# THE JAMES A. BAKER III INSTITUTE FOR PUBLIC POLICY OF RICE UNIVERSITY

## JAPANESE ENERGY SECURITY AND CHANGING GLOBAL ENERGY MARKETS:
### *AN ANALYSIS OF NORTHEAST ASIAN ENERGY COOPERATION AND JAPAN'S EVOLVING LEADERSHIP ROLE IN THE REGION*

## OIL AND STRATEGIC DEVELOPMENT OF SUBSTITUTE TECHNOLOGY

KAZ MIYAGIWA
*ASSOCIATE PROFESSOR OF ECONOMICS*
*LOUISIANA STATE UNIVERSITY*

AND

YUKA OHNO
*ASSISTANT PROFESSOR OF ECONOMICS*
*RICE UNIVERSITY*

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# 1. Introduction

Japan is a resource poor country and relies heavily on imports to satisfy its energy demand. The majority of Japan's oil imports (81 percent) come from countries that are members of the Organization of Petroleum Exporting Countries (OPEC). Japan's overwhelming dependence on OPEC for energy supplies poses serious economic and political risks. When OPEC promotes high oil prices, it is a burden to Japan's economy and balance of trade. Japan also has to worry about the occasional threat of oil disruptions that enhance OPEC's monopoly power and cause oil price volatility.

One way to combat the monopoly power exercised by OPEC is to develop a substitute technology such as nuclear fusion or fuel cell energy supply. However, inventing a substitute technology can be quite expensive and risky. There is no guarantee that a new technology can produce energy more cheaply than oil. These considerations have led some policymakers and opinion leaders to question the economic validity of R&D projects in search of substitute technologies. They argue that R&D projects are too costly relative to the cost savings due to the invention of a substitute technology because oil is not expensive enough to render the new technology commercially profitable. For this reason, policy makers often argue that R&D projects should remain on hold until oil becomes so expensive that R&D becomes a vital necessity, presumably some time in the future.

In this paper, we point out that there is a dramatic and important additional benefit of starting R&D projects immediately. We argue that the impact of developing new energy technologies has immediate positive consequences. If this benefit is taken into the standard cost-benefit analysis, R&D projects that are regarded as too expensive today may, in fact, make economic sense.

Where is this additional benefit? It comes because a substitute technology can lower the oil price before it is actually invented or utilized. We intend to show through our theoretical development the following logic regarding the benefit of substitute technology. It is well understood that a substitute technology could potentially decrease Japan's dependency on OPEC. A very successful technology could even obviate importing oil altogether. Therefore, OPEC, if rationale, will want to sell as much oil as possible before a substitute technology is invented. To sell more oil, however, OPEC will have to lower its price. Thus, R&D projects started today can influence OPEC’s decision process by prompting the organization to lower its prices today, well before any research is finished. Japan, then, benefits from this lower oil price.

If R&D can yield such benefits to Japan, the question might be raised: who should be doing R&D? Should it be undertaken as a government project or should it be left to the private sector? In this respect we are inclined to favor the private sector. Here is why.

Suppose that a firm in the private sector conducts R&D research. As we pointed out above, the R&D research lowers the oil price immediately but the benefit accrues to Japanese consumers, not to the firm. Thus, the firm does not consider this benefit when figuring out how much to invest in R&D. Rather, the firm’s investment decision is based only on the revenue it can earn once the technology is innovated. In contrast, the government agency is concerned with social surplus, and internalizes the beneficial effect of lower oil prices today. Put this way, it might appear that the government is in a better position than the private firm to respond to OPEC’s pricing strategy. However, we demonstrate that R&D may limit OPEC’s monopoly power if better implemented by a private firm. The government loses some of the power to influence the oil price precisely because it is concerned with social welfare before the invention of a substitute technology. Thus, we conclude that the Japanese government should leave R&D to the private sector and promote it indirectly with R&D subsidies.

## 2. A Simple Cost-Benefit Analysis of the Substitute Technology

Most nations generate their incomes from production of goods and services. Since the stock of capital and labor that are used in production do not change much over time, incomes from one year to another can be regarded more or less unrelated. That is not the case with OPEC however. Unlike most nations OPEC derives its incomes almost entirely from selling oil to foreigners. Since it has the limited stock of oil, selling more oil to generate more income today leaves OPEC less oil to sell and less income to live on in the future. Thus, OPEC's current and future incomes are negatively related, and its pricing strategy is inherently dynamical.

In this section we present a simple analysis showing how OPEC sets its oil price in a dynamic setting, and examine the way an R&D project can affect the oil price today. In doing so it is convenient to ignore all other countries and focus on strategic interactions between OPEC and Japan. We also assume for simplicity that OPEC can extract each unit of oil at the constant cost, C.

Begin with the simple identity.

Total income ≡ current income + future income

≡ current revenue - current cost + future income.

Exporting one more unit of oil today increases the current revenue and the current cost of extraction. OPEC's future income falls, however, because it has a unit less oil to sell in the future. Under the optimal pricing strategy OPEC balances these benefits and the costs at the margin, that is, it sets the price such that the following equality holds:

an increase in current revenue

= an increase in current cost + a decrease in future income.

An increase in current revenue is called marginal revenue. An increase in current cost is called marginal cost and equals just C in the present analysis. A 'decrease in future income' is known as the shadow price of oil and represents the true value of oil. Using these terms we can rewrite OPEC's optimal pricing rule as:

(1) marginal revenue = marginal cost of extraction + shadow price of oil.

The optimal price is illustrated in Figure 1. In the figure the line D is Japan's demand for oil and the line MR is marginal revenue. The marginal cost is constant at C. The shadow price of oil increases when its current oil sales increase because the oil reserve is being depleted more quickly. This explains why the shadow price of oil is rising. OPEC sets its current level of oil exports so that the MR line intersects the (C + shadow price) curve. The monopoly price is read off the demand curve at $P^m$. In contrast, if the oil market is competitive, the oil price will be at $P^c$, where the (C + shadow price) curve meets the demand curve D. This price difference reflects OPEC’s monopoly power.

Suppose that Japan’s demand for oil is stable over time. Then marginal revenue is also stable. Since the marginal cost of extraction is constant, the only term that changes over time is the shadow price of oil. Oil becomes more valuable as its reserve is depleted so the shadow price of oil must increase over time. Accordingly, the actual price of oil increases over time. In fact, the monopoly price of oil follows the well-known rule called the Hotelling’s (1931) principle, increasing over time at the rate equal to the rate of interest.

Having described how OPEC sets its monopoly price, we now turn to discussing the effect of R&D for a substitute technology. When the technology is invented, the value of oil decreases (probably to zero). As discussed in the Introduction, the possibility of invention of a substitute technology lowers the shadow price of oil today, shifting down the "C + shadow price" curve as in Figure 2, resulting in a lower oil price today. The falling oil price increases Japan’s consumer surplus (shaded area in Figure 2) before a substitute technology is invented. This represents the additional benefit of R&D noted in the Introduction.

When the additional benefit is taken into account, the total value of an R&D project reads:

(2) total value of R&D project

= increase in consumer surplus due to lower oil price (before invention)

+ value of new technology (after invention).

The first term can be very large because it sums up all the shaded trapezoids in Figure 2 from now until the day a substitute technology is invented.

A substitute technology need not be cost effective to affect today's oil price. Consider the following example. Suppose that Japan conducts R&D and expects to invent a substitute technology in five years. Then the future price of oil and the cost of oil production (including the shadow price) can be estimated from the expected stock of oil existing five years from now. Let $P^c$ in Figure 1 be the expected cost of oil production in five years.

Suppose that the new technology can produce an alternative energy at the unit cost $C^a$. If $C^a$ exceeds $P^c$, the new technology cannot compete with oil when it is invented. It will remain unused for a long time until the price of oil exceeds $C^a$. Even so, the new technology can benefit Japan. To see this, suppose that $C^a$ is lower than today's monopoly price $P^m$. Then when the new technology becomes available, OPEC will have to lower the price to $C^a$ to stop the substitute technology from being adopted. In short, even if unlikely to be adopted immediately at the time of invention, a substitute technology is beneficial to Japan.

The next issue concerns the timing of initiating R&D projects. Should we begin an R&D project immediately or wait until the oil price rises high enough to make the new technology cost-effective at the time of invention? On this account we favor beginning R&D right away, even for a substitute technology that is unlikely to be used at the time of invention. There are three reasons why. First, OPEC has to compete with a substitute technology when it is invented. This future impact affects the shadow price of oil and lowers the oil price today. Second, once a substitute technology is invented, OPEC has to keep the oil price low enough to prevent adoption of the technology. Third, as the stock of oil depletes the new technology will eventually be adopted and benefit society by providing an alternative energy.

The next question is: which substitute technology should Japan choose if it has options? The answer depends on the effect of each option on the shadow price of oil. The shadow price will fall more if a substitute technology can provide alternative energies more cheaply. Therefore Japan should concentrate on developing the technology that can provide energy most inexpensively once it becomes available.

The final issue we address is who should be doing R&D. In the Introduction we argued that R&D conducted by the private sector has a greater impact on today's oil price than by the government. We also gave an intuitive explanation there. Demonstrating this result formally however requires a dynamic model of interactions between Japan and OPEC. We do this in the next section.

# 3. Strategic Development of the Substitute Technology: A Formal Analysis

This section presents a formal analysis of strategic development of a substitute technology. Dynamic interactions between Japan and OPEC are modeled as a dynamic game in an infinite-horizon discrete-time setting. Time is indexed by t. Within a period t = 1, 2,.., Japan and OPEC make their moves simultaneously. OPEC chooses the volume of oil exports and Japan a level of investment in R&D to invent a substitute technology. The both countries discount future values at the common discount factor $\delta < 1$.

The R&D process is uncertain. It is known however that investing the amount $k_t$ in R&D generates probability $h(k_t)$ of success at time t, conditional on the substitute technology not having been invented yet. The probability function h(.) is assumed to satisfy Assumption 1 (primes denote derivatives):

*Assumption 1* (A) $h(0) = 0$, $h(\infty) = 1$, (B) $h' > 0$, $h'' < 0$, (C) $h'(0) = \infty$, $h''(\infty) = 0$.

Assumption 1A says that there is no discovery without investment in R&D and no finite level of investment in R&D guarantees a success. Assumption 1B says that an increase in investment raises probability of success subject to diminishing returns. Assumption 1C rules out corner solutions for Japan's optimal R&D program.

Japan's demand for energy per period is given by the time-invariant inverse demand function P(X). Importing $X_t$ units of oil at time t generates the consumer surplus

$u(X_t) = \max \{ P(y)dy - P(X_t)X_t \}$.

It is assumed that the substitute technology can generate energy so cheaply that it ends Japan's dependency on OPEC. After the invention, given the stationary environment, Japan enjoys the constant flow of social surplus, the discounted sum of which is denoted by $\omega$. The surplus $\omega$ is measured in current values so it is independent of the date of invention.

In solving the dynamic game between Japan and OPEC, we focus on Markov-perfect equilibrium. It is a natural solution concept in the present context because it rules out essentially all types of implicit collusion between Japan and OPEC. One implication of Markov-perfect equilibrium is that a level of investment in R&D at time t is a function of OPEC's oil reserve at time t, $R_t$, the only state variable of the model.

# 3A. Research by the Japanese Private Firm

This subsection assumes that a firm in the private sector conducts R&D in Japan. Suppose that the substitute technology has not been invented before time *t* and the firm invests $k_t$ in R&D to maximize the expected total profit. The firm will succeed with probability $h(k_t)$ and will fail with probability $[1 - h(k_t)]$. If the investment is successful, the game ends. The firm is rewarded with a flow of profit that starts at time t + 1 and sums to $\gamma$. The total profit $\gamma$ is measured in current values and so does not depend on the actual date of invention. In the case of a failure, the firm faces a similar optimization problem at time t + 1.

We can solve the firm's optimal R&D problem using dynamic programming techniques. Consider the subgame starting at time j. Let $k^*_j$ be the firm's optimal strategy at time j, and let $\pi(k^*_j)$ denote the firm's optimal-value function, or its maximized expected total profit, from this subgame. Naturally we have that $\pi(k^*_j) < \gamma$ for all j because $\gamma$ is the firm's total profit under certainty while $\pi(k^*_j)$ contains failures with positive probabilities.

Bellman's Principle of Optimality yields the following equation:

(3) $$\pi(k_t^*) = \max \{ - (1 - s)k_t + \delta[h(k_t)\gamma + [1 - h(k_t)]\pi(k^*_{t+1})] \}$$

where s is the government R&D subsidy rate to the firm. The firm chooses $k_t$, taking OPEC's exports $X_t$ as given. The optimal value of $k_t$ satisfies the first-order condition:

(4) $- (1 - s) + \delta h'(k_t)[\gamma - \pi(k^*_{t+1})] = 0.$

Observe that $\pi(k^*_{t+1})$, the maximum expected profit, does not depend on $R_t$ or $X_t$. Therefore, the firm's optimum level of investment is constant over time with respect to $X_t$. The optimal investment still depends on the subsidy rate s, though, and is denoted by k*(s).

The firm will invest more in R&D when it is subsidized. To check this, apply the implicit-function theorem to (4) to obtain

(5) $dk^*(s)/ds = - 1/\{\delta h''(k^*(s))[\gamma - \pi(k^*(s))]\}.$

Because $\gamma > \pi(k^*(s))$ and $h''(.) < 0$, the derivative in (5) is positive as expected.

Turn now to OPEC's optimization problem. OPEC discounts its income flows by the discount factor $\delta$ and probabilities of the substitute technology being invented. Probability of invention depends on the firm's investment $k_t$. Since $k_t$ is found to be constant over time, we drop the time subscript, and write OPEC's total income as:

$$\sum_{t=0}^{\infty} [1 - h(k)]^t \delta^t [P(X_t)X_t - CX_t].$$

Given k, OPEC chooses the volume of exports to maximize total income subject to the constraint that the sum of exports is equal to the initial oil reserve, $R_0$:

$$\sum_{t=0}^{\infty} X_t = R_0.$$

Let $\pi(R_j)$ denote OPEC's maximized total income in the subgame starting with the oil reserve $R_j$. Bellman's Principle of Optimality yields

$\pi(R_t) = \max \{P(X_t)X_t - CX_t + \delta[1 - h(k)]\pi(R_{t+1})\}$

where $R_{t+1} \equiv R_t - X_t$. The maximization problem on the right-hand side implies the first-order condition

(6) $P'X_t + P(X_t) - C - \delta[1 - h(k)]\pi'(R_t - X_t) = 0.$

The first two terms in (6) represent OPEC's marginal revenue, which, at the optimum, equals the sum of the marginal cost of oil extraction C and the shadow price of oil, the last term on the right of (6). Equation (6) implicitly defines OPEC's best-response function at time t, which we write as $X_t = B(k; R_t)$.

How does OPEC respond to an increase in Japan's investment in R&D? By an application of the implicit-function theorem to (6):

(7) $\partial X_t/\partial k = - h'(k)\Pi'(R_{t+1})/(SOC).$

A larger stock of oil means a greater income for OPEC so $\pi'(R_{t+1}) > 0$. The term

$SOC \equiv 2p' + p''X_t + \delta[1 - h(k)]\pi''(R_{t+1})$

is negative by the second-order condition; therefore,

$\partial X_t/\partial k > 0;$

that is, at given oil reserve OPEC's best-response function slopes upward. The intuition is that an increase in R&D increases the probability that the game ends sooner, and prompts OPEC to export more to avoid being caught with unusable oil.

**Proposition 1:** An increase in Japan's investment in R&D for the substitute technology increases OPEC's rates of oil exports at a given reserve size.

How does OPEC's best-response function change over time? To answer this question apply the implicit-function theorem to (6) to obtain:

$$\partial X_t/\partial R_t = \delta[1 - h(k)]\Pi''(R_{t+1})/(SOC).$$

The shadow price of oil increases when the oil reserve diminishes so $\pi''(R_{t+1}) < 0$. The negative term SOC then implies that $\partial X_t/\partial R_t > 0$Since the oil reserve $R_t$ diminishes over time, this inequality says that at given k the rate of exports decreases monotonically. Put differently, OPEC's best-response function shifts inward over time.

Figure 3 illustrates the equilibrium at time t. Since in a Markov-perfect equilibrium the Japanese firm's optimal investment in R&D is constant, its best-response function is vertical at k*(0) with no subsidies. A positive subsidy raises the level of investment to k*(s) and shifts the best-response function to the right as shown earlier. OPEC's best-response function slopes up. OPEC's optimal volume of oil exports is given by the intersection of the two countries' best-response functions, and is denoted by

(8) $X^*(R_t, s) = B[k^*(s); R_t]$.

As $R_t$ diminishes over time, OPEC's best response function shifts down, decreasing its rate of exports over time (see Figure 3). The following Propositions summarize the main results obtained so far.

**Proposition 2:** When the private firm in Japan conducts R&D for the substitute technology, its levels of investment in R&D remain constant over time. OPEC's oil exports decline over time.

**Proposition 3:** The R&D subsidy induces the Japanese firm to invest more in R&D, which in turn increases OPEC's rates of oil exports to Japan, at any given stock of oil.

Figure 4 presents the equilibrium time paths of exports, conditional on the substitute technology not having been invented. The path AA' describes the case of no R&D. The path BB' obtains when the firm invests in R&D without government subsidies, and the path CC' with subsidies. The rate of exports falls monotonically in each case. The areas under the three paths are identical because they all represent the initial reserve $R_0$. The fact that the path AA' is flatter than the other two indicates the lowest oil extraction rates and the maximum income for OPEC.

An increase in the rate of oil exports as in the path BB' means a lower oil price for Japan today. In this sense, investing in R&D reduces the monopoly power of OPEC before the substitute technology is invented. As shown by the path CC', OPEC's monopoly power further diminishes if the firm receives government R&D subsidies.

# 3B. Research by the Japanese Government Agency

This subsection describes the alternative case in which R&D is conducted by the Japanese government agency. While the private firm is concerned only with the total profit, the government is concerned with Japan's overall social welfare. It is recalled that Japan's (discounted) total social surplus is denoted by w. Let $v(R_t)$ represent Japan's maximum expected sum of instantaneous social surplus for a subgame starting with the oil reserve $R_t$, conditional on the substitute technology not having been invented yet. Since Japan must finance R&D and pay higher prices for imported oil before it invents the substitute technology, $\omega > v(R_t)$ for all t.

The government agency's problem can be stated as follows. Suppose that that the substitute technology has not been invented before time t. Conditional on that, the government agency spends kt on R&D and generates the net social surplus $u(X_t) - k_t$. With probability $h(k_t)$ the agency invents the substitute technology and enjoys the total social welfare w thereafter. With probability $[1 - h(k_t)]$ it fails and faces a similar problem at time t + 1. In the subgame starting at t + 1, the maximum expected welfare is $v(R_{t+1})$.

Therefore, the government agency solves:

$$\max \{u(X_t) - k_t + \delta\{h(k_t)\omega + [1 - h(k_t)]v(R_{t+1})\}\}.$$

The optimal level of investment satisfies first-order condition is:

$$(9) \qquad - 1 + \delta h'(k_t)[\omega - v(R_{t+1})] = 0.$$

Since $R_{t+1} \equiv R_t - X_t$, (9) implicitly defines the agency's best-response function depends on $X_t$, that is, $k_t = b^G(X_t; R_t)$.

The agency's best-response function slopes upward because

$$\partial k_t/\partial X_t = - h'(k_t)v'(R_{t+1})/\{h''(k_t)[\omega - v(R_{t+1})]\},$$

is positive with $h''(.) < 0$ and $v'(R_{t+1}) > 0$. Also $\partial k_t/\partial R_t = - \partial k_t/\partial X_t < 0$; that is, the Japanese government's best-response function shifts out as OPEC's oil reserve diminishes over time.

We now turn to the optimization problem facing OPEC. Since $k_t$ is no longer constant over time, OPEC's expected income takes the expression:

$$\sum_{t=0}^{\infty} \text{Prob(no innovation before t)}\delta^t[P(X_t)X_t - CX_t]$$

where $k_0 \equiv 0$, and

$$\text{Prob(no innovation before t)} \equiv \prod_{z=0}^{t} [1 - h(k_z)].$$

Let $\pi^G(R_j)$ denote OPEC's maximized total income in the subgame starting with the oil reserve Rj. The Principle of Optimality yields the first order condition analogous to (6)

(6') $P'X_t + P(X_t) - C - \delta[1 - h(k)]\pi^{G}{}'(R_t - X_t) = 0$,

which implies OPEC's best-response function $X_t = B^G(k_t, R_t)$. As before, OPEC's best-response function shifts down over time. Solving the two best-response functions simultaneously, we obtain the Markov-Perfect equilibrium $\{k^{**}(R_t), X^{**}(R_t)\}$.

We now characterize the equilibrium. Substituting $k^{**}(R_t)$ and $R^{**}(R_t)$ into Japan's first-order condition (9), we have

$$- 1 + \delta h'[k^{**}(R_t)][\omega - v(R_{t+1})] = 0.$$

Total differentiation yields

$$dk^{**}/dR_t = \frac{h'v'(dR_{t+1}/dR_t)}{h''[\omega - v(R_{t+1})]} < 0$$

since $(d_{Rt+1}/dR_t) > 0$, $h' > 0$, $v' > 0$, $h'' < 0$, and $\omega - v > 0$. Hence, the government agency increases investments in R&D over time. When the oil reserve $R_t$ is very large, $dk^{**}/dR_t$ is small since v' is small, i. e., a small change in the size of oil reserves does not affect Japan's social welfare significantly. As oil grows scarcer, the Japanese government gets more concerned with the oil reserves and behaves more responsively to small changes in the size of the oil reserves. We state this result formally in

**Proposition 4:** The government agency that conducts R&D for the substitute technology increases the level of investment in R&D over time.

The time path of oil exports is more complicated. Substituting the equilibrium levels of investment in R&D and oil exports to (6') and differentiating yields:

$$dX^{**}/dR_t = \delta\{[1 - h(k^{**})]\pi^{G''} - h'(dk^{**}/dR_t)\pi^{G'}(R_t - X_t)\}/SOC^G.$$

Since $SOC^G$ is negative by the second-order condition, the change in the rate of oil exports over time depends on the sign of the expression in the numerator. There, the first term is positive because the shadow price of oil is positive ($\pi^{G'} > 0$). The second term is also positive because the shadow price of oil increases when the oil reserve diminishes ($\pi^{G''} < 0$) and $dk^{**}/dR_t$ is negative. The relative magnitude of these two terms determines whether the oil export increases or decreases over time.

When the oil reserve $R_t$ is very large, $dk^{**}/dR_t$ tends to be small, hence the first term dominates the second, implying decreasing rates of oil exports over time. This is the normal scenario. However, as the $R_t$ becomes smaller, the Japanese government increases investment in R&D, which raises $h(k^{**})$. If this probability becomes large enough, the second term may come to dominate the first, indicating the possibility that the rate of oil exports actually increases over time.

Figure 5 illustrates this curious possibility. In the figure, OPEC's best-response function shifts down while Japan's best-response function shifts to the right over time. The curve arrow traces the equilibrium trajectory, showing the possibility of increased oil exports in the future.

We now compare the equilibrium levels of investment in R&D made by the private firm ($k^*$) and the government agency ($k^{**}_t$) and the corresponding levels of oil exports, $X^*$ and $X^{**}$. First, consider Japan's best-response functions. A direct comparison of (4) and (9) says that

$$k^* > b^G(X_t) \text{ if and only if } \gamma - \pi(k^*) > \omega - v(R_t - X_t).$$

Since $v' > 0$, this implies that when $R_t$ is large the government agency is likely to invest less than $k^*$ (Figure 6).

Turning to OPEC, we can show that when $R_t$ is large its best-response oil exports are smaller when R&D is conducted by the government agency than by the private firm.[1] This is because the shadow price of oil is sensitive to who conducts the R&D in Japan. To see this, suppose that OPEC reduces oil exports by one unit at time t. This raises $R_{t+1}$ by one unit, and increases OPEC's future exports and income. An increase in oil reserves induces the government agency to invest less in R&D ($dk^{**}/dR < 0$), and pushes back the date of invention. Thus, when the government agency is conducting R&D, OPEC's future income increases even more.

The second effect is absent when R&D is conducted by the private firm. Therefore, the shadow price of oil is higher if the government agency conducts R&D. As oil reserves become smaller however the government agency increases investment. This reduces the shadow price of oil. It also increases the best-response oil exports.

Figure 6 illustrates the above discussion. When R is very large, the levels of oil exports are smaller when the government agency conducts R&D. When R is small, the result is reversed. Figure 7 illustrates the oil export paths when the initial reserve size is large.

# 4. Concluding Remarks

This paper has shown that Japan's effort in R&D to develop a substitute technology decreases the shadow price of oil before the technology is invented. The falling shadow price of oil depresses the oil prices today. The lower oil prices benefit consumers in Japan. This benefit should be included in the usual cost-benefit analysis of the economic feasibility of R&D for the substitute technology.

The private firm disregards the external benefit of lower oil prices accruing to consumers before the invention. Therefore, there are insufficient private incentives for R&D. In contrast, the government, concerned with total social welfare, internalizes the positive externalities to consumers. Thus, it appears at first sight that the government is more effective in taming OPEC's monopoly power than the private sector. However, the very fact that the government can adjust its research intensity to the size of the oil reserves implies that OPEC can reduce the rates of oil exports to discourage the government's R&D effort. To avoid manipulation by OPEC, the Japanese government should leave R&D to the private sector and promote it indirectly with R&D subsidies.

[1]See Appendix for discussion.

# Appendix

We compare the shadow prices of oil when R&D is conducted by the government agency and by a private firm. Consider the subgame starting with the oil reserve $R_{t+1}$. Let $\tilde{k}(R_{t+1})$ denote Japan's equilibrium investment path and $\tilde{X}(R_{t+1})$ OPEC's equilibrium export path in this subgame. Then, OPEC's equilibrium expected income equals

$$\Psi[\tilde{X}(R_{t+1}), \tilde{k}(R_{t+1})]$$

$$\equiv \Phi[\tilde{X}_{t+1}(R_{t+1})] + \sum_{j=1}^{\infty} \{ \prod_{z=1}^{j} \{1 - h[\tilde{k}_{t+z}(R_{t+1})]\} \} \delta^j \Phi[\tilde{X}_{t+j+1}(R_{t+1})]$$

where $\tilde{X}_j(R_{t+1})$ denote the equilibrium level of exports at time j, and $\tilde{k}_j(R_{t+1})$ the equilibrium level of investment at time j.

OPEC's problem at time t is to choose $X_t$, given $k_t$, to

$$\max \{P(X_t)X_t - CX_t + \delta[1 - h(k_t)]\Psi[\tilde{X}(R_{t+1}), \tilde{k}(R_{t+1})] \}.$$

The first two terms together represent the profit at time t and the third the maximum discounted expected profit, should Japan's R&D fail to invent at time t. The optimal level of exports fulfills the first-order condition:

$$\text{(A1)} \qquad P'X_t + P - C - \delta[1 - h(k_t)](\Psi_X\tilde{X}_R + \Psi_k\tilde{k}_R) = 0.$$

A unit reduction of oil exports at time t reduces OPEC's profit by the marginal profit (the first three terms), but increases its future profit by increasing $R_{t+1}$ by one unit (the fourth term). A unit increase in $R_{t+1}$ increases OPEC's future income through two effects. One effect occurs through OPEC's future oil exports. An increase in $R_{t+1}$ increases future oil exports, thereby increasing OPEC's future profits; therefore, $\Psi_X\tilde{X}_R > 0$.[2] The other effect occurs through changes in Japan's future investment in R&D and represented by $\Psi_k \tilde{k}_R$ in the fourth term of (A1). The derivative $\Psi_k$ is negative because an increase in investment in R&D raises probability of invention. The term, $\tilde{k}_R$, shows how an increase in the oil reserves affects Japan's R&D effort in equilibrium. When the government conducts R&D, $\tilde{k}_R$ is negative so $\Psi_k \tilde{k}_R$ is positive, meaning that an increase in $R_{t+1}$ increases OPEC's future profit by increasing future oil exports and also discouraging Japan's future R&D efforts. In contrast, if R&D is conducted by the private firm, $\tilde{k}_R = 0$ and the second effect does not exist. Hence, as long as k** does not increase too quickly in the near future, which is the case when $R_t$ is large, the shadow price is higher when the government agency conducts R&D.

[2] Although OPEC is a monopoly, because it is subject to a resource constraint, its total profits increase if exports rise at all $t$ ($\Psi_X > 0$).

# References

Hotelling, H., 1931, The economics of exhaustible resources, Journal of Political Economy 39, 137-175.

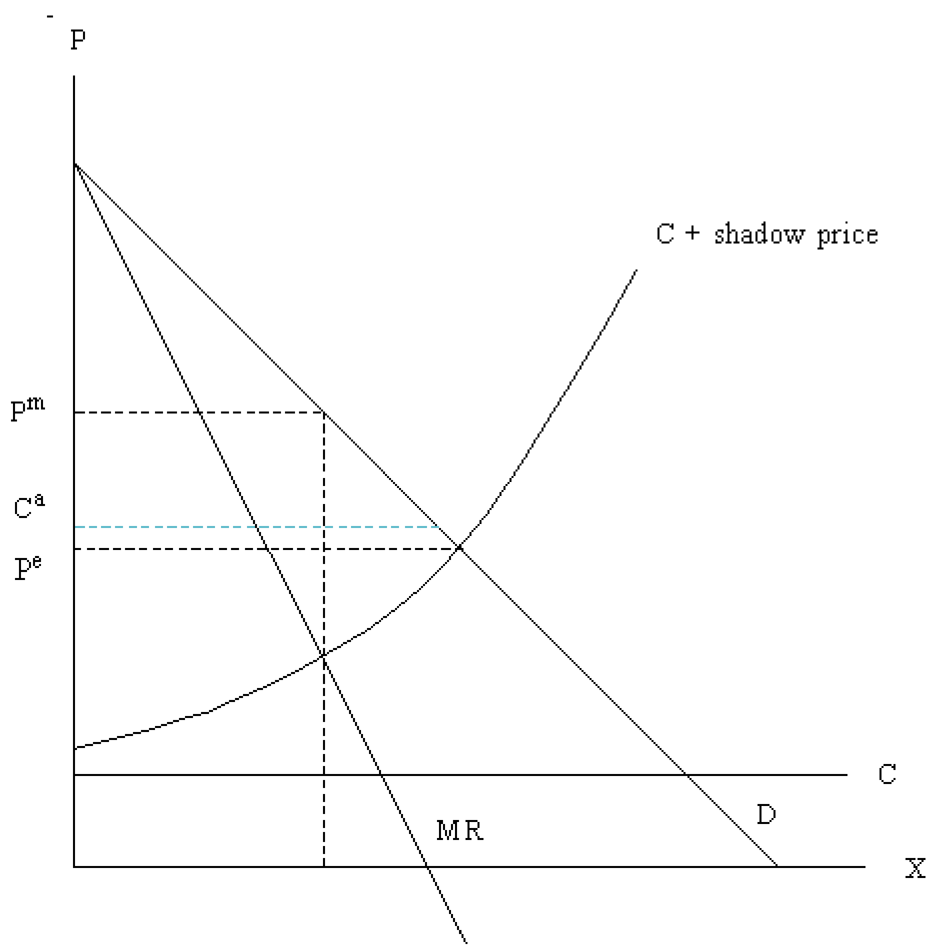



Figure 1

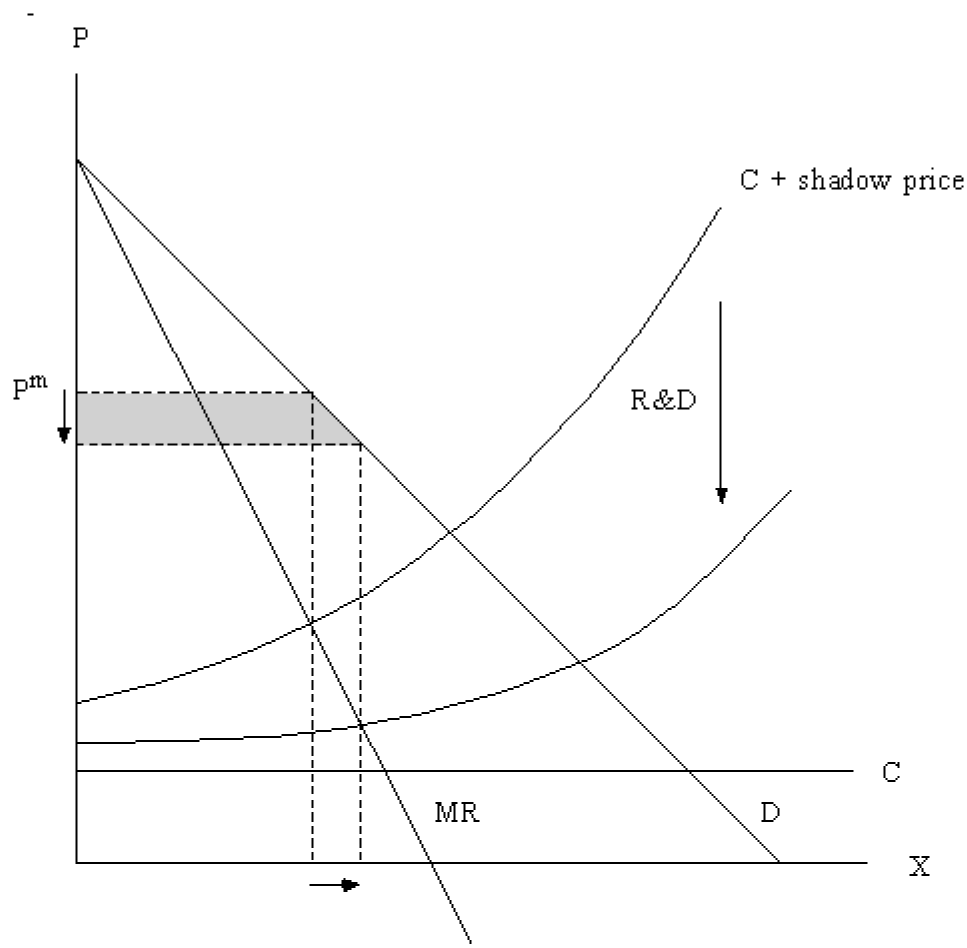
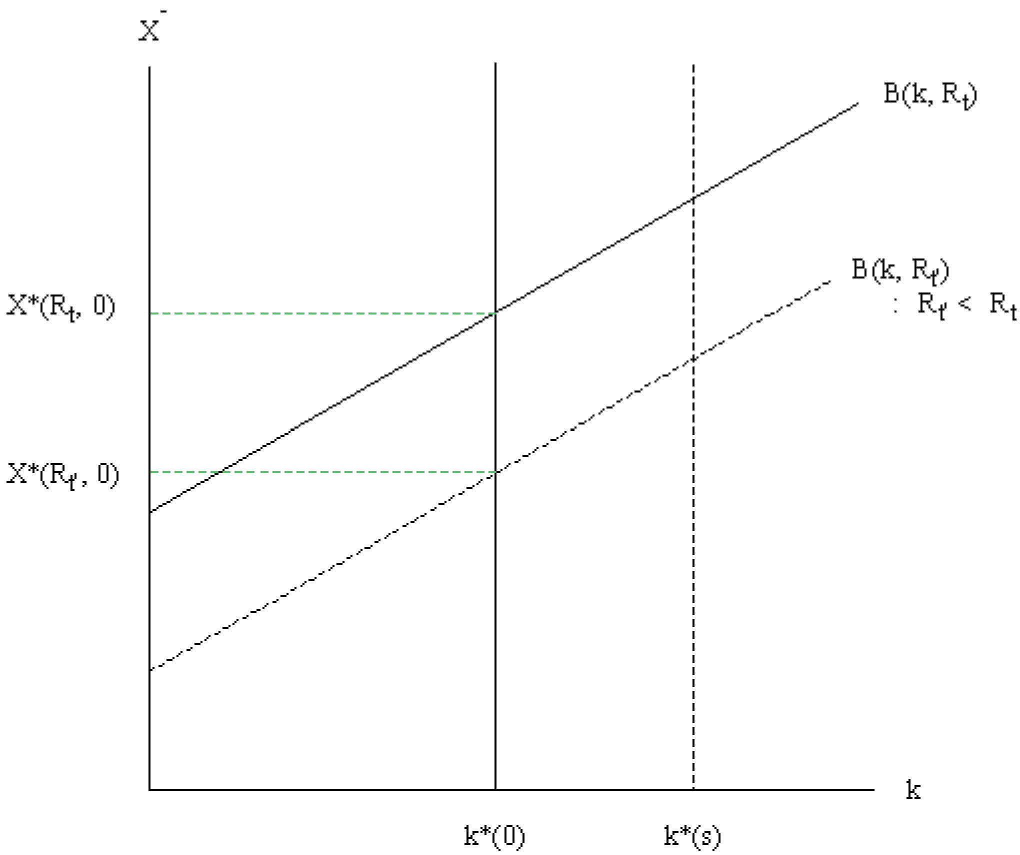



Figure2

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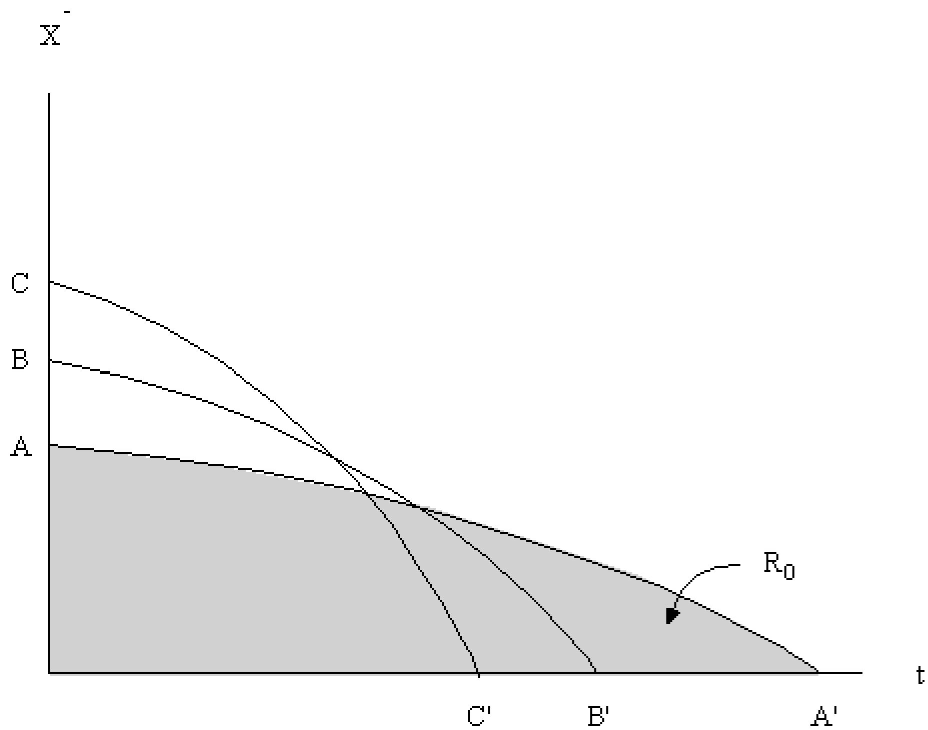


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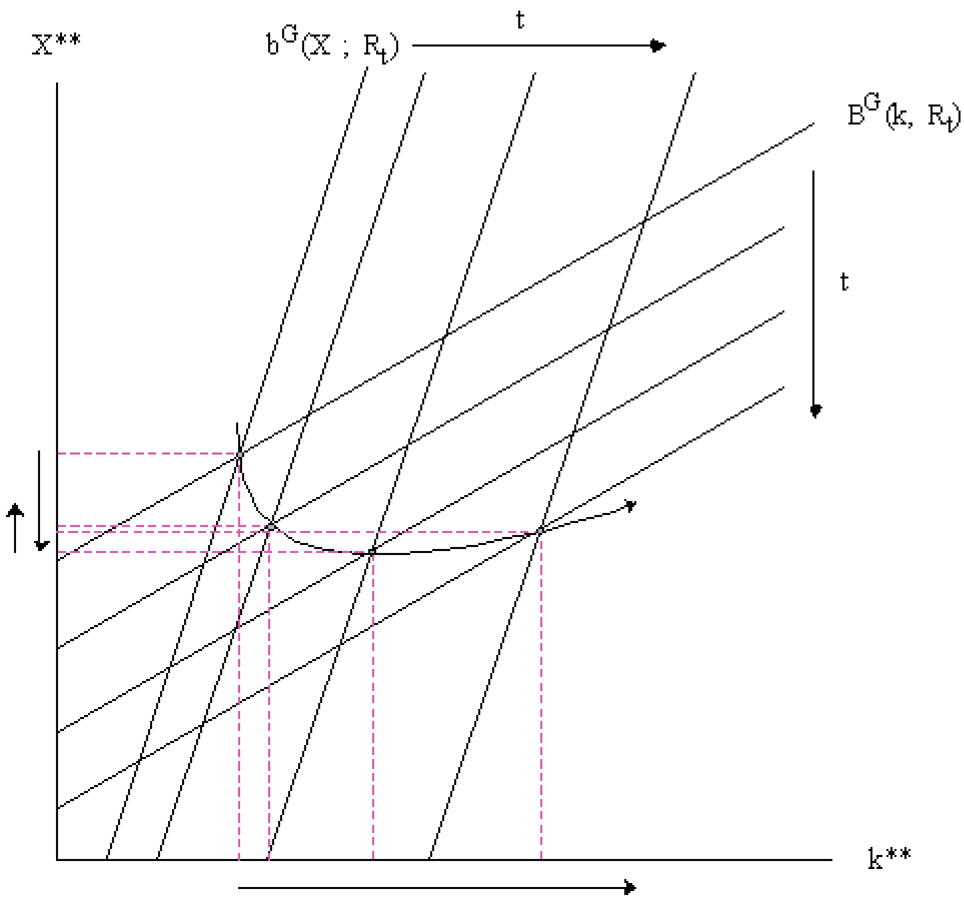


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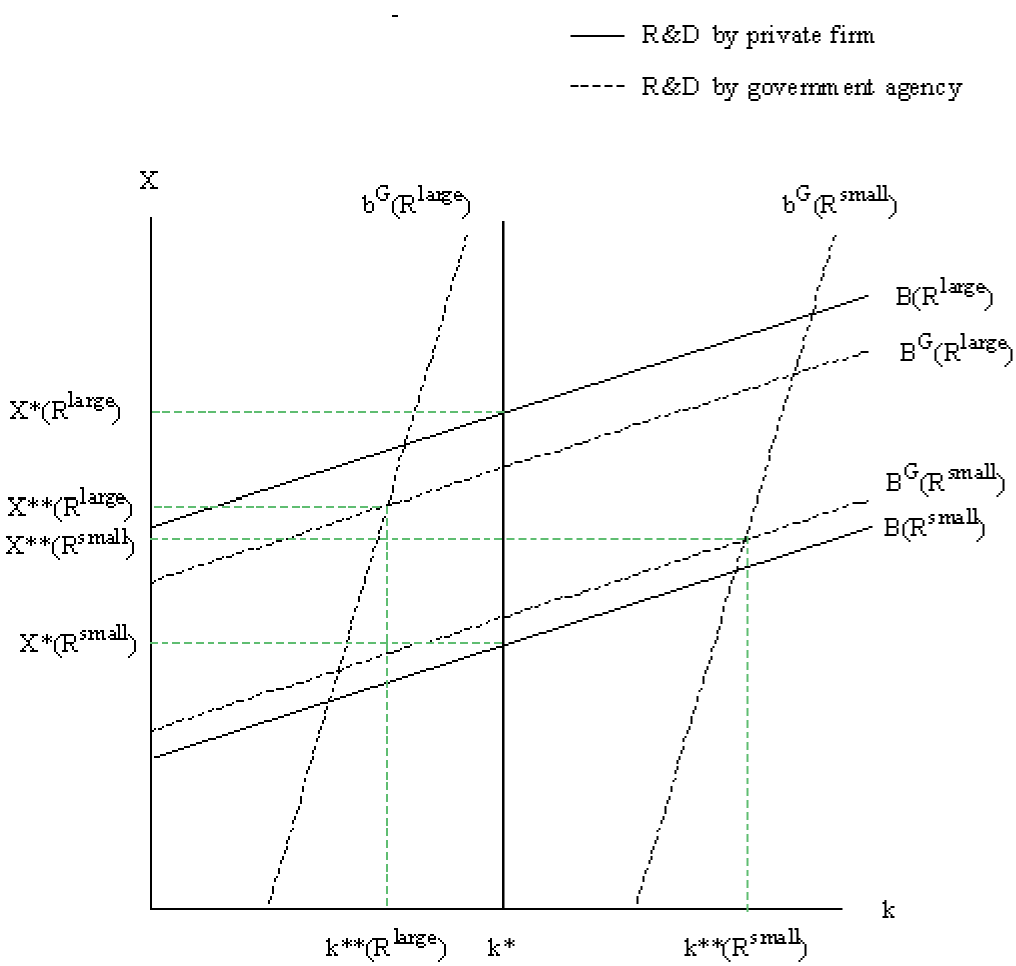
R&D by private firm
R&D by government agency
X
$b^G(R^{large})$
$b^G(R^{small})$
$B(R^{large})$
$B^G(R^{large})$
$B^G(R^{small})$
$B(R^{small})$
$X^*(R^{large})$
$X^{**}(R^{large})$
$X^{**}(R^{small})$
$X^*(R^{small})$
k
$k^{**}(R^{large})$
$k^*$
$k^{**}(R^{small})$

Figure 6

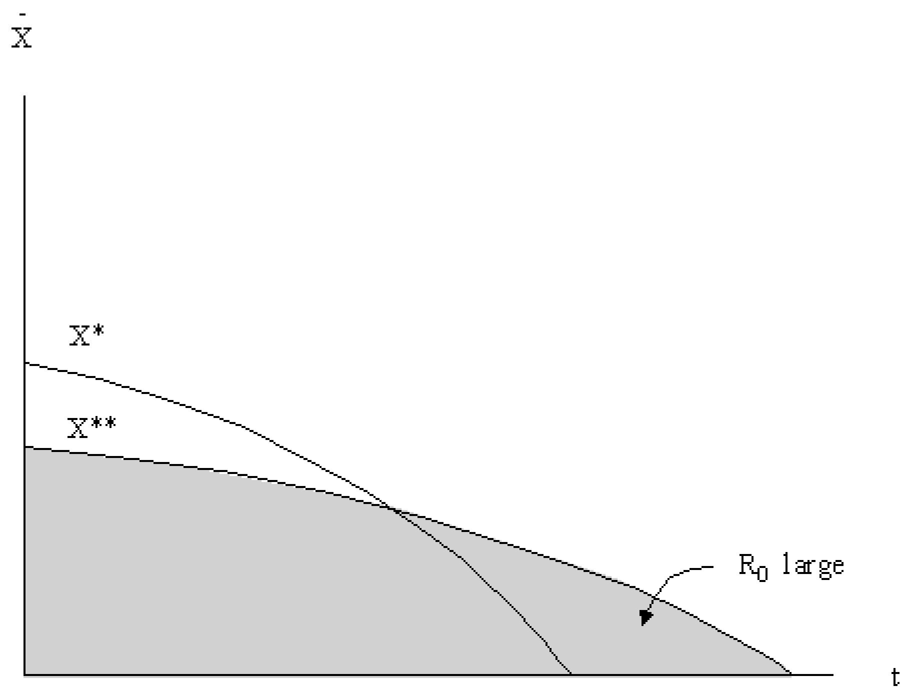


Figure 7