Misreporting of Natural Resource Reserves*

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This Draft:
April 2008

Abstract

A number of oil market experts argue that OPEC members substantially overreport their reserves. The potential damage for the world economy calls for an analysis of the motives and the preconditions for successful misreporting of natural resource reserves. Based on a signalling game within an international trade model, this article develops a framework for such an analysis. Exporting countries with private information about total reserves use current supply as a signal for remaining reserves. An exporting country is said to engage successfully in misreporting when current supply is uninformative about remaining reserves – i.e. when a pooling equilibrium prevails. It is shown that a pooling equilibrium exists if and only if, first, R&D for substitutes of the natural resource is responsive to expected future supply and second, the signal's cost is limited. Finally, regardless of information asymmetries exporters of the natural resource backload supply to discourage substitution R&D.

Keywords: Exhaustible Resource, Substitution Technology, Signalling

JEL Classifications: F10, F16, D82.

*I would like to thank Raphael Auer, Martin Brown, Andreas Fischer, Werner Herrmann, Marcel Peter, Andrea Pescatori, Rick van der Ploeg, and Hosny Zoabi for helpful comments. All remaining errors are mine.

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1 Introduction

Over the past decade world demand for natural resources has grown at rates world supply could not keep up with. In importing countries this tightening of the markets has raised increasing concerns about supply security, which are particularly pronounced in the crude oil market. Now, in addition to geological and political imponderabilities, a growing number of market pundits points at overreporting of the remaining crude oil reserves as one, possibly dramatic, source of uncertainty.[1] The Economist (2006) reports warnings that "reserves figures of national governments must be viewed with caution" and suppliers as "Kuwait might have only half of the [...] oil reserves" officially reported. Bentley (2002) argues that "various estimates for Saudi Arabian [...] reserves differ by a factor of about two", and that similar overreporting is widespread. The Energy Watch Group, a Germany-based think tank reckons that, when applying "the same criteria which are common practice with western companies, [...] Saudi Aramco's [Saudi Arabia's state-owned oil company] statement of proven reserves should be devalued by 50%" (EWG (2007), p. 53). These figures, taken seriously, suggest that international crude oil supply is near or even past its peak. While many experts disagree with the peak-oilers, renowned institutions like the International Energy Agency frequently express 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), p. 123). In sum, the opaque, state-owned companies that control major parts of the world's oil reserves possibly, but not necessarily overreport their remaining crude oil reserves by far.

Clearly, it would be deeply displeasing if good parts of what is considered future oil supply turned out to be fictitious. The actual motives of the alleged overreporting, however, remain largely unclear[2] and to the economist, generally unfamiliar with geological details but trained to handle rational expectations, a certain type of questions occurs. Why would oil suppliers misreport? Under which conditions would their misreporting be credible and are these conditions likely to be satisfied? After all, should oil suppliers not under- instead of overreport, because anticipated shortages raise current prices? The present paper addresses these questions. It shows that under asymmetric information about oil reserves credible overreporting can emerge from two standard assumptions of the economics of exhaustible resources: directed technical change and monopolistic supply. According to the first assumption, economic agents can engage in costly development of oil-substitution

[1] Reserves of crude oil are defined in many different ways. The claims quoted here refer to the standard definitions proven and proven and probable reserves (quantities of 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 upward revised their respective oil reserves (see Campbell and Laherrèr (1998) and Bentley (2002)). Yet, if such a strategic quota game was obviously taking place, market participants should entirely discount the spurious revisions. Since this is not the case, the question recurs whether oil exporters strategically deceive the markets.

technologies – henceforth called substitution R&D. Under standard demand structures the returns to such substitution R&D is decreasing in the volume of future oil supply. Consequently, as successful overreporting of reserves increases expected future supply, it discourages substitution R&D and thus increases future market power of the incumbent supplier. As a monopolist (according to the second assumption), the incumbent supplier benefits from such increases in market power via increases in profits, which explains overreporting in the first place. Under rational expectations two necessary conditions for this mechanism to bite are, first, that information about oil reserves are private, and second, that successful misreporting is credible and backed by the observable actions. The supplier's observable action is contemporaneous supply, which acts as a signal for remaining reserves and hence for future supply. In this framework of a signalling game between rational agents, misreporting is said to be successful if current supply is uninformative about remaining reserves – i.e. when a pooling equilibrium prevails. Costs of misreporting arise since the supply strategies in a pooling equilibrium must deviate from the first best strategies under full information. Finally, supply of the natural resource is back-loaded under successful overreporting. More precisely, conditional on reported reserves and relative to the unconstrained optimal, oil supply of early periods is partially postponed after resolution of private information.

The present paper predicts that exporters of natural resources tend to overreport if first, substitution R&D reacts significantly to expected future supply of the natural resource and if second, the cost of the required signal does not exceed the benefits of reduced substitution R&D. Moreover, under successful overreporting oil supply is partially delayed since this discourages substitution R&D. How do these results square with the motivating example of the oil market? First, empirical work shows that substitution R&D has indeed been responsive to oil prices (see Newell et al (1999) and Popp (2002)), which underpins one of both necessary conditions. Plotting crude oil prices and total R&D expenditure on non-oil energy sources in IEA member countries, Figure 1 illustrates these findings in a rather suggestive way. According to the second necessary condition, the cost of the signal must be smaller than the benefits of overreporting. Somewhat surprisingly, the present paper shows that the signal's cost may be negligible or even negative. The theory does not establish a lower bound on the costs and, consequently, no unambiguous criterion can be deduced from the second necessary condition. Thus, the attention rests on the relation of current and expected supply. This criterion, of course, must account for the supply structure of the world oil market, which can be loosely interpreted as a colluding OPEC and a competitive fringe. Indeed, it might be argued that the OPEC's scarification of supply reported by some empirical studies (see Griffin (1985) and Smith (2003)) can be read as the undersupply predicted by the theory.

In sum, the rough and tentative evaluation based on the model's qualitative results cannot dismiss the claims that OPEC member states overreport their crude oil reserves. This

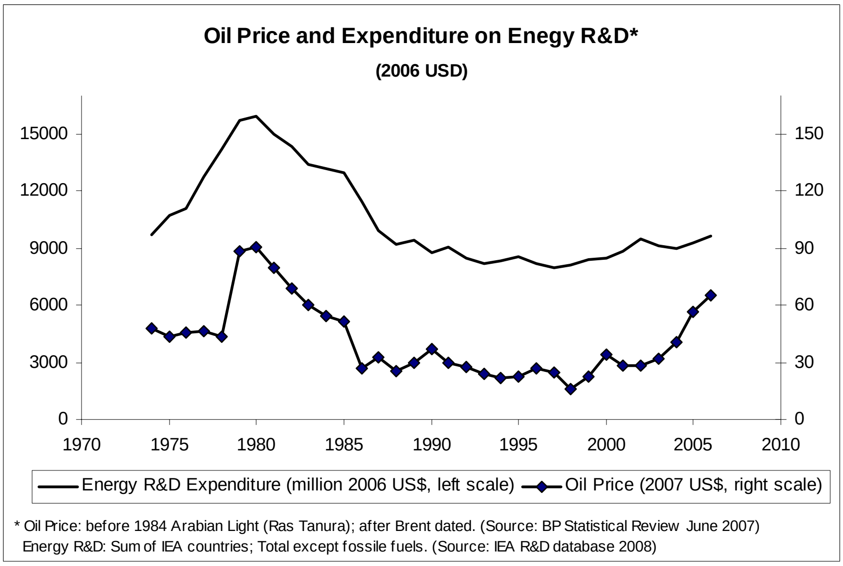

Figure 1: Oil Price and Expenditure on Energy R&D*

finding calls for a quantitative assessment of the matter. A thorough cost-benefit analysis of overreporting that incorporates the key characteristics of today's oil market must stand at the centre of such an assessment.

To frame the theory, the present paper develops a two-country model with international trade in two goods, one of which represents oil. This setup shall reflect the fundamental dichotomy between exporters and importers in the global oil market. At the same time, it comprises the effects of oil supply on aggregate production and, given that all policies maximize domestic citizens' utility, captures motives of consumption smoothing in oil exporting countries. These aspects generally affect the exporter's optimal intertemporal supply rule and hence its incentives to misreport. Finally, the model incorporates tariffs of the oil-exporting country so that potential impacts of information asymmetries on the exporter's market power can be read from the optimal tariffs and result in changes of monopolistic rents.

The paper connects to various literatures. The analytic framework rests on two fundamental elements of macroeconomics modelling. The first of these elements is the supplier's market power, which generates markups over marginal costs in equilibrium. In the context of trade between large countries, this principle makes countries charge positive tariffs to generate gains from export markets (see Helpman and Krugman (1989) for a comprehensive reference). The second key element is directed technical change, which takes an important place in modern macroeconomics. Recent work highlights its importance, among others, for international trade (see Acemoglu (2002), and Acemoglu (2003)). In support of the present paper's premises, empirical studies document significant response of R&D to prices in the energy market (see Newell et al (1999) and Popp (2002)).

Market structure and technical change stand out, too, as key concepts in the economics of exhaustible resources. Since its foundations by Hotelling (1931), the suppliers' market power is at the centre of this rich literature. Not surprisingly research intensified with the oil shocks of the 1970s, focussing 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 of 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). Dasgupta and Heal (1974) sparked a line of research on substitution of exhaustible resources, analyzing on the one hand the role of endogenous exploration (Burt and Cummings (1970), Arrow and Chang (1982) and Quyen (1988)) and on the other hand directed technical change to substitute scarce resources (e.g. Davidson (1978) and Deshmukh and Pliska (1983)). The present paper rests on both basic modelling elements – supplier's market power and substitution efforts in the form of directed technical change – to analyze motives of misreporting under necessarily private information about remaining reserves of the exhaustible resource. The paper thus connects to earlier work on private information in natural resource markets like Gaudet et al (1995) and Osmundsen (1998) who analyze information asymmetries of the reserves of natural resources and show that firms have incentives to underreport reserves: given that extraction costs are higher for lower reserves, underreporting of reserves is equivalent to overreporting of costs, which, finally, saves taxes of profits. In contrast to these studies, the present paper addresses private information of sellers vis-à-vis the buyer, drawing entirely different conclusions.

Finally, the present paper adds to research motivated by the renewed interest in global energy markets, partly focussing on the dynamics of aggregate supply itself (Amigues et al (1998), Backus and Crucini (2000), Cuddington and Moss (2001), Popp (2002), and Gaudet (2007)) and partly driven by the rising sensitivity to environmental issues (as Chakravorty, Roumasset, and Tse (1997), Tahvonen and Salo (2001), Tsur and Zemel (2003), and André and Cerdá (2006)).

The remainder of the paper is organized as follows. Section 2 outlines the model economy, describes the action of individuals and sets up the strategic game involving the governments' decisions. Section 3 solves the strategic game under full information while section 4 solves the game under asymmetric information and discusses the main results of the paper. Finally, Section 5 concludes.

2 The Model

In this section a model will be developed with which to analyze the incentives of the exporter of a non-renewable natural resource to mis-report remaining reserves. To handle the technicalities that necessarily arise from a signalling game within a two country trade setup, the model is stripped down to a very basic framework.

2.1 General Setup

The world economy consists of two countries O (*) and W (no *) which are populated by individuals of mass one each. 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.[3]

Production. 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. The 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 the second period is $N^* - n_1^*$. Mining costs of N are negligible, yet once N is mined, it becomes perishable.[4] Before period one country W's total reserves of N are uncertain and distributed according to

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

with $\xi \in (0, 1)$. The parameters $\bar{N}$, ξ, and π are common knowledge, the realization of N^*, however is only known 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 $n_1^* + n_2^* \leq N^*$. For simplicity, 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

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

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

$$u(c_n, c_y) = \ln(c_n + 1) + c_y \tag{3}$$

[3] 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".

[4] 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.

This specification has a number of advantages. First, the quasi-linear form implies that income is perfectly transferable across periods[5] so that country O maximizes the sum of profits in the export market on the world market. Second, the logarithm gives rise to a simple closed form solution of country O's optimal tariffs. The additive unit in the argument of the logarithm ensures that tariffs are bounded; it can be read as a flow of a perishable substitute to the natural resource in each country.

Government policies. Consumers and firms are atomistic so that only governments take strategic decisions. For simplicity "the strategy of country X's government" will simply be referred to as "country X's strategy" strategies. With this terminology country O is said to control supply n_t^* and, in addition, sets ad valorem export tariffs T_t^* within each of the two periods. Under ad valorem tariffs T_t^* domestic prices of good N are p_t in country O and $T_t^* p_t$ in country W. Since country W does not set tariffs by assumption, prices of good Y in both countries equalize and can be normalized to unity. Hence, p_t and $T_t^* p_t$ reflect relative domestic prices in country O and W, respectively.

Country W decides whether to invest in a technology with which to produce a substitute of the natural resource N.[6] More precisely, country W may incur $A > 0$ units of the good Y in period $t = 1$ to develop a technology, which, effective in period $t = 2$, enables country W to produce a perfect substitute of good N out of good Y with the marginal rate of transformation B, i.e.

$$n_2 = B y_{2,n}$$

where $B > 1$ is assumed. Country W's investment decision is reflected by the choice variable $a_1 \in \{0, A\}$. Productivity of this substitution technology can be summarized by

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

For convenience of notation let country W's first period output and second periods investment be denoted by $n_1 = 0$ and $a_2 = 0$.

The R&D process defined by (4) is particularly simple, characterized by either full engagement or non at all. As a common assumption in the literature this reflects mayor technological breakthroughs for substitution, the development of which exhibits increasing returns to scale to a substantial degree (see e.g. Dasgupta and Heal (1974), Deshmukh and Pliska (1983), Quyen (1988), and Barrett (2006)).

Timing. The timing of actions in the game between governments is determined as follows. First, nature decides in the realization of N^*, which only country O observes. Then,

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

[6] The government of 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.

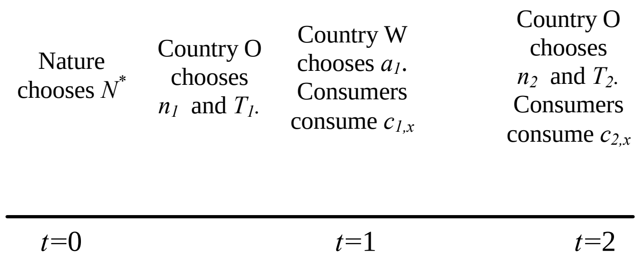

Figure 2: Timing of actions.

country O decides supplies the quantity n_1^* and sets the tariffs T_1^*. Next, country W decides on the investment a_1 and first period consumption is realized. Finally country O sets the second period's tariffs T_2^*, supplies $n_2^* \leq N^* - n_1^*$ and the second period's equilibrium quantities are consumed. Figure 2 summarizes this time-line.

In case 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 both, its supply and private information, to prevent substitution R&D. The costs and benefits from so doing are central to the following analysis. Before turning to the strategic aspects of the game, however, consumer's choice and static tariffs will be computed.

2.2 Consumers' Optimization

At each point in time consumers purchase their optimal consumption basket taking as given domestic prices and the quantities n_t^* and n_t. The optimal consumption basket maximizes sub-utilities (3) subject to the respective per capita budgets constraints

$$T_t^* p_t c_{n,t} + c_{y,t} \leq E_t \qquad \text{and} \qquad p_t c_{n,t}^* + c_{y,t}^* \leq E_t^*$$

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

$$\begin{array}{ll} c_{n,t} = 1/(T_t^* p_t) - 1 & c_{y,t} = E_t - 1 + T_t^* p_t \\ c_{n,t}^* = 1/p_t - 1 & c_{y,t}^* = E_t^* - 1 + p_t \end{array} \tag{5}$$

When the natural resource market clears, i.e. when $c_{n,t} + c_{n,t}^* = n_t^* + n_t \equiv \bar{n}_t$ holds, the relative world prices are

$$p_t = \frac{1 + 1/T_t^*}{\bar{n}_t + 2} \tag{6}$$

(remember $n_1 = 0$ so that $\bar{n}_1 = n_1^*$.) With this expression of the prices, country W's income per capita net of investments is

$$E_t = y_t + n_t \frac{T_t^* + 1}{\bar{n}_t + 2} - \frac{n_t}{B} - a_t$$

Country O's nominal tariff revenues $(T_t^* - 1)p_t(n_t^* - c_{n,t}^*)$ are distributed lump-sum to its citizens so that their per capita income is

$$E_t^* = (T_t^* + 1)\frac{n_t^* + 1}{\bar{n}_t + 2} - \left(\frac{T_t^* + 1}{T_t^*}\right)\frac{1}{\bar{n}_t + 2} - T_t^* + 1$$

These expressions lead to equilibrium consumption

$$\begin{aligned} c_{n,t} &= \frac{\bar{n}_t + 2}{T_t^* + 1} - 1 \qquad & c_{y,t} &= y_t + (T_t^* + 1)\frac{n_t + 1}{\bar{n}_t + 2} - 1 - \tfrac{n_t}{B} - a_t \\ c_{n,t}^* &= T_t^* \frac{\bar{n}_t + 2}{T_t^* + 1} - 1 \qquad & c_{y,t}^* &= 1 - (T_t^* + 1)\frac{n_t + 1}{\bar{n}_t + 2} \end{aligned} \tag{7}$$

and sub-utilities are

$$\begin{aligned} u_t &= \ln\left(\frac{\bar{n}_t + 2}{T_t^* + 1}\right) + y_t + (T_t^* + 1)\frac{n_t + 1}{\bar{n}_t + 2} - 1 - \tfrac{n_t}{B} - a_t \\ u_t^* &= \ln\left(T_t^* \frac{\bar{n}_t + 2}{T_t^* + 1}\right) + 1 - (T_t^* + 1)\frac{n_t + 1}{\bar{n}_t + 2} \end{aligned} \tag{8}$$

Countries employ their respective policies (n_t^*, T^*, and a_1) to maximize the sum of sub-utilities (8). The next subsection proceeds by computing country O's optimal tariffs.

2.3 Optimal Tariffs

Both countries use their respective policies to maximize total utilities (2). Country O's optimal tariffs T_t^*, however, can be computed on a period-by-periods basis for the following reason. The first period's tariff T_1^* affects neither the cost of investment A nor the returns to it, which accrue in the second period only. Hence, T_1^* is independent of county W's investment decision and is set without any intertemporal aspects. But, in the second period, the game ends and, without earlier commitment on policies, tariff T_2^* must trivially maximize u_2^*. Consequently, optimal tariffs T_t^* can be computed by maximizing u_t^* from (8) at given n_t^*.

There are two cases to consider, first $b_t = 0$ and second $b_t = B$. In the first case, the quantities $n_t = 0$ are trivially given and maximization of u_t^* from (8) leads to the expression[7]

$$T_t^* = \sqrt{\frac{5}{4} + \frac{n_t^* + 1}{n_t + 1}} - \frac{1}{2} \tag{9}$$

If second $b_2 = B$ holds, the country O's optimal tariff generally differs from (9). In particular, the price ratio $T_2^* p_2$ cannot exceed the marginal rate of transformation $1/B$ and country O's equilibrium tariff must satisfy the constraint $T_2^* p_2 \leq 1/B$. When this constraint binds the equilibrium price (6) leads to

$$T_2^* = \frac{\bar{n}_2 + 2}{B} - 1 \tag{10}$$

According to equation (10) any increase above the level $T_2^* = \frac{n_t^*+2}{b} - 1$ is compensated by an increase in n_2 to keep the relative price $T_2^* p_2$ constant. With (8) it is straight forward to check that, under (10) and at constant n_2^*, sub-utility u_2^* is decreasing in n_2 if and only if $T_2^* \geq 1$ or $\bar{n}_2 \geq 2(B-1)$. Thus, under condition $b_2 = B$ country O's optimal tariff is $T_2^* = \max\{(n_2^* + 2)/B - 1, 1\}$ and its optimal tariffs are summarized by

$$T_t^*(n_t^*) = \begin{cases} \sqrt{\frac{9}{4} + n_t^*} - \frac{1}{2} & \text{if } b_t = 0 \\ \max\left\{\frac{n_t^*+2}{B} - 1, 1\right\} & \text{if } b_t = B \end{cases} \tag{11}$$

Equations (10) and (11) have been derived under the condition that the constraint $T_2^* p_2 \leq 1/B$ binds, i.e. when $T_2^*(n_2^*)|_{b_2=B}$ falls short of (9). This is the case if B is large compared to country O's second period's supply:

$$B^2 + B - 2 > n_2^* \tag{12}$$

Thus, equilibrium consumption (7) of both countries depends on country W's substitution technology. Conditional on b_2 world consumption can be summarizes by the following expressions. If $b_2 = 0$ (implying $n_t = 0$) quantities are

$$\begin{array}{ll} c_{n,t} = \frac{n_t^*+2}{T_t^*+1} - 1 & c_{y,t} = y_t + \frac{T_t^*+1}{n_t^*+2} - 1 - a_t \\ c_{n,t}^* = T_t^* \frac{n_t^*+2}{T_t^*+1} - 1 & c_{y,t}^* = 1 - \frac{T_t^*+1}{n_t^*+2} \end{array} \tag{13}$$

If $b_2 = B$, instead, equations (6), (7), (11), and $T_2^* p_2 = 1/B$ lead to

$$\begin{array}{ll} c_{n,2} = B - 1 & c_{y,2} = y_2 - \frac{B-1}{B} \\ c_{n,2}^* = \min\{n_2^*, B-1\} & c_{y,2}^* = (B - 1 - n_2)/B \end{array}$$

[7] Note that $n_t^* > n_t$ implies $T_t^* > 1$. This, in turn, guarantees that $p_t < 1$ and consumed quantities $c_{n,t}^{(*)}$ from (5) are positive.

Combining both cases, sub-utilities (8) are

$$u_t = \begin{cases} \ln\left(\frac{n_t^*+2}{T_t^*+1}\right) + y_t + \frac{T_t^*+1}{n_t^*+2} - 1 - a_t & \text{if } n_t = 0 \\ \ln(B) + y_2 - \frac{B-1}{B} & \text{if } t = 2 \text{ and } n_2 > 0 \end{cases}$$

$$u_t^* = \begin{cases} \ln\left(T_t^* \frac{n_t^*+2}{T_t^*+1}\right) + 1 - \frac{T_t^*+1}{n_t^*+2} & \text{if } n_t = 0 \\ \ln(\min\{n_2^*+1, B\}) + \frac{B-1-n_2}{B} & \text{if } t = 2 \text{ and } n_2 > 0 \end{cases} \tag{14}$$

Equations (11) and (14) determine the equilibrium utility under optimal tariffs, given supply n_t^* and investment a_1. Moreover, these equations imply some important observations. First, the sub-utility u_t^* is increasing in n_t^* and thus the resource constraint of N binds. Consequently, country O's supply in the second period equals the residual $n_2^* = N^* - n_1^*$, which represent the remaining reserves of N about which exporters might misreport.

This implies second, that the game reduces to country O first choosing supply and country W deciding on investment subsequently. Thus, the sequential game summarized in Figure 2 reduces to a two-stage game with n_1^* determined in the first and a_1 in the second stage.

Third, observe that conditional on $b_t = 0$, u_t^* is concave in n_t^* as

$$\left.\frac{d^2 u_t^*}{(dn_t^*)^2}\right|_{b_t=0} = \frac{-2}{(T_t^*)^3(2T_t^*+1)} < 0 \tag{15}$$

holds. Thus, conditional on country W not investing ($a_1 = 0$), total utility (2) is maximized when the natural resource is supplied evenly across the periods[8]

$$n_1^* = n_2^* = N^*/2 \tag{16}$$

This supply rule is a basic version of Hotelling's optimal rule, which states that - correcting for time preference rates - optimal supply is smooth. Early literature suggests that a monopolistic supplier partially delays supply, inducing a back-loaded supply structure (e.g. Hotelling (1931) and Quyen (1988)). In the present model the lack of a non-trivial time preference rate implies that no effects arise through the standard interaction of monopolistic profit maximization and discounting. Hence, any deviation from optimal supply rules can be attributed to substitution R&D activity through direct or indirect effects.

Fourth, combining (16) and (12) shows that county O's maximization is constrained when the parameter B of by W's investment opportunity is large relative to the amount N^*

$$B^2 + B - 2 > N^*/2 \tag{17}$$

[8] It is quick to check that (16) describes country O's optimal supply rule also in case it cannot set tariffs.

Obviously, country O's utility (2) falls short of the first best in this constrained case.

Finally, if country O's supply in the second period is large enough ($n_2^* > 2(B-1)$) country W does not produce the substitute at all ($n_2 = 0$). In this case the sole return to the first period's investment in development of technology B is a reduction of domestic prices $T_2^* p_2$ in the second. Consequently, R&D leading to the substitution technology B must be entirely financed by country W's government.

To provide a benchmark case, the equilibrium of the two-stage game is solved under full information next. The role of information asymmetries is addressed subsequently.

3 Full Information Equilibrium

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 above that all strategic interaction can be reduced to a two-stage game in which country O first chooses n_1^* and country W decides on a_1 subsequently while tariff and consumption choices follow from static optimization. The game is solved by backward induction.

2^{nd} stage: optimal investment a_1. Country W's gains from investment $a_1 = A$ accrue in the second period in form of lower import prices $T_2^* p_2$. Thus, it refrains from investing (playing $a_1 = 0$) if and only if the second period's net gains fall short of the first period's costs ($u_2|_{b_2=B} - u_2|_{b_2=0} \leq A$). With expressions (11) and (14) this condition is

$$\ln\left(B\frac{\sqrt{\frac{9}{4}+n_2^*}+\frac{1}{2}}{n_2^*+2}\right)+\frac{1}{B}-\frac{\sqrt{\frac{9}{4}+n_2^*}+\frac{1}{2}}{n_2^*+2}\leq A \tag{18}$$

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

$$a_1 = \begin{cases} 0 & \text{if (18) holds} \\ A & \text{else} \end{cases}$$

This trade-off between costs and benefits of substitution R&D are trivial if the cost A are prohibitive and exceed the gains even under zero imports in the second period. To rule out this case, assume that () is violated under $n_2^* = 0$, i.e.[9]

$$\ln(B) + \frac{1}{B} - 1 > A \tag{19}$$

In case of zero imports in $t = 2$, country W rationally invests in substitution R&D.

[9] The expression on the left is positive by $B > 1$.

1^{st} stage: optimal supply n_1^*. When setting n_1^* country O can take two qualitatively different decisions: first, preventing country W's substitution R&D or second, accommodating to it. In the first case country O needs to satisfy condition (18), which establishes a constraint on country O's first period supply $n_1^* = N^* - n_2^*$. More precisely, since the term on the left of (18) is decreasing in n_2^* condition (18) defines an upper bound on n_2^*. Let this upper bound, which satisfies (18) with equality, be labelled n_P^*. Notice that the expression on the left of (18) is negative whenever $n_2^* > B^2 + B - 2$. This, together with assumption (19) implies

$$n_P^* \in (0, B^2 + B - 2)$$

With the unconstrained optimal supply rule (16), country O first period supply, conditional on inducing $a_1 = 0$, is hence

$$n_1^* = \min\{N^* - n_P^*, N^*/2\} \tag{20}$$

This rule reflects country O's optimal supply if it prevents country W's substitution R&D. When condition $2N^* > n_P^*$ holds, country O naturally prevents substitution R&D, i.e. simply by playing its unconstrained optimal strategy.

As an alternative strategy, country O may accommodate to W's investment $a_1 = A$. In this case the optimal supply in first period's, n_1^*, takes the expression (see appendix)

$$n_C^* \equiv \begin{cases} \frac{1}{2}\left[N^* - B - \frac{1}{4} + \sqrt{\frac{N^*-B}{2} + \frac{33}{16}}\right] & \text{if } N^* \geq 3B + \sqrt{B} - 4 \\ B + \sqrt{B} - 2 & \text{if } N^* \in \left(2B - \frac{\sqrt{4B+5}+1}{2}, 3B + \sqrt{B} - 4\right) \\ \frac{1}{2}N^* + \frac{1}{8}\sqrt{8N^* + 25} - \frac{5}{8} & \text{if } N^* \leq 2B - \frac{\sqrt{4B+5}+1}{2} \end{cases} \tag{21}$$

Quantity n_C^* stands for the first period's optimal quantity n_1^* conditional on conceding to $a_1 = A$. One can check that in all three cases, $n_C^* < N^*$ holds. It is worth noticing that the expression in the first line falls short of $N^*/2$ while for $N^* > 0$ the term in the third line is strictly larger than $N^*/2$.[10] In sum, the function $n_C^*(N^*)$ exceeds $N^*/2$ for small resources N^* and falls short of $N^*/2$ for large values of N^*. This change of signum of $N^* - n_C^*$ reflects two opposite effects of the constraint $T_2^* p_2 \leq 1/B$ that applies in the second period. On the one hand, the constraint reduces markups and profits that accrue in the second period and hence induces country O to reallocate supply to the first period. On the other hand, the constraint is less tight at higher quantities n_2^*, which makes country O to increase the second period's supply. As the opportunity cost for high supply n_2^* decreases with total resource N^* the second effect dominates at high N^* and the expression $n_C^* - N^*/2$ changes its signum from positive to negative as N^* increases.

In sum, country O's supply in the first period is either set following (20) to prevent

[10] Under condition (17) $B + 1/4$ exceeds the value of the square root.

substitution R&D or else following (21) to accommodate to substitution R&D. The actual choice depends on which strategy renders higher utility. For the analysis of that trade-off it is convenient to define the utility under given supply and investment decisions as

$$V^*(n_1^*, n_2^*, b_2) \equiv \max_{T_1^*, T_2^*} \{u_1^* + u_2^*\} \qquad \text{given } n_1^*, n_2^*, b_2 \tag{22}$$

With this definition, country O's optimal strategy conditional on preventing country W's investment renders total utility $V^*(\min\{N^* - n_P^*, N^*/2\}, \max\{n_P^*, N^*/2\}, 0)$ while utility from conceding to country W's investment is $V^*(n_C^*, N^* - n_C^*, B)$. The optimal 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

$$(n_1^*, a_1) = \begin{cases} (n_C^*, A) & \text{if } N^* < N_0 \\ (N^* - n_P^*, 0) & \text{if } N^* > N_0 \end{cases} \tag{23}$$

Proof. First, define $\Delta V^*(N^*) = V^*(N^* - n_P^*, n_P^*, 0) - V^*(n_C^*, N^* - n_C^*, B)$. It is sufficient to show that $\Delta V^*(n_P^*) < 0$, $\Delta V^*(2n_P^*) > 0$, and $d\Delta V^*(N^*)/dN^* > 0$. This is done by first observing 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 $n_C^* < N^*$ and (15) were used in the last step. Second,

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

where the inequality holds since the optimal unconstrained strategy is to equalize quantities across periods. 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 (15) this expression is positive whenever $N^* - n_P^* < n_C^*$ holds. If $N^* - n_P^* \geq n_C^*$ holds O's optimal strategy trivially induces $b_2 = 0$. ■

Proposition 1 reflects the following basic intuition: country O's two antagonistic aims are, on the one hand, to smooth supply according to the rule (16) and, on the other, to

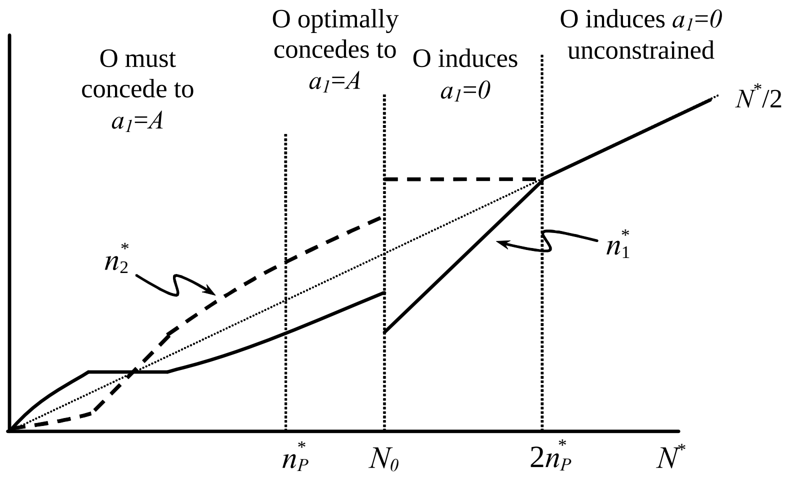

Figure 3: Country O's optimal quantities under full information.

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 (16) - and hence utility losses - is relatively large whenever the total reserves N^* are low. Thus, utility losses dominate gains from preventing investment if N^* falls short of a certain threshold in which case country O accommodates 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 physically incapable 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; third, for $N^* \in [N_0, 2n^*_P]$ country O optimally prevents country W's investment and $a_1 = 0$, the slope of $n^*_1(N^*)$ is one in this range; finally, if $N^* > 2n^*_P$ country O's optimal strategy is not constrained and country W plays $a_1 = 0$. As a reference, Figure 3 includes the unconstrained optimum i.e. the equal allocation over both periods $n^*_1 = n^*_2 = N^*/2$. Deviations from this rule 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 result is in line with earlier work where monopolistic market power leads to a the 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 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 consequently discourage country W's substitution R&D. The causality between future supply, incentives to engage in time-consuming R&D, and optimal current supply has clear orientation on the time-line and suggests that this deviation from the Hotelling rule is quite robust.[11]

Finally, country O looses from country W's investment opportunity relative to a world where this option does not exist ($A = \infty$). This statement is confirmed by verifying that

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

for $N^* < 2n_P^*$. This result is fairly intuitive, since under $a_1 = A$ the increase in competition in world production of N cuts into country O's profits while under $a_1 = 0$ the mere threat it already induces deviations from the individually optimal strategies. It is less intuitive that country W loses from its investment opportunity as well within a wide range of parameter values. To see this, observe that under $a_1 = 0$ the optimal tariff (11) and utilities (8) imply $d^2 u_t/(dn_t^*)^2\big|_{b_t=0} < 0$ i.e. that u_t is a concave function of n_t^*. Consequently, U from (2) is maximized at $n_1^* = n_2^* = N^*/2$. Thus, for all $N^* \in [N_0, 2n_P^*]$ country W's equilibrium utility falls short of that under $A = \infty$. In this case, the country W's option to investment in R&D distorts country O's supply without being realized. The resulting efficiently loss affects both countries adversely.

Proposition 1 and Figure 3 have provided a description of the full information equilibrium. Moreover, Figure 3 suggests that country O, endowed with low reserves, can benefit from making country W believe that reserves of N are abundant, thus discouraging substitution R&D. These incentives to misreport reserves will be analyzed in the next section.

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

4 Asymmetric Information Equilibrium

This section formalizes country W's misreporting on reserves of N. It does so under – necessarily – private information about reserves, analyzing the consequences of the information asymmetries on supply, investment, and consumption patterns. 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 successfully if her observable actions (her signals) do not reveal her type. In this sense, a pooling equilibrium will be read as successful misreporting.

Following this idea, when country O states its reserves in the current model, such reporting is viewed as cheap talk unless it is backed by observable actions. The observable action in $t = 1$, the period of private information, is contemporaneous supply of the natural resource n_1^*. Thus, n_1^* acts as a signal for total reserves N^*, or, for that matter, for future supply ($n_2^* = N^* - n_1^*$). Successful misreporting is said to occur if, by the adequate signal n_1^*, a country O conceals its private information, leaving country W uninformed about the actual realization $N^* \in \{\bar{N}, \xi\bar{N}\}$. This subjective uncertainty generally distorts country W's investment decision $a_1 \in \{0, A\}$, possibly generating benefits for country O.

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 $N^* = \xi\bar{N}$, where $\xi < 1$. In the first stage country O can signal its type, using 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 updates its believes and chooses investment $a_1 \in \{0, A\}$ optimally. Tariffs and consumption are no strategic components and are captured by the expressions (11) and (13) as in the previous section. Formally, the strategies $(n_{1,H}^e, n_{1,L}^e, a_1^e(n_{1,H}^e), a_1^e(n_{1,L}^e))$ 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 believes, and updating rules.

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

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

Further, the equilibrium strategies of both players are denoted by

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

Country W's equilibrium technology in the second period is labelled $b_{2,\theta}^e \in \{0, B\}$, where θ stands for country O's type $\theta = H, L$. In a pooling equilibrium $b_{2,H}^e = b_{2,L}^e$ holds.

For further references, it is useful to denote country O's full information equilibrium strategies (23) under type $\theta = L, H$ as

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

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

In general, the existence and the properties of the Perfect Bayesian Equilibria in a signalling game is sensitive to the specification of the receiver's full set of 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 believes, which implies that equilibria are non-unique in many cases. In the present paper, 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) $\quad \tilde{n} \in [0, \bar{N}] \quad \tilde{b}$ outcome of W's optimal $a_1^e(\tilde{n})$ under $\mu(\tilde{n}) = \pi$.
$V^*(\tilde{n}, \bar{N} - \tilde{n}, \tilde{b}) > V^*(n_{1,H}^e, \bar{N} - n_{1,H}^e, b_{2,H}^e)$
$V^*(\tilde{n}, \xi\bar{N} - \tilde{n}, \tilde{b}) > V^*(n_{1,L}^*, \xi\bar{N} - n_{1,L}^*, b_{2,L}^*)$
$\Rightarrow \quad \mu(\tilde{n}) = \pi$.

A(v) $\quad \tilde{n} \in [0, \bar{N}] \quad \tilde{b}$ outcome of W's optimal $a_1^e(\tilde{n})$ under $\mu(\tilde{n}) = \pi$.
$V^*(\tilde{n}, \bar{N} - \tilde{n}, \tilde{b}) < V^*(n_{1,H}^e, \bar{N} - n_{1,H}^e, b_{2,H}^e)$
$V^*(\tilde{n}, \xi\bar{N} - \tilde{n}, \tilde{b}) > V^*(n_{1,L}^e, \xi\bar{N} - n_{1,L}^e, b_{2,L}^e)$
$\Rightarrow \quad \mu(\tilde{n}) = 0$.

Assumptions A(i) and A(ii) simply reflect Bayesian updating, a requirement of any Bayesian Nash Equilibrium. 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 it.[12] Hence, A(iii) establishes the full information equilibrium as the default outcome. This implies that a pooling equilibrium only exist 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.

With these definitions and refinements the equilibrium will be calculated next.

4.2 Equilibrium: Characterization

To determine the equilibrium of the signalling game, country W's optimal decision rule is derived first. The information asymmetries changes country W's situation to the extent that it faces subjective uncertainty about the second period's supply of the natural resource when taking its investment decision a_1. Consequently, its optimal strategy is now based on expected returns to substitution R&D. More precisely, country W acts according to the probabilistic analog of inequality (18), where expectations are formed using subjective probabilities. With optimal tariffs (11) and the definition of μ the probabilistic analog of (18) can be written as

$$\begin{aligned} \ln(B) + \tfrac{1}{B} - \mu(n^*_1)\left\{\ln\left(T^*_2(\bar{N} - n^*_1)\right) + \frac{1}{T^*_2(\bar{N} - n^*_1)}\right\} - ... \\ ...(1 - \mu(n^*_1))\left\{\ln\left(T^*_2(\xi\bar{N} - n^*_1)\right) + \frac{1}{T^*_2(\xi\bar{N} - n^*_1)}\right\} \leq A \end{aligned} \tag{24}$$

[12] This statement follows from the observation that $n^*_{1,H}$ is O_H's unique optimal strategy under full information, while asymmetric information adds one more constraint to its optimization program (the incentive compatibility constraint in the case of a separating and (24) with $\mu(n^*_1) = \pi$ is the case of a pooling equilibrium). Finally, whenever O_L looses from pooling to $n^e_{1,H} = n^*_{1,H}$ A(iii) grants that $n^e_{1,H} = n^*_{1,H}$ implies $a^e_1(n^e_{1,H}) = 0$, hence $n^e_{1,H} = n^*_{1,H}$ is O_H's unique optimal strategy.

Here, $T_2^*(.)$ stands for the optimal tariff under $b_2 = 0$ as in (11). Condition (24) determines country W's investment behavior and[13]

$$a_1(n_1^*) = \begin{cases} 0 & \text{if (24) holds} \\ A & \text{else} \end{cases}$$

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 signalling, country O's aim is to prevent country W's investment in the substitution R&D, while bearing the costs 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

$$V^*(n_C^*, N^* - n_C^*, B) - V^*(m, N^* - m, 0) = 0 \tag{25}$$

By this definition m depends on total reserves N^* and some of its properties can be inferred from (25).

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

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

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

Proof. First notice that with (11) and (14) the definition of $V^*(n_1^*, n_2^*, 0)$ by (22) can formally be extended to $n_t^* \in (-1, N^*+1)$ and the extension is continuously differentiable. Further, define the expression on the left of the identity (25) by $\Gamma(N^*, m)$. For $m \in (-1, N^*/2)$ the derivative $\partial_m \Gamma$ (subscripts stand for partial derivatives to the respective arguments) is negative

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

[13] 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 $a_1(n_1^*)$. This observation shows that signalling games cannot be solved by backward induction.

by the definition of V^* (22) and concavity of u_t^* (15).

(i) Check with equations (11), (14), and $b_1 = 0$ that $\lim_{m\to-1}\{u_1^* + u_2^*\} = -\infty$ so that $\lim_{m\to-1} V^*(m, N^* - m, 0) = +\infty$ and

$$\lim_{m\to-1} \Gamma(N^*, 0) = +\infty$$

Further, $\Gamma(N^*, N^*/2) < 0$ holds by optimality (16) so that there is a solution to (25) with $m < N^*/2$. By $\partial_m \Gamma < 0$ this solution is unique.

(ii) The definition 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 (26).

(iii) $V^*(n_C^*, N^* - n_C^*, 0) > V^*(n_C^*, N^* - n_C^*, B)$ and (25) imply

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

By the concavity of u_t^* this shows the statement.

(iv) Use the envelope theorem to compute

$$\partial_{N^*}\Gamma = V_2^*(n_C^*, N^* - n_C^*, B) - V_2^*(m, N^* - m, 0) > 0 \tag{27}$$

The inequality holds by concavity of u_t^* and (iii). (26) and (27) together prove $0 < dm/dN^*$. With (26) and (27) the second inequality is equivalent to

$$V_2^*(n_C^*, N^* - n_C^*, B) < V_1^*(m, N^* - m, 0)$$

Optimality of n_C^* and independence of u_1^* from b_2 imply

$$V_2^*(n_C^*, N^* - n_C^*, B) = V_1^*(n_C^*, N^* - n_C^*, B) = V_1^*(n_C^*, N^* - n_C^*, 0)$$

so that $dm/dN^* < 1$ follows again from $m < n_C^*$.

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

By Proposition 2 (i) the threshold m is a function of N^* and can be written as $m(N^*)$. Concavity of u^* (see (15)) 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 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

$$M(N^*) \equiv N^* - m(N^*)$$

establishes the corresponding upper bound on the quantities n_1^*. Figure 4 illustrates these bounds $m(N^*)$ and $M(N^*)$ as dashed lines, the equilibrium n_1^* is represented by the bold

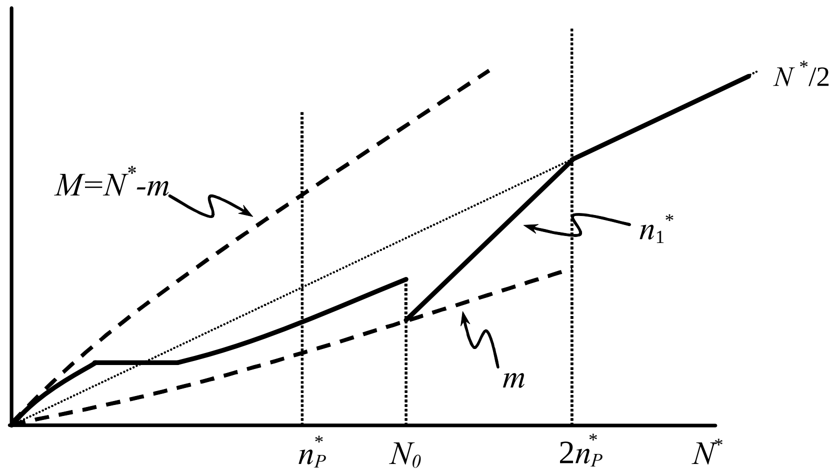

Figure 4: Boundaries of O's net benefits from preventing W's R&D.

line. By Proposition 2 (iv) and (v) both functions $m(N^*)$ and $M(N^*)$ are increasing in N^* and lie within the interval $(0, N^*)$. 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 (inducing $a_1 = 0$). 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 Proposition 2 it is possible to give a first irrelevance result, i.e. 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 3 Assume that at least one of the following conditions holds

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

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

then the unique subgame perfect equilibrium in pure strategies is a separating equilibrium with the full information strategies (23).

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 $n_{1,H}^*$.

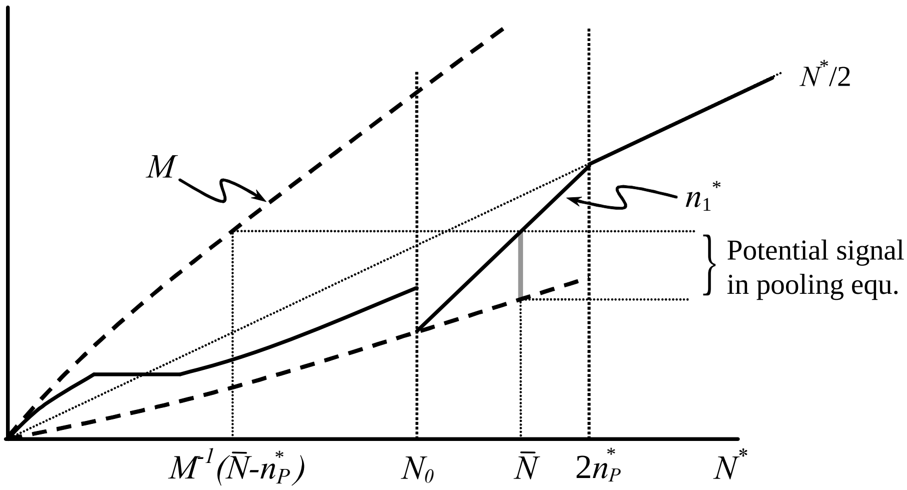

Figure 5: O_L's incentives to imitate O_H and equilibrium signals.

(i) By construction of M and m, condition $M(\xi\bar{N}) = \xi\bar{N} - m(\xi\bar{N}) < \bar{N} - n_P^*$ implies

$$V^*(n_{1,L}^*, \xi\bar{N} - n_{1,L}^*, B) > V^*(M(\xi\bar{N}), \xi\bar{N} - M(\xi\bar{N}), 0) > V^*(\bar{N} - n_P^*, \xi\bar{N} - (\bar{N} - n_P^*), 0)$$

(ii) If $\bar{N} < N_0$ W's plays $a_1 = A$ in all full information equilibria. Thus, for O_L $n_{1,L}^*$ dominates $n_{1,H}^*$ by construction.

If $\bar{N} > 2n_P^*$ O_H's full information strategy is $n_{1,H}^* = \bar{N}/2$. 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 (20). Hence by (15) and symmetry of $V^*(.,.,0)$ is the first arguments

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

If second $b_{2,L}^* = B$

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

holds. Thus, $n_{1,L}^*$ dominates pooling to $n_{1,H}^*$ in all cases. ■

Figure 5 illustrates the results of Proposition 3. 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 (refinement A(iii) is relevant here). The other part of the proposition, related to condition (ii), reflects, first, 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. Second, 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. In all cases, the two types resort to the respective full information strategies.

Having excluded the existence of pooling equilibria for the parameter range specified by conditions (i) and (ii) in Proposition 3, the attention rests on the intermediate range of resources and the remainder of the section will focus on the cases where the conditions

$$\xi \in [M^{-1}(\bar{N} - n_P^*)/\bar{N}, 1) \tag{28}$$

and

$$\bar{N} \in (N_0, 2n_P^*) \tag{29}$$

are satisfied. Conditions (28) and (29) assure that the type O_L aims to pool to O_H's full information strategy $n_{1,H}^*$ if that discourages substitution R&D. Yet, under those pooling attempts, country W adapts its beliefs and strategy and $n_{1,H}^*$ is no equilibrium signal. Instead, the natural candidate for the signal of a pooling equilibrium is the quantity n_1^* that solves (24) with equality, given $\mu \equiv \pi$. Let this value be denoted by n_P^e, defined as the implicit solution of

$$\begin{aligned} \ln(B) + \tfrac{1}{B} - \pi \left\{ \ln\left(T_2^*(\bar{N} - n_P^e)\right) + \frac{1}{T_2^*(\bar{N} - n_P^e)} \right\} - ... \\ ...(1-\pi) \left\{ \ln\left(T_2^*(\xi\bar{N} - n_P^e)\right) + \frac{1}{T_2^*(\xi\bar{N} - n_P^e)} \right\} = A \end{aligned} \tag{30}$$

where $T_2^*(.)$ stands for the second period's tariff (11) under $b_2 = 0$. Notice that the expression on the left of (30) is decreasing in tariffs and hence, by (11), increasing in n_1^*. Further, (11) 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. Moreover, the expression is decreasing in ξ. Consequently, by the implicit function theorem, n_P^e is increasing in ξ and π. Finally, at $\pi = 1$ condition (30) coincides with (18) in which case $n_P^e = \bar{N} - n_P^*$ while at $\pi = 0$ (30) leads to $n_P^e = \xi\bar{N} - n_P^*$. These properties of n_P^e are summarized by

$$\frac{d}{d\xi} n_P^e \;>\; 0 \tag{31}$$

$$\frac{d}{d\pi} n_P^e \;>\; 0 \tag{32}$$

$$\lim_{\pi \to 1} n_P^e \;=\; \bar{N} - n_P^* \tag{33}$$

$$\lim_{\pi \to 0} n_P^e \;=\; \xi\bar{N} - n_P^* \tag{34}$$

The difference between n_P^e and n_P^* reflects that country W reacts to the pooling of type O_L by adapting expectations upon future supply.

But type O_H may as well react to O_L's pooling attempts, choosing not to discourage substitution R&D any more, in which case O_L's incentives to pool cease to exist. This introduces an additional condition to be satisfied under pooling equilibria, requiring that the relevant signal $n^e_{1,H} = n^e_{1,L}$ be element of the set $[m(\bar{N}), M(\bar{N})]$. Since conditions (32) and (33) imply $n^e_P < \bar{N} - n^*_P$ and since $\bar{N} - n^*_P < \bar{N}/2$ by (29), the relevant constraint is thus

$$n^e_P \geq m(\bar{N}) \tag{35}$$

Since n^e_P is a function of π and ξ, condition (35) implicitly defines a constraint on the parameters ξ and π. In particular, the equation $n^e_P = m(\bar{N})$ defines a schedule on the (ξ, π)-plane which, by virtue of properties (31) and (32), 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 (35) 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 (28) and (29), the requirement (35) is necessary for a pooling equilibrium to exists. The following proposition identifies conditions (28), (29), and (35) as jointly sufficient, granting that the two-stage signalling game has a pooling equilibrium in pure strategies that is – modulo country W's off-equilibrium beliefs μ and strategies – unique.

Proposition 4 If (28), (29), and (35) hold, a subgame perfect Bayesian Nash Equilibrium in pure strategies exists, is unique, and includes the strategies

$$(n^e_{1,H}, n^e_{1,L}) = (n^e_P, n^e_P) \quad \text{and} \quad a^e_1(n^e_{1,H}) = a^e_1(n^e_{1,L}) = 0 \tag{36}$$

Proof. See Appendix ■

Figure 6 illustrates the two key conditions (28) and (35) that delimit the parameter range for which pooling equilibria prevail. Condition (28) sets a minimum that ξ needs to exceed, represented by the dashed vertical line in the figure. Condition (35) defines a minimum $\underline{\pi}(\xi)$ that the ex ante probability π must exceed to grant (35). The function $\underline{\pi}(\xi)$ is marked as a bold line. Both conditions are satisfied for parameters within the area **A**. Notice that for ξ larger than $\left[m(\bar{N}) + n^*_P\right]/\bar{N}$ the value n^e_P 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 $\left[m(\bar{N}) + n^*_P\right]/\bar{N}$. (For $\bar{N}$. N_0 it is quick to check that this value falls short of one.)

To the left of the dashed line, in area **B**, condition (28) is violated. Hence Proposition 3 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).

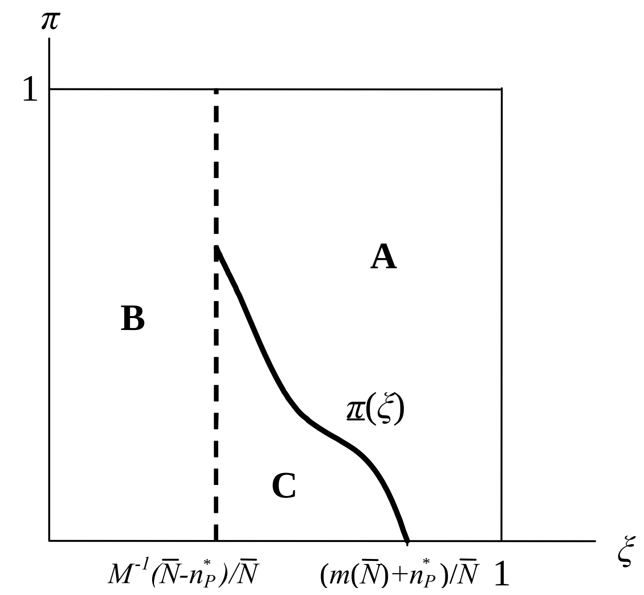

Figure 6: Three different types of equilibria.

For completeness, consider the case when (28) holds but (35) is violated (area **C** in Figure 6). In this case 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 can easily be shown to follow the supply rules (21) for $N^* = \xi\bar{N}, \bar{N}$, respectively.

4.3 Discussion of Equilibrium Properties

The previous paragraphs have shown that an exporter with low realization of resources credibly overreports if and only if the high realization of resources lies in intermediate ranges satisfying (29) and the low realization of resources does not fall short of the minimum which is jointly determined by (28) and (35).

In a somewhat looser but more intuitive reformulation, the necessary and sufficient conditions for overreporting are the following. First, current substitution R&D is responsive to expected future supply of the natural resource within the range set by the possible realizations of reserves (the lower bound of condition (29)). Second, cost of the signal is limited for both, the low and the high type, i.e. their deviations of the respective full information supply are limited.

Maybe surprisingly, the second of these conditions can turn out not to be restrictive at all. As for the high type, property (33) shows that the signal can be arbitrarily close to the full information strategy while the low type's cost of the signal can even be negative. This latter fact can be quickly checked by going back to Figure 5 and observing that for any potential signal n_P^e that lies on the grey vertical bar (i.e. satisfying conditions (28) and

(35)) there is a range of parameters ξ so that the n_P^e lies closer to the unconstrained optimal supply $\xi\bar{N}/2$ than the full information strategy $n_{1,L}^*$ (i.e. $\left|\xi\bar{N}/2 - n_P^e\right| \leq \left|\xi\bar{N}/2 - n_{1,L}^*\right|$ holds). Under this condition, concavity of the sub-utility u^* (see (15)) implies that the first period's utility loss from signalling is negative (i.e. the signal itself benefits O_L) so that the low type actually benefits from both, the negative costs of the signal and the positive effect of preventing country W's substitution R&D. The intuition of this results is the following. Under full information, the impending substitution R&D distorts O_L's supply, which generates a utility loss. This effect is present under asymmetric information as well, but in addition the signal requires type O_L to deviate further. The direction of the additional deviation is, under the adequate parameter values, opposite to the initial one, in which case initial losses are partially or fully compensated. Thus, the process of signalling can generate gains by itself. – Overall, these considerations show that theory does not establish a meaningful lower bound on neither of the types' cost of signalling.

When turning to the implications of asymmetric information on the real economy, the dominant characteristic of the pooling equilibrium is its effect on supply rule. It has been shown that, relative to its unconstrained full information strategy, the high type O_H partially delays supply in a pooling equilibrium ((32), (33), and (29) imply $n_P^e < \bar{N} - n_P^* < \bar{N}/2$). Hence, supply unambiguously increases when private information is resolved. Under low realization, however , n_P^e may exceed or fall short of smooth supply ($n_P^e > \xi\bar{N}/2$ or $n_P^e < \xi\bar{N}/2$) and hence supply may jump up or down when uncertainty is revealed to country W. Using the earlier identification of overreporting and concealing one's type in the signalling game, these observations can be summarized by the statement that, conditional on reported reserves (i.e. conditional on high realizations), successful overreporting implies that the stream of supply of the natural resource is back-loaded.[14]

This paper has set out to analyze the questions why, how, and under what necessary conditions oil suppliers misreport, and, moreover, to assess whether these necessary conditions are satisfied in today's oil market. The central propositions show that oil-exporting countries do indeed have motives to misreport and, given some conditions on the parameter values, they can credibly do so under rational expectations. Moreover, the mechanism formulated in the paper's model induces oil-exporting countries to over- instead of underreport, which is in line with recent claims of some market pundits. Proposition 4 summarizes the relevant conditions, which are formulated above in an intuitive way. The remaining task (and the most relevant one when it comes to policymaking) is to evaluate if the alleged overreporting in today's oil market can be refuted.

A quick and preliminary answer to this question can be based on the necessary conditions

[14] Notice that this effect is intrinsically different form effects related to market power as put forward in Hotelling (1931) and Quyen (1988). The aim to discourage current investment in substitution R&D by granting high future supply gives an unambiguous direction for the distortion of supply flow, while effects of market power are generally ambiguous (see Stiglitz (1976)).

for the existence of a pooling equilibrium: a substantial reaction of substitution R&D to supply and the cost of the signal. First, empirical studies like Newell et al (1999) and Popp (2002) strongly suggest that substitution R&D is indeed responsive to supply. To illustrate this relation, Figure 1 plots total expenditure on non-oil energy R&D in IEA member countries and oil prices. Both time series strongly comove with a contemporaneous correlation of 0.85.[15] The peak of energy R&D in the late 1970s was largely driven by government programs, which, in response to oil price shocks, were designed to reduce dependence on energy imports by promoting nuclear energy mostly (administered e.g. in the US through the Energy Reorganization Act of 1974). Thus, based on a qualitative assessment, the first of the necessary condition is satisfied. As for the second one, it has been argued above that theory does not establish a meaningful lower bound on the relevant costs and hence does not serve as a criterion to discard the possibility of overreporting.

A review of the preconditions for the existence of a pooling equilibrium does not lead to an unambiguous conclusion and the attention rests on the main implication concerning current and expected supply. The model predicts that a monopolistic exporter supplies less than its unconstrained optimum in the periods when asymmetric information prevails. In reality, of course, world oil market structure – roughly consisting of the cartel-like OPEC and a competitive fringe – is more complex than simply monopolistic. Thus, there is a number of possible benchmark policies relative to which current supply can be expected to be delayed. In particular, OPEC's benchmark behavior may be oligopolistic, partially, or fully collusive.[16] Unfortunately, the empirical literature on OPEC policies does not provide an unambiguous picture. Some recent quantitative studies indicate that in the years following the counter-oil shock (i.e. from the mid 19980s onwards, about the period following the last revision of OPEC's reserve data), 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)). If these findings prove right, the deviations from optimal supply are, if any, opposite of what is to be observed under credible misreporting. This would clearly indicate that overreporting does not prevail in today's oil markets. However, other empirical studies as Griffin (1985) and Smith (2003) report substantial coordination and cartel discipline of OPEC members and a significant shortage of contemporaneous supply. Whether these findings can be read as indication of undersupply in the sense of the present paper's theory depends on the preferred benchmark with which to compare supply. Hence, the result is a matter of interpretation to a large extent. On the base of these latter studies, however, the claims of overreporting cannot be dismissed.

[15] Strictly speaking, expected future supply is the determinant of substitution R&D and contemporaneous supply is irrelevant. This logical gap is bridged when prices follow a random walk in the medium term, in which case current is the best prediction of future supply.

[16] Focussing on OPEC's supply rule is motivated first, by its position as a dominant and formally coordinated body of suppliers and second, by the fact that alleged overreporting is limited to OPEC members.

In sum, the possibility of overreporting in today's oil market cannot be easily refuted by applying the present paper's predictions qualitatively. The last and, form the viewpoint of policymaking, the most urgent of the questions remains unanswered.[17] This observation calls for a thorough quantitative evaluation of the issue. Such further research is to resolve whether the definition of OPEC is to be extended to a cartel of not only supply but of information as well.

In the general discussion about supply security of the oil market misreporting of reserves is only one of many aspects. It therefore seems appropriate to put the role of misreporting into perspective and discuss it relative to other sources of oil shortages. Quite generally, the matter is very simple in a deterministic world, for which the economics of exhaustible resources sketch a comforting image: continued decreases in the stock of natural resources raises the returns to resource-saving substitution technologies, which intensified research will eventually generate (see Davidson (1978), Deshmukh and Pliska (1983) and Tsur and Zemel (2003)). In this process, forward-looking firms anticipate future profits and, motivated by consumer's willingness to pay for smooth consumption flows, provide smooth a transition between a resource- and a substitution-based regime. Those who believe in that fundamental economic mechanism will not fear oil shortages. The picture changes, of course, when remaining oil reserves are uncertain since information shocks can cause severe ex-post inefficiencies; in this case the focus is thus on uncertainty itself. Traditionally, geological imponderabilities are viewed as an important source of uncertainty. The advances in the relevant exploration technology, however, allow accurate assessments of the size of oil fields and major surprises due to technological failure seem unlikely (see e.g. Cuddington and Moss (2001) for a recent assessment of technological advances in the oil industry that generate efficiency and precision gains). Compared to geological aspects, man-made uncertainty may be substantial. Within this category, political instability is usually focussed on with a special emphasis on the geopolitical situation of the Middle East (see e.g. IEA (2005)). Yet, if alleged overreporting eventually turned out to be occur, the resulting supply shocks would be dire indeed. Since, moreover, overreporting is consistent with rational expectations under asymmetric information and standard assumptions of the economics of exhaustible resources, it might after all deserve some more attention.

[17] Notice that credible misreporting – defined on the base of a pooling equilibrium – can discarded with certainty by simply showing that the relevant conditions are violated. Conversely, misreporting cannot be proven with certainty because for a pooling equilibrium of a signalling game to exist the probability that an agent is of the type he claims (π is the present model) must be positive. This statement applies for the periods before private information is revealed.

5 Conclusion

Concerns about supply security of natural resources such as crude oil are rising. 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 misreport. The main elements of the theory are, first, market power of the supplier of the exhaustible resource, second, the possibility to engage in R&D for technologies that substitute the natural resource, and third, private information about reserves of the exhaustible resources. 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. More precisely, exporting countries tend to overreport when substitution R&D is sensitive to future supply and the necessary signal involved generates limited costs. The latter condition translates into the requirement that dispersion of possible realizations of reserves be limited. Finally, conditional on the reported realizations of reserves, supply is partly delayed under successful overreporting; underreporting never occurs. In a tentative application of the main results to the crude oil market overreporting cannot be easily dismissed, which calls for further quantitative research on the topic.

To keep the analytical framework tractable, the paper's model is reduced to the very basic elements and leaves numerous interesting issues unanswered. Potential extensions include, first, a non-degenerate distribution of reserves, generating a continuum of types of country O; second, questions of coordination among supplier and buyer countries can be analyzed in a multi-country setup. Finally, a quite ambitious but possibly rewarding extension could rely on an infinite horizon to endogenize the timing of revelation of types.

Appendix

Proof of (21). For $n_2 = 0$ use u_t^* from (14) 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 (11) with $b_1 = 0$ was used in the second step. Use (11) with $b_2 = b$ and (14) 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 (11) and $n_1^* + n_2^* = N^*$ rewrite this as $(\sqrt{n_1^* + \frac{9}{4}} - \frac{1}{2})^2 = N^* - n_1^* + 2 - b$ 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 $N^* = b - 1 \Rightarrow n_1^* = 0$. This proves (21). 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 $N_o = 3b + \sqrt{b} - 4$.

Consider now $N^* < N_o$ as long as O exports N (i.e. $c_{n,2}^* < n_2^*$) (14) 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 $N^* \in \left(2B - \left(\sqrt{4B+5} + 1\right)/2, 3B + \sqrt{B} - 4\right)$. 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 Proposition 4. The proof consists of two parts: (i) Under (28) and (35) the strategies (36) and belief μ with A(i) - A(v) characterize an equilibrium. (ii) Under (28), (35), and A(i) - A(v) no other equilibria exist.

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

E(i) $n_{1,H}^* = n_{1,L}^* = n_P^e$ and Bayesian updating requires $\mu(n_P^e) = \pi$.

E(ii) By $\mu(n_P^e) = \pi$ (24) holds for n_P^e and $a_1^e(n_P^e) = 0$ follows.

E(iii) Maximization of O$_H$. For a deviation $\tilde{n}$ of O$_H$ with $\tilde{n} \in [0, m^*(\bar{N}))$ the construction of m^* this implies

$$V^*(\tilde{n}, \xi\bar{N} - \tilde{n}, 0) < V^*(n_C^*(\bar{N}), \bar{N} - n_C^*(\bar{N}), B) < V^*(n_P^e, \bar{N} - n_P^e, 0)$$

where the last inequality follows by (29) and (35).

For a deviation $\tilde{n}$ with $\tilde{n} \in [m(\bar{N}), n_P^e)$ W's optimal off-equilibrium strategy induces either

$\tilde{b} = 0$ or $\tilde{b} = B$. In both cases

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

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

Consider a deviation $\tilde{n} > n_P^e$. In the case $\tilde{n} \in (n_P^e, \bar{N} - n_P^*]$ conditions (28), (35), $n_P^e < \tilde{n} < \bar{N}/2$, and A(iv) imply $\mu(\tilde{n}) = \pi$ so that (24) is violated and W's optimal strategy is $a_1^e(\tilde{n}) = A$. If $\tilde{n} > \bar{N} - n_P^*$ W's optimal strategy is $a_1^e(\tilde{n}) = A$ regardless of its beliefs. Thus, all deviations $\tilde{n} > n_P^e$ imply $\tilde{b} = B$ and

$$V^*(\tilde{n}, \bar{N} - \tilde{n}, B) < V^*(n_C^*(\bar{N}), \bar{N} - n_C^*(\bar{N}), B) < V^*(n_P^e, \bar{N} - n_P^e, 0)$$

Here again, the last inequality follows by (29) and (35). Hence, O_H optimal strategy is $n_{1,H}^* = n_P^e$.

Maximization of O_L. Consider a deviation of O_L with $\tilde{n} > n_P^e$. In the case $\tilde{n} \in (n_P^e, \bar{N} - n_P^*]$ conditions (28), (35), $n_P^e < \tilde{n} < \bar{N}/2$, and A(iv) imply $\mu(\tilde{n}) = \pi$ and W's optimal strategy is $a_1^e(\tilde{n}) = A$. If $\tilde{n} > \bar{N} - n_P^*$ W's optimal strategy is $a_1^e(\tilde{n}) = A$ regardless of its beliefs. Thus, all deviations $\tilde{n} > n_P^e$ imply $\tilde{b} = B$ and

$$V^*(\tilde{n}, \xi\bar{N} - \tilde{n}, \tilde{b}) < V^*(n_{1,L}^*, \xi\bar{N} - n_{1,L}^*, b_{2,L}^*) < V^*(n_P^e, \bar{N} - n_P^e, 0) \qquad (37)$$

where the last inequality follows by (28), $m(\xi\bar{N}) < m(\bar{N})$ and (35).

Consider O_L's deviation $\tilde{n} < n_P^e$. If $\left|\xi\bar{N}/2 - \tilde{n}\right| < \left|\xi\bar{N}/2 - n_P^e\right|$, $\tilde{n} < n_P^e < \bar{N}/2$ and A(v) implies $\mu(\tilde{n}) = 0$. Thus, (37) applies again. If $\left|\xi\bar{N}/2 - \tilde{n}\right| \geq \left|\xi\bar{N}/2 - n_P^e\right|$ O_L's total utility cannot increase. Hence, O_L optimal strategy is $n_{1,L}^* = n_P^e$.

(ii) Assume there is an equilibrium with $n_{1,H}^e \neq n_P^e$. By A(iv) O_H's deviation to $\tilde{n} = n_P^e$ induces $a_1^e(\tilde{n}) = 0$ and thus gives O_H higher payoffs. Hence $n_{1,H}^e = n_P^e$ in any equilibrium. By construction of n_P^e and (35) O_L's pooling to $n_{1,H}^e$ induces $a_1^e(n_P^e) = 0$. By A(v) and (28) this renders higher utility than any other strategy of O_L. ∎

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