Overreporting Oil Reserves*

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Abstract

An increasing number of oil market experts argues that OPEC members substantially overstate their oil reserves. While the implied outlooks for the world economy are disastrous, the incentives for overreporting remain unclear. This paper shows that oil exporting countries may rationally overreport to raise expected future supply, discourage oil-substituting R&D, and hence improve their future market conditions. Yet, credible overreporting must be backed by observable actions and therefore induces costly distortions of supply. Surprisingly, these distortions can cancel with others that arise in the strategic game of dynamic supply and substitution. In this case, overreporting is rational, credible, and cheap.

Keywords: Exhaustible Resource, Substitution Technology, Signaling

JEL Classifications: F10, F16, D82.

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1 Introduction

The recent tightening in the oil market has revived concerns about energy supply. In addition to geological and political imponderability, a growing number of market pundits points out that overreporting of crude oil reserves is one, possibly dramatic, source of uncertainty.[1] Bentley (2002) observes that "Saudi Arabia and Iran may well have significantly smaller reserves than listed" publicly. The Economist (2006) reports warnings that suppliers as "Kuwait might have only half of the [...] oil reserves" officially reported. The Energy Watch Group, a Germany-based think tank claims that, when applying "the same criteria which are common practice with western companies, ...[Saudi Arabia's] statement of proven reserves should be devalued by 50%" (Energy Watch Group (2007)). International Energy Agency (IEA) expresses doubts "about the reliability of official MENA [Middle Eastern and North African] reserves estimates, which have not been audited by independent auditors" for decades (IEA (2005)). The Wall Street Journal (2008) summarizes an unpublished IEA study, reporting that "[f]uture crude oil supplies could be far tighter than previously thought." These quotes combine to a simple picture: opaque national oil companies hold private information on major parts of world crude oil reserves, which they potentially overreport.

Needless to say, the world economy would lurch heavily if these allegations turned out to be true. Yet, while the claims seem alarming, the actual motives of overreporting remain unclear.[2] To the economist, unfamiliar with geological details but trained to handle rational expectations, the following type of questions occurs: Why would oil suppliers overreport their reserves? When would this be credible and do the necessary conditions hold? After all, shouldn't oil suppliers underreport reserves, since anticipated shortages raise current prices?

The present paper addresses these questions. It shows that incentives to overreport naturally emerge from two standard assumptions of the economics of exhaustible resources by the following simple mechanism. Market participants can engage in oil-substituting R&D and rationally do so when expected future supply of conventional oil is sufficiently low. Thus, oil-exporters overreport their oil reserves to raise the expected future oil supply, discourage oil-substituting R&D and thus improve their future market conditions.

This mechanism relies on two fundamental assumptions, both of which are standard within the economics of exhaustible resources. First, technological change is the outcome of

[1] Many definitions of *crude oil reserves* exist. Quotations refer to the standard definitions *proven* and *proven and probable* reserves (oil in place with 90% and 50% probability, respectively).

[2] It is sometimes argued that OPEC members overreport reserves to increase their allotted production quotas. In fact, OPEC's quota system was formally established in March 1983, around the time when many OPEC members substantially increased their reported oil reserves (see Campbell and Laherrèr (1998) and Bentley (2002)). If a strategic quota game was the obviously and sole reason, however, market participants would discount those spurious revisions. As such discounting did not happen the central question recurs whether oil exporters have motives to strategically deceive the markets.

directed R&D activity, which grants the negative response of oil-substituting R&D to expected future oil supply. Second, oil supply is not competitive. This assumption is necessary since, by definition, price-taking suppliers do not internalize the impact of their supply on the market conditions and hence are unable to manipulate them.

Under rational expectiations, overreporting generally induces costs because of the following requirement: successful overreporting needs to be credible, i.e., backed by observable actions. Since contemporaneous supply is observable, it needs to correspond to reported reserves. This requirement implies that, under overreporting, supply deviates from the optimal supply rule and is, therefore, costly. In general, these costs of overreporting will limit the oil-exporter's willingness to overreport.

This paper shows, however, that the cost of overreporting can be negligible or even negative for a wide range of parameters. The intuition for this surprising result is the following. According to the economics of exhaustible resources, the key problem of an oil-supplier is how to allocate reserves over time. In the absence of technological change, it is dynamically optimal to smooth supply over time. However, under potential oil-substituting R&D, the oil-supplier deviate from their optimal supply to prevent oil-substituting R&D by decreasing current and increasing future supply. In contrase, overreporting typically requires an increase of current supply and thus brings the overreporting country closer to its unconstrained optimal supply. Thus, the deviation due to overreporting cancels with the earlier one, in which case the costs of overreporting are said to be negative.

This paper's argument is framed with a signalling game, a standard tool to analyze the rents from information asymmetries. An oil-exporting country holds private information about its total stock of oil, which is a random variable, and decides how to allocate it between two periods. The oil-importing country decides whether to invest in oil-substituting R&D. The oil-exporter is said to misreport successfully if its signal – current supply – is uninformative about remaining reserves and if, in addition, the resulting pooling equilibrium generates strictly higher benefits than the respective full information equilibrium. By definition, misreporting and beneficial pooling are one and the same thing.

The present paper predicts that oil exporters tend to overreport if substitution R&D reacts significantly to expected future oil supply and if the market is not competitive. Finally, overreporting occurs if its costs are limited. This last requirement, however, generates no meaningful criterion in a qualitative application of the argument since theory is consistent with negative costs of signaling. Hence, the attention rests on the two central preconditions. Concerning the first, empirical work shows that substitution R&D has indeed been responsive to oil prices (see Newell et al (1999) and Popp (2002)). Figure 1 illustrates these findings in a suggestive way with the crude oil prices and total R&D expenditure on non-oil energy sources in IEA member countries between 1973 and 2006.[3]

[3] Throughout the period, contemporaneous prices comove with expected future prices (see Lynch

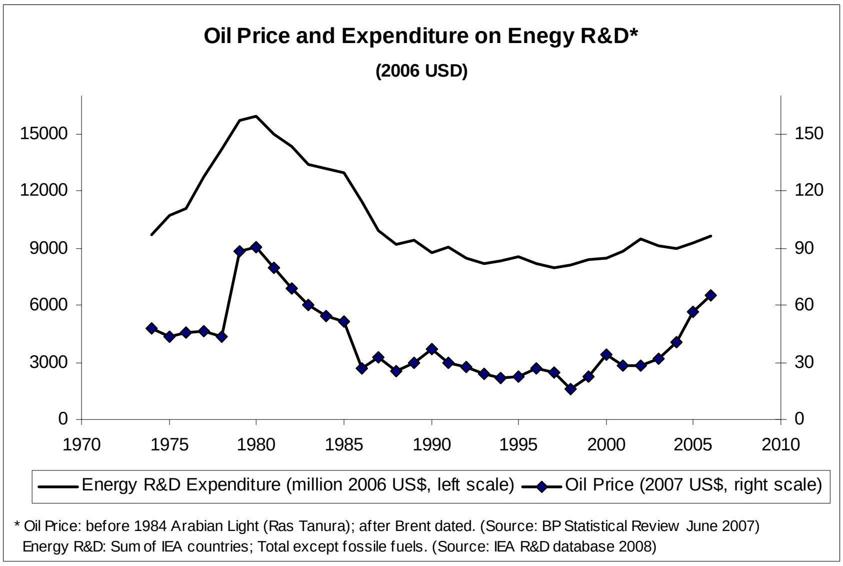

Figure 1: Oil Price and Expenditure on Energy R&D*

The second requirement of non-competitive oil markets seems intriguing. Contrary to conventional wisdom, however, empirical evidence on OPEC's market power is mixed. Nevertheless, some recent studies make the case that the OPEC successfully sacrificed supply following the counter oil shock of 1986 (Smith (2003)). In this case, a rough and tentative application of the model cannot refute that OPEC member states overreport their crude oil reserves. This finding calls for a quantitative assessment of the matter.

The paper contributes to the rich literature on the economics of exhaustible resources. Since the seminal article by Hotelling (1931), this literature has highligheted the suppliers' market power. Not surprisingly, the oil shocks of the 1970s intensified the focus on the effects of monopoly power and cartel formation on aggregate supply (see Stiglitz (1976), Salant (1976), Pindyck (1978), Ulph and Folie (1980), and Gaudet and Moreaux (1990)), paralleled by empirical work on the collusive behavior of world oil suppliers (e.g. Griffin (1985), for recent contributions see Smith (2003), Almoguera and Herrera (2007), Lin (2007), and the references therein). About the firt oil shock Dasgupta and Heal (1974) sparked a line of research on substitution of exhaustible resources analyzing either the exploration (see Burt and Cummings (1970), Arrow and Chang (1982) and Quyen (1988)) or the closely related directed technical change for substitution (e.g., Davidson (1978) and Deshmukh and Pliska (1983)). The present paper rests on these two prominent features of the literature – monopolistic power and substitution efforts – as basic modeling elements to analyze the motives of the misreporting of natural resource reserves. It also connects to earlier work on private information in natural resource markets like Gaudet et al (1995) and Osmundsen (1998), which analyzes information asymmetries about the

(2002)). This latter is the key variable according to this paper's argument.

reserves of natural resources and shows that firms have incentives to underreport reserves: given that extraction costs are higher for lower reserves, underreporting of reserves means overreporting of costs, which, finally, saves taxes on profits. In contrast to these studies, the present paper addresses private information of sellers vis-à-vis the buyers and draws entirely different conclusions. Finally, Gerlagh and Liski (2007) analyze a setup where asymmetric information about natural resource reserves impacts the consumers' decision to invest in substitution technologies. While close to the present paper, this earlier study places no weight on the seller's potential to signal its type and focuses on the buyer's investment decision under uncertainty.

The remainder of the paper is organized as follows. Section 2 outlines the model economy, describes the action of economic agents and sets up the strategic game involving the governments' decisions. Sections 3 and 4 solve the strategic game under full information and under asymmetric information, respectively, and discuss the main results. Finally, Section 5 concludes.

2 The Model

To analyze the incentives of an oil-exporter to misreport their reserves, this section develops a two-country model with international trade in two goods, one of which represents oil or a natural resource in general. The setup reflects the dichotomy between oil exporters and importers and captures consumption smoothing motives in oil exporting countries that affect the exporter's optimal intertemporal supply rule.

2.1 General Setup

The world economy consists of two countries O (*) and W (no *) which are populated by individuals of mass L and L^*, respectively. Let the relaitve population size be $L/L^* = \lambda$ and L^* be normalized to unity. These countries engage in cross-border trade in two consumption goods within each of two periods, $t = 1, 2$. After the second period, the world ends. The two periods represent long time intervals, defined by the time it takes to develop a technology with which to substitute the natural resource.[4]

Production. In each period, country W produces y_t units of a perishable consumption good Y. Country O is endowed with N^* units of a second consumption good N. Good N represents a natural resource and N^* is country W's total reserve of it. Hence, when supplying n_1^* units in period one, country W's maximal supply in period two is $N^* - n_1^*$.

[4] In a recent study Lovins et al (2005) reckon that US oil demand projected for 2025 can be cut to half by the use of substitutes and energy-saving technologies. In this sense, periods are "long".

The mining costs of N are negligible, yet once N is mined, it becomes perishable.[5] Before period one, country W's total reserves of N are uncertain and distributed according to

$$N^* = \begin{cases} \bar{N} & \text{with probability } \pi \\ \xi \bar{N} & \text{with probability } 1 - \pi \end{cases} \quad (1)$$

with $\xi \in (0, 1)$. The parameters $\bar{N}$, ξ, and π are common knowledge, information about the realization of N^*, however, is private to country O, which supplies n_t^* units of the good N each of the two periods under the constraints $n_t^* \geq 0$ and $n_1^* + n_2^* \leq N^*$. All uncertainty about total reserves is costlessly resolved to country O. Moreover, total reserves do not depend on prices.

Preferences. The individuals' preferences are reflected by total utility

$$U^{(*)} = \sum_{t=1,2} u\left(c_{n,t}^{(*)}, c_{y,t}^{(*)}\right) \quad (2)$$

where $c_{x,t} \geq 0$ are consumed quantities of good $x = n, y$ at time $t = 1, 2$. The sub-utility takes the specific form

$$u(c_n, c_y) = \ln(c_n) + c_y \quad (3)$$

This specification has a number of advantages. First, the quasi-linear form implies that income is transferable across periods[6] so that country O – when maximizing the total utility of its citizens – simply maximizes the sum of profits in the export market on the world market. Further, the logarithm gives rise to a simple closed form solution of country O's optimal export taxes. The additive term in the argument of the logarithm ensures that export taxes are bounded and can be read as a flow of a perishable substitute to the natural resource in each country.

Government policies. Since consumers and firms are atomistic governments are the only strategic players. For simplicity "the strategy of country X's government" will simply be referred to as "country X's strategy."

With this terminology, country O is said to supply n_t^* in periods $t = 1, 2$. Country W can develop a so-called substitution technology which enables it to produce a substitute of the natural resource N out of good Y.[7] More precisely, country W may incur $\ln(A) > 0$ units of the good Y in period $t = 1$ to develop a technology that becomes available in period $t = 2$ and enables country W to produce a perfect substitute of good N out of good Y

[5] This assumption reflects prohibitive storage costs; in the case of oil production, the storage cost are considerable, impeding storage of quantities needed to cover supply for the "long" periods.

[6] The condition for this statement to hold is $c_{y,t}^{(*)} > 0$, which will be satisfied throughout.

[7] The government of a country may induce private R&D through according subsidies, which are financed by lump-sum taxes. It will become clear that private firms do not necessarily engage in R&D without such additional incentives.

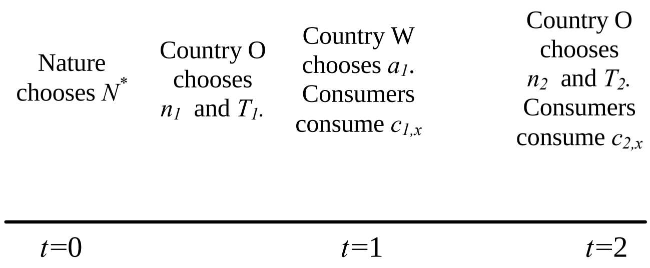

Figure 2: Timing of actions.

with the technology reflected by $n_2 = By$. Thus, country W's substitution technology can be summarized by

$$b_1 = 0 \qquad \text{and} \qquad b_2 = \begin{cases} 0 & \text{if } \ a_1 = 0 \\ B & \text{if } \ a_1 = \ln(A) \end{cases} \tag{4}$$

In the following $B > 1$ is assumed to hold. For a convenient notation let country W's first period output and second periods investment be denoted by $n_1 = 0$ and $a_2 = 0$, respectively.

The discrete R&D process defined in (4) reflects a major technological breakthrough in substitution technologies, a common assumption in the literature (see, e.g., Dasgupta and Heal (1974), Deshmukh and Pliska (1983), Quyen (1988), and Barrett (2006)).

NO Ts HERE

Timing. The timing of actions in the game between governments is the following. First, nature decides in the realization of N^*, which is revealed to country O only. Next, country O supplies the quantity n_1^*. Then, country W chooses the investment a_1 and first period consumption is realized. Finally, country O supplies $n_2^* \leq N^* - n_1^*$ and the second period's equilibrium quantities are consumed. Figure 2 summarizes this time-line.

The fact that country O's strategy n_1 is determined before country W's decision on a_1 is noteworthy. It reflects that country W can condition its strategy a_1 on n_1. A departure from this assumption implies that overreporting need not be backed by observable actions in which case the signaling game collapses.

If country W engages in substitution R&D, country O will lose from intensified competition in the N-market in period $t = 2$. Hence, country O may use its supply and private information, to discourage R&D activity. The costs and benefits from doing so are central to the following analysis. Before turning to the strategic aspects of the game, however, demand curves will be derived from (3).

2.2 Consumers' Optimization

At each point in time, consumers maximize sub-utilities (3) subject to the respective budgets constraints

$$p_t c_{n,t}^{(*)} + c_{y,t}^{(*)} \leq E_t^{(*)}$$

taking prices and the quantities n_t^* and n_t as given. $E_t^{(*)}$ is respective net per capita income. Provided that interior solutions prevail ($c_{x,t}^{(*)} > 0$ for $x = n, y$), optimal quantities are

$$c_{n,t}^{(*)} = 1/p_t \qquad c_{y,t}^{(*)} = E_t^{(*)} - 1$$

When the natural resource market clears, i.e., under $\lambda c_{n,t} + c_{n,t}^* = n_t^* + n_t \equiv \bar{n}_t$, the relative price p_t is (remember $n_1 = 0$ so that $\bar{n}_1 = n_1^*$)

$$p_t = \frac{\lambda + 1}{\bar{n}_t} \tag{5}$$

With this expression of the price, country W's income net of investments is

$$E_t = y_t + n_t \frac{\lambda + 1}{\bar{n}_t} - \frac{n_t}{B} - a_t$$

while country O's per capita income is

$$E_t^* = n_t^* \frac{\lambda + 1}{\bar{n}_t}$$

These expressions lead to equilibrium consumption

$$\begin{aligned} c_{n,t} &= \frac{\bar{n}_t}{\lambda + 1} \qquad & c_{y,t} &= y_t + n_t \frac{\lambda + 1}{\bar{n}_t} - \frac{n_t}{B} - a_t - 1 \\ c_{n,t}^* &= \frac{\bar{n}_t}{\lambda + 1} \qquad & c_{y,t}^* &= n_t^* \frac{\lambda + 1}{\bar{n}_t} - 1 \end{aligned} \tag{6}$$

and the sub-utilities

$$\begin{aligned} u_t &= \ln\left(\frac{\bar{n}_t}{\lambda + 1}\right) + y_t + n_t \frac{\lambda + 1}{\bar{n}_t} - \frac{n_t}{B} - a_t - 1 \\ u_t^* &= \ln\left(\frac{\bar{n}_t}{\lambda + 1}\right) + n_t^* \frac{\lambda + 1}{\bar{n}_t} - 1 \end{aligned} \tag{7}$$

Countries employ their respective policies (n_t^* and a_1) to maximize the sum of their citizen's sub-utilities (7).

3 Full Information

This section analyzes the Nash equilibrium of the sequential game outlined in the previous section, assuming that the amount of total reserves N^* is common knowledge. It has been shown that all strategic interaction can be reduced to a two-stage game in which country O first chooses n_1^* and then country W decides on a_1. Export tax and consumption choices follow from static optimization. The game is solved by backward induction.

2^{nd} stage: Optimal Investment a_1. Country W does not engage in substitution R&D if and only if the net gains fall short of the costs $\left(u_2|_{b_2=B} - u_2|_{b_2=0} \leq A\right)$. Country W's local price of N is $p_2 = 1/B$ whenever $n_2 > 0$ under $b_2 = B$. Thus, with (5) and (7) the incentive compatibility constraint is $\ln\left(B\left(\lambda+1\right)/\bar{n}_t\right) \leq \ln(A)$ or

$$B\left(\lambda+1\right)/A \leq \bar{n}_2 \tag{8}$$

and country W's optimal strategy is expressed by the rule

$$a_1 = \begin{cases} 0 & \text{if (8) holds} \\ A & \text{else} \end{cases}$$

Notice that at $n_2^* \to 0$ country W engages in R&D fo all $A < \infty$.

1^{st} stage: Optimal Supply n_1^*. In the first stage country O has two options: either to prevent country W's substitution R&D or to adjust to it. Since country O's unconstrained optimal strategy is to smooth supply over both periods, country O's optimal supply, conditional on $a_1 = 0$, is captured by

$$n_{1,P}^* = \min\left\{N^* - B\left(\lambda+1\right)/A, N^*/2\right\} \tag{9}$$

If country O aims to depress W's substitution R&D, it's supply of the natural resource N in the second period must be high enough to depress country W's gains from R&D below rentability. Whenever total resources N^* are large (i.e., $N^* > B\left(\lambda+1\right)/A$ holds), country O is not constrained by this requirement and plays its unconstrained optimal strategy $n_1^* = N^*/2$.

Country O may, alternatively, adjust to country W's R&D. If $1/c_{n,2} > 1/B$ country O would like but cannot import N in lack of an export good. Thus, its optimal supply in the first period is calculated by $1/c_{n,2}^* = p_2^{domestic}$, $1/c_{n,2}^* = 1/c_{n,1}^*$, and $1/c_{n,1}^* = p_1$ in this case. Otherwise, $1/c_{n,2} = 1/B$ holds and

$$n_{1,C}^* \equiv \begin{cases} N^* \frac{\lambda+1}{\lambda+2} & \text{if } B \geq N^*/\left(\lambda+2\right) \\ B\left(\lambda+1\right) & \text{if } B\left(\lambda+2\right) < N^* \leq 2B\left(\lambda+1\right) \\ N^*/2 & \text{else} \end{cases} \tag{10}$$

In the third case, however, where $N^*/(\lambda+1) > 2B$ country W does not engage in costly R&D for zero returns.

$$u_1^*|_{b_2=0} + u_2^*|_{b_2=0} - \left(u_1^*|_{b_2=B} + u_2^*|_{b_2=B}\right) = \ln()$$

$$\ln\left(\frac{\bar{n}_t}{\lambda+1}\right) + n_t^* \frac{\lambda+1}{\bar{n}_t} - 1$$

In sum, country O's supply in the first period is either set following strategy (9) to prevent substitution R&D or else following (10) to adjust to substitution R&D. The equilibrium depends on the respective utilities under both strategies. For this trade-off, it is convenient to define total utility under given supply and investment decisions as

$$V^*(n_1^*, n_2^*, b_2) \equiv \max_{T_1^*, T_2^*} \{u_1^* + u_2^*\} \qquad \text{given } n_1^*, n_2^*, b_2 \tag{11}$$

Clearly, if country O concedes to country W's R&D it gets total utility $V^*(n_C^*, N^* - n_C^*, B)$ while preventing R&D renders $V^*(\min\{N^* - n_P^*, N^*/2\}, \max\{n_P^*, N^*/2\}, 0)$. The equilibrium strategy can be read from the sign of the difference of both expressions. The following proposition shows that the optimal decision rule - and hence the equilibrium strategy - depends in a simple way on total reserves N^*.

Proposition 1 *Under full information* $\exists\, N_0 \in [n_P^*, 2n_P^*]$ *so that a subgame perfect Nash Equilibrium exists, is unique, and is described by the strategies*

$$(n_1^*, a_1) = \begin{cases} (n_C^*, A) & \text{if } N^* < N_0 \\ (N^* - n_P^*, 0) & \text{if } N^* > N_0 \end{cases} \tag{12}$$

Proof. Define $\Delta V^*(N^*) \equiv V^*(N^* - n_P^*, n_P^*, 0) - V^*(n_C^*, N^* - n_C^*, B)$. It is sufficient to show first that $\Delta V^*(n_P^*) < 0$, second, that $\Delta V^*(2n_P^*) > 0$, and third, that $N^* - n_P^* < n_C^*$ implies $d\Delta V^*(N^*)/dN^* > 0$ (for $N^* - n_P^* > n_C^*$ implies $b_2 = 0$ in any case). First, observe that

$$\begin{aligned} \Delta V^*(n_P^*) &= V^*(0, n_P^*, 0) - V^*(n_C^*, n_P^* - n_C^*, B) \\ &= V^*(n_P^*, 0, 0) - V^*(n_C^*, n_P^* - n_C^*, B) \\ &= V^*(n_P^*, 0, B) - V^*(n_C^*, n_P^* - n_C^*, B) < 0, \end{aligned}$$

where $n_C^* < N^* = n_P^*$ and (**??**) were used in the last step. Second,

$$\Delta V^*(2n_P^*) = V^*(n_P^*, n_P^*, 0) - V^*(n_C^*, 2n_P^* - n_C^*, B) > 0,$$

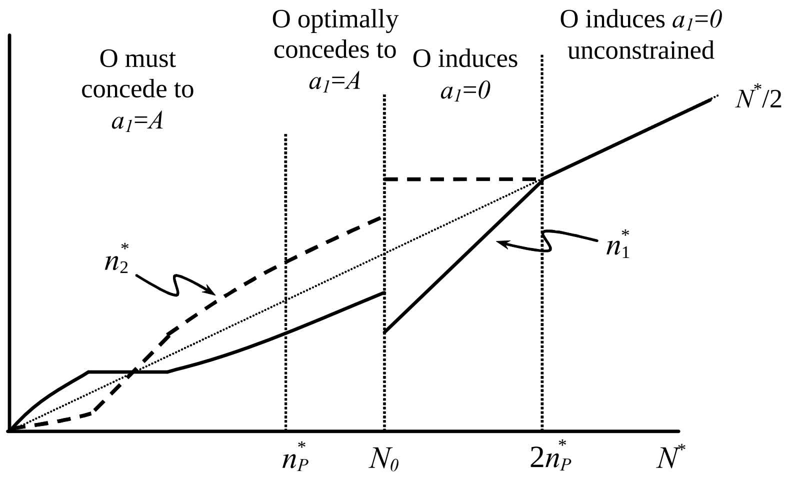

Figure 3: Country O's optimal quantities under full information.

which follows from (**??**). Third, the Envelope Theorem implies

$$\frac{d\Delta V^*(N^*)}{dN^*} = \left.\frac{du_1^*}{dn_1^*}\right|_{n_1^*=N^*-n_P^*} - \left.\frac{du_1^*}{dn_1^*}\right|_{n_1^*=n_C^*}.$$

Since u_1^* is concave in n_1^* by (**??**) this expression is positive whenever $N^* - n_P^* < n_C^*$. ■

The result of Proposition 1 is quite intuitive. Country O's two goals are, on the one hand, to smooth supply according to the rule (**??**) and, on the other, to discourage country W from investing in the substitution technology. Since a minimum supply in the second period ($n_{2,t}^*$) is necessary to reach the second goal, the deviation from the optimal unconstrained path (**??**) - and hence utility losses - is relatively large whenever the total reserves N^* are low. Thus, the utility losses dominate the gains from preventing investment if N^* falls short of a threshold N_0. In this case, country O adjusts to $a_1 = A$.

Figure 3 illustrates country O's optimal supply n_1^* (solid line) and n_2^* (dashed line) as functions of N^*. There are four different ranges of N^*. First, for $N^* < n_P^*$ country O is not able to prevent country W's investment and country W plays $a_1 = A$. Second, under $N^* \in [n_P^*, N_0]$ country O could possibly prevent W's investment but optimally chooses not to do so. Third, for $N^* \in [N_0, 2n_P^*]$ country O optimally prevents country W's investment under the binding constraint (8); the slope of $n_1^*(N^*)$ is one in this range. Finally, if $N^* > 2n_P^*$, country O's optimal strategy is not constrained. As a reference, Figure 3 includes the unconstrained optimum i.e., the equal allocation over both periods, $n_1^* = n_2^* = N^*/2$, as a dotted line. Deviations from this strategy reflect either country O's need to react to W's substitution capacity ($b_2 = B$) or, alternatively, its aim to prevent country W's investment. At N_0 where country O is indifferent between preventing and conceding, n_1^* jumps down since

$$V^*(N_0 - n_P^*, n_P^*, 0) = V^*(n_C^*, N_0 - n_C^*, B) < V^*(n_C^*, N_0 - n_C^*, 0)$$

implies $N_0 - n_P^* < n_C^*$. Apart from this discontinuity, supply in both periods is (weakly) increasing in N^*.

Before closing this section it is instructive to contemplate the distortion of supply under prevention of country W's investment. If country O chooses to prevent W's investment, world supply of N is distorted away from the optimal rule ($n_1^* = n_2^*$) towards a more back-loaded supply rule ($n_1^* < n_2^*$). This finding resembles those of earlier work, in which monopolistic supply leads to a partial delay of supply. Hotelling (1931) calls this "retardation of production under monopoly" and Quyen (1988) confirms that "the monopolist is excessively conservationist." These studies predict that the monopolist scarifies supply in early periods, which creates a front-loaded stream of profits and possibly a longer duration of supply period. Stiglitz (1976), however, shows that these results do not stand up to robustness checks, including generalized demand function and extraction costs. The mechanism presented here, instead, is qualitatively different. Supply is partly delayed in order to generate abundant future supply and thus discourage country W's substitution R&D. The causality between future supply, incentives to engage in time-consuming R&D, and optimal supply has a clear orientation on the time-line and suggests that this deviation from the Hotelling rule is quite robust.[8]

With a good idea about the nature of the distortions that country W's R&D opportunities create, one can ask for the gains and losses they induce. Intuitively, country O suffers from the potential increase of competition in the N-market and the distortions this induces to its optimal supply. This intuition is confirmed by verifying

$$V^*\left(n_1^*, N^* - n_1^*, b_2\right) \leq V^*\left(n_1^*, N^* - n_1^*, 0\right) < V^*\left(N^*/2, N^*/2, 0\right)$$

for all $N^* < 2n_P^*$. It might be less intuitive that, for all $N^* \in [N_0, 2n_P^*]$, country W loses from its investment opportunity as well. To see this, check that, under $a_1 = 0$, the optimal export tax (**??**) and utilities (7) imply $d^2u_t/(dn_t^*)^2\big|_{b_t=0} < 0$ so that u_t is concave in n_t^* and country W's total utility (2) is maximized at $n_1^* = n_2^* = N^*/2$. Consequently, country W's equilibrium utility falls short of the utility it would obtain in a alternative world without R&D opportunities, by the deviations from a smooth supply performed by country O to prevent R&D activity.

Proposition 1 and Figure 3 have provided a description of the full information equilibrium. The nest section turns to the main objective of the paper and analyzes the incentives to

[8] A rigorous analysis of this mechanism in continuous time would be interesting but is beyond the scope of this paper.

overreport under asymmetric information about reserves.

4 Asymmetric Information

This section formalizes country W's incentives to misreport the reserves of the natural resource N. The standard framework for an analysis of the strategic use of private information is the signaling game and its equilibrium concept of Perfect Bayesian Equilibria.

Within this framework, a player with private information can be said to deceive other players if conceals its type and benefits from doing so. In particular, one of country O's types is said to misreport successfully if its signal is not informative about remaining reserves and if, in addition, this type enjoys higher utility in the resulting pooling equilibrium than in the full information equilibrium. By definition, successful misreporting and beneficial pooling are one and the same.[9]

To assess if and how misreporting can arise in this model, the equilibrium concept needs to be specified.

4.1 Equilibrium: Definition

The specification of the game, summarized in Figure 2, shall be briefly repeated. The total amount of the natural resource reserves, N^*, is a random variable, distributed as specified by (1). In stage zero, Nature decides on the realization of N^*, which country O observes but country W does not. The realization of the reserve N^* defines two different types of country O, which are indexed by $\theta = H, L$ and labeled country O_H in the case $N^* = \bar{N}$ and country O_L if $N^* = \xi\bar{N}$ $(\xi < 1)$. In the first stage, country O can signal its type with the first period's supply n_1^* as a signal. In a separating equilibrium, the signal n_1^* differs across types while it equalizes in a pooling equilibrium. In the second stage, country W rationally updates its beliefs and chooses investment $a_1 \in \{0, A\}$. As shown in Section 2.3, export taxes and consumption are no strategic components and follow expressions (**??**) and (**??**). Formally, the strategies $(n_{1,H}^e, n_{1,L}^e, a_1^e(n_1^*))$ are said to characterize a Perfect Bayesian Equilibrium if they satisfy the following criteria

E(i)	W rationally updates its prior believes given O's strategies,
E(ii)	$a_1^e(n_1^*)$ maximizes expected total utility U under W's updated beliefs,
E(iii)	for each type $\theta = H, L$, $n_{1,\theta}^e$ maximizes total utility U^*, given W's strategy, prior beliefs, and updating rules.

[9] Strictly speaking, any reporting is discounted as cheap talk by the market and can be regarded as entirely irrelevant in the model. Yet, acknowledging the fact that some types gain from imitating other's this definition of misreporting is a natural one.

The full specification of an equilibrium involves country W's updated beliefs that satisfy requirement E(i). These beliefs are denoted by the function $\mu(.) : [0, \bar{N}] \to [0, 1]$, which represents country W's subjective probabilities that country O is of high type conditional on observing supply n_1^* or

$$\mu(n_1^*) \equiv \mathbb{P}(N^* = \bar{N} \mid n_1^*)$$

Further, the equilibrium strategies of both players are denoted by

$$\left(n_{1,H}^e, n_{1,L}^e\right) \in [0, \bar{N}] \times [0, \xi\bar{N}] \quad \text{ and } \quad a_1^e(\tilde{n}) : [0, \bar{N}] \to \{0, A\}$$

Country W's equilibrium technology in the second period is labeled $b_{2,\theta}^e \in \{0, B\}$, where θ stands for country O's type $\theta = H, L$. In a pooling equilibrium, a_1 cannot be conditioned on country O's type and $b_{2,H}^e = b_{2,L}^e$ must hold.

For further references, it is useful to denote country O's full information equilibrium strategies (12) under type $\theta = L, H$ as

$$\begin{aligned} n_{1,H}^* &\in [0, \bar{N}] \quad && \text{and} \quad a_{1,H}^*(\tilde{n}) : [0, \bar{N}] \to \{0, A\} \\ n_{1,L}^* &\in [0, \xi\bar{N}] \quad && \text{and} \quad a_{1,L}^*(\tilde{n}) : [0, \xi\bar{N}] \to \{0, A\} \end{aligned}$$

The variable $b_{2,\theta}^* \in \{0, B\}$ will stand for country W's substitution technology in the second period given country W's type is θ.

The existence and the characteristic of the signaling game's equilibrium is sensitive to the specification of the receiver's beliefs, including the off-equilibrium beliefs. The minimal requirement that the updating of beliefs be rational (i.e. following the Bayes' rule) leaves a wide range of off-equilibrium beliefs, which implies that equilibria are non-unique in many cases. In the present analysis, however, posterior beliefs μ will be restricted to satisfy the following set of assumptions.

A(i) $\quad n_{1,H}^e \neq n_{1,L}^e \quad \Rightarrow \quad \mu(n_{1,H}^e) = 1$ and $\mu(n_{1,L}^e) = 0.$

A(ii) $\quad n_{1,H}^e = n_{1,L}^e \quad \Rightarrow \quad \mu(n_{1,H}^e) = \pi.$

A(iii) $\quad V^*(n_{1,L}^*, \xi\bar{N} - n_{1,L}^*, b_{2,L}^*) > V^*(n_{1,H}^*, \xi\bar{N} - n_{1,H}^*, b_{2,H}^*) \quad \Rightarrow \quad \mu(n_{1,H}^*) = 1.$

A(iv) $\quad \tilde{n} \in [0, \bar{N}] \qquad \tilde{b}$ outcome of W's optimal $a_1^e(\tilde{n})$ under $\mu(\tilde{n}) = \pi$.

$$V^*(\tilde{n}, \bar{N} - \tilde{n}, \tilde{b}) > V^*(n_{1,H}^e, \bar{N} - n_{1,H}^e, b_{2,H}^e)$$
$$V^*(\tilde{n}, \xi\bar{N} - \tilde{n}, \tilde{b}) > V^*(n_{1,L}^*, \xi\bar{N} - n_{1,L}^*, b_{2,L}^*)$$
$$\Rightarrow \qquad \mu(\tilde{n}) = \pi.$$

A(v) $\quad \tilde{n} \in [0, \bar{N}] \qquad \tilde{b}$ outcome of W's optimal $a_1^e(\tilde{n})$ under $\mu(\tilde{n}) = \pi$.

$$V^*(\tilde{n}, \bar{N} - \tilde{n}, \tilde{b}) < V^*(n_{1,H}^e, \bar{N} - n_{1,H}^e, b_{2,H}^e)$$
$$V^*(\tilde{n}, \xi\bar{N} - \tilde{n}, \tilde{b}) > V^*(n_{1,L}^e, \xi\bar{N} - n_{1,L}^e, b_{2,L}^e)$$
$$\Rightarrow \qquad \mu(\tilde{n}) = 0.$$

Assumptions A(i) and A(ii) simply formulate the requirement of Bayesian updating; assumptions A(iii) - A(v), however, constitute non-trivial refinements of the off-equilibrium beliefs. Loosely speaking, among all Bayesian Nash Equilibria assumptions A(iii) - A(v) single out the one that maximizes the high type's payoffs. – A(iii) requires that, if O_L does not gain from imitation of O_H's full information strategy ($n^*_{1,H}$) relative to its own full information strategy ($n^*_{1,L}$), then W, when observing $n^*_{1,H}$, believes in $\theta = H$ with certainty. This assumption implies that O_H plays its full information strategy whenever it does not pay for O_L to pool to $n^*_{1,H}$. Hence, A(iii) establishes the full information equilibrium as the default outcome.[10] Conversely, this implies that a pooling equilibrium only exists if no separating equilibrium including the full information strategies exists. – A(iv) requires that, if O_H gains from a deviation to $\tilde{n}$ relative to an equilibrium outcome $n^e_{1,H}$ provided that $\mu(\tilde{n}) = \pi$ and if, further, O_L prefers to pool to that deviation $\tilde{n}$ rather than to resort to its full information equilibrium, then W, when actually observing strategy $\tilde{n}$, is agnostic about O's type and sticks to its prior beliefs ($\mu(\tilde{n}) = \pi$). This assumption eliminates all equilibria that render the high type less utility than the pooling equilibrium with maximal utility for the high type. – Finally, A(v) requires that, whenever O_H looses from a deviation to $\tilde{n}$ relative to the equilibrium provided that $\mu(\tilde{n}) = \pi$ while O_L gains from a deviation to $\tilde{n}$ relative to its current equilibrium outcome provided that $\mu(\tilde{n}) = \pi$, then W, when observing strategy $\tilde{n}$, believes in $\theta = L$ with certainty ($\mu(\tilde{n}) = 0$). This assumption ties O_L to the equilibrium strategy that is beneficial for O_H.

Making use of the definition and the refinements the equilibrium will be calculated next.

4.2 Equilibrium: Characterization

To determine the equilibrium of the signaling game, country W's optimal decision rule is derived first. The information asymmetries changes country W's situation to the extent that, at the time of making the R&D decision it may face subjective uncertainty about the second period's supply of the natural resource. Consequently, its optimal strategy is now taken on the basis of *expected returns* to substitution R&D, where expectations are formed using subjective probabilities. More precisely, country W's strategy is based on the probabilistic analog of inequality (8), which, using the definition of μ, can be written

[10] This statement follows from two observations: First, $n^*_{1,H}$ is O_H's unique optimal strategy under full information. Second, asymmetric information adds one more constraint to O_H's optimization program (the incentive compatibility constraint in the case of a separating and the probabilistic equivalent of (8) with prior probabilities π and $1-\pi$ in the case of a pooling equilibrium) so that in all equilibria of the signaling game O_H obtains weakly less utility than in the full information equilibrium. Thus, whenever O_L looses from pooling to $n^e_{1,H} = n^*_{1,H}$, A(iii) grants that O_H can obtain its full information utility by playing $n^e_{1,H} = n^*_{1,H}$ and implying $a^e_1(n^e_{1,H}) = 0$, which is, by Proposition 1, O_H's unique optimal strategy.

as

$$\begin{aligned}\ln(B)+\tfrac{1}{B}-\mu(n_1^*)\left\{\ln\left(T_2^*(\bar{N}-n_1^*)\right)+\frac{1}{T_2^*(\bar{N}-n_1^*)}\right\}-...\\ ...(1-\mu(n_1^*))\left\{\ln\left(T_2^*(\xi\bar{N}-n_1^*)\right)+\frac{1}{T_2^*(\xi\bar{N}-n_1^*)}\right\}\leq A\end{aligned}\tag{13}$$

In (13) $T_2^*(.)$ stands for the optimal export tax under $b_2=0$ from (**??**). Condition (13) determines country W's investment behavior and[11]

$$a_1(n_1^*)=\begin{cases}0 & \text{if (13) holds}\\ A & \text{else}\end{cases}$$

Unfortunately, country O's optimal strategy does not follow such a handy rule. As in the case of full information, country O gains from depressing the investment in substitution R&D but loses from deviations of its optimal supply rules. When engaging in signaling, country O aims to prevent country W's substitution R&D at the cost of distorted supply. This trade-off between country O's costs and benefits of the signal is central for the computation of the equilibrium. It will prove useful to define the limits on the first period's supply n_1^* which, disregarding information asymmetries, set the bounds of country O's willingness to discourage substitution R&D. Such thresholds must leave country O indifferent between successfully inducing $a_1=0$ and conceding to $a_1=A$. A lower bound, labeled m, is implicitly defined by $m<N^*/2$ and

$$V^*(n_C^*,N^*-n_C^*,B)-V^*(m,N^*-m,0)=0\tag{14}$$

By this definition, m depends on total reserves N^* and some of its properties can be inferred from (14).

Claim 1 *m satisfies the following properties.*

(i) m is well defined and unique for $N^*\in[0,2n_P^*]$.

(ii) $m<N^*-n_P^*$ if and only if $N^*\in(N_0,2n_P^*]$.

(iii) $N^*/2-m>|N^*/2-n_C^*|$.

(iv) $0<\frac{dm}{dN^*}<1$.

(v) m is positive on $N^*\in(0,2n_P^*]$.

Proof. See appendix. ■

By Claim 1 (i), the threshold m is a function of N^* and can be written as $m(N^*)$. Concavity of u^* (see (**??**)) and $m<N^*/2$ implies that the value $m(N^*)$ constitutes a lower bound on the quantities which country O, endowed with N^*, is willing to supply

[11] Notice that this seemingly simple decision rule involves the updated beliefs μ. These beliefs must satisfy A(i) - A(v) and hence depend on the payoffs of the types O_θ, which in turn depend on $a_1(n_1^*)$.

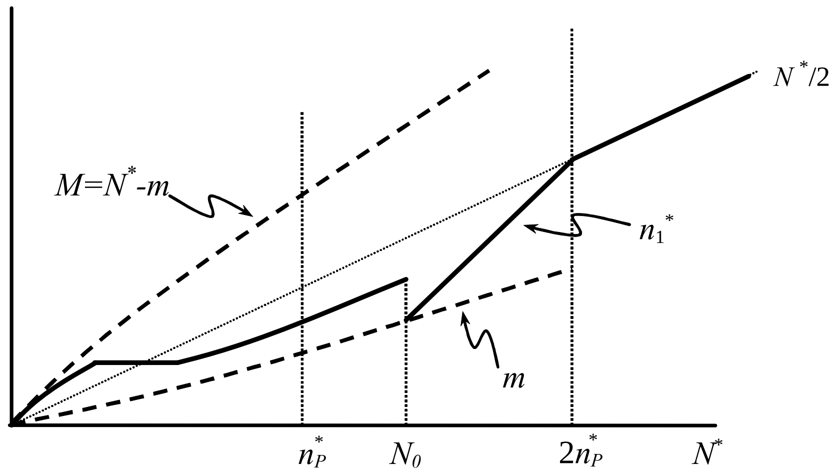

Figure 4: Boundaries of O's net benefits from preventing W's R&D.

in the first period to prevent country W from engaging in substitution R&D. Finally, the symmetry of $V^*(n_1^*, n_2^*, 0)$ in the first two arguments implies that the function

$$M(N^*) \equiv N^* - m(N^*) \tag{15}$$

establishes the corresponding upper bound on the quantities n_1^*. Figure 4 illustrates these bounds $m(N^*)$ and $M(N^*)$ as dashed lines, the full information equilibrium n_1^* is represented by the bold line. By Claim 1 (iv) and (v), the functions $m(N^*)$ and $M(N^*)$ are increasing in N^*, lie within the interval $(0, N^*)$, and satisfy $m(N^*) < N^*/2 < M(N^*)$. Country O, endowed with N^*, is willing to supply any $n_1^* \in [m(N^*), M(N^*)]$ in the first period if this prevents substitution R&D in country W (i.e., induces $a_1 = 0$). Notice that, since country O optimally concedes to $a_1 = A$ for $N^* < N_0$, the threshold $m(N^*)$ lies above the line $N^* - n_P^*$ in this range, i.e., $N^* < N_0$ implies $m(N^*) > N^* - n_P^*$. Conversely, for $N^* > N_0$ country O optimally prevents investment in R&D, hence $m(N^*) < N^* - n_P^*$ in this range. The functions $m(N^*)$ and $N^* - n_P^*$ intersect at the value $N^* = N_0$ where country O is indifferent between conceding to $a_1 = A$ and preventing it.

With the definitions of m and M and the properties summarized in Claim 1 it is possible to give a first irrelevance result and to formulate specific conditions for the realizations $\xi\bar{N}$ and $\bar{N}$ under which the information asymmetries do not impact the real world economy at all. These conditions are spelled out in the following proposition.

Proposition 2 *Assume that at least one of the following conditions holds*

(i) $\bar{N} \notin [N_0, 2n_P^*]$

(ii) $M(\xi\bar{N}) < \bar{N} - n_P^*$

then the unique subgame perfect equilibrium in pure strategies is a separating equilibrium characterized by the full information strategies (12).

Proof. By assumption A(iii) it is sufficient to show that O_L's full information strategy $n^*_{1,L}$ dominates pooling to O_H's full information strategy $n^*_{1,H}$.

(i) If $\bar{N} < N_0$ W plays $a_1 = A$ in the full information equilibria under $N^* = \bar{N}$. Thus, for O_L, $n^*_{1,L}$ dominates $n^*_{1,H}$ by construction.

If, instead, $\bar{N} > 2n^*_P$ O_H's full information strategy is $n^*_{1,H} = \bar{N}/2$ by (9). Now distinguish two cases: first, if $b^*_{2,L} = 0$, $n^*_{1,L} = \min\left\{\xi\bar{N} - n^*_P, \xi\bar{N}/2\right\}$ holds by (9). Hence by (**??**) and symmetry of $V^*(n^*_1, n^*_2, 0)$ is the first two arguments

$$V^*(n^*_{1,L}, \xi\bar{N} - n^*_{1,L}, 0) > V^*(\bar{N}/2, \xi\bar{N} - \bar{N}/2, 0)$$

holds. If, second, $b^*_{2,L} = B$ then

$$V^*(n^*_{1,L}, \xi\bar{N} - n^*_{1,L}, B) > V^*(\xi\bar{N} - n^*_P, n^*_P, 0) > V^*(\bar{N}/2, \xi\bar{N} - \bar{N}/2, 0)$$

holds. Thus, $n^*_{1,L}$ dominates pooling to $n^*_{1,H}$ in this last case, too.

(ii) By (i) one can focus on $\bar{N} \in [N_0, 2n^*_P]$. Condition (ii) and definition (15) imply $m(\xi\bar{N}) > \xi\bar{N} - (\bar{N} - n^*_P) > \xi\bar{N} - n^*_P$ and hence $b^*_{2,L} = B$. Thus, by construction of M and m

$$\begin{aligned} V^*(n^*_{1,L}, \xi\bar{N} - n^*_{1,L}, B) &= V^*(m(\xi\bar{N}), \xi\bar{N} - m(\xi\bar{N}), 0) \\ &= V^*(M(\xi\bar{N}), \xi\bar{N} - M(\xi\bar{N}), 0) \\ &> V^*(\bar{N} - n^*_P, \xi\bar{N} - (\bar{N} - n^*_P), 0) \end{aligned}$$

holds and proves the statement. ■

The first part of the proposition, related to condition (i), reflects, that for very large $\bar{N}$, the low type's pooling strategy is more costly than inducing $a_1 = 0$ directly, i.e., under revelation of its type. Similarly, for small $\bar{N}$ ($\bar{N} < N_0$) even the high type optimally concedes to $a_1 = A$ and there is no gain for O_L that compensates for the cost of pooling.

Figure 5 illustrates the result of Proposition 2 related to condition (ii). Whenever $\xi\bar{N}$ is small and lies below the value $M^{-1}(\bar{N} - n^*_P)$, the figure shows that the high type's full information strategy $\bar{N} - n^*_P$ lies outside the interval $[m(\xi\bar{N}), M((\xi\bar{N}))]$, which comprises all signals O_L is willing to set in order to induce $a_1 = 0$. Consequently, the low type's pooling to the strategy $\bar{N} - n^*_P$ leads to strictly less utility than its optimal strategy under full identification of its type. Hence, the full information equilibrium prevails. In all cases, the two types resort to the respective full information strategies.

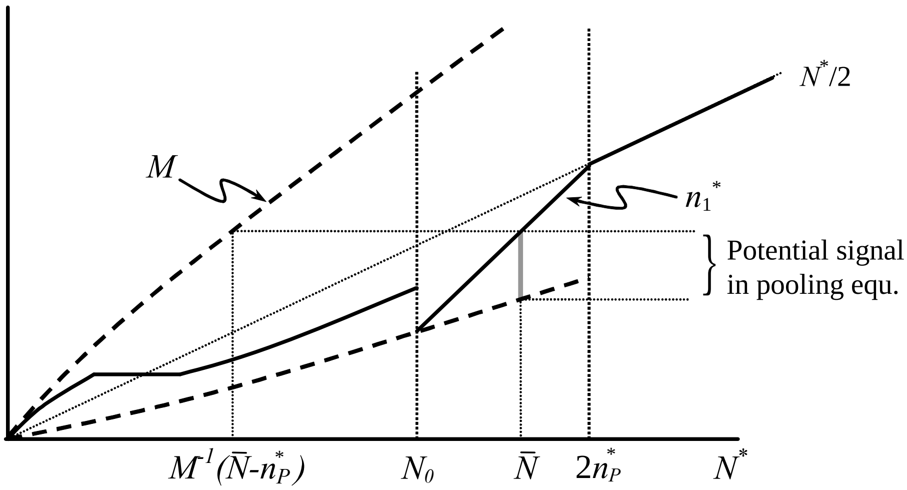

Figure 5: O_L's incentives to imitate O_H and equilibrium signals.

Proposition 2 has excluded the existence of pooling equilibria for some parameter range. Thus, the attention rests on the intermediate range of resources and the remainder of the section will focus on the cases where the conditions

$$\bar{N} \in (N_0, 2n_P^*) \tag{16}$$

and

$$\xi \in [M^{-1}(\bar{N} - n_P^*)/\bar{N}, 1) \tag{17}$$

are satisfied. Conditions (16) and (17) assure that type O_L gains from imitating O_H's full information strategy $n_{1,H}^*$ if that discourages substitution R&D. Yet, under such pooling attempts, country W adapts its beliefs so that $n_{1,H}^*$ is not an equilibrium signal. Instead, the natural candidate for the signal of a pooling equilibrium is the quantity that solves (13) with equality under prior beliefs $\mu \equiv \pi$. Let this value be denoted by n_P^e, defined as the implicit solution of

$$\begin{aligned} \ln(B) + \tfrac{1}{B} - \pi \left\{ \ln\left(T_2^*(\bar{N} - n_P^e)\right) + \frac{1}{T_2^*(\bar{N} - n_P^e)} \right\} - \ldots \\ \ldots(1-\pi) \left\{ \ln\left(T_2^*(\xi\bar{N} - n_P^e)\right) + \frac{1}{T_2^*(\xi\bar{N} - n_P^e)} \right\} = A \end{aligned} \tag{18}$$

where $T_2^*(.)$ stands for the second period's export tax (**??**) under $b_2 = 0$. It is quickly verified that the expression on the left of (18) is decreasing in export taxes and, hence, by (**??**), increasing in n_P^e. Further, (**??**) implies that the term in the first slanted brackets is larger than the term in the second slanted brackets and thus, the whole expression on the left is decreasing in π. Further, it is quick to check that the expression on the left on (18) is decreasing in ξ. Consequently, by the implicit function theorem, n_P^e is increasing in ξ

and π. Finally, at $\pi = 1$ condition (18) coincides with (8) in which case $n_P^e = \bar{N} - n_P^*$ while at $\pi = 0$ (18) leads to $n_P^e = \xi \bar{N} - n_P^*$. These properties of n_P^e are summarized by

$$\begin{aligned}
\frac{d}{d\xi} n_P^e &> 0 && (19)\\
\frac{d}{d\pi} n_P^e &> 0 && (20)\\
\lim_{\pi \to 1} n_P^e &= \bar{N} - n_P^* && (21)\\
\lim_{\pi \to 0} n_P^e &= \xi \bar{N} - n_P^* && (22)
\end{aligned}$$

The gap between n_P^e and n_P^* reflects that country W reacts to the pooling of type O_L by adapting expectations and, relative to the full information equilibrium under $N^* = \bar{N}$, a downward revision of expected future supply. To compensate for this drop of expected future supply, the O_H must further increase the second period supply in order to discourage country W's R&D activity; hence $n_P^e < \bar{N} - n_P^*$ holds.

In addition to country W, type O_H also reacts to O_L's pooling attempts, and may choose not to discourage substitution R&D any more. In this case, O_L's incentives to pool cease to exist. This introduces an additional condition to be satisfied in a pooling equilibrium: the relevant signal $n_{1,H}^e = n_{1,L}^e$ must be element of the set $[m(\bar{N}), M(\bar{N})]$. Since conditions (20) and (21) imply $n_P^e < \bar{N} - n_P^*$ and since $\bar{N} - n_P^* < \bar{N}/2$ by (16), the relevant constraint is thus

$$n_P^e \geq m(\bar{N}) \tag{23}$$

Since n_P^e is a function of π and ξ, condition (23) implicitly defines a constraint on the parameters ξ and π. In particular, the equation $n_P^e = m(\bar{N})$ defines a schedule on the (ξ, π)-plane which, by virtue of properties (19) and (20), represents a decreasing function $\underline{\pi}(\xi)$ that marks the limits for a pooling equilibrium to exist. For values of $\pi < \underline{\pi}(\xi)$, condition (23) is violated and type O_H does not induce $a_1 = 0$ but optimally concedes to $a_1 = A$, in which case O_L lacks incentives to imitate O_H.

These observations suggest that – in addition to the necessary conditions (16) and (17) – the requirement (23) is necessary for a pooling equilibrium to exists. The following proposition identifies conditions (16), (17), and (23) as jointly sufficient, granting that the two-stage signaling game has a pooling equilibrium in pure strategies that is – modulo country W's off-equilibrium beliefs μ and strategies – unique.

Proposition 3 *If (16), (17), and (23) hold, a subgame perfect Bayesian Nash Equilibrium in pure strategies exists and includes the strategies*

$$(n_{1,H}^e, n_{1,L}^e) = (n_P^e, n_P^e) \quad \textit{and} \quad a_1^e(n_{1,H}^e) = a_1^e(n_{1,L}^e) = 0 \tag{24}$$

Proof. The proof consists of two parts: (i) Under (17) and (23) the strategies (24) and belief μ with A(i) - A(v) characterize an equilibrium. (ii) Under (17), (23), and A(i) - A(v) no other equilibria exist.

(i) E(i) - E(iii) are to be established.

E(i) $n^*_{1,H} = n^*_{1,L} = n^e_P$ and Bayesian updating requires $\mu(n^e_P) = \pi$.

E(ii) By $\mu(n^e_P) = \pi$ (13) holds for n^e_P and $a^e_1(n^e_P) = 0$ follows.

E(iii) Maximization of O_H. If O_H deviates to $\tilde{n} < n^e_P$, W's optimal off-equilibrium strategy induces either $\tilde{b} = 0$ or $\tilde{b} = B$. In both cases

$$V^*(\tilde{n}, \bar{N} - \tilde{n}, \tilde{b}) < V^*(n^e_P, \bar{N} - n^e_P, 0)$$

holds since $\tilde{n} < n^e_P < \bar{N}/2$.

If O_H deviates to $\tilde{n} \in (n^e_P, \bar{N} - n^*_P]$, condition (16) implies $n^e_P < \tilde{n} < \bar{N}/2$ and (17), (23), and A(iv) lead to $\mu(\tilde{n}) = \pi$ so that, finally, (13) is violated and W plays $a^e_1(\tilde{n}) = A$. If, instead, O_H deviates to $\tilde{n} > \bar{N} - n^*_P$ W's optimal strategy is $a^e_1(\tilde{n}) = A$ regardless of its beliefs. Thus, all deviations $\tilde{n} > n^e_P$ imply $\tilde{b} = B$. But

$$V^*(\tilde{n}, \bar{N} - \tilde{n}, B) < V^*(n^*_C(\bar{N}), \bar{N} - n^*_C(\bar{N}), B) < V^*(n^e_P, \bar{N} - n^e_P, 0)$$

(the last inequality follows by (16) and (23)).so that O_H's optimal strategy is $n^*_{1,H} = n^e_P$.

Maximization of O_L. If O_L deviates to $\tilde{n} \in (n^e_P, \bar{N} - n^*_P]$, condition (16) implies $n^e_P < \tilde{n} < \bar{N}/2$ and (17), (23), and A(iv) lead to $\mu(\tilde{n}) = \pi$ so that, finally, (13) is violated and W plays $a^e_1(\tilde{n}) = A$. If, instead, O_L deviates to $\tilde{n} > \bar{N} - n^*_P$ W's optimal strategy is $a^e_1(\tilde{n}) = A$ regardless of its beliefs. Thus, all deviations $\tilde{n} > n^e_P$ imply $\tilde{b} = B$, but

$$V^*(\tilde{n}, \xi\bar{N} - \tilde{n}, B) \leq V^*(n^*_{1,L}, \xi\bar{N} - n^*_{1,L}, b^*_{2,L}) < V^*(n^e_P, \xi\bar{N} - n^e_P, 0) \qquad (25)$$

holds. The second inequality holds since either $b^*_{2,L} = B$ and $m(\xi\bar{N}) < m(\bar{N}) < n^e_P$ by Claim 1 (iv) and condition (23), or else $b^*_{2,L} = 0$ and (20) and (22) imply $n^e_P > \xi\bar{N} - n^*_P$ while (16), (20), and (21) imply $n^e_P < \bar{N} - n^*_P < n^*_P$.

If O_L deviates to $\tilde{n} < n^e_P$ with $\left|\xi\bar{N}/2 - \tilde{n}\right| < \left|\xi\bar{N}/2 - n^e_P\right|$, then $\tilde{n} < n^e_P < \bar{N}/2$ and A(v) imply $\mu(\tilde{n}) = 0$. Thus, (25) applies again. If O_L deviates to $\tilde{n} < n^e_P$ with $\left|\xi\bar{N}/2 - \tilde{n}\right| \geq \left|\xi\bar{N}/2 - n^e_P\right|$ O_L's total utility decreases under the deviation. Hence, O_L optimal strategy is $n^*_{1,L} = n^e_P$.

(ii) Assume there is an equilibrium with $n^e_{1,H} \neq n^e_P$. By A(iv) O_H's deviation to $\tilde{n} = n^e_P$ induces $a^e_1(\tilde{n}) = 0$ by construction of n^e_P. This deviation gives O_H higher payoffs. Hence $n^e_{1,H} = n^e_P$ in any equilibrium. By (i) this implies that $n^e_{1,P} = n^e_P$ and proves the claim. ■

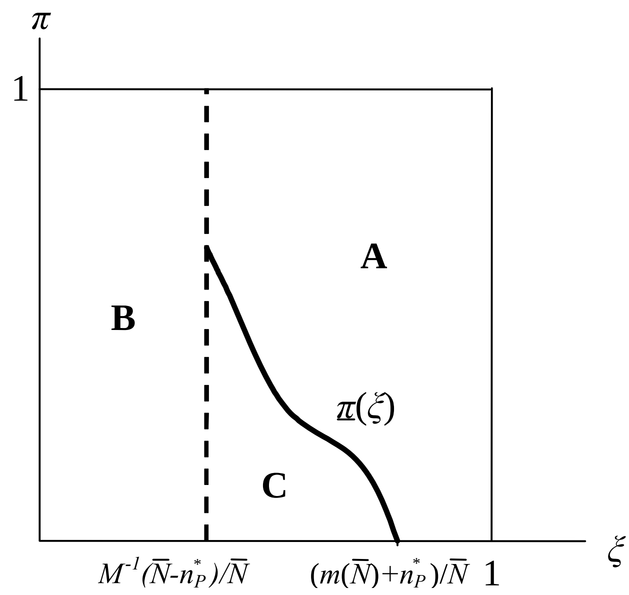

Figure 6: Three different types of equilibria.

Figure 6 illustrates the two key conditions (17) and (23) that delimit the range for the parameters ξ and π which pooling equilibria prevail. Condition (17) sets a minimum that ξ needs to exceed, represented by the dashed vertical line in the figure. Condition (23) defines a minimum $\underline{\pi}(\xi)$ that the ex ante probability π must exceed to grant (23). The function $\underline{\pi}(\xi)$ is marked as a bold line. Both conditions are satisfied for parameters within the area **A**. Notice with (20) and (22) that for $\xi > \left[m(\bar{N}) + n_P^*\right]/\bar{N}$, the value n_P^e exceeds $m(\bar{N})$ for *any* probability $\pi \in [0, 1]$, in which case the requirements on π are empty and hence the bold line hits the ξ-axis at the value $\left[m(\bar{N}) + n_P^*\right]/\bar{N}$.[12]

To the left of the dashed line, in area **B**, condition (17) is violated. Hence Proposition 2 (ii) applies and the unique equilibrium in pure strategies are those replicating the full information equilibrium ($n_{1,\theta}^*$ and $a_1^*(n_{1,\theta}^*)$ for $\theta = H, L$, respectively).

Finally, in the case when (17) holds but (23) is violated (area **C** in Figure 6), type O_H optimally chooses not to induce $a_1 = 0$ under O_L's pooling attempts. Consequently, O_L lacks incentives to pool and the equilibrium strategies are shown to follow the supply rules (10) for $N^* = \xi\bar{N}, \bar{N}$, respectively. This is the case of a separating equilibrium, where O_H deviates from its full information strategies.

4.3 Discussion of Results

Proposition 3 has shown that a pooling equilibrium exists for a non-trivial parameter range. Compared to its full information equilibrium, the low type benefits from imitating

[12] For $\bar{N} \gtrsim N_0$ it is quick to check that this value falls short of one.

the high (granted by condition (17)). Conversely, the high type must loose from pooling (conditions (16), (20) and (21) imply $n_P^e < \bar{N} - n_P^* < \bar{N}/2$). Thus, according to the interpretation of pooling equilibria at the start of this section, the low type overreports its reserve and claims to be the high type. Underreporting, however, does not occur.

Necessary Conditions. The preconditions for Proposition 3, and hence for credible overreporting are simple and intuitive. First, the lower bound of condition (16) requires that, under full information, the high type prevents country W's R&D activity. In other words, under high realizations of reserves N^* there is no substitution R&D in equilibrium. If this were not the case, substitution R&D would always take place and the incentives of overreporting cease to exist since the goal of overreporting is, precisely, to prevent substitution R&D. Second, the costs of the signal must be limited for the low type who overreports its reserves. Accordingly, the upper bound of (16) and condition (17) imply that the low type gains from overreporting. If these conditions are violated, the necessary signal introduces excessive distortions of supply and is too costly. Similarly, if the high type's distortions from the pooling equilibrium are too costly, i.e., if condition (23) is violated, then the pooling equilibrium ceases to exist since in that case the high type retreats by adjusting to R&D activity.

The fact that credible overreporting naturally emerges from standard assumptions is noteworthy already. Yet, it is even more surprising that the costs of the signal do not pose severe restrictions on the overreporting party. If intuition demands that substantial overreporting involve substantial costs, then this intuition is wrong. In fact, the general principle, according to which the low type trades off the gains from pooling against the costs of the signal, fails to apply here. Instead, the low type's cost of the signal can be zero or even negative so that the very act of signaling generates benefits.

The intuition for this result is the following. First, observe that in absence of R&D activity, country O's first best supply follows (**??**) and is constant over time. Country W's option to engage in R&D, however, makes country O deviate from this first best supply either to prevent R&D by back-loading supply (i.e., by increasing future supply) or else by adjusting to the R&D activity. In either case, potential R&D activity introduces a deviation from the first best supply. Now, under private information, overreporting requires an additional deviation of supply. If this last deviation cancels with the earlier one, it mitigates the original welfare losses, in which case the costs of overreporting are said to be negative. In fact, Figure 5 indicates that $\left|\xi\bar{N}/2 - n_P^e\right| \leq \left|\xi\bar{N}/2 - n_{1,L}^*\right|$ under the appropriate ξ and π.[13] This implies that supply n_P^e is closer to the low type's first best supply rule (**??**)

[13] For a formal proof, observe that n_P^e is increasing in ξ and $n_P^e = n_{1,H}^* < \xi\bar{N}/2$ if $\xi = 1$ and $n_P^e > \xi\bar{N}/2 = 0$ if $\xi = 0$. Thus, for π constant there is a $\xi_0 \in (0,1)$ with $\xi_0 = 2(\bar{N} - n_P^e)/\bar{N}$. For this ξ_0 the signal coinsides with the unconstrained optimal strategy (**??**) and hence pooling renders strictly higher utility than the full information equilibrium for the low type. By continuity, the statement holds for ξ in a neighborhood of ξ_0.

than $n^*_{1,H}$ under the full information equilibrium. Hence, by concavity of u^* (see (**??**)), its utility is higher.

At this point it is important to note that the high type cannot signal its type by increasing the first period's supply because it is constrained by the incentive compatibility constraint (13). Any increase in the first period's supply would reduce the remaining reserves, decrease the second period's supply and hence increase country W's incentives to engage in substitution R&D.

Robustness. The analysis above relies on a set of convenient assumptions that make the model tractable. For a better understanding of this paper's mechanism, it is thus necessary to discuss which of the assumptions are indispensable.

First, good N is supplied monopolistically. This assumption is relevant for the mechanism because it enables the exporter of good N to control the intertemporal distribution of aggregate reserves. Consequently, the exporter is able to discourage the importer's substitution R&D, which is critical to the mechanism to bite. To exemplify this point, imagine that there is a continuum of identical and atomistic suppliers of the N who maximizing their citizen's utility at given world prices. Each of them knows the aggregate realization of N^* (but none can sell this information to country W). Under successful pooling, country W's optimal strategy is $a_1 = 0$ irrespective of the realization of N^*. At the same time, perfect competition implies with $T^*_t = 1$ and the price (5) $p_1 = p_2 = 4/(\bar{N} + 4)$ if $N^* = \bar{N}$ while $p_1 = p_2 = 4/(\xi\bar{N} + 4)$ if $N^* = \xi\bar{N}$. This contradicts the requirement $p_1|_{N^*=\xi\bar{N}} = p_1|_{N^*=\bar{N}}$ of a pooling equilibrium.

Second, following the literature, substitution R&D is assumed to be a binary choice (see Dasgupta and Heal (1974), Deshmukh and Pliska (1983), Quyen (1988), and Barrett (2006)). This is a convenient simplification but not a crucial assumption. Relaxing it generalizes productivity B from (4) to a function of R&D expenditure a_1. Intuitively, under full information, the equilibrium $B(a_1)$ is then a decreasing function of the second period's supply n^*_2 and of total reserves N^*. Hence, the scenario preserves the basic incentive to overreport reserves in order to discourage substitution R&D at the margin and reduce the intensity of competition in period two. Under private information, then, the low type's signal can still be arbitrarily close to its first best supply $n^*_t = N^*/2$ and all results of the discrete case apply.

Third, according to the model's setup, only one country imports good N. Country W's gains from substitution R&D accrue via reductions in export taxes while domestic production is zero for a wide parameter range.[14] Consequently, no private firm can recoup the investment $a_1 = A$, which must be financed publicly. If there are many small countries importing N, this creates coordination problems. Yet, the mechanism outlined in this

[14] The range for N^* is $(3B + \sqrt{B} - 4, N_0)$ under full information (see the proof of (10) in the Appendix).

paper remains unchanged in a world where the technology B, once invented, delivers a flow of good N. Similarly, the argument applies if consumers, anticipating future prices, choose between alternative durable equipment thus affecting aggregate demand for N. In that sense, the the assumption of a two-country world is not essential to the paper.

Fourth, only the importer of good N may engage in substitution R&D by assumption. This assumption can be justified by a comparative advantage in the R&D sector. Moreover, country W benefits more from substitution R&D since it does not only expand its production possibility frontier but also trims country O's export taxes. Hence, it is more likely to incur the R&D costs.

Fifth, the exporting country sets export taxes. While incentives to discourage substitution R&D are present when imposing the restriction $T_t^* = 1$, it can be shown that a low type overreports with a signal that involves a reduction of its reduces its supply in the first period. This unattractive feature is reduced if country O can price discriminate between the domestic and the export market via export taxes. Further, export taxes allow the exporter to mitigate the impact of distorted supply in its domestic market and expand the range of overreporting. Finally, as argued in the previous paragraph, the export tax helps to justify the assumption that only country W engages in substitution R&D.

Lastly, any aggregate uncertainty about resources and the R&D outcomes has been eliminated from the model. Introducing such additional uncertainties, the trade-off between country W' cost and benefits of substitution R&D and country O's prevention of R&D is based on expected utilities (affecting conditions (8), (11), and (13)). It is unlikely that this can overturn the qualitative results.

4.4 The Crude Oil Market

Motivated by rising concerns about supply security, this paper has raised the questions why, how, and under what conditions natural resource reserves are overreported? It shows that exporting countries indeed have motives to overreport and that they can credibly do so under rational expectations. The necessary conditions for overreporting to occur are intuitive: substitution R&D must respond significantly to expected and the costs of the required signal need to be limited. This subsection tries to answer the remaining question regarding the motivating example of the oil market: can the alleged overreporting of today's oil market be refuted?

First, the model's key assumptions are to be checked: a strong reaction of substitution R&D to expected and monopolistic supply. Concerning the first condition, evidence suggests that substitution R&D indeed responds to shortages of the market. Figure 1 illustrates the relation between non-oil energy R&D in IEA member countries and world oil prices for the period 1973-2006.[15] Moreover, current prices strongly correlate with price forecasts in the relevant period (see Lynch (2002) and IMF (2003)), which implies a comovement between expected future supply and R&D activity. Of course, a simple correlation does not imply causality. Yet, hard evidence shows that energy saving R&D is indeed responsive to supply shortages (see Newell et al (1999) and Popp (2002)). Thus, the first of the necessary conditions seems to be satisfied. The second requirement of non-competitive oil markets seems obvious. Contrary to conventional wisdom, however, empirical literature is inconclusive about OPEC's actual market power. Some quantitative studies indicate that in the years following the counter-oil shock in 1986, OPEC countries failed to behave as a cartel and over-supplied the world market instead of under-supplying it (Almoguera and Herrera (2007) and Lin (2007)). Other empirical studies such as Griffin (1985) and Smith (2003), report, however, substantial coordination and cartel discipline of OPEC members and a significant shortage of contemporaneous supply. In the latter case, a rough and tentative application of the model cannot refute that OPEC member states overreport their crude oil reserves.

Finally, Proposition 3 applies only if the respective costs of the signal, induced by the required supply deviations, are limited. A thorough quantitative assessment of the likelihood of overreporting must involve these costs. Within a first qualitative application of the theory, however, this requirement does not serve as a meaningful criterion since there is no positive lower bound on these costs of signaling.

In sum, the possibility of overreporting in today's oil market cannot be easily refuted by applying the present paper's predictions qualitatively. Thus, the last and – from the viewpoint of policymaking – the most urgent of the initial questions remains unanswered.[16] This observation calls for a thorough quantitative research of the issue, which thereby will answer the question whether the interpretation of OPEC is to be extended to a cartel of not only supply but also of information.

In the discourse on supply security of crude oil overreporting of reserves is only one of many aspects and thus needs to be discussed in a broader picture. In absence of uncertainty the economics of exhaustible resources sketch a comforting image: the continued exhaustion of a natural resources raises the returns to oil-saving substitution technologies, which are eventually generated by intensifying research (see Davidson (1978), Deshmukh and Pliska (1983) and Tsur and Zemel (2003)). In this process forward-looking firms

[15] Strictly speaking, expected future supply is the determinant of substitution R&D and contemporaneous supply is irrelevant. The logical gap is bridged when the current price is the best predictor of future prices.

[16] Notice that credible overreporting – as defined above – can be refuted when the relevant conditions are violated. Conversely, however, misreporting cannot be proven before private information is revealed. Under credible overreporting the probability that reserves are high (π is the present model) must be positive.

anticipate future profits and, motivated by consumer's willingness to pay for steady consumption flows, grant a smooth transition between a resource- and a substitution-based regime. This picture, however, changes when oil reserves are uncertain and information shocks cause ex-post inefficiencies. Hence, one must focus on the sources and magnitudes of uncertainty. Traditionally, geological and political unknowns are viewed as the major sources of uncertainty. Today, advanced exploration technology allows accurate assessments of the size of oil fields and tough surprises due to technology seem unlikely (see e.g. Cuddington and Moss (2001)). Thus, man-made uncertainty appears to be the main source of worries. Within that category, political instability is usually focused on with a special emphasis on the geopolitical situation of the Middle East (see, e.g., IEA (2005)). Yet, if overreporting turned out to happen as reported, then the resulting supply shocks could easily dominate those stemming from the political field. In sum, overreporting may deserve some more attention after all.

5 Conclusion

Concerns are rising about the supply security of crude oil. In addition to geological and political risks, some experts are pointing at overreporting as one – possibly significant – source of uncertainty. This paper has provided a simple but suggestive framework for the analysis of the incentive to overreport. The main elements of the theory are, first, market power of the oil supplier, second, the possibility to engage in R&D for technologies that substitute oil, and third, private information about its remaining reserves. It has been shown that, within this framework, the only incentive to overreport can be attributed to the aim of exporters to discourage importers' R&D for substitution technologies. Surprisingly, an exporter with low reserves can pretend high reserves at zero or even negative costs. Finally, conditional on the reported realizations of reserves, supply is partly delayed under successful overreporting. In a tentative application of the main results to today's crude oil market overreporting cannot be dismissed.

Appendix

Proof of (10). For $n_2 = 0$ use u_t^* from (**??**) to compute with the help of the envelope theorem

$$\frac{du_1^*}{dn_1^*} = \frac{T_1^* + 1}{(n_1^* + 2)^2} + \frac{1}{n_1^* + 2} = \frac{1}{(T_1^*)^2}$$

where (**??**) with $b_1 = 0$ was used in the second step. Use (**??**) with $b_2 = B$ and (**??**) to write $u_2^* = \ln(bT_2^*) + y_2^* + 1 - 1/B$ so that $du_2^*/dT_2^* = 1/T_2^*$. With $dT_2^*/dn_2^* = 1/B$ and

$dn_1^*/dn_2^* = -1$ optimality requires

$$(T_1^*)^2 = BT_2^*$$

With (**??**) and $n_1^* + n_2^* = N^*$ rewrite this as $(\sqrt{9/4 + n_1^*} - 1/2)^2 = N^* - n_1^* + 2 - B$ or

$$2n_1^* + \tfrac{1}{2} - N^* + B = \sqrt{n_1^* + \tfrac{9}{4}}$$

Taking squares on both sides and solving for n_1^* leads to

$$n_1^* = 1/2\left[N^* - B - 1/4 \pm \sqrt{(N^* - B)/2 + 2 + 1/16}\right]$$

The negative root is ruled out with the condition $N^* = B - 1 \Rightarrow n_1^* = 0$. The relevant condition for $n_2 = 0$ to hold is $n_2^* > 2(B-1)$, which is equivalent to $N^* > N_o$ where solves

$$N_o - n_1^* = 2(B-1) = 1/2\left[N_o + B + 1/4 - \sqrt{(N_o - B)/2 + 2 + 1/16}\right]$$

or $N_o = 3B + \sqrt{B} - 4$. This proves the fist line of (10).

Consider now $N^* < N_o$ as long as O exports N (i.e. $c_{n,2}^* < n_2^*$) (**??**) applies and $n_2^* + n_2 + 2 = 2B$ imply $du_2^*/dT_2^* = 1/B$ so that optimality requires $(T_1^*)^2 = B$ or $n_1^* = B^2 + B - 2$. The relevant conditions for $n_2 > 0$ and $c_{n,2}^* < n_2^*$ to hold is

$$n_2^* = N^* - \left(B^2 + B - 2\right) \in ((B-1), 2(B-1))$$

or $N^* \in (2B - (\sqrt{4B+5} + 1)/2, 3B + \sqrt{B} - 4)$. Finally, if $N^* < 2B - \left(\sqrt{4B+5} + 1\right)/2$ optimality requires $c_{n,1}^* = c_{n,2}^* = n_2^*$ or $n_1^* = N/2 + 1/8\sqrt{8N + 25} - 5/8$. ■

Proof of Claim 1. First, define the expression on the left of the identity (14) by $\Gamma(N^*, m)$. Now, by the definition (11) of $V^*(n_1^*, n_2^*, 0)$ and concavity of u_t^* (**??**) the partial derivative $\partial_m \Gamma$ is negative

$$\partial_m \Gamma = -\left[V_1^*(m, N^* - m, 0) - V_2^*(m, N^* - m, 0)\right] < 0 \tag{26}$$

for $m \in (0, N^*/2)$. (Subscripts stand for partial derivatives.)

(i) Check with (11) that

$$\begin{aligned}\Gamma(N^*, 0) &= V^*\left(n_C^*, N^* - n_C^*, B\right) - V^*\left(0, N^*, 0\right) \\ &= V^*\left(n_C^*, N^* - n_C^*, B\right) - V^*\left(N^*, 0, B\right) > 0\end{aligned}$$

Further, $\Gamma(N^*, N^*/2) < 0$ holds by optimality (**??**) so that there is a solution to (14) with $m < N^*/2$. By $\partial_m \Gamma < 0$ this solution is unique.

(ii) The definition (11) of N_0 implies that $\Gamma(N^*, N^* - n_P^*) > 0$ if and only if $N^* \in (N_0, 2n_P^*]$ and the claim follows with $\Gamma(N_0, N_0 - n_P^*) = 0$ and (26).

(iii) $V^*(n_C^*, N^* - n_C^*, 0) > V^*(n_C^*, N^* - n_C^*, B)$ and (14) imply

$$V^*(n_C^*, N^* - n_C^*, 0) > V^*(m, N^* - m, 0)$$

By the concavity of u_t^* (**??**) and $m < N^*/2$ this shows the statement.

(iv) Compute

$$\begin{aligned}
\partial_{N^*}\Gamma &= V_2^*(n_C^*, N^* - n_C^*, B) - V_2^*(m, N^* - m, 0) \\
&= V_1^*(n_C^*, N^* - n_C^*, B) - V_1^*(N^* - m, m, 0) \\
&= V_1^*(n_C^*, N^* - n_C^*, 0) - V_1^*(N^* - m, m, 0)
\end{aligned}$$

The second equality holds by optimality of n_C^* and symmetry; the third since u_1^* is independent of b_2. The last expression is positive by (iii) and concavity of u_1^*, i.e. (**??**). Thus, with (26) the derivative

$$\frac{dm}{dN^*} = -\frac{\partial_{N^*}\Gamma}{\partial_m \Gamma} = \frac{V_1^*(n_C^*, N^* - n_C^*, 0) - V_2^*(m, N^* - m, 0)}{V_1^*(m, N^* - m, 0) - V_2^*(m, N^* - m, 0)}$$

is positive. As numerator and denominator are positive and $V_1^*(n_C^*, N^* - n_C^*, 0) < V_1^*(m, N^* - m, 0)$ holds by (iii), this shows $dm/dN^* < 1$.

(v) Follows from $\lim_{N^* \to 0} \Gamma(N^*, 0) = 0$ and (iv). ■

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