,

(1996).

[22] Recall that profit $\pi(q)$ is concave so it is optimal to allocate the remaining stock evenly, or leave some stock left if this would imply exceeding the monopoly quantity q^m. In the presence of discounting, the sales path is not flat, but declining as in Hotelling (1931). However, it still holds that all strategic interactions end at the investment date. See the section on discounting.

then $W(s_t) \geq W^I(s_t)$ and

$$u_t^0 = \bar{u} + q_t^0 W'(s_t). \tag{10}$$

This is the key indifference throughout this paper. It says that the consumer surplus under continuation of the resource dependence, u_t^0, covers the direct cost from continuing, $\bar{u}$, and the marginal reduction in payoff from the fact that the stock available for consumption during the remaining overall time interval of resource dependence is depleted, $q_t^0 W'(s_t)$.

4.3 The seller's problem

Let $V^I(s_T)$ denote the seller's payoff if the buyer makes the decision to end the relationship at stock level s_T. This value is simply given by

$$V^I(s_T) = \begin{cases} k\pi(s_t/k) \text{ if } s_T < kq^m \\ k\pi(q^m) \text{ otherwise.} \end{cases} \tag{11}$$

To consider the seller's problem before the decision is made, let $V(s_t)$ denote the value of the remaining stock to the seller conditional on no investment before t. For short time interval ε, and given the buyer's strategy $d_t = \mu(s_t, q_t^0)$, supply in the next ε units of time is q_t^0 if $\mu(s_t, q_t^0) = 0$. The economy immediately moves to the investment stage if $\mu(s_t, q_t^0) = 1$. The seller's best response satisfies

$$V(s_t) = \max_{\{q_t^0\}} \{[\varepsilon\pi(q_t^0) + V(s_t - \varepsilon q_t^0)](1 - \mu(s_t, q_t^0)) + V^I(s_t)\mu(s_t, q_t^0)\}. \tag{12}$$

When ε approaches zero, this value can be approximated by (letting $\mu(\cdot) = \mu(s_t, q_t^0)$):

$$V(s_t) = \max_{\{q_t^0\}} \{[\varepsilon\pi(q_t^0) - \varepsilon q_t^0 V'(s_t) + V(s_t)](1 - \mu(\cdot)) + V^I(s_t)\mu(\cdot)\} \tag{13}$$

Given $\mu(s_t, q_t^0)$, the seller can choose if there will be investment or not. If choice $\mu = 0$ is implemented, then by (13), we must have

$$-q_t^0 V'(s_t) + \pi(q_t^0) = 0. \tag{14}$$

If choice $\mu = 1$ is implemented, then

$$V(s_t) = V^I(s_t). \tag{15}$$

From these conditions we can immediately see that the seller always prefers to continue the relationship irrespective of the stock level. Recall that s^* denotes the stock level at which the buyer's first-best is to invest.

Lemma 1 *If $q_t^0 \leq s_t/k$ for all $s_t \geqslant s^*$, then the seller prefers continuation to stopping. In particular, $V(s^*) = V^I(s^*)$, $V'(s_t) > V^{I\prime}(s_t)$ for all $s_t \geqslant s^*$, and thus $V(s_t) > V^I(s_t)$.*

Proof. Equality at s^* follows from the buyer's choice to invest at s^*: $V(s^*) = V^I(s^*)$. Assuming $q_t^0 \leq s_t/k$, we have

$$V'(s_t) = \psi(q_t^0) \geq \psi(\frac{s_t}{k}) > \psi(\frac{s_t}{k}) + \frac{s_t}{k}\psi'(\frac{s_t}{k}) \geq V^{I\prime}(s_t).$$

The first equality follows from (14), the second (weak) inequality is by assumption ($q_t^0 \leq s_t/k$), the third (strict) inequality follows from a negative price slope, and the last (weak) inequality follows from (11). By integration, $V(s_t) > V^I(s_t)$ follows. ■

Thus, the 'smooth pasting' condition does not hold for the seller for an intuitively obvious reason: the buyer's decision to invest implies a binding time-to-sell constraint for the seller.[23] The seller will never end the dependence before the buyer wants to end it, as it is always profitable to extend the sales time interval beyond $T + k$ when discounting is absent.[24] For this reason, when the stock level is public knowledge and $q_t^0 \leq s_t/k$, it will be the buyer's indifference that determines the time to end the resource dependency.

4.4 Equilibrium

Establishing and characterizing equilibrium supply is a simple undertaking based on the analysis of buyer's indifference between continuation and stopping, given that the seller side never prefers stopping. We first prove that (7) defines the buyer's welfare any time before investment:

Lemma 2 *In equilibrium, the buyer is indifferent between continuing the resource dependence and investing at any given t prior to the investment date:*

$$W(s_t) = W^I(s_t) \text{ for all } s_t \geq s^* \tag{16}$$

[23]The lemma shows that the model can easily be extended to cover the case when the seller has the opportunity to sell its stock after the arrival of the substitute. The important feature is that the marginal value of the resource after the arrival of the substitute must be less than $\psi(q^*)$. Assume that the substitute has marginal production costs mc. The marginal value of the resource after the arrival of the substitute is thus mc. As long as marginal substitute costs are sufficiently small, $mc < \psi(q^*)$, the lemma will hold. Constant extraction costs do not change the trade-off between supply before and after the arrival of the substitute.

[24]We will derive this same condition also with discounting but there we need restrictions on the utility formulation.

Proof. The proof is by contradiction. Assume $W(s_t) > W^I(s_t)$ at some $s_t > s^*$. The inequality implies that the buyer will always choose $d_t = 0$ in (8), irrespective of the seller's supply. In turn, the seller is not constrained to reduce supplies and he can extend the time interval of resource dependence to obtain higher prices from all dates. Supply will fall arbitrarily close to zero, the utility excursion compared to $\bar{u}$ becomes negative for a time interval of unbounded length, and $W(s_t)$ becomes negative (2), which contradicts $W(s_t) > W^I(s_t)$. ■

It is thus the buyer's indifference that determines equilibrium supply policy, $q_t^0 = \eta(s_t)$. The buyer's indifference condition (16) together with (10) requires

$$u(q_t^0) = \bar{u} + q_t^0 u'(s_t/k) \text{ if } s_t < kq^m \tag{17}$$

$$u(q_t^0) = \bar{u} \text{ otherwise.} \tag{18}$$

This is a slightly adjusted version of (6) because $W_t'(s_t) = u'(s_t/k)$ when $s_t < kq^m$, but $W_t'(s_t) = 0$ otherwise as the stock level does not affect supply if $s_t > kq^m$. We have already illustrated this indifference for a concave surplus u in Fig. 2. Recall that the investment point satisfies $q_t^0 = s^*/k = q^*$, which is the buyer's first-best supply as it maximizes the buyer's payoff from this stock level onwards. The seller cannot compensate the buyer for continuation after the stock has fallen just below s^* because the buyer can implement his first-best by ending the relationship there. Alternatively put, the scarcity cost exceeds the maximal marginal value of the resource,

$$W'(s_t) > \lambda^* = [u(q^*) - \overline{u}]/q^*,$$

when $s_t < s^*$ and u is (locally) concave.

We describe now the general case with u not necessarily concave. Recall that the buyer's first-best supply q^* satisfies

$$u(q^*) = \bar{u} + q^* u'(q^*)$$

and that the buyer never accepts stock levels below kq^*, as buyers can always implement their first-best from time t onwards if they end the relationship at $s_t = kq^*$. In the following it is convenient to redefine s^* not to be the investment point in the buyer's first best, but to be the equilibrium investment point. It is clear that we must have $s^* \geq kq^*$. However, since the consumer surplus is not generally concave, the buyer may also end the relationship at some higher stock level $s_t > kq^*$, because the scarcity cost $u'(s/k)$ may locally increase above $\lambda^* = u'(q^*)$ as s_t/k declines from s_0/k towards q^*. To deal with this, we define s^* to be the first stock level below s_0 such that $u'(s^*/k) = \lambda^*$. Stock s^* is unique for given s_0, and we have by construction

$$u'(s_t/k) < u'(q^*)$$

for all $s^* < s_t \leq kq^m$. By continuity of $u(.)$, $q_t^0 = \eta(s_t)$ satisfying (17) to keep the buyer indifferent between stopping and continuing exists and varies with the remaining stock for $s^* < s_t < kq^m$.

Proposition 3 *There exists a unique Markov-perfect equilibrium with s^* as defined above, q_t^0 defined by (17)-(18), and $q_t^1 = s^*/k$.*

Proof. It suffices to prove that s^* is determined properly. Clearly, we cannot take s^* to be smaller as such would imply an infeasible resource supply from (17). We will now prove that s^* cannot be larger either. For this, it is sufficient to prove that s^* maximizes the value of the resource to the seller. But this follows from Lemma 1: the seller maximizes profits by continuing as long as possible. ■

Under nonconcave surplus, the increase in supply over time may not be monotonic as the buyer's scarcity cost $u'(s_t/k)$ may not be monotonic (u'' may change sign). However, when the equilibrium path approaches the investment point, supplies must increase, so that our main conclusion holds irrespective of the utility functional form.

Proposition 4 *The equilibrium supply path q_t^0 is*

1. *constant at level $u^{-1}(\bar{u})$ when $s_t > kq^m$;*
2. *varying over time in $u^{-1}(\bar{u}) \leq q_t^0 \leq q^*$ when $s^* < s_t < kq^m$, but ultimately increasing to q^* as s_t approaches s^*;*
3. *strictly increasing for all $s^* < s_t < kq^m$ if consumer surplus $u(.)$ is concave*

4.5 Discussion

The assumption that it takes time to change the demand is necessary for our result that supplies increase over time. When the time-to-build delay k is extremely short, the buyer knows that the alternative surplus flow $\bar{u}$ will arrive almost immediately after investment. Then, the buyer's outside option is just the long-run surplus, and the seller needs to supply only $u^{-1}(\bar{u})$ to keep him indifferent. The seller will receive the whole surplus and, therefore, he will implement the first best.

A larger k captures the idea of having capacity constraints in making a fast transition to the substitute. The buyer will feel the scarcity cost from a decreasing stock for a longer period and, therefore, will require a larger compensation to continue without investment. A larger k thus means that the buyer will realize earlier that there is scarcity during the transition period, and the upward pressure on supplies will start ealier, i.e., at higher current stock levels. In this sense, the buyer's outside option is more sensitive to the stock level s_t, and he will be able capture larger part of the overall surplus.

The above simple formalization of the time-to-build delay captures quite well a general idea. Let us now briefly discuss alternative but qualitatively equivalent ways of formalizing the transition to the substitute. First, the buyer's decision could trigger a gradual adjustment of the demand rather than the above one-time event taking place after the time-to-build period. One way to formalize a gradual adjustment is to assume an exogenous rate of decline for the fraction of the demand still depending on the resource. This would change essentially nothing in our main model. Another way to proceed is to assume that at each period after making the decision $d = 1$, the buyer chooses an investment rate, i.e., how many units of demand to switch. If investment cost is linear, the buyer can switch all units at once, which would lead an equilibrium equivalent to the one obtained when k is almost zero in our main model. When adjustment (investment) costs are strictly convex, possibly with a per period capacity constraint on the rate of change, then the buyer cannot change his dependence on the resource quickly, and the equilibrium dynamics come close to those achieved under $k > 0$ in our model. In this sense, k captures adjustment costs in the demand change.

Second, uncertainty regarding the transition to the substitute can be captured in many ways. A simple extension is to treat k as a random variable, which would not affect the nature of our results in any material way. Alternatively, the buyer's decision $d = 1$ could trigger a random process with a downward trend for the fraction of demand still depending on the resource. The seller would face stochastic demand over stochastic time horizon but the ex ante values from entering this phase could still be evaluated in a straightforward way for both players, and the strategic interaction before investment would not essentially differ from our what we have described.

Let us then finally discuss our assumption that the resource cannot compete with the substitute, once in place. Recall that we abstract from the substitute's marginal production costs and resource extraction costs. We could as well have assumed that marginal production costs for the substitute fall short of resource extraction costs so that the resource has no use when the substitute is in place. Even if the resource can compete with the substitute, the three main features that support our analysis can be maintained.[25] First, if supplied in large quantities, the buyer prefers the resource to the substitute. This feature gives the seller some bargaining power as it ensures that the buyer has an interest in exhausting the resource. Second, profits for the resource owner decrease when the substitute is available compared to the situation without the substitute. This feature ensures that the seller will try to delay the investment in the substitute and it transfers some bargaining power to the buyer. Third, early investment in the substitute is costly. This feature ensures that the substitute does not become available before it is used capping the buyer's strategic power.

5 Discounting

Discounting is an important element in resource use when the relevant time horizon is decades at least. In the traditional Hotelling model, discounting is what distinguishes markets at different dates, which, in the presence of market power, leads to intertemporal price discrimination. Discounting is thus one reason to discriminate buyers at different dates. Another reason is the buyer's changing opportunity cost of continuing the resource dependence due to stock depletion, which we have identified in the undiscounted analysis. The purpose of this section is two-fold. First, we show that the discounted equilibrium converges to the undiscounted limit we have described. Second, we explain how the above two distinct reasons for price discrimination evolve as the stock depletion progresses. We present a situation where supplies initially decline, when the stock is large, as in a traditional Hotelling exhaustible resource market. However, ultimately supplies must increase, when stock declines and the buyer's outside option starts to drive the equilibrium dynamics as in the undiscounted case.

Let now the continuous-time discount rate be positive, $r > 0$. Apart from discounting, the model is the same as before. In the post-investment phase, discounting does not change much: for the seller, there is a unique profit-maximizing supply path, equalizing present-value marginal revenues over the remaining sales time interval, and resulting in an associated value function $V^I(s_T)$ at the time of investment when the remaining resource stock is s_T.

In the pre-investment time interval, at each stock level, the seller's optimal sale q_t^0 is

[25] In the footnote after Lemma 1, we show that the equilibrium does not change qualitatively if the substitute and the resource can compete.

a best-response to the buyer's stopping rule $\mu(s_t, q_t^0)$ satisfying

$$V(s_t) = \max_{\{q_t^0\}}\{[\varepsilon\pi(q_t^0) + e^{-\epsilon r}V(s_t - \varepsilon q_t^0)](1 - \mu(s_t, q_t^0)) + V^I(s_t)\mu(s_t, q_t^0)\}, \quad (19)$$

where, as in the undiscounted equation (12), the strategies are defined over some discrete period of time ε. In the limit of short time period ε, the value function $V(s_t)$ satisfies

$$-q_t^0 V'(s_t) + \pi(q_t^0) - rV(s_t) = 0. \quad (20)$$

The unique seller's supply path after investment also defines the buyer's welfare $W^I(s_T)$, where we note that since $W^I(s_T)$ measures only value of the excursion above the long-run situation where flow payoff $\bar{u}$ is achieved, the overall welfare at the investment time is equal to $W^I(s_T) + \bar{u}/r - I$. The buyer's payoff before investment is now given by

$$\begin{aligned} W(s_t) + \bar{u}/r - I \quad = \quad & \max_{d_t \in \{0,1\}}\{[\varepsilon u(\eta(s_t)) + e^{-\epsilon r}W(s_t - \varepsilon\eta(s_t)) + e^{-\epsilon r}\bar{u}/r - e^{-\epsilon r}I](1 - d_t) \\ & + W^I(s_t)d_t\}. \end{aligned} \quad (21)$$

Letting ε converge to zero, we find the positive discounting equivalent of (10):

$$u_t^0 = \bar{u} - rI + rW^I(s_t) + q_t^0 W^{I\prime}(s_t). \quad (22)$$

When the buyer is indifferent between continuation and stopping, (22) holds as an equality with obvious interpretation: waiting cost of continuation is now $\bar{u} - rI$ and, in addition to the depletion effect $q_t^0 W^{I\prime}(s_t)$, buyers must receive return on the asset they are holding (investment option), $rW^I(s_t)$. Assuming that the buyer's indifference condition is uniformly continuous in (s_t, q_t^0), it is also continuously differentiable in r, and so it is clear that for $r \to 0$, the equilibrium uniformly converges to the zero-discounting equilibrium. Thus, the zero-discounting equilibrium describes well the equilibrium features of a low-discount rate equilibrium. The investment point $s_T = s^*$ occurs when the seller cannot compensate the buyer for any lower stock level, that is, when

$$u'(q_T) = W^{I\prime}(s_T).$$

For zero discounting, we have seen that this condition is equivalent to $u'(q^*) = u'(s^*/k)$, $q_t^0 = q^*$, which ensures that supply (immediately) after investment s^*/k, which we labeled as q_T^1, is equal to supply immediately before investment, $q_T^0 = q^* = q_T^1$. With positive discounting, there may be a jump up (or down) in supply at the moment of investment if $u'(q_T^1) \neq W^{I\prime}(s^*)$. To ensure continuity, we need restrictions on demand.

We can solve the equilibrium explicitly by assuming constant elasticity of demand $\epsilon = -\frac{1}{1-\sigma}$, generated by utility function, $\widetilde{u}(q) = q^\sigma$, with $0 < \sigma < 1$. Thus, $\psi(q) = \sigma q^{\sigma-1}$, $\pi(q) = \sigma q^\sigma$, and $u(q) = (1-\sigma)q^\sigma$. Under positive discounting, the supply q_t after investment satisfies $\pi'(q_t) = e^{r(t-T)}\lambda$, for some $\lambda > 0$ (marginal revenues are equalized in present value). Using this condition, some manipulation gives

$$\begin{aligned} V^I(s) &= \sigma A s^\sigma \\ W^I(s) &= (1-\sigma)As^\sigma - \frac{1-e^{-rk}}{r}\bar{u}, \end{aligned}$$

where $A = \left(\frac{\omega}{1-e^{-\omega k}}\right)^\sigma \left(\frac{1-e^{-\omega\sigma k}}{\omega\sigma}\right)$ and $\omega = \frac{r}{1-\sigma}$. For the investment to yield a positive return, we assume $\frac{e^{-rk}}{r}\bar{u} - I > 0$. The buyer's indifference condition (22) becomes

$$q^\sigma = \frac{e^{-rk}\bar{u} - rI}{1-\sigma} + rAs^\sigma + q\sigma As^{\sigma-1}. \tag{23}$$

where, for convenience of notation, we substituted q for q_t^0.

Notice that when $r \to 0$, $A \to k^{1-\sigma}$ and we get

$$\begin{aligned} W^I(s) &= k[(1-\sigma)(s/k)^\sigma - \bar{u}] \\ V^I(s) &= k\sigma(s/k)^\sigma \\ (1-\sigma)q^\sigma &= \bar{u} + q\sigma(1-\sigma)(s/k)^{\sigma-1}, \end{aligned}$$

consistent with equations (7), (11), and (17).

In the appendix, we show that supply is continuous at investment point: $q_T^1 = q^*$. This requires $u'(q_T^1) = W^{I\prime}(s)$. This finding is used to prove that the seller prefers continuation to stopping at the investment point, which ensures that (23) holds up to the point where investment takes place. We can then use continuity of supply and (23) to establish the values for the resource stock and supply level at the investment point. Given σ, assume k and r satisfy

$$\sigma(1-e^{-\omega k})^\sigma > 1 - e^{-\omega\sigma k} \tag{24}$$

we then have

$$\begin{aligned} s^* &= \left[\frac{e^{-rk}\bar{u} - rI}{(1-\sigma)^2 A^{\frac{-\sigma}{1-\sigma}} - (1-\sigma)rA}\right]^{-1/\sigma} \\ q^* &= A^{\frac{1}{\sigma-1}} s^* \end{aligned}$$

These findings lead to the following:

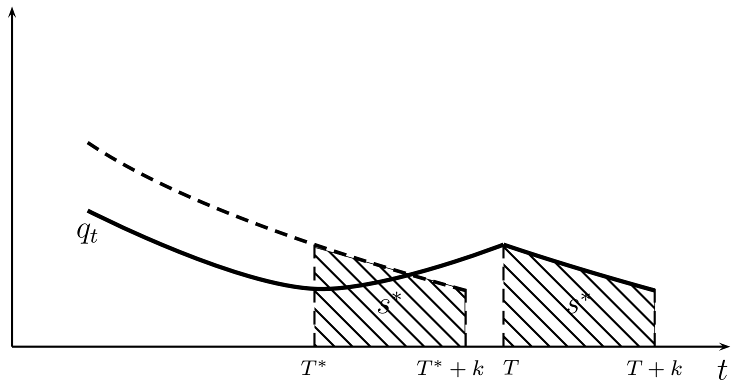

Figure 3: Equilibrium supply path under discounting

Proposition 5 *For constant elasticity of demand and (24) satisfied, pre-investment equilibrium supplies first decline and then increase over time when s_0 is sufficiently large.*

Proof. See Appendix. ■

We depict the equilibrium time path for supply in Fig. 3, as well as the buyer's optimal path. The latter involves choosing the highest supply path such that (i) prices are equal in present value, and (ii) the stock remaining at the investment time, T^*, is consumed during the technology transition time interval. The equilibrium s^* is, like in the undiscounted case, exactly equal to the buyer's optimal s^* because, due to constant elasticity of demand, in the post-investment phase the seller supplies a competitive path in both cases as the constant demand elasticity eliminates the possibility of price discrimination at different dates after the investment (see Gilbert 1978). The two paths in Fig. 3 are therefore identical during the technology transition time interval, starting at T^* and T, respectively. However, before investment, the strategic seller can discriminate buyers at different dates according to (22) (the explicit constant elasticity of demand solution is given in (23)) and delay the arrival of the substitute as in the undiscounted case. When the stock is still large, supplies decrease over time as in the standard Hotelling model. When the stock becomes smaller and approaches s^*, supplies increase over time as in the undiscounted case because the buyer's indifference becomes binding.

6 Concluding remarks

In this paper, we considered strategic interactions between the seller of a depletable resource and consumers who have interests in ending their dependence on the resource. We modeled the situation using a framework that departs from explicit bargaining but allows offers and responses such that neither party is in explicit leadership. The approach seems relevant since there is significant coordination of actions on both sides of the oil market, for example, but at the same time explicit cooperation of the two sides is not feasible by the difficulty of enforcing international agreements. The key question in the relationship is when to start the process ending the resource dependence, that is, when to change the demand. The process changing the demand takes time and therefore a potentially significant fraction of the resource has to be saved for the transition time interval. Our insights to the problem follow from this simple allocation problem.

The main insight from our analysis is that producers' market power is reduced over time as continuing the relationship becomes more costly to consumers when the stock available for the demand transition is depleted. This means that changing the demand infrastructure becomes more relevant as a choice, leading to the conclusion that producers must increase supplies over time to postpone the buyer's action. In contrast with previous approaches to such strategic dependence, the basic implications of the Hotelling (1931) model are reversed.

What are the main lessons from these results for understanding the oil market? We believe it is the insight that energy technology policies in oil-importing countries can act as an increasingly effective strategic instrument, in part destroying producers scarcity rents. While in general this insight is not new, our approach is new as it accounts for the fact that the transition is not an immediate event, and this insight results in explicitly increasing supplies in a stationary market environment.

There are several well-established explanations why scarcity rents do not seem to drive supply behavior in oil or other exhaustible resource markets: declining extraction costs due to technological progress can lead to U-shaped price paths; durability of the final good; learning of new reserves; and imperfect competition (see Gaudet 2007) for a review of the literature). Our explanation is complementary and distinct from any of explanations presented in this literature.

On a theoretical level, there are some obvious extensions. As we have seen, the size of the remaining stock is what determines the seller's ability to entice the buyer side to postpone actions ending the resource dependence: it is critical for the buyer to observe how much resource is left for the transition, otherwise the seller can take advantage of the buyer's imperfect information for the right timing of the demand change. Recall that the larger is the stock, the lower is the equilibrium supply (at earlier points on the sales path stocks are larger). In this precise sense, a large stock implies more power to reduce supplies than a small stock. If the stock is not observed by the buyer side, a small seller can potentially mimic large seller's policy of reducing supplies and, thereby, extend the investment date from what would otherwise hold for the small seller.

The above observation suggests an extension to situations where there is asymmetric information about the size of the seller's resource stock. The study of asymmetric information in resource extraction can also be motivated by the developments in the oil market. The core reserves of cheap oil are not managed like most productive assets in market economies; management of cheap oil is characterized by secrecy. The dynasties of Middle East do not disclose technical production information and make efforts to prevent auditing of the reserves. The future availability of conventional oil is a major public concern in oil importing countries; industry experts' opinions on the size of economically viable stocks diverge widely.[26] We have presented a preliminary analysis of the asymmetric information equilibrium in our working paper Gerlagh-Liski (2007).

Other extensions are the following. Adding a fringe of competitive producers would reduce the seller's market power in a rather straightforward way; the fringe would free-ride on the seller's market power by selling first when the prices are high. Uncertainty about the technology transition time interval would affect the precise timing of investment and the level of the supply path, but not the basic insights. A less straightforward extension is a reversed asymmetric information situation where the buyer side privately knows whether the adoption decision has been made but the resource stock size is public information. Alternatively, under the R&D interpretation, the buyer privately knows the state of the technology. We leave these interesting topics open for future research.

[26]These concerns are reviewed in the Hirsch report. A book by Matthew R. Simmons (2005) explicates carefully the industry experts concerns regarding the Saudi stocks. While it is hard to judge the validity of the arguments in general, one cannot escape the fact that the market cannot evaluate the maturity of the main Saudi oil fields; Saudi Aramco has not disclosed technical production information since the early 1980 (Simmons).

7 Appendix: Proof of Proposition 5

We prove Proposition 5, through a series of lemmas. The first lemma shows that supply is continuous at investment point: $q_T^1 = q^*$. As noted in the main text, this requires $u'(q_T^1) = W^{I\prime}(s)$. The second lemma uses this finding to prove that sellers prefer continuation to stopping at the investment point, which ensures that (23) holds up to the point where investment takes place. The third lemma then uses continuity of supply and (23) to establish the values for the resource stock and supply level at the investment point. It also shows that the slope for (s,q) defined by (23) is downwards for values of s close to s^*, but upwards for large values of s.

Lemma 3 *Under constant elasticity of demand, equilibrium supply is continuous at the investment point.*

Proof. Let q_T^1 refer to optimal monopoly supply immediately after investment. With zero discounting, we had $u'(q_T^1) = W^{I\prime}(s^*)$ as q_T^1 equals the consumption level throughout the post-investment phase until the substitute arrives. With positive discounting, this equation does not always hold. Let q_T^1 be supply immediately after investment, so that $\lambda = \pi'(q^I)$. Thus, when the resource stock increases by small amount Δs, then supply changes Δq_t satisfy $\pi''(q_t)\Delta q_t = e^{r(t-T)}\Delta\lambda$, for some $\Delta\lambda$ such that $\int_T^{T+k} \Delta q_t dt = \Delta s$, that is, $\int_T^{T+k} \frac{e^{r(t-T)}}{\pi''(q_t)} dt = \Delta s/\Delta\lambda$. For notation, let us use $\mu_t = \frac{\pi'(q_t)}{u'(q_t)} = \frac{q\widetilde{u}''(q_t)}{\widetilde{u}'(q_t)} + 1$. The value of μ measures one minus the relative risk aversion.

$$\begin{aligned} W^{I\prime}(s^*) &= \frac{\Delta W^{I\prime}(s)}{\Delta s} = \frac{\int_T^{T+k} e^{-r(t-T)} u'(q_t)\Delta q_t dt}{\int_T^{T+k} \Delta q_t dt} = \frac{\int_T^{T+k} e^{-r(t-T)} \mu_t \pi'(q_t)\Delta q_t dt}{\int_T^{T+k} \Delta q_t dt} \\ &= \frac{\int_T^{T+k} \mu_t \Delta q_t dt}{\int_T^{T+k} \Delta q_t dt}\lambda = \frac{\int_T^{T+k} \mu_t \Delta q_t dt}{\int_T^{T+k} \mu_T \Delta q_t dt} u'(q_T^1). \end{aligned} \tag{25}$$

The difference between $W^{I\prime}(s^*)$ and $u'(q_T^1)$ is caused by the difference between the average value of μ_t over the post-investment time interval $[T, T+k]$, and its value at time T. It is clear that, for utility with constant relative risk aversion, $W^{I\prime}(s^*) = u'(q_T^1)$. If utility has decreasing relative risk aversion, relative risk aversion will increase with decreasing q_t, and μ_t will increase, so that $W^{I\prime}(s^*) \geqslant u'(q_T^1)$. Similarly, if utility has increasing relative risk aversion, $W^{I\prime}(s^*) \leqslant u'(q_T^1)$. ■

Lemma 4 *Under constant elasticity of demand, the sellers prefer continuation to stopping at the investment point.*

Proof. We will show that the seller's value function has a kink at the time of investment, $V'(s^*) > V^{I\prime}(s^*)$ when $W^{I\prime}(s^*) = u'(q_T^1)$, so the sellers would always prefer continuation rather than stopping in such a situation. Changes in k play a role in the argument, and so we write the seller's payoff as a function of both the stock level and the transition time length k. We write $V^I(s_t, k)$ and $V^I(s_t)$ interchangeably, and similarly $V_s^I(s_t, k)$ and $V^{I\prime}(s_t)$. Flow profits are concave by assumption, and supplies strictly positive at the end of the overall sales time interval, $q_{T+k} > 0$, so it is clear that the seller's value of the resource increases with the transition time length k, $V_k^I(s_t, k) > 0$. After investment, the value function satisfies the following Bellman equation

$$V^I(s^*, k) = \varepsilon\pi(q_T^1) + e^{-\epsilon r}V(s^* - \varepsilon q^I, k - \varepsilon). \tag{26}$$

Taking the limit for $\varepsilon \to 0$ (leaving k out of notation), we get

$$\pi(q_T^1) - rV^I(s^*) - q_T^1 V_s^I(s^*) - V_k^I(s^*) = 0. \tag{27}$$

Thus, $\pi(q_T^1) > rV^I(s^*) + q^I V^{I\prime}(s^*)$. This together with continuous supply implied by Lemma 3 and value matching, $V(s^*) = V^I(s^*)$, implies $V'(s^*) > V^{I\prime}(s^*)$. ■

Lemma 5 *Given σ, assume k and r satisfy*

$$\sigma(1 - e^{-\omega k})^\sigma > 1 - e^{-\omega\sigma k}. \tag{28}$$

Then,

$$\begin{aligned} s^* &= [\frac{e^{-rk}\bar{u} - rI}{(1-\sigma)^2 A^{\frac{-\sigma}{1-\sigma}} - (1-\sigma)rA}]^{-1/\sigma} \\ q^* &= A^{\frac{1}{\sigma-1}} s^* \end{aligned} \tag{29}$$

For $s \geq s^*$ but sufficiently close to s^*, seller's supply $q_t^0 = \eta(s_t)$ is defined by (23) and declining in s_t. For s sufficiently large, $q_t^0 = \eta(s_t)$ is increasing in s_t.

Proof. We find the equilibrium s^* in the lemma by using $W^{I\prime}(s^*) = u'(q)$, which defines q^*, in (23) and noting that the buyer's indifference can hold only if (28) holds; we can focus on buyer's indifference based on Lemma 4.

Given (28), we verify that $q_t^0 = \eta(s_t)$ defined by (23) is decreasing in s for $s > s^*$. Condition (23) implicitly defines two values of q given $s > s^*$. The equilibrium strategy must satisfy $dV'(s)/dq < 0$ where $V'(s)$ is given by (20) and evaluated at $(s, q) = (s^*, q^*)$. Condition (28) ensures that this holds and implies that the lower trajectory ending at

(s^*, q^*) is the equilibrium strategy. Thus, equilibrium supply $q_t^0 = \eta(s_t)$ defined by the buyer's indifference (23) is decreasing for levels of s_t close to s^*. The downward slope of $q_t^0 = \eta(s_t)$ continues until a point is reached where $q_t^0 = \omega s_t$. After this point, q_t^0 defined by (23) becomes increasing in s_t. Since, at the investment point, (28) ensures that $q^* > \omega s^*$, we must have that the point with $q_t^0 = \omega s_t$ is reached for $s_t > s^*$. At the same time, the seller's profit maximization also defines a supply level that increases with the stock level for reasons similar to the Hotelling rule. Thus, for large stock levels, whether the sellers prefer to sell more than needed to prevent the buyer from investing, or whether the buyer's indifference condition determines supplies, for large stocks, supplies will initially fall when the stock is depleted. ■

Condition (28) can be seen as a restriction on rk, the cumulative discount rate over the entire transition time. For $rk = 0$, LHS=RHS=0 in (28). For $rk \downarrow 0$, the LHS derivative w.r.t. rk becomes infinite (the LHS is proportional to $\sigma(\frac{rk}{1-\sigma})^\sigma$), while the RHS becomes proportional to $\frac{rk\sigma}{1-\sigma}$, thus the inequality holds. For rk large, the LHS converges to σ, while the RHS converges to 1, thus the inequality fails. If either the discount rate r or transition time k is sufficiently large, investment will take place immediately without any time interval of strategic interaction. In terms of the equations, this can be seen as follows. When (28) comes close to an equality, the denominator of s^* in (29) goes to zero, and so s^* goes to infinity.

The proposition in text is now proved by Lemmas 3-5.

References

[1] Bergemann, D., and J. Välimäki (1996), Learning and Strategic Pricing, Econometrica, Vol. 64, No. 5, pp. 1125-1149.

[2] Gallini, N., T. Lewis, and R.Ware (1983), Strategic Timing and Pricing of a Substitute in a Cartelized Resource Market, The Canadian Journal of Economics, Vol. 16, No. 3., pp. 429-446.

[3] Hirsch, R.L., R., Bedzek, and R. Wendling (Feb. 2005), Peaking of World Oil Production: Impacts, Mitigation, and Risk Management, report prepared for the U.S. Department of Energy, www.netl.doe.gov/publications/others/pdf/Oil_Peaking_NETL.pdf

[4] Hoel, M. (1983), Monopoly Resource Extraction under the Presence of Predetermined Substitute Production, Journal of Economic Theory 30, 201-212

[5] Hotelling, H. (1931), The economics of exhaustible resources, *Journal of Political Economy* 39, 137-175.

[6] Dasgupta, P., R. Gilbert, and J. Stiglitz (1983), Strategic Considerations in Invention and Innovation: The Case of Natural Resources, Econometrica 51, 1439-1448.

[7] Dasgupta, P., Heal, G., (1974) The optimal depletion of exhaustible resources. *Review of Economic Studies* (Symposium), 3-28.

[8] Dutta, P. (1991), What Do Discounted Optima Converge To? A Theory of Discount Rate Asymptotics in Economic Models, *Journal of Economic Theory* 55, 64-94.

[9] Felli, L., and C. Harris (1996), Learning, Wage Dynamics, and Firm-Specific Human Capital , *Journal of Political Economy*, vol. 104, no. 4.

[10] Gaudet, G., Natural resource economics under the rule of Hotelling, *Canadian Journal of Economics*, 40(4), 1034-1059

[11] Gerlagh, R., and M. Liski (2007), Strategic Oil Dependence, HECER discussion paper no. 165.

[12] Gilbert, R. (1978), Dominant Firm Pricing with Exhaustible Resources, *Bell Journal of Economics* 9, 385-395.

[13] Harris, C., and J. Vickers (1995), Innovation and Natural Resources: A Dynamic Game with Uncertainty, The RAND Journal of Economics 26, 418-430.

[14] J. Hörner, and M. Kamien (2004), Coase and Hotelling: A Meeting of the Minds, *Journal of Political Economy*, vol. 112, no. 3.

[15] Karp, L. and D. Newbery (1993), Intertemporal Consistency Issues in Depletable Resources, In *Handbook of Natural Resource and Energy Economics* vol. 3, A.V. Kneese and J.L. Sweeney (Eds.), Amsterdam, North Holland.

[16] Krautkraemer, J. (1999). Nonrenewable resource scarcity. *Journal of Economic Literature* XXXVI, 2065-2107.

[17] Lewis, T., R. Lindsey, and R. Ware (1986), Long-Term Bilateral Monopoly: The Case of an Exhaustible Resource, The RAND Journal of Economics, Vol. 17, No. 1., pp. 89-104.

[18] Lewis, T. and R.Schmalensee (1980), On oligopolistic markets for nonrenewable resources, *Quarterly Journal of Economics* 95, 475-491.

[19] Loury, G. (1986), A theory of 'oil'igopoly: Courtnot–Nash equilibrium in exhaustible resources markets with fixed supplies. *International Economic Review* 27, 285–301

[20] Maskin; E., and D. Newbery (1990), Disadvantageous Oil Tariffs and Dynamic Consistency, The American Economic Review 80, No. 1 , pp. 143-156.

[21] Nordhaus; W.D. (1973), The Allocation of Energy Resources, *Brookings Papers on Economic Activity* 1973 (3): 529-570.

[22] Polansky, S. (1992), Do oil producers act as 'oil'ilopolists?, *Journal of Environmental Economics and Management* 23, 216–247.

[23] Salant, S.W. (1976), Exhaustible resources and industrial structure: A Nash-Cournot approach to the world oil market, *Journal of Political Economy* 84, 1079-1093.

[24] Salo, S., and O. Tahvonen (2001), Oligopoly equilibria in nonrenewable resource markets, *Journal of Economic Dynamics and Control,* Volume 25, Issue 5, 671-702

[25] Simmons, M.R. (2005), Twilight in the Desert: The Coming Saudi Oil Shock and the World Economy.

[26] Stern, Nicholas, "The economics of climate change: the Stern review", Cambridge, UK: Cambride University Press, 2006.

[27] Tahvonen, O., and S. Salo (2001), Economic growth and transitions between renewable and nonrenewable energy resources, *European Economic Review* 45, 1379-1398.