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STRATEGIC CONSIDERATIONS IN INVENTION AND INNOVATION: THE CASE OF NATURAL RESOURCES

BY PARTHA DASGUPTA, RICHARD GILBERT, AND JOSEPH STIGLITZ[1]

Strategic considerations may induce a resource importing country to invent a substitute earlier than it intends to put it to use. There are also circumstances in which it would wish to delay an invention date even if it could obtain it at an earlier date at no extra cost. Similar paradoxical results obtain if resource cartels behave strategically. Setting prices high may be a way of deterring invention. If those engaged in R & D are not resource users, and the cartel has access to similar R & D technology, it will pre-empt rivals. This may not be the case if resource users can also engage in R & D.

1. INTRODUCTION

COST BENEFIT STUDIES of research and development (R & D) programs for alternative energy sources (e.g., National Research Council [6]) typically ignore strategic considerations, in particular the fact that the choice of an R & D program influences the decisions of resource owners, and thereby the current energy market. In this article we present a framework for analyzing such interactions.

Towards this we consider the simplest of technological environments. We suppose that there is a single-grade of an exhaustible natural resource and a potential manufacturing process (a "backstop" technology) which, if developed, will enable a perfect substitute to be produced at constant unit cost. To have an interesting problem we suppose, as is realistic, that unit extraction cost is less than the unit cost of production with the new technology once development has been completed. We suppose further that the entire resource stock has been cartelized, and that the cartel's market is restricted to a single consumer which we shall refer to as the importing country. We ignore uncertainty entirely, so that we may highlight strategic interactions. In particular, we model the R & D technology as a deterministic function relating capitalized expenditure at the initial date to the date development is completed—the latter date being nearer, the larger is capitalized expenditure.[2]

In the next section we shall analyze optimal R & D programs for the importing country. For simplicity of exposition we shall suppose there that the importing country's government faces no rivals in R & D, and that it makes the first move; in doing so it takes into account the cartel's response to its R & D strategy. Quite clearly, the nature of the intertemporal equilibria depends on which agents have access to the R & D technology, what is the order of moves, and what kinds of

[1] In preparing this article we have benefited greatly from the comments of Nancy Gallini and the Editors and from financial support from the National Science Foundation. Gallini et al. [3] have independently developed an analysis similar to the one presented in Section 2.

[2] This is often called a "time-cost" curve in the R & D literature. See, e.g., Mansfield et al. [5].

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commitments it is possible to undertake. In Section 3, therefore, we comment briefly on the implications of alternative assumptions regarding this.

2. R&D STRATEGY FOR AN IMPORTING COUNTRY

2.1. *The Model*

The model is partial equilibrium. A foreign cartel is assumed to own the entire stock of an exhaustible natural resource, which is costless to extract. Remaining reserves at date $t(\geq 0)$ are denoted by S_t, and it is supposed that the initial stock, S_0, is known. The importing country is the sole demander of the resource and the market demand in this country at each date for the flow of the resource is given by the continuously differentiable function $Q = f(p) \geq 0$, where p denotes the resource price. It is assumed that $f'(p) < 0$, and we write $p(Q) \equiv f^{-1}(Q)$. We suppose, for expositional ease, that the elasticity of demand is a nonincreasing function of output. Write $R(Q) = Qp(Q)$ as the revenue function and $m(Q) \equiv R'(Q)$ for marginal revenue. In what follows we suppose that $R(Q)$ is strictly concave in Q. The social rate of discount in the importing country is taken to be a positive number, r. For simplicity of exposition we take it that the cartel uses r in discounting its profits (rents).

We shall suppose that the government of the importing country finances its R&D expenditure through general taxation. Once development is completed the backstop technology will enable a perfect substitute to be produced at unit cost $C(> 0)$. We assume that $p(0) > C$. We also assume that the government will not be engaged in production, but will make the new technology publicly available. Thus, the sector producing the substitute will be perfectly competitive.

We turn finally to the R&D technology. Assume that there is a monotonically decreasing and continuously differentiable function $X(T)$, with $X(T) > 0$ for all $T \geq 0$, which has the interpretation that completion of R&D at date T requires a commitment of capitalized expenditure $X(T)$ at date $t = 0$.[3] For expositional simplicity assume $X(0) = \infty$ and $X(\infty) = 0$.

The importing nation's payoff is the present discounted value of the flow of its net social surplus. The government makes the first move by announcing the date development will be completed. By hypothesis the announcement is credible because it is backed by R&D commitment. The cartel makes the second move by announcing its extraction policy. The cartel's payoff is the present discounted value of the flow of profits. The importing nation behaves stategically by taking the cartel's response into account when choosing its R&D policy. Let $U(Q) = \int_0^{\infty} p(Q')\,dQ'$, and let Y_t denote output of the substitute at t. It follows that

[3]This is the simplest possible characterization of an R&D technology. (See Dasgupta and Stiglitz [1] for this and some generalizations.) It implicitly supposes that T is a deterministic functional of the time path of the flow of R&D expenditures x_t (for $0 \leq t \leq T$), say $T = F(\{x_t\})$. Then we may define $X(T)$ as:

$$X(T) \equiv \min_{\{x_t\}} \int_0^T e^{-rt} x_t\,dt, \qquad \text{subject to} \quad T \geq F(\{x_t\})$$

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equilibrium of this two-move game can be obtained by solving the following constrained optimization problem:

$$\underset{T,\,Y_t \geq 0}{\text{maximize}}\left[\int_0^T U(\tilde{Q}_t(T))e^{-rt}\,dt + \int_T^\infty \left[U(\tilde{Q}_t(T)+Y_t)-CY_t\right]e^{-rt}\,dt - X(T)-\pi\right]$$

(1) where $\tilde{Q}_t(T)$ maximizes

$$\int_0^T R(Q_t)e^{-rt}\,dt + \int_T^\infty \min\{R(Q_t), CQ_t\}e^{-rt}\,dt = \pi$$

$$\text{subject to} \quad \int_0^\infty Q_t\,dt = S_0, \quad Q_t \geq 0.$$

2.2. *Optimal R & D*

We first consider the cartel's response, that is, the suboptimization problem in (1). Let $\overline{Q}(>0)$ solve $p(Q)=C$, and let $T_3(\leq\infty)$ denote the date at which the cartel would exhaust its stock if $T=\infty$. (T_3 is the earliest date of invention for which the cartel is unconstrained. $T_3<\infty$ if the demand curve has a choke-off price.) Let $\mu(T)$ denote the multiplier associated with the resource constraint in (1). Routine control theoretic arguments can then be used to establish that there exists a date T_1 (with $T_3>T_1>0$) and, for each T there is a date $\tilde{T}$ (with $T_3>\tilde{T}>T_1$), such that:

(2) $$m(\tilde{Q}_t(T)) = \mu(T)e^{rt} \quad \text{for} \quad 0 \leq t < T^*,$$

$$\text{where} \quad T^* = \min\{\max\{T_1, T\}, T_3\}$$

$$\left(T^* = \min\{T, T_3\} \text{ if } m(\overline{Q}) < \mu(T)e^{r\min\{T,T_3\}}\right);$$

(3) $$\tilde{Q}_t(T) = \overline{Q} \quad \text{for} \quad T^* \leq t \leq \tilde{T}, \quad \text{with} \quad \mu(T)e^{r\tilde{T}} = C;^{4} \quad \text{and}$$

(4) $$\tilde{Q}_t(T) = 0 \quad \text{for} \quad t > \tilde{T}$$

($\tilde{T}$ is the date of resource exhaustion.)

In words, if $T \leq T_1$ marginal revenue rises at the rate r until T_1, at which date price equals C, after which it remains at C. If $T_1 < T < T_3$ marginal revenue rises at the rate r until T, at which date price falls discontinuously to C. (At T there may or may not be any remaining reserves. See below.) If $T \geq T_3$, marginal

[4] We shall note presently that there exists a date T_2 ($T_1 < T_2 < T_3$) such that if $T \geq T_2$, then $\tilde{T} = T^*$; that is, if $T \geq T_2$, then the cartel does not pursue the extraction phase characterized by (3).

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revenue rises at the rate r until T_3 at which date reserves are exhausted, and the market is inoperative during (T_3, T).

Hoel [4] has analyzed the cartel's response to our problem for the case $T = 0$. He has shown that if $-f'(p)p/f(p) > 1$ at $p = C$, there exists $\hat{S}$ such that if $S_0 > \hat{S}$, then $T_1 > 0$ and $S_{T_1} > 0$. For concreteness we shall assume that this is so.[5] It is then obvious that the cartel's response is invariant to T if $0 \leq T \leq T_1$. From this we may conclude that the importing nation will choose $T \geq T_1$.

Since $S_{T_1} > 0$, it follows by continuity of the state variable that $S_T > 0$ if T is slightly larger than T_1. Condition (3) implies then that *for T slightly larger than T_1*

$$\mu(T)e^{rT} = Ce^{-rS_T/Q}, \tag{5}$$

and (2) implies that

$$S_T = S_0 - \int_0^T m^{-1}\left(\mu(T)e^{rt}\right)dt. \tag{6}$$

From (5) and (6) we can therefore conclude that

$$\int_0^T m^{-1}\left(\mu(T)e^{rt}\right)dt + (\bar{Q}/r)\log(C/\mu(T)) = S_0 + \bar{Q}T. \tag{7}$$

Differentiating (7) with respect to T, and writing $q(\cdot) \equiv m^{-1}(\cdot)$, we have

$$\tilde{Q}_T^-(T) + \int_0^T \mu'(T)e^{rt}q'\left(\mu(T)e^{rt}\right)dt - (\bar{Q}/r)\,\mu'(T)/\mu(T) = \bar{Q}, \tag{8}$$

where $\tilde{Q}_T^-(T) \equiv \lim_{t \to T-0} \tilde{Q}_t(T)$. But $\tilde{Q}_T^-(T) < \bar{Q}$, from (2) and (3). Therefore (8) implies that $\mu'(T) < 0$. From (2) it follows that $d\tilde{Q}_t(T)/dT > 0$, and therefore that $dS_T/dT < 0$. In fact, from (5) and (6) it follows that there exists a negative number, $-\delta$, such that

$$-\delta > dS_T/dT > -Q. \tag{9}$$

Since (9) implies that dS_T/dT is bounded away from zero, we can conclude that there exists a date T_2, such that $S_T = 0$ if $T \geq T_2$, and $S_T > 0$ if $T < T_2$. This means that $\tilde{T} = \min\{T, T_3\} \equiv T^*$ if $T \geq T_2$, and $T_2 > \tilde{T} > T$ if $T < T_2$. Furthermore, $\tilde{T}$ is increasing in T in the interval (T_1, T_2).[6]

We have established the somewhat surprising result that $\mu(T)$—and hence the initial price $p(Q_0(T))$—is decreasing in T, and $\tilde{Q}_t(T)$ is increasing in T in the interval (T_1, T_2). It is simple to check that $\mu(T)$, and hence $p(Q_0(T))$, is increasing (and therefore $\tilde{Q}_t(T)$ is decreasing) in T if $T_3 \geq T > T_2$. (By defini-

[5] The remaining possibilities can similarly be analyzed, but we wish to avoid a complete taxonomy here.

[6] To see this, note that if $T < T_2$, then $\tilde{T} = T + S_T/\bar{Q}$. Thus $d\tilde{T}/dT = 1 + (dS_T/dT)/\bar{Q} > 0$, on using (9).

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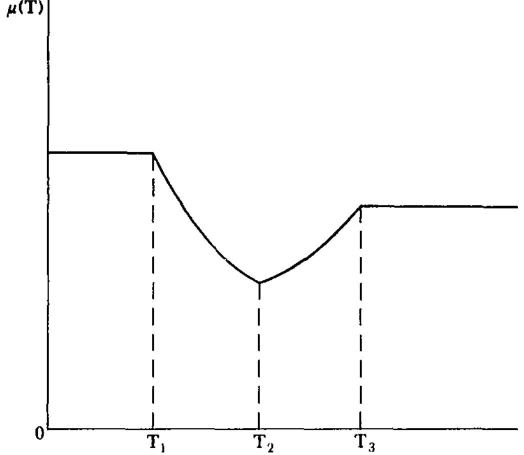

(T3=∞ if demand function does not have choke off price)

FIGURE 1.

tion of T_3, $\mu(T)$ and $\tilde{Q}_t(T)$ are invariant to T if $T \geq T_3$.) Thus $\mu(T)$ attains its minimum value at $T = T_2$. (See Figure 1.)[7] The intuition behind this result is easy to see. Let $T_1 < T < T_2$. We know that $S_T > 0$. Now suppose that the invention date is delayed slightly, say, to $T + \Delta T$, but suppose that the cartel does not alter its initial price in response to this change. Then, by (2) and (3) the amount sold by date $T + \Delta T$ would be slightly less than on the initial trajectory. Therefore, the date of exhaustion, $\tilde{T}(T + \Delta T)$, would be slightly later. The present value of the marginal revenue at that date is $Ce^{-r\tilde{T}}$, and this is smaller than it previously was. But by hypothesis, marginal revenue at $t = 0$ remains the same. To restore equality the cartel must lower its initial price slightly, by an amount which is sufficiently small that $\tilde{T}$ remains larger than it originally was.

Turning now to the importing country's optimization problem in (1) we note first that optimal Y_t is the form: $Y_t = 0$ for $0 \leq t \leq \tilde{T}$ and $Y_t = \bar{Q}$ for $t > \tilde{T}$ if $T \leq T_3$; $Y_t = 0$ for $0 \leq t < T$ and $Y_t = \bar{Q}$ for $t \geq T$ if $T > T_3$. We note next that if $T < T_2$ there is a lag between the date at which development is completed and the date at which it is brought into line. But if $T \geq T_2$ the invention is brought into line the day development is completed. *We now show that, provided that technological possibilities are favorable, it is optimal for the importing country to choose T in the interval* (T_1, T_2); *that is, it is optimal to complete development of the backstop technology before the cartel plans to exhaust its reserves.* Naturally, advancing the completion date increases R&D costs. Nevertheless, such "crash

[7]Note that $\mu(T)$ is differentiable everywhere except at T_1, T_2, and T_3.

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programs" can be optimal precisely because they are a *credible* means of forcing the cartel to pursue a more favorable intertemporal pricing policy.

To confirm this, suppose that optimum $T \leq T_3$. Since we know that $T \geq T_1$, we may use (2) and (3) to re-express the importing country's objective as

$$\text{(10)} \qquad \underset{T \geq T_1}{\text{maximize}} \left[\int_0^T V(\tilde{Q}_t(T)) e^{-rt}\, dt + V(\bar{Q}) e^{-rT}/r - X(T) \right],$$

$$\text{where} \quad V(Q) \equiv U(Q) - p(Q))Q$$

Notice first that even if $X''(T) > 0$, (10) is not necessarily concave in T. However, on the assumption that optimum $T \in (T_1, T_3)$ and does not equal T_2, it must satisfy the social cost-benefit rule:

$$\text{(11)} \qquad \int_0^T V'(Q_t(T)) \left[d\bar{Q}_t(T)/dT \right] e^{-rt}\, dt + \left[V(\tilde{Q}_T^-(T)) - V(\bar{Q}) \right] e^{-rT}$$

$$= X'(T).^8$$

The first term on the left-hand side of (11) yields the effect of a delay in the date of R&D completion on social surplus generated in the importing country before that date. We have seen that it is positive if $T_1 < T < T_2$, and is negative if $T_2 < T < T_3$. (For $T \geq T_3$ it is zero.) However, each additional moment's delay results in a loss in social benefits due to the fact that market price just before this date exceeds C (i.e., $p(\tilde{Q}_T^-(T)) > C$). The second term on the left-hand side of (11) is negative, and measures this loss. The sum of these two effects must equal the R&D expenditure saved because of this delay, which is the right-hand side of (11). In Figure 2 we have drawn the *gross* benefit function of the importing country (the first two terms in (10)). We have seen that its slope is negative for $T > T_2$. It is simple to confirm that its slope is negative if T is slightly less than T_2. It follows that by suitably choosing $X(T)$, and therefore the right-hand side of (11), we can ensure that optimum T is less than T_2, establishing the result we have emphasized above. But note that the gross benefit function is *positively* sloped in a neighborhood to the right of T_1. This implies that optimal T is outside this neighborhood. What this means is that there is a precise sense in which one may have an invention too early. *It pays the importing country to delay making the invention until sometime after* T_1, *not only because it saves on R & D costs but also, somewhat paradoxically, because it benefits from a more favorable pricing policy on the part of the cartel.* One notes in particular that in this interval a delay in the completion date is beneficial to *both* parties.

[8] Expression (10) is not differentiable at T_1, T_2, and T_3, although right and left derivatives exist. If optimum T exceeds T_3 and is finite, it must satisfy the cost-benefit rule:

$$-\left[V(\bar{Q}) - V(0) \right] e^{-rT} = X'(T)$$

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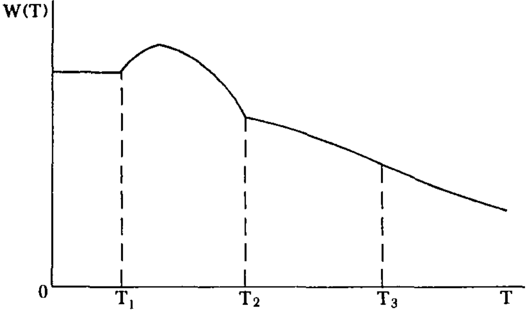

FIGURE 2.

$(W(T) \equiv \int_0^T V(Q_t(T))e^{-rt}\,dt + V(\bar{Q})e^{-rT}/r$ if $T \leq T_3$; and
$W(T) \equiv \int_0^{T_3} V(\tilde{Q}_t(T))e^{-rt}\,dt + \int_{T_3}^{T} V(0)e^{-rt}\,dt + \int_T^{\infty} V(\bar{Q})e^{-rt}\,dt$ if $T \geq T_3$.)

2.3. *Optimal Taxation and R & D*

Suppose that the importing country has an additional control: the taxation of resource imports. If, as we have been assuming so far, the importing country moves first, it can impose a 100 per cent advalorum tax, and thereby appropriate *all* rents from the cartel. If, in addition, demand is iso-elastic (with elasticity greater than unity), marginal revenue is proportional to price, and so the equilibrium outcome is equivalent to the optimum resource extraction and R & D program in a centrally planned economy. (For an analysis of this last, see Dasgupta et al. [2].) But if demand is not iso-elastic then, even though all rents can be appropriated by the importing country, it cannot enforce the optimal intertemporal allocation of the exhaustible resource.

The matter is a great deal more complex if the cartel has the first move. The extent to which it can avoid being taxed depends on the means there are at its disposal for making retaliations credible.

3. DETERRENCE AND PRE-EMPTION

The preceding analysis was based on the hypothesis that the government of the importing country had sole access to the R & D technology, and that it made the first move. In this section we briefly discuss the implications of dropping each of these hypotheses.

Begin by dropping the second hypothesis.[9] Suppose the cartel can, at date $t = 0$, commit itself to any sales path over the interval $[0, \hat{T}]$. We take it that $\hat{T} < T_1$, to capture the fact that futures contracts extend only for short periods.

[9]We revert to the construct of Section 2.2 and suppose that the only control available to the importing country is R & D.

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Consider the case where the cartel and the importing country move simultaneously.[10] Suppose $T > T_1$. (We shall see that (Nash) equilibrium T exceeds T_1.) Given T, it is simple to calculate the cartel's response: it is the solution of the sub-optimization problem of (1). This yields $S_{\hat{T}}(T)$, the remaining reserves at $\hat{T}$. It remains to analyze the importing country's response. From the analysis presented in Section (2.2) we may infer that (Nash) equilibrium T will not be less than T_1. If the cartel does commit itself to a sales policy during $[0, \hat{T}]$ the importing country cannot influence the cartel's extraction of its remaining reserves in this period, but it can from $\hat{T}$ onwards. It follows that if equilibrium $T \leq T_3$ the importing country's problem is:

$$\text{(12)} \qquad \underset{T \geq T_1}{\text{maximize}} \left[\int_{\hat{T}}^{T} V(\tilde{Q}_t(T)) e^{-rt}\, dt + V(\bar{Q}) e^{-rT}/r - X(T) \right],$$

subject to $S_{\hat{T}}$ being available at $\hat{T}$.

The solution of (12), assuming it to be unique, yields the reaction function of the importing country. Let T_n be the Nash equilibrium date of invention.[11] It can be shown that if $T_n < (>) T_2$, then T_n is less than (greater than) the optimum date of invention in the model of Section 2.2. But this means that if $T_n < T_2$, the cartel would prefer to follow rather than move simultaneously—or in other words, prefer not to bind itself to any contract for the period $(0, \hat{T})$. In this case the equilibrium outcome would be the same as the one in Section 2.2.

Let us now drop the hypothesis that the importing country has sole access to the R&D technology. To begin with, continue to assume that the *cartel's* R&D technology is vastly inferior to its rivals', so that it does not enter the R&D race. In order to assess the incentives for developing the substitute product two broad categories of agents must be distinguished: resource *users* and R&D firms. By the latter we mean firms that are not resource users themselves. Such a firm is indifferent to the cartel's current pricing policy, except insofar as it influences the size of remaining reserves at the date the firm's R&D program is completed—the value of the invention to the firm being smaller, presumably, the larger are remaining reserves. Resource *users*, on the other hand, *do* care about the cartel's current extraction policy, as expression (10) makes clear. In Section 2.2 we analyzed the incentives that a particular type of resource user (an importing country) has for developing a substitute product. Consider now by way of contrast the case where there is a patent race *only* among R&D firms, with the winner taking all. For concreteness, we may suppose that the cartel makes the first move and commits itself to an extraction policy, and that this is followed by R&D competition. If reserves are positive at the date the patent is awarded, the market at the date is one of duopoly. Let $Z(S_T)$ be the present value of profits to the patent winner at T if S_T denotes remaining reserves at T. Suppose that free-entry among R&D firms results in zero profit as an equilibrium condition.

[10] The analysis for the case where the cartel moves first can likewise be developed.

[11] It is clear that if $\hat{T} = 0$ the present model reduces to the one in Section 2.2.

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Then equilibrium T must be the smallest solution of the equation:

$$Z(S_T)e^{-rT} = X(T). \quad (13)$$

It is natural to assume that $Z'(S) < 0$. This and (13) imply that, contrary to what is often thought, a high price for a resource today does not imply that the incentives among R&D firms to invent a substitute is high. *R&D deterrence involves the cartel maintaining a high price for its resource.* Indeed, it is a simple matter to confirm that equilibrium in this game involves a higher resource price than would have prevailed in a market where there is no threat of entry by R&D firms. But the welfare effects are ambiguous, since resource price after the invention is lower.

Now suppose that the cartel also has access to the R&D technology, but continue to assume that no resource *user* can engage in R&D. In this case it is easy to see that the cartel will pre-empt its rivals and win the patent.[12] The reason is this. For any given level of remaining reserves the cartel's combined profits from resource sales and substitute production (were it to win the patent) exceeds the sum of the profits accruing to it from resource sales and to the patent winner from substitute production (were the cartel not to win the patent). It follows that given any level of remaining reserves the cartel makes positive profits at all R&D levels for which rivals earn zero profit.

If the cartel can engage in R&D it has two sets of controls to deter rivals: the resource price and R&D expenditure. One might conjecture that the cartel resorts less to the former if pre-emptive patenting is an option. It is a simple matter to confirm this intuition if demand is iso-elastic and the initial stock is "large." In such a situation a market in which the cartel can engage in R&D has prices lower at all dates prior to the date of invention. Invention and innovation both occur earlier than in the case where the cartel cannot compete in R&D. Moreover, the dates of R&D completion and innovation do not coincide: there are "sleeping patents."

The argument establishing pre-emptive patenting on the part of the cartel does *not* hold if resource *users* also have access to the R&D technology. The cartel's combined profits from resource sales and substitute production do not necessarily exceed the sum of benefits accruing to it from resource sales and the benefits to the patent winner if the winner is a resource user. In particular, the payoff to the resource user from making the invention depends not only on the size of remaining reserves at the date development is completed, but also on the cartel's pricing policy prior to this date.

4. CONCLUSIONS

Strategic considerations are clearly central to the design of R&D policies by resource importing countries and to the determination of extraction policies by

[12] The general argument is given in Dasgupta and Stiglitz [1].

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resource cartels. Yet national energy studies rarely take them into account. In this article we have attempted to provide a framework for such an analysis. Strategic considerations may induce a resource user (e.g. an importing country) to complete the development of the substitute product at a date earlier than the date at which it intends to introduce it, even though this involves additional R & D expenditure. Concomitant with this are circumstances in which an importing country deliberately delays R & D completion, *even* if it could complete at an earlier date at no extra cost, because such a delay induces the cartel to *lower* its price at all dates prior to R & D completion.

Similar paradoxical results obtain if the resource cartel behaves strategically. The threat of the development of a substitute by R & D firms induces the cartel to *raise* its price and, if the cartel also has access to a similar R & D technology, it pre-empts its rivals, thereby maintaining its monopoly position. This pre-emption argument, however, does not carry over if resource users compete in the R & D race.

London School of Economics,
University of California, Berkeley,
and
Princeton University

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