Overreporting Oil Reserves

Philip Sauré

SCHWEIZERISCHE NATIONALBANK
BANQUE NATIONALE SUISSE
BANCA NAZIONALE SVIZZERA
BANCA NAZIUNALA SVIZRA
SWISS NATIONAL BANK

2010-7

Swiss National Bank Working Papers

The views expressed in this paper are those of the author(s) and do not necessarily represent those of the Swiss National Bank. Working Papers describe research in progress. Their aim is to elicit comments and to further debate.

ISSN 1660-7716 (printed version)
ISSN 1660-7724 (online version)

Overreporting Oil Reserves*

Philip Sauré†
Swiss National Bank

This Version: January 2010

Abstract

An increasing number of oil market experts argue that OPEC members substantially overstate their oil reserves. While the economic implications could be dire, the incentives for overreporting remain unclear. This paper analyzes these incentives, showing that oil exporters may overreport to raise expected future supply, thereby discouraging oil-substituting R&D and improving their own future market conditions. In general, however, overreporting is not costless: it must be backed by observable actions and therefore induces losses through supply distortions. Surprisingly, these distortions offset others that arise when suppliers internalize the buyers' motives for R&D. In this case, overreporting is rational, credible, and cheap.

Keywords: Exhaustible Resource, Substitution Technology, Signaling

JEL Classifications: F10, F16, D82.

---

*I would like to thank Raphael Auer, Martin Brown, Eddie Dekel, Andreas Fischer, Elhanan Helpman, Werner Herrmann, Eugene Kandel, Marcel Peter, Andrea Pescatori, Rick van der Ploeg, Anthony Venables, Hosny Zoabi, the participants at Hebrew, Oxford, Tel Aviv University and ZEW and one anonymous referee for helpful comments. All remaining errors are mine.

†Swiss National Bank, Börsenstrasse 15, CH-8022 Zurich, Switzerland. E-mail: philip.saure@snb.ch. The views expressed in this paper are the author's and do not necessarily represent those of the Swiss National Bank.

1 Introduction

The recent hike of crude oil prices has revived old fears about energy security. In addition to political and geological imponderability, a small but growing number of market pundits points out that deliberate overreporting of OPEC's crude oil reserves is one, possibly dramatic, source of uncertainty.[1] Thus, Bentley (2002) observes that "Saudi Arabia and Iran may well have significantly smaller reserves than listed" in their statistics. The Economist (2006) reports warnings that suppliers as "Kuwait might have only half of the [...] oil reserves" they officially report. 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%" (EWG (2007)). Consequently, the privately funded UK Industry Taskforce on Peak Oil & Energy Security reckons that "the world's supposedly proved reserves of 1,200 billion barrels are probably overstated by at least 300 bn barrels" (ITPOES (2008)). The 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)) and The Wall Street Journal (2008) reports that "[f]uture crude oil supplies could be far tighter than previously thought."

These quotes combine to the following picture: opaque national oil companies hold private information on major parts of world crude oil reserves, the amount of which they grossly overreport to the rest of the world. Yet, while the economic consequences of such a scenario would be dire, the actual motives of overreporting remain unclear.[2] To the economist, unfamiliar with the technical details of oil markets but trained to handle rational expectations, the following type of questions occurs: Why would oil suppliers overreport their reserves? After all, shouldn't they rather underreport reserves, since anticipated shortages raise current prices? Under which conditions can misreporting in general be credible and are these conditions likely to hold?

The present paper addresses these questions. It shows that in an ordinary setting of exhaustible resources, incentives to overreport emerge naturally through the following mechanism. Oil importers rationally decide to engage in resource-saving R&D whenever expected future supply of conventional oil is sufficiently low. Oil-exporters, in turn, overreport their reserves to raise expectations of future oil supply, discourage resource-saving R&D and thereby improve their future market conditions.

[1] Many definitions of *crude oil reserves* exist. Quotations refer to the standard definitions *proven* and *proven and probable* reserves (conventional crude 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, which are based on reserves. Indeed , after OPEC's quota system was established in 1983, members increased their reported oil reserves (see Campbell and Laherrèr (1998) and Bentley (2002)). Market observers as the IEA or the EIA did not simply substract the reported increases and the question remains whether OPEC can manipulate expected future supply and the market's reactions to it.

The two assumptions underlying this mechanism are common in the literature of exhaustible resource: first, technological change is the outcome of directed and costly R&D; this assumption implies that high expected future oil supply depresses resource-saving R&D. Second, oil supply is not competitive, so that oil suppliers internalize the impact of their supply on the market conditions and can actively manipulate them.

The paper frames the argument with a signaling game – a standard and suitable tool to analyze information rents. On the one side, an oil-supplier holds private information about the realization of its total stock of reserves and decides how to allocate it between two periods. An oil-consumer, on the other side, decides whether or not to invest in time- and resource-intensive oil-substituting R&D. Now, the oil-supplier can be said to misreport credibly (over- or underreport) if (i) observable current supply – the signal – is uninformative about its "type", *i.e.*, the remaining reserves and if (ii) the resulting pooling equilibrium generates higher benefits than the respective full information equilibrium. By this definition, misreporting and beneficial pooling are one and the same thing.

Credibility requires that overreporting be backed by observable actions, and therefore is, in general, costly. More precisely, observable contemporaneous supply must correspond to the pretended amount of reserves and hence does not coincide with supply under full information. This requirement generates a *cost of overreporting*, which generally limit the supplier's willingness to overreport.

The analysis shows, however, that the cost of overreporting can be negligible and indeed even negative for a wide parameter range. The intuition for this surprising result is the following. Regardless of information asymmetries, the key problem of the oil-supplier is how to allocate the resource over time. In the absence of technological change, it is dynamically optimal to smooth supply across periods. Under the threat of resource-saving R&D, however, the smooth supply rule is no longer optimal but the supplier decreases current and increases future supply to discourage oil-substituting R&D. This effect is present under full information. Now, overreporting under private information generally requires an increase of current supply and hence brings the overreporting country closer to its unconstrained optimal – the smooth supply rule. Consequently, the distortions from overreporting eliminate the earlier distortions due to technological change, in which case the costs of overreporting can be said to be negative.

Two specific features of the model require a word of explanation. First, a two country setup is adopted. This feature allows for utility losses of the oil exporting country, whose population may suffer from self-generated disruptions in global oil supply. Abstracting from these costs (*e.g.*, by assuming that a monopolist maximizes net present value of profits) would bias the model in favor of the final result, *i.e.*, the existence of credible overreporting. Second, the oil-exporter is allowed to levy export taxes. This assumption is necessary since the importer benefits from substitution R&D mainly through a reduction

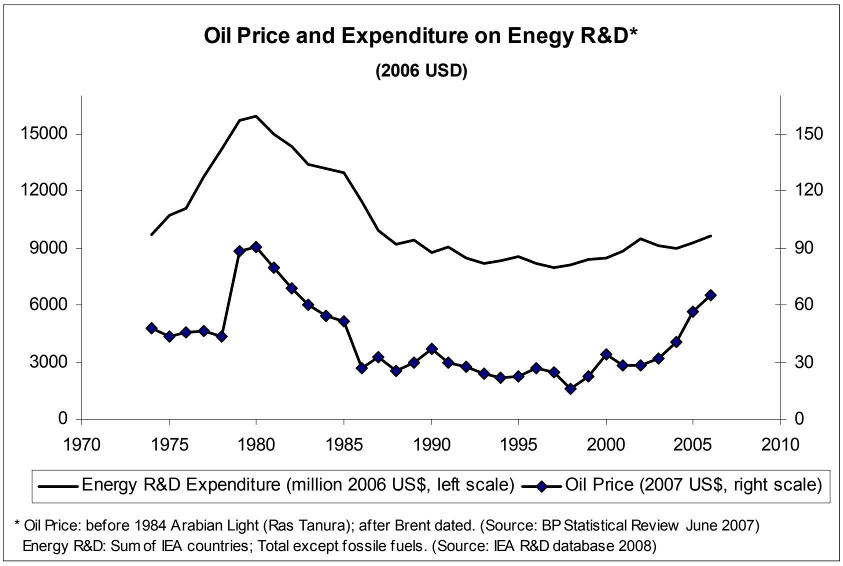

Figure 1: Oil Price and Expenditure on Energy R&D*

of the exporter's market power. The analysis must therefore involve the prime tool through which the exporter exercises market power in the foreign market. This tool is an export tax.

The paper predicts that oil exporters tend to overreport if, first, substitution R&D reacts significantly to expected future oil supply, second, if oil supply is not competitive and finally, if the costs of overreporting are limited. As argued above, the last requirement is no meaningful qualitative criterion since theory does not establish a positive lower bound on the cost of signaling. Hence, the attention rests on preconditions one and two. 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 this relation in a suggestive way by jointly plotting the time-series of total R&D expenditure on non-oil energy sources in IEA member countries and crude oil prices for the years 1973-2006.[3] Concerning the second requirement, the proposition of non-competitive oil markets seems intriguing. Indeed, while empirical evidence on OPEC's effective market power is mixed, some recent studies argue that OPEC members successfully sacrificed supply following the counter oil shock of 1986 (*e.g.* Smith (2003)). In this case, a first qualitatively application of the model cannot refute that OPEC member states overreport their crude oil reserves and further quantitative research is needed to quantitatively assess the issue.

The paper connects to the literature on the economics of exhaustible resources. Since its

[3] Expected future prices strongly comove with contemporaneous prices (see Lynch (2002)). The expected future price, in turn, is the key statistic for R&D expenditure according to this paper's argument.

very foundation by Hotelling (1931), a good part of this literature analyzes the effects of monopolistic market power. Following the oil shocks of the 1970s this research intensified (see Stiglitz (1976) and Pindyck (1978)), extending to cartel formation, both theoretically (Salant (1976), Ulph and Folie (1980), and Gaudet and Moreaux (1990)) as well as empirically (e.g. Griffin (1985), for recent contributions see Smith (2003), Almoguera and Herrera (2007), Lin (2007), and the references therein). About the same time Dasgupta and Heal (1974) sparked a line of research concerned with the substitution of exhaustible resources, either via exploration (see Burt and Cummings (1970), Arrow and Chang (1982) and Quyen (1988)) or directed technical change for substitution (e.g., Davidson (1978) and Deshmukh and Pliska (1983)). The present paper's mechanism results from the interaction of both key elements of the above-mentioned literature – monopolistic supply and substitution efforts.

Only a small number of papers analyze asymmetric information about resource reserves. Thus, Gaudet et al (1995) and Osmundsen (1998) show 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. A recent study by Gerlagh and Liski (2007) analyzes how asymmetric information about resource reserves impacts the consumers' decision to invest in substitution technologies. In a rich dynamic setting, the authors focus on buyer's exposure to endogenous uncertainty of supply. The present paper, in contrast, emphasizes the seller's incentive and potential to conceal or to signal its type.

Finally, the present paper contributes to the ample literature on signaling games. It encapsulates a standard framework à la Spence (1973) in a two-period general equilibrium trade model. Recent extensions of the classical two-stage setup analyze signaling in an infinite horizon setup. Thus, Kaya (2009) studies separating equilibria in an infinitely repeated signaling game, where each period the informed player plays against a different uninformed player, the latter having observed previous signals. Gryglewicz (2009), instead, analyzes the endogenous revelation of types in a stochastic, continuous-time game between one informed and one uninformed player. Such a setup seems indeed promising to frame the case of continued oil supply under asymmetric information. The interaction between the signals (initial supply) and the final payoff (distribution of supply over time), however, causes analytical difficulties that make this route excessively complicated. Hence my choice to resort to a two-period setup.

Before turning to the main body of the paper it seems appropriate to contemplate what insights one can expect to obtain when applying a signaling model to the oil market. On the one hand, one can reasonably expect to refute overreporting – *e.g.*, if the costs of signaling due to supply distortions exceed the benefits. On the other hand, it will be impossible to actually prove overreporting: if the model revealed actions that constitute unmistakable indicators of overreporting, the concept of a pooling equilibrium would be violated, making overreporting non-credible. Disproving overreporting might work; attempts to actually prove overreporting must fail.

The remainder of the paper is organized as follows. Section 2 outlines the model economy, describes the economic agents and the space of their actions, thus describing the game. Sections 3 and 4 solve the strategic game under full information and under asymmetric information, respectively, and discuss the results. Finally, section 5 concludes.

2 The Model

2.1 General Setup

The world economy consists of two countries: country O (like the Oil-exporter, variables marked with *) and country W (like the Western or Weakly-informed country, no *). Both countries are populated by individuals of mass one and 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 periods are meant to represent long time intervals, defined by the time it takes to develop a technology with which to substitute the natural resource.[4]

Production. In $t = 1, 2$, country W produces y_t units of a perishable consumption good Y. Country O is endowed with a grand total of N^* units of a second consumption good N, which represents a natural resource. The mining costs of N are negligible, but once N is mined, it becomes perishable.[5] Initially, country O's total reserves are uncertain and distributed according to

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

where $\xi \in (0, 1)$.

The model's setup is common knowledge, but realization of N^* is known to country O only, which supplies n_t^* units in $t = 1, 2$ under the constraints $n_t^* \geq 0$ and $n_1^* + n_2^* \leq N^*$.

Preferences. Individuals receive total utility

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

[4] 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".

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

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

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

The convenient choice of this sub-utility has expositional reasons. First, quasi-linearity implies that income is transferable across periods, so that country W's (country O's) trade-off between the cost and the benefits of R&D (of overreporting) simplifies.[6] The logarithmic specification ensures that export taxes are bounded and have explicit analytic solutions; the additive term in the argument grants finiteness of export taxes.[7]

Government policies. Central authorities, or governments, act strategically. For simplicity "the strategy of country X's government" will simply be referred to as "country X's strategy." In this sense, country O supplies n_t^* in periods $t = 1, 2$. In addition, country O sets gross export taxes T_t^*.

Country W's decides whether to develop a *substitution technology*.[8] More precisely, country W may incur $A > 0$ units of good Y in period $t = 1$ to develop a constant returns to scale technology that becomes available in period $t = 2$ and enables country W to convert good Y into a perfect substitute of good N with the marginal rate of transformation $B > 1$. Country W's substitution technology can be summarized by

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

The output generated by this technology will be denoted by n_2 and one can write

$$n_t = b_t y_{n,t}$$

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.

Substitution R&D has two key characteristics. First, it is defined as a binary process (4), so that engagement in R&D is either zero or big time. This assumption is common to the literature (see, e.g., Dasgupta and Heal (1974), Deshmukh and Pliska (1983), Quyen (1988), and Barrett (2006)) and shall reflect a major technological breakthrough in substitution technologies. Further below I argue that this first feature is not crucial. Second, there is the time-lag between R&D expenditure and availability of the substitution technology. This assumption captures the fact that major technological innovations need

[6] Income is transferable if $c_{y,t}^{(*)} > 0$ holds, which will be the case throughout the paper.

[7] The additive term in the argument can be read as a flow of a perishable substitute to the natural resource in each country.

[8] It will become clear that part of the return to substitution R&D is not appropriable so that substitution R&D must be centralized (or centrally subsidized), the costs are financed by lump-sum taxes.

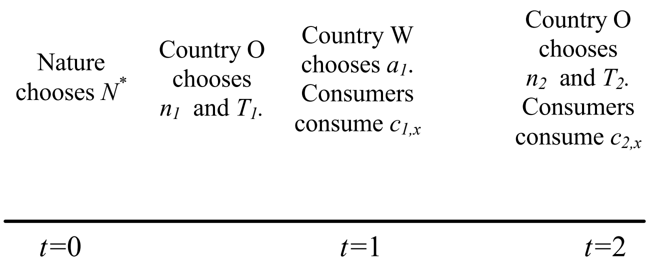

Figure 2: Timing of actions.

time to be developed and to become applicable[9]. This second assumption is crucial to the paper's mechanism, as the argument relies on the fact that technological progress cannot be generated instantaneously. Clearly, if technologies became operable at the time of investment, R&D decisions would be delayed until uncertainty is resolved and information rents would vanish.

Timing. The timing of actions, summarized in Figure 2, is the following. at $t = 0$ nature chooses the realization of N^*, which is revealed to country O only. At the start of period $t = 1$ country O supplies the quantity n_1^* and sets the export tax T_1^*. Country W subsequently chooses the investment a_1 and first-period consumption is realized. At $t = 2$, country O sets export taxes T_2^*, supplies $n_2^* \leq N^* - n_1^*$ and the second period's equilibrium quantities are consumed.

Notice that country W chooses its strategy a_1 after n_1 and T_1 are set. This assumption implies that country W can condition its strategy a_1 on T_1 and on n_1. If a_1, n_1, and T_1 were taken simultaneously, country O's overreporting via observable actions could not influence country W's strategies and would thus be irrelevant for the equilibrium. The signaling game has no strategic content if the receiver of the signal cannot condition her actions on the observed signal.

Intuitively, country W's substitution R&D harms country O by generating competition of N-supply in period $t = 2$. To avoid such losses, 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.

2.2 Consumers' Optimization

At $t = 1, 2$ consumers maximize sub-utilities (3) subject to the respective budgets constraints $T_t^* p_t c_{n,t} + c_{y,t} \leq E_t$ and $p_t c_{n,t}^* + c_{y,t}^* \leq E_t^*$, where the price of Y has been normalized

[9] Lovins et al (2005) reckon that US oil demand projected for 2025 can be cut to half by when beginning to adopt substitutes and energy-saving technologies 20 years in advance.

to unity, p_t is the price of good N and $E_t^{(*)}$ is respective net per capita income. Consumers take domestic prices and the quantities n_t^* and n_t as given. Provided that interior solutions prevail ($c_{x,t}^{(*)} > 0$ for $x = n, y$), optimal quantities are

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

When the N-market clears (*i.e.*, $c_{n,t} + c_{n,t}^* = n_t^* + n_t \equiv \bar{n}_t$) the world price is

$$p_t = \frac{1 + 1/T_t^*}{\bar{n}_t + 2} \tag{5}$$

With this expression of the price, country W's expenditure on consumption goods equals the value of its production in domestic prices minus the value of inputs for R&D plus N-production, *i.e.*

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

Country O's revenue from the export tax $(T_t^* - 1)p_t(n_t^* - c_{n,t}^*)$ is distributed lump-sum so that income of its citizens 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

$$\begin{aligned} c_{n,t} &= \frac{\bar{n}_t + 2}{T_t^* + 1} - 1 \qquad & c_{y,t} &= y_t + (T_t^* + 1)\frac{n_t + 1}{\bar{n}_t + 2} - 1 - \tfrac{n_t}{B} - a_t \\ c_{n,t}^* &= T_t^* \frac{\bar{n}_t + 2}{T_t^* + 1} - 1 & c_{y,t}^* &= 1 - (T_t^* + 1)\frac{n_t + 1}{\bar{n}_t + 2} \end{aligned} \tag{6}$$

and the sub-utilities

$$\begin{aligned} u_t &= \ln\left(\frac{\bar{n}_t + 2}{T_t^* + 1}\right) + y_t + (T_t^* + 1)\frac{n_t + 1}{\bar{n}_t + 2} - 1 - \tfrac{n_t}{B} - a_t \\ u_t^* &= \ln\left(T_t^* \frac{\bar{n}_t + 2}{T_t^* + 1}\right) + 1 - (T_t^* + 1)\frac{n_t + 1}{\bar{n}_t + 2} \end{aligned} \tag{7}$$

The optimal policies (n_t^*, T^*, and a_1) maximize the sum of the sub-utilities (7).

2.3 Optimal Export Tax

Both countries use their policies to maximize the respective total utilities (2), which involves an intertemporal trade-off between periods. Equation (7), however, shows that the first period's export tax T_1^* affects neither the cost of country W's R&D nor its returns, which accrue in the second period only. Hence, a_1 is independent of T_1^* and so is

u_2^*. Also, when T_2^* is set in $t = 2$ all first-period variables are taken as given, so that u_2^* is independent of T_2^*. Hence, the optimal export taxes T_t^* maximizes the sub-utilities u_t^*.

No substitution technology. In case $b_t = 0$, country W is not capable of N-production, $n_t = 0$ holds trivially and maximization of u_t^* from (7) leads to[10]

$$T_t^* = \sqrt{9/4 + n_t^*} - 1/2 \tag{8}$$

Substitution technology. If, in contrast, $b_2 = B$ holds, the price ratio $T_2^* p_2$ cannot exceed the marginal rate of transformation $1/B$ and country O's equilibrium export tax must satisfy the constraint $T_2^* p_2 \leq 1/B$. When this constraint binds, expression (5) yields

$$T_2^* = \frac{\bar{n}_2 + 2}{B} - 1 \tag{9}$$

Equation (9) implies that any increase of the export tax T_2^* above the level $\frac{n_t^*+2}{b} - 1$ induces an increase in n_2 that keeps the relative price $T_2^* p_2$ constant. With (7) it is straight forward to check that, under (9) and at constant n_2^*, sub-utility u_2^* is decreasing in n_2 if and only if $T_2^* \geq 1$ or, equivalently, $\bar{n}_2 \geq 2(B-1)$ holds. Consequently, under condition $b_2 = B$, country O's optimal export tax is $T_2^* = \max\{(n_2^* + 2)/B - 1, 1\}$ and the optimal export taxes are summarized by

$$T_t^*(n_t^*) = \begin{cases} \sqrt{\frac{9}{4} + n_t^*} - \frac{1}{2} & \text{if } b_t = 0 \\ \max\left\{\frac{n_t^*+2}{B} - 1, 1\right\} & \text{if } b_t = B \end{cases} \tag{10}$$

Equation (10) has been derived assuming that the constraint $T_2^* p_2 \leq 1/B$ binds. With (5) and (8), this is the case if $T_2^*|_{b=0} < B$, or if B is large compared to country O's second period's supply:

$$B^2 + B - 2 > n_2^* \tag{11}$$

In that case, equilibrium consumption (6) of both countries depends on country W's substitution technology. In particular, under $b_2 = 0$ quantities are

$$\begin{array}{ll} c_{n,t} = \frac{n_t^*+2}{T_t^*+1} - 1 & c_{y,t} = y_t + \frac{T_t^*+1}{n_t^*+2} - 1 - a_t \\ c_{n,t}^* = T_t^* \frac{n_t^*+2}{T_t^*+1} - 1 & c_{y,t}^* = 1 - \frac{T_t^*+1}{n_t^*+2} \end{array} \tag{12}$$

while under $b_2 = B$ equations (6) and (10) lead to

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

[10] Notice that (5) and (8) imply $T_t^* p_t < 1$ so that consumed quantities $c_{n,t}^{(*)}$ from (6) are positive.

Combining both cases, sub-utilities (7) are

$$
u_t = \begin{cases} \ln(B) + y_2 - \frac{B-1}{B} & \text{if } t = 2 \text{ and } a_1 = A \\ \ln\left(\frac{n_t^*+2}{T_t^*+1}\right) + y_t + \frac{T_t^*+1}{n_t^*+2} - 1 - a_t & \text{else} \end{cases}
$$

$$
u_t^* = \begin{cases} \ln(\min\{n_2^*+1, B\}) + \frac{B-1-n_2}{B} & \text{if } t = 2 \text{ and } a_1 = A \\ \ln\left(T_t^* \frac{n_t^*+2}{T_t^*+1}\right) + 1 - \frac{T_t^*+1}{n_t^*+2} & \text{else} \end{cases} \tag{13}
$$

Together, equations (10) and (13) determine the equilibrium utility for given supply n_t^* and investment a_1 and imply the following observations.

First, the sub-utility u_t^* is increasing in n_t^*, hence the resource constraint $n_1^* + n_2^* \leq N^*$ binds and the second period's supply equals the residual $n_2^* = N^* - n_1^*$. This is a simple verification of Walras' Law.

Second, conditional on $b_t = 0$ (i.e. $a_1 = 0$), u_t^* is concave in n_t^* by

$$
\left.\frac{d^2 u_t^*}{(dn_t^*)^2}\right|_{b_t=0} = \frac{-2}{(T_t^*)^3(2T_t^*+1)} < 0 \tag{14}
$$

Thus, conditional on country W not investing in R&D, country O's total utility (2) is maximized when the natural resource is supplied evenly across the periods

$$
n_1^* = n_2^* = N^*/2 \tag{15}
$$

This supply rule is a degenerate version of Hotelling's optimal rule, which states that – correcting for time preference rates – optimal supply is smooth. Any deviation from optimal supply rules can directly or indirectly be attributed to substitution R&D activity.

Third, combining equations (11) and (15) shows that the possibility to engage in R&D affects world prices if and only if

$$
B^2 + B - 2 > N^*/2 \tag{16}
$$

holds. Intuitively, technology B can affect the price of N only if either the substitution technology is very efficient (B is large) or country O's endowment N^* is small. For the rest of the paper condition (2) will be assumed to hold.

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 ($n_2 = 0$) even under $b_2 = B$. In this case country W's return to R&D consists of a reduction of import prices $T_2^* p_2$ in the second period. The returns to costly R&D are positive but non-appropriable, wherefore substitution R&D must be centrally financed in country W (compare footnote 8).

3 Full Information

This section provides a benchmark by analyzing the Nash equilibrium of the sequential game, 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 ($u_2|_{b_2=B} - u_2|_{b_2=0} \leq A$). With expressions (10) and (13) this condition is

$$\ln\left(B\frac{\sqrt{\frac{9}{4}+n_2^*}+\frac{1}{2}}{n_2^*+2}\right)+\frac{1}{B}-\frac{\sqrt{\frac{9}{4}+n_2^*}+\frac{1}{2}}{n_2^*+2}\leq A. \tag{17}$$

Country W's optimal strategy is thus expressed by the rule

$$a_1 = \begin{cases} 0 & \text{if (17) holds} \\ A & \text{else} \end{cases}$$

The trade-off between costs and benefits of substitution R&D are trivial if the cost A is prohibitive even under minimal (zero) supply of N in the second period. To rule out this case, assume that (17) is violated under $n_2^* = 0$, i.e.,[11]

$$\ln(B)+\frac{1}{B}-1 > A \tag{18}$$

1^{st} stage: Optimal Supply n_1^*. In the first stage country O may either prevent country W's substitution R&D or, alternatively, concede to it. If it prevents substitution R&D, n_2^* must satisfy condition (17). Since the term on the left of (17) is decreasing in n_2^*, condition (17) implicitly defines a lower bound on n_2^*, labeled n_P^* and satisfying (17) with equality. Noticing that the expression on the left of (17) is negative whenever $n_2^* > B^2 + B - 2$, one has, by assumption (18)

$$n_P^* \in (0, B^2+B-2) \tag{19}$$

By concavity of u^* (see (14)), country O's optimal supply, conditional on $a_1 = 0$, is

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

Intuitively country O can prevent substitution R&D by supplying enough of N in the second period so that it does not pay for W to develop the substitution technology.

[11] The expression on the left of (18) is positive by $B > 1$.

Clearly, whenever total resources N^* are large (i.e., $N^* > 2n_P^*$ holds), country O is not constrained by this requirement and plays its unconstrained optimal strategy $n_1^* = N^*/2$.

If preventing substitution R&D is too costly, country O may, alternatively, adjust to country W's R&D. In this case country O's optimal supply in the first period is (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^* is the first period's optimal supply conditional on conceding to $a_1 = A$. One can check that $n_C^* \in (0, N^*)$ holds in all cases.[12]

In sum, country O sets first-period supply either to (20), preventing substitution R&D or it sets (21), adjusting to substitution R&D. The equilibrium depends on the respective utilities under both strategies. To evaluate this trade-off, it is convenient to define total utility under given supply and investment decisions as

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

Clearly, if country O concedes to W's R&D it obtains total utility $V^*\left(n_C^*, N^* - n_C^*, B\right)$ 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 *$\exists\ N_0 \in [n_P^*, 2n_P^*]$ so that under full information 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. Use (22) to define $\Delta V^*(N^*) \equiv V^*(N^* - n_P^*, n_P^*, 0) - V^*(n_C^*, N^* - n_C^*, B)$. It is sufficient to show (i) $\Delta V^*(n_P^*) < 0$, (ii) $\Delta V^*(2n_P^*) > 0$, and (iii) $N^* - n_P^* < n_C^*$ implies $d\Delta V^*(N^*)/dN^* > 0$ ($N^* - n_P^* > n_C^*$ implies $b_2 = 0$ in any case).

[12] Note also that the expression in the first line falls short of $N^*/2$ since under condition (16) $B + 1/4$ exceeds the value of the square root. For $N^* > 0$, however, the term in the third line is strictly larger than $N^*/2$.

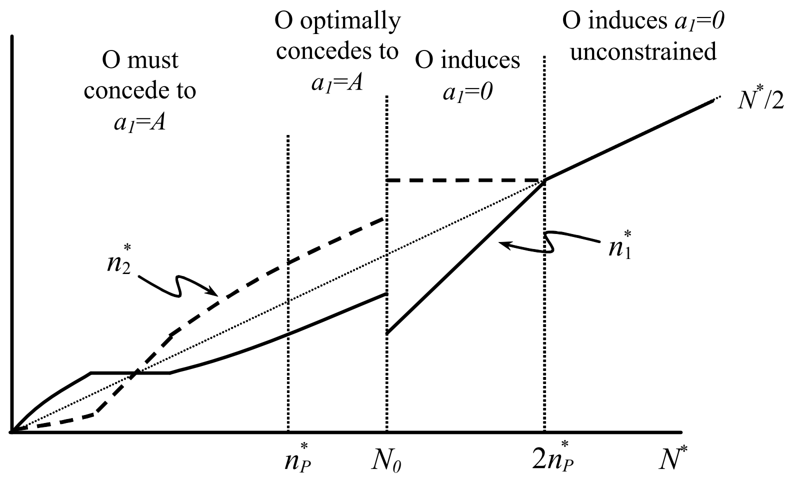

Figure 3: Country O's optimal quantities under full information.

(i) observe that

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

where $n_C^* < N^* = n_P^*$ and (14) were used in the second step. For (ii)

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

which follows from (15). For (iii), observe that 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 (14) this expression is positive whenever $N^* - n_P^* < n_C^*$. ■

The intuition of the proposition is straight forward: country O's two goals are, on the one hand, to smooth supply according to the unconstrained rule (15) 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 (15) - and the associated utility loss - is relatively large whenever the total reserves N^* are low. Thus, the utility losses dominate the gains from preventing investment if and only 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 (17). 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 worth contemplating the distortion of supply under prevention of country W's R&D. 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 ($n_1^* < n_2^*$). This finding is reminiscent of earlier work on natural resource extraction and market structure: Hotelling (1931) writes of a "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 a possibly longer duration of supply period.[13] 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.

Proposition 1 has provided a description of the full information equilibrium. The next section analyzes the incentives to misreport under asymmetric information of reserves.

4 Asymmetric Information

This section formalizes country O's incentives to misreport the reserves of the natural resource N. The suitable framework for this analysis is a Perfect Bayesian Equilibrium in a signaling game.

[13] Stiglitz (1976) shows that these results do not stand up to robustness checks.

Within this framework, a player with private information can be said to actively deceive other players if he conceals his type and benefits from doing so. Applying this concept to the current model, one of country O's types will be said to misreport successfully if its signal is not informative about remaining reserves and if, in addition, this specific type enjoys higher utility in the resulting pooling equilibrium than under full information. By definition, successful misreporting and beneficial pooling are the same thing.[14]

With this definition I turn to the formal equilibrium concept next.

4.1 Equilibrium - Definition

The relevant actions of the signaling game are the following (compare Figure 2). In the first stage Nature decides on the realization of N^* according to (1); country O observes the realization of N^* but country W does not. The realization of N^* defines two different types of country O indexed by $\theta = H, L$ and labeled country O_H in the case $N^* = \bar{N}$ and country O_L if $N^* = \xi\bar{N}$. In the second stage country O signals its type with the first period's supply $\tilde{n}_1$. (The tilde indicates all possible levels of supply, including those off-equilibrium.) In the third stage country W rationally updates its beliefs and chooses investment $a_1 \in \{0, A\}$. As shown in Section 2.3, export taxes follow expressions (10) and (12). The strategies

$$(n^e_{1,H}, n^e_{1,L}, a^e_1(\tilde{n}_1))$$

are said to be part of a Subgame Perfect Bayesian Equilibrium (SPBE) if they satisfy the following criteria

- **E(i)** given W's strategies, $n^e_{1,\theta}$ maximize O's total utility for $\theta = H, L$.
- **E(ii)** given O's strategies, W updates its believes using Bayes' rule
- **E(iii)** $a^e_1(\tilde{n}_1)$ maximizes W's expected total utility under the updated beliefs.

Country W's 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^e_1 or

$$\mu(\tilde{n}_1) \equiv \mathbb{P}(N^* = \bar{N} \mid n^*_1 = n^e_1)$$

The equilibrium strategies of both players are indexed with the superscript ^{e} and are denoted by

$$\left(n^e_{1,H}, n^e_{1,L}\right) \in [0, \bar{N}] \times [0, \xi\bar{N}] \quad \text{and} \quad a^e_1\left(\tilde{n}_1\right) : [0, \bar{N}] \to \{0, A\}$$

[14] Obviously, any costless reporting is discounted as cheap talk and entirely irrelevant to the model. Acknowledging the fact that countries do report their reserves, however, this definition captures the "real" side of the misreporting process and is therefore a natural one.

Country W's equilibrium technology in the second period is $b^e_{2,\theta} \in \{0, B\}$, where $\theta = H, L$. In a pooling equilibrium, a_1 cannot be conditioned on country O's type and $b^e_{2,H} = b^e_{2,L}$ holds.

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

$$\begin{aligned} n^*_{1,H} &\in [0, \bar{N}] \quad \text{and} \quad a^*_{1,H}(\tilde{n}_1) : [0, \bar{N}] \to \{0, A\} \\ n^*_{1,L} &\in [0, \xi\bar{N}] \quad \text{and} \quad a^*_{1,L}(\tilde{n}_1) : [0, \xi\bar{N}] \to \{0, A\} \end{aligned}$$

Similarly, the variable $b^*_{2,\theta} \in \{0, B\}$ stands for country W's substitution technology in the second period of the full information equilibrium, given country O's type θ.

The existence and the characteristics 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 follow Bayes' rule leaves a wide range of off-equilibrium beliefs that generally sustain a large number of equilibria. The equilibria will therefore be constrained by the following reasonable refinements of beliefs.[15]

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

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

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

A(iv) $\tilde{n}_1 \in [0, \bar{N}]$ $\quad \tilde{b}$ outcome of W's optimal $a^e_1(\tilde{n}_1)$ under $\mu(\tilde{n}_1) = \pi$.
$$V^*(\tilde{n}_1, \bar{N} - \tilde{n}_1, \tilde{b}) > V^*(n^e_{1,H}, \bar{N} - n^e_{1,H}, b^e_{2,H})$$
$$V^*(\tilde{n}_1, \xi\bar{N} - \tilde{n}_1, \tilde{b}) > V^*(n^*_{1,L}, \xi\bar{N} - n^*_{1,L}, b^*_{2,L})$$
$$\Rightarrow \quad \mu(\tilde{n}_1) = \pi.$$

A(v) $\tilde{n}_1 \in [0, \bar{N}]$ $\quad \tilde{b}$ outcome of W's optimal $a^e_1(\tilde{n}_1)$ under $\mu(\tilde{n}_1) = \pi$.
$$V^*(\tilde{n}_1, \bar{N} - \tilde{n}_1, \tilde{b}) < V^*(n^e_{1,H}, \bar{N} - n^e_{1,H}, b^e_{2,H})$$
$$V^*(\tilde{n}_1, \xi\bar{N} - \tilde{n}_1, \tilde{b}) > V^*(n^e_{1,L}, \xi\bar{N} - n^e_{1,L}, b^e_{2,L})$$
$$\Rightarrow \quad \mu(\tilde{n}_1) = 0.$$

Assumptions A(i) and A(ii) simply formulate the requirement of Bayesian updating. 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 $n^*_{1,H}$. A(iii) thereby establishes the full information equilibrium as the default outcome.[16] Conversely, this implies that a pooling equilibrium only exists if no separating equilibrium exists, which includes the full

[15] Refinements A(iii) - A(v) are remniscent of the of the *Intuitive Criterion* in Cho and Kreps (1987).

[16] 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

information strategies. – A(iv) requires that, if O_H gains from a deviation to $\tilde{n}_1$ relative to an equilibrium outcome $n^e_{1,H}$ provided that $\mu(\tilde{n}_1) = \pi$ and if, further, O_L prefers to pool to that deviation $\tilde{n}_1$ rather than to resort to its full information equilibrium, then W, when actually observing strategy $\tilde{n}_1$, is agnostic about O's type and sticks to its prior beliefs ($\mu(\tilde{n}_1) = \pi$). 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 $\tilde{n}_1$ relative to the equilibrium provided that $\mu(\tilde{n}_1) = \pi$ while O_L gains from a deviation to $\tilde{n}$ relative to its current equilibrium outcome provided that $\mu(\tilde{n}_1) = \pi$, then W, when observing strategy $\tilde{n}_1$, believes in $\theta = L$ with certainty ($\mu(\tilde{n}_1) = 0$). This assumption ties O_L to the equilibrium strategy that is beneficial for O_H.

4.2 Equilibrium - Characterization

TO characterize the equilibria under asymmetric information, consider first country W's choice. Compared with the full information, country W's situation changes 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 the *expected returns* to substitution R&D, where expectations are formed using subjective probabilities. More precisely, country W's strategy is based on a probabilistic analog of inequality (17), which, when using the definition of μ, can be written as

$$\begin{aligned} \ln(B) + \tfrac{1}{B} - \mu(\tilde{n}_1)\left\{\ln\left(T_2^*(\bar{N} - \tilde{n}_1)\right) + \frac{1}{T_2^*(\bar{N} - \tilde{n}_1)}\right\} - ... \\ ...(1 - \mu(\tilde{n}_1))\left\{\ln\left(T_2^*(\xi\bar{N} - \tilde{n}_1)\right) + \frac{1}{T_2^*(\xi\bar{N} - \tilde{n}_1)}\right\} \leq A \end{aligned} \tag{24}$$

In (24) $T_2^*(.)$ stands for the optimal export tax (10) under $b_2 = 0$. Condition (24) determines country W's investment behavior and[17]

$$a_1(\tilde{n}_1) = \begin{cases} 0 & \text{if (24) holds} \\ A & \text{else} \end{cases} \tag{25}$$

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

(the incentive compatibility constraint in the case of a separating and the probabilistic equivalent of (17) with prior probabilities π and $1-\pi$ in the case of a pooling equilibrium – see (24)) 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 $a^e_1(n^e_{1,H}) = 0$ (Proposition 1 grants that O_H actually does so).

[17] This seemingly simple decision rule involves the updated beliefs μ, must satisfy A(i) - A(v) and hence depend on the payoffs of the types O_θ. The payoffs, in turn, depend on $a_1(n^*_1)$.

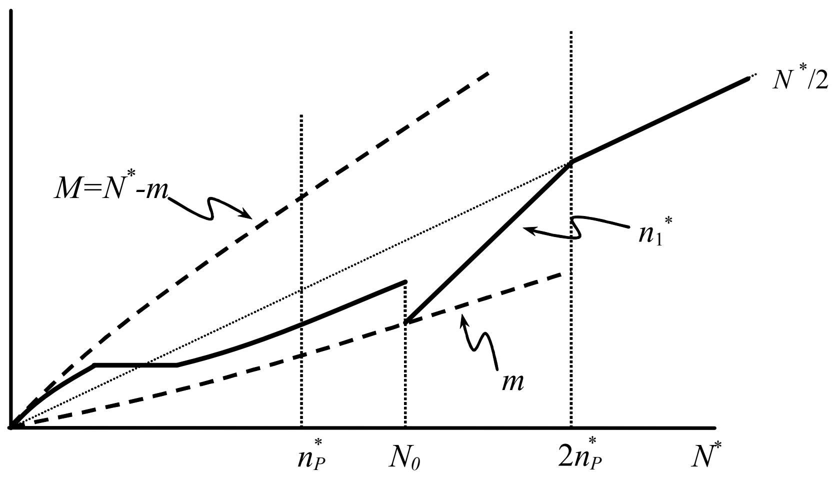

Figure 4: Boundaries of O's net benefits from preventing W's R&D.

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 to the computation of the equilibrium. It will prove useful to define the limits on the first period's supply $\tilde{n}_1$ 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 $a_1 = A$. Using (22), a lower bound m is implicitly defined by $m < N^*/2$ and

$$V^*(n_C^*, N^* - n_C^*, B) - V^*(m, N^* - m, 0) = 0 \tag{26}$$

By this definition, m depends on total reserves N^* and some of its properties can be inferred from (26).

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 $u^*|_{b_2=0}$ (see (14)) 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

$$M(N^*) \equiv N^* - m(N^*) \tag{27}$$

establishes the corresponding upper bound on the quantities n_1^*. Figure 4 illustrates these bounds $m(N^*)$ and $M(N^*)$ as dashed lines, the solid line represents the equilibrium n_1^* under full information. 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 SPBE in pure strategies is unique and characterized by the full information strategies (23). In particular, the SPBE is a separating equilibrium.

Proof. Observe first that A(iii) implies that O_H plays its full information strategy $n_{1,H}^*$ whenever it does not pay for O_L to pool to $n_{1,H}^*$, i.e. when

$$V^*(n_{1,H}^*, \xi\bar{N} - n_{1,H}^*, b_{2,H}^*) < V^*(n_{1,L}^*, \xi\bar{N} - n_{1,L}^*, b_{2,L}^*) \tag{28}$$

holds. This statement follows from two basic observations. First, $n_{1,H}^*$ is O_H's unique optimal strategy under full information. Second, O_H obtains weakly less utility in an equilibrium of the signaling game than under full information, because asymmetric information adds one constraint to O_H's optimization program (the incentive compatibility constraint in the case of a separating and (24) in the case of a pooling equilibrium). Now, whenever (28) holds A(iii) grants that O_H obtains its maximum (full information) utility by playing $n^e_{1,H} = n^*_{1,H}$. It is thus sufficient to show (28).

Assume now that (i) holds. If $\bar{N} < N_0$ W plays $a_1 = A$ in the full information equilibria under $N^* = \bar{N}$. In this case

$$V^*(n^*_{1,H}, \xi\bar{N} - n^*_{1,H}, 0) < V^*(n^*_{1,L}, \xi\bar{N} - n^*_{1,L}, 0)$$

by optimality of $n^*_{1,L}$ under full information.

If, instead, $\bar{N} > 2n^*_P$, (20) implies that O_H's full information strategy is $n^*_{1,H} = \bar{N}/2$. Distinguish now two cases: first, under $\xi\bar{N} > 2n^*_P$ then (28) holds since

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

Second, under $\xi\bar{N} < 2n^*_P$ one has

$$\begin{aligned} V^*(\bar{N}/2, \xi\bar{N} - \bar{N}/2, 0) &= V^*(\xi\bar{N} - \bar{N}/2, \bar{N}/2, 0) \\ &< V^*(\xi\bar{N} - n^*_P, n^*_P, 0) \leq V^*(n^*_{1,L}, \xi\bar{N} - n^*_{1,L}, b^*_{2,L}) \end{aligned}$$

where the first line employs symmetry of $V^*(.,.,0)$, the strict inequality follows from (14) together with symmetry of $V^*(.,.,0)$ and the weak inequality from follows from (23).

Assume next that (i) is violated so that $n^*_{1,H} = \bar{N} - n^*_P$ but (ii) holds. These conditions and the definition of M (27) 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

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

holds. This 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, it can be ruled out that the low type pools to the strategy $\bar{N} - n^*_P$, since this would render strictly less

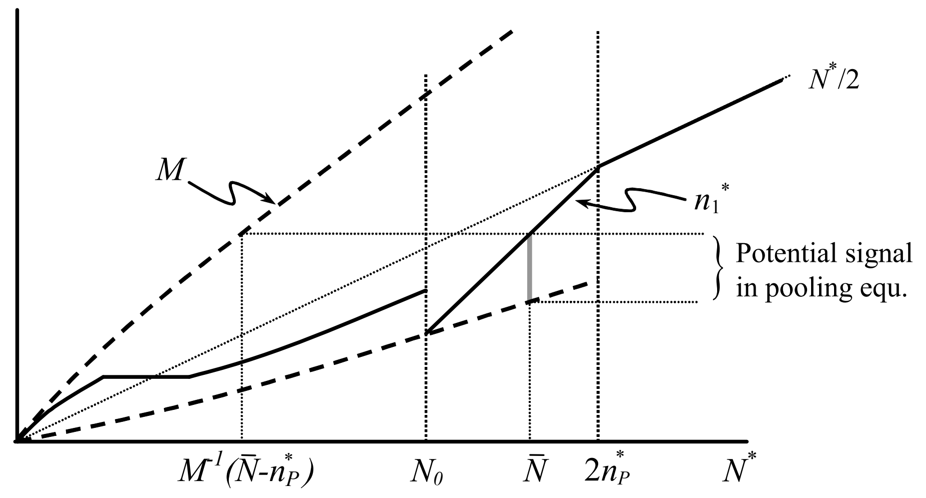

Figure 5: O_L's incentives to imitate O_H and equilibrium signals.

utility than her full information strategy. Thus, under any of these conditions, the two types resort to the respective full information strategies.

Having excluded the existence of pooling equilibria for some parameter range, the attention rests on the remaining parameter range. Thus, rest of the section will focus on the cases where conditions

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

and

$$\xi \in [M^{-1}(\bar{N} - n_P^*)/\bar{N}, 1) \tag{30}$$

are satisfied. Conditions (29) and (30) assure that type O_L gains from imitating O_H's full information strategy $n_{1,H}^*$ if that discourages substitution R&D. Under such pooling attempts, however, country W adapts its beliefs so that the full information strategy $n_{1,H}^*$ cannot be part of a pooling equilibrium. Instead, the natural candidate for the signal of a pooling equilibrium is the quantity that solves (24) with equality under prior beliefs $\mu \equiv \pi$. Let this value be denoted by n_P^e, defined as the implicit solution of

$$\begin{aligned} \ln(B) + \tfrac{1}{B} - \pi \left\{ \ln\left(T_2^*(\bar{N} - n_P^e)\right) + \frac{1}{T_2^*(\bar{N} - n_P^e)} \right\} - ... \\ ...(1-\pi) \left\{ \ln\left(T_2^*(\xi\bar{N} - n_P^e)\right) + \frac{1}{T_2^*(\xi\bar{N} - n_P^e)} \right\} = A \end{aligned} \tag{31}$$

where $T_2^*(.)$ stands for the second period's export tax (10) under $b_2 = 0$. One quickly verifies that the expression on the left of (31) is decreasing in export taxes and, hence, by (10), is increasing in n_P^e. Equation (10) implies further that the term in the first slanted brackets is larger than the term in the second slanted brackets and, therefore, the whole expression on the left of (31) is decreasing in π. Finally, the expression on the left on (31) is decreasing in ξ. These observations, together with the implicit function theorem, imply that the threshold n_P^e is increasing in ξ and π. Notice also that at $\pi = 1$ condition (31) coincides with (17) in which case $n_P^e = \bar{N} - n_P^*$ while at $\pi = 0$ (31) leads to $n_P^e = \xi\bar{N} - n_P^*$. Summarizing, one has

$$\begin{aligned} \frac{d}{d\xi} n_P^e &> 0 & (32) \\ \frac{d}{d\pi} n_P^e &> 0 & (33) \\ \lim_{\pi \to 1} n_P^e &= \bar{N} - n_P^* & (34) \\ \lim_{\pi \to 0} n_P^e &= \xi\bar{N} - n_P^* & (35) \end{aligned}$$

The difference $n_P^e - (\bar{N} - n_P^*) < 0$ between n_P^e and O_H's full information strategy reflects that country W reacts to O_L's incentives to pool, by revising expected future supply of N downward relative to the full information equilibrium under $N^* = \bar{N}$. To compensate for this drop of expected future supply, O_H must further increase the second period supply if she wants to discourage country W's R&D. 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 indeed choose not to discourage substitution R&D. 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_P^e must be element of the set $[m(\bar{N}), M(\bar{N})]$. Since conditions (33) and (34) imply $n_P^e < \bar{N} - n_P^*$ and since $\bar{N} - n_P^* < \bar{N}/2$ by (29), the relevant constraint is

$$n_P^e \geq m(\bar{N}) \tag{36}$$

Now remember that n_P^e is a function of π and ξ so that condition (36) 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 (32) and (33), represents a decreasing function $\underline{\pi}(\xi)$ that limits the region within which a pooling equilibrium may exist. For values of $\pi < \underline{\pi}(\xi)$, condition (36) 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 (29) and (30) – the requirement (36) is necessary for a pooling equilibrium to exists. The following proposition identifies conditions (29), (30), and (36) as jointly sufficient, granting that the two-stage signaling game has a pooling equilibrium in pure strategies, which is – modulo country W's off-equilibrium beliefs μ and strategies – unique.

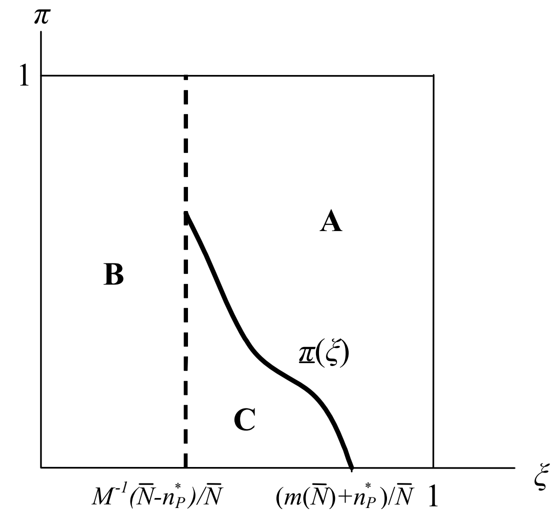

Figure 6: Three different types of equilibria.

Proposition 3 *If (29), (30), and (36) hold, a SPBE in pure strategies exists. Moreover, all SPBE in pure strategies include the strategies*

$$(n^e_{1,H}, n^e_{1,L}) = (n^e_P, n^e_P) \quad \textit{and} \quad a^e_1(n^e_{1,H}) = a^e_1(n^e_{1,L}) = 0 \tag{37}$$

Proof. See Appendix. ■

Figure 6 illustrates the two key conditions (30) and (36) that delimit the range for the parameters ξ and π where pooling equilibria prevail. Condition (30) sets a minimum that ξ needs to exceed, represented by the dashed vertical line in the figure. Condition (36) defines a minimum $\underline{\pi}(\xi)$ that the ex ante probability π must exceed to grant (36). The function $\underline{\pi}(\xi)$ is marked as a bold line. Both conditions are satisfied for parameters within the area **A**. Notice with (33) and (35) that for $\xi > \left[m(\bar{N}) + n^*_P\right]/\bar{N}$, 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 $\left[m(\bar{N}) + n^*_P\right]/\bar{N}$.[18]

To the left of the dashed line, in area **B**, condition (30) 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, if (30) holds but (36) 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. While a formal proof is omitted here, the equilibrium strategies can be shown to follow the supply rules (21) for $N^* = \xi\bar{N}, \bar{N}$, respectively: a separating equilibrium prevails, with O_H deviating from its full information strategies.

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

One important feature of the pooling equilibria characterized in Proposition 3 remains to be highlighted. This feature concerns the *cost of signaling*. Observe that the signal, which the low type must incur in order to imitate the high type is restricted to lie on the grey vertical line in Figure 5. For the adequate size of low reserves ($\xi \bar{N}$) this implies that the signal of the pooling equilibrium (n_P^e) lies strictly closer to the unconstrained optimal supply ($\xi \bar{N}/2$) of the low type, thus generating additional benefits. Formally, this property can be stated as follows.

Corollary to Proposition 3. *If* $\xi/2 \in (m(\bar{N})/\bar{N}, (1 - n_P^*/\bar{N}))$ *there are* π_1, π_2 *with* $\underline{\pi}(\xi) < \pi_1 < \pi_2 < 1$ *so that for all* $\pi \in [\pi_1, \pi_2]$

$$C \equiv U^*(n_L^*)|_{a_1=0} - U^*(n_L^e)|_{a_1=0} < 0 \tag{38}$$

holds. The set $(m(\bar{N})/\bar{N}, (1 - n_P^*/\bar{N}))$ *is non-empty for* $\bar{N} - n_P^* > m(\bar{N})$ *for* $\bar{N} > N_0$*.*

Proof. At $\pi = 1$ $n_P^e = \bar{N} - n_P^*$ holds, implying $n_P^e > \xi \bar{N}/2$ by assumption; at $\pi = \underline{\pi}(\xi)$ $n_P^e = m(\bar{N}) < \xi \bar{N}/2$. Since n_P^e is increasing and continuous in π there is a π_0 so that $n_P^e = \xi \bar{N}/2$. Again, by continuity of $n_P^e(\pi)$ there are π_1, π_2 with the stated properties so that $\left|\xi \bar{N}/2 - n_P^e\right| < \left|\xi \bar{N}/2 - n_L^*\right|$ for $\pi \in [\pi_1, \pi_2]$. This proves the claim. ■

To what extent does the Corollary relate to the cost of signaling? Quite generally in signaling games, one of the informed types receives information rents by making the uninformed player choose a strategy that benefits the informed type compared to its full information payoffs. Obviously, when separating the cost from the benefit of the signal, the cost must be defined by holding constant the induced benefit. In this sense, the cost of signaling can be defined as the change in the informed type's payoffs that the necessary signal generates, *conditional on inducing the (desired) asymmetric information strategy of the uninformed player.* The change is measured relative to the natural benchmark, *i.e.*, relative to the full information strategy. Applying this definition to the present setting, the cost that the low type O_L incurs by setting the signal is captured by the expression C in equation (38).

When read in this way, the corollary presents a striking insight of the model. It shows that, for a wide parameter range, the cost of signaling is actually *negative* for the low overreporting type O_L. Put differently, the overreporting supplier gains not only from preventing W's substitution R&D but also form the very fact of signaling itself.

This fact is somewhat surprising. One could reasonably expect that this cost is proportional to the degree by which reserves are actually overstated – so that "bigger lies bear bigger costs". This guess proves wrong. Instead, an overreporting exporter may actually gain not only from the implication of overreporting but also from signaling (or "lying") itself. Thus, the general principle, according to which the low type trades off the gains from pooling against the cost of the signal, does not apply in the present model.

The fundamental reason for this result is the following. The high type, O_H, who loses from pooling vis-a-vis separation, would like to signal her high reserves. Since high reserves come along with high supply the obvious way to signal would seem to increase the first period's supply. But this is not viable signal, since the preventing R&D precisely requires a minimum supply in the second period. Any increase in the first period's supply would thus reduce the remaining reserves, decrease the second period's (expected) supply and hence trigger country W's R&D. The natural way to signal high reserves is barred by the incentive compatibility constraint (24).

Consequently, the costs of signaling do not impost a clear quantitative restriction on the existence of pooling equilibria.

4.3 Pooling Equilibrium - Discussion

By the earlier definition type O_θ is said to misreport its reserves if its equilibrium action $n^*_{1,\theta}$ does not reveal its type and its utility in the resulting pooling equilibrium is higher than in the respective full information equilibrium.

Applying this definition and observing that, relative to the full information outcome, the low type benefits from pooling (granted by condition (30)), the low type O_L is said to overreport its reserves in all equilibria characterized in Proposition 3. Conversely, the high type looses in all pooling equilibria (check that conditions (29), (33) and (34) imply $n^e_P < \bar{N} - n^*_P < \bar{N}/2$ and apply (14)). The analysis thus shows that, under the stated conditions, oil suppliers have incentives to over- but not to underreport.

Without formally extending the model, the next paragraphs will discuss the conditions of the main results as well as the modelling framework under which they have been derived.

The Pooling Equilibrium. The conditions for credible overreporting (Proposition 3) can be summarized by two simple and intuitive requirements. First, the lower bound of condition (29) requires that, under full information, the high type prevents country W's R&D activity. If this condition is violated, substitution R&D took place irrespective of the realization N^* and the goal to prevent substitution R&D could not be realized by overreporting – rendering overreporting useless. Second, the costs arising from the signal must be limited for both players: the upper bound of (29) and condition (30) imply that the low type's costs of overreporting do not exceed the gains. Similarly, if the high type's distortions from the pooling equilibrium are too costly (condition (36) is violated) then the pooling equilibrium ceases to exist since, in that case, the high type concedes to R&D activity. If any of these conditions is violated, the necessary signal introduces excessive distortions of supply and is too costly.

Finally, underreporting does not occur. This observation raises the question why, in the current model, anticipated future oil shortages do not raise current prices, thereby motivating oil suppliers to underreport. This result is due to the fact that storage cost are assumed to be prohibitive: it is well known that the marginal cost of storage reflects the inter-temporal price spread (see, e.g., Working (1949)) as long as demand for storage is positive. Prohibitive storage costs, in turn, decuple inter-temporal markets and market prices, thus eliminating incentives to misreport. In this sense, the model's setup is loaded in favor of overreporting. I do not, however, apologize for this bias. Including these incentives to underreport would add a simple mechanism at the considerable cost of further complication. The present paper, instead, focusses on modelling the less intuitive incentives to overreport.

Modelling framework. The analysis above relies on a set of assumptions that made the model tractable but require a brief discussion.

First, good N is supplied monopolistically. This assumption is crucial since it enables the exporter of good N to control the intertemporal distribution of aggregate reserves and thereby manipulate the importer's substitution R&D. The assumption can be read as a simplification for non-competitive supply in general, as in Pindyck (1978). Extensions to oligopolistic supply, however, should be possible. Thus, in the (natural) case of competition through quantities, the incentives for suppliers to prevent R&D and overreport are reduced but do not vanish, since oligopolists still partially internalize the incentives that operate on the industry-level.

Second, substitution R&D is a binary choice.[19] This is a convenient simplification but not a crucial assumption. A natural generalization would introduce the productivity B of the substitution technology in (4) as a continuous function of total R&D expenditure $a_1 \in \mathbb{R}_+$. 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 country O's incentives to overreport in order to discourage *marginal* substitution efforts and reduce the intensity of foreign competition in period two. Also, in a pooling equilibrium the signal may still be arbitrarily close to the low type's first best supply $n_t^* = \xi \bar{N}/2$, rendering negative signaling cost for the low type.

Third, there is only one importer of 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.[20] Consequently, no private enterprise can recoup the investment $a_1 = A$, which must therefore be financed publicly. Whenever many small countries import N, free-riding effects among these N-importers arise regarding R&D expenditures, thus harming the paper's mechanism. One may, however, conjecture that the paper's logic remains intact in a world where substitution technologies, once invented, deliver a flow of good N (as in the

[19] This assumption follows Dasgupta and Heal (1974), Deshmukh and Pliska (1983), Quyen (1988), and Barrett (2006).

[20] The range for N^* is $(3B + \sqrt{B} - 4, N_0)$ under full information (see the proof of (21) in the Appendix).

case of some renewable energies) or, in another scenario, where consumers choose between alternative durable equipment that affect future aggregate demand for N. In such cases, the returns to substitution R&D are appropriable and mitigate the free-riding problem.[21] The paper's key insight can be expected to carry over to such scenarios.

Fourth, there is no aggregate uncertainty about resources and outcomes of R&D. Under such additional uncertainty, the trade-off between country W's cost and benefits of substitution R&D and country O's prevention of R&D is based on expected utilities (affecting conditions (17), (22), and (24)). It appears unlikely that this change can overturn the qualitative results.

Fifth, oil is traded between two countries – instead of a generic profit-maximizing seller and a generic buyer. Adopting this standard framework instead would neglect the oil exporter's utility losses that arise from by her own signaling and the accompanying distortions of global oil supply.[22] Abstracting from these costs of overreport would bias the model – and load it to generate pooling equilibria.

Finally, the oil-exporter levies export taxes T_t^*. This additional policy tool tends to complicate the analysis. For a justification of this complication, recall that country W's benefit from R&D accrue mainly through a reduction of country O's market power in the oil-market at $t = 2$ (see also the discussion following equation (16)). A comprehensive analysis must therefore involve the prime tool through which country O exercises its market power in the foreign market. This tool is traditionally quantity control or, equivalently, export taxes.[23] More importantly, in absence of a meaningful tool to extract monopoly rents, it is *a priori* unclear which of the two types, O_H or O_L, loses more from country W's R&D and which of them, therefore, rather decides to prevent this R&D. With this question unanswered, an analysis that tries to assess which type imitates whom must necessarily remain shaky.

4.4 The Crude Oil Market

Motivated by rising concerns about energy security, this paper has developed a model to address the questions why, how, and under what conditions crude oil reserves may be overreported. It has shown that exporting countries indeed have motives to overreport and that they can credibly do so under rational expectations. The minimal conditions for overreporting are intuitive: substitution R&D must respond significantly to expected

[21] Part of the free-riding problem remains as non-investing agents gain from reduced prices of the conventional resource due to a drop in demand.

[22] Consumers' optimality condidtions imply $(c_{t,n}^* + 1)/(c_{t,n} + 1) = T_t^*$. This condition, together with (10) and market clearing ($c_{t,n}^* + c_{t,n} = \bar{n}_t$) determines consumption $c_{t,n}^{(*)}$. It is quick to check that under $n_1^* = \bar{n}_1 = n_P^e$ and $n_1^* = \bar{n}_1 = N^* - n_P^e$ as in Proposition 3, country O's consumption is optimal ($c_{1,n}^* = c_{2,n}^*$) only in knife-edge cases. Hence there are real losses from overreporting.

[23] Export taxes are also equivalent to import tariffs (see Helpman and Krugman (1989)).

future supply and supply itself needs to be non-competitive. This subsection briefly addresses the remaining of the initial questions: Can overreporting be refuted for today's oil market?

To answer this question the two key assumptions of the model are to be checked: a strong reaction of substitution R&D to expected future supply and supply needs to be non-competitive. Concerning the first condition, evidence suggests that substitution R&D indeed responds to shortages of the market. Figure 1 illustrates that non-oil energy R&D in IEA member countries and world oil prices comove in the period 1973-2006. In addition, current prices strongly correlate with price forecasts in the relevant period (see Lynch (2002) and IMF (2003)). Together, these observations imply a comovement between expected future supply and R&D activity. Of course, raw correlations do not imply causality. Yet, empirical studies show that energy saving R&D is indeed responsive to supply shortages (see Newell et al (1999) and Popp (2002)) so that the first of the necessary conditions seems to be satisfied. The second requirement of non-competitive oil markets may appear 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)). Yet, other empirical studies such as Griffin (1985) and Smith (2003), report strong coordination and cartel discipline of OPEC members and a significant shortage of contemporaneous supply. If the latter studies are to be believed, the present paper's two fundamental assumptions do hold.

Finally, Proposition 3 requires that the cost of the signal be limited. A thorough quantitative assessment of the likelihood of overreporting must clearly involve these costs. Within a first qualitative application of the theory, however, this requirement does not serve as a meaningful criterion since, by the Corollary to Proposition 3, there is no positive lower bound on the cost 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 to the policymaker the most relevant – of the initial questions remains unanswered.[24] This observation calls for a thorough quantitative research of the issue, which may at the same time answer the question whether the interpretation of OPEC as a cartel of supply is to be extended to a cartel of information.

[24] Recall that credible overreporting can be refuted, while it cannot be proven before private information is revealed. Under credible overreporting the probability that reserves are high (π from (1)) are positive.

5 Conclusion

Concerns are rising about the supply security of crude oil. In addition to geological and political risks, some experts point at overreporting as one – possibly significant – source of uncertainty, claiming that crude oil reserves are much lower than commonly assumed. While many market experts disagree with the assertions of the "Peak Oilists," the economic consequences of potential supply disruptions could arguably be dire.

Motivated by these observations, the present paper has provided a simple but suggestive model for the analysis of the exporters' costs and incentives to overreport crude oil reserves. The key assumptions of the theory are, first, market power of oil suppliers, second, the possibility to engage in R&D to substitute oil, and third, private information about remaining oil reserves. It has been shown that, within this framework, the one 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 to own high reserves at negligible or even negative costs. Finally, conditional on the reported realizations of reserves, supply is partly delayed under successful overreporting.

The standard discourse on security of crude oil supply involves a number of technical and political aspects, among which overreporting ranks rather low. It is therefore appropriate to briefly consider the broader picture, which the economics of natural resources sketches. This general image is very comforting when uncertainties are absent: the continued exhaustion of a natural resource raises the returns to resource-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 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 under uncertainty, when (information) shocks cause ex-post inefficiencies. Since such efficiency losses typically grow with the degree of uncertainty, the relevant issue is to identify the sources and magnitudes of uncertainties. Traditionally, geological and political unknowns are considered as the major sources of uncertainty. Today, advanced exploration technology allows quite accurate assessments of the size of oil fields and tough surprises due to technological drawbacks are argued to be unlikely (see e.g. Cuddington and Moss (2001)). Thus, man-made or on-the-ground uncertainty appears to be the remaining source of uncertainty. Within that category, political instability is usually focused on – in particular that arising from the geopolitical situation in the Middle East (see, e.g., IEA (2005)). Yet, if alleged overreporting of about a quarter of world crude oil reserves cannot be refuted, then the resulting supply shocks could prove most damaging. Therefore, at last, overreporting may deserve a bit more attention after all.

A Appendix

Proof of (21). For $n_2 = 0$ use u_t^* from (13) 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 (10) with $b_1 = 0$ was used in the second step. Use (10) with $b_2 = B$ and (13) 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 (10) 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 (21).

Consider now $N^* < N_o$ as long as O exports N (i.e. $c_{n,2}^* < n_2^*$) (13) 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 (26) by $\Delta(N^*, m)$. Now, by the definition (22) of $V^*(n_1^*, n_2^*, 0)$ and concavity of u_t^* (14) the partial derivative $\partial_m \Delta$ is negative

$$\partial_m \Delta = -\left[V_1^*(m, N^* - m, 0) - V_2^*(m, N^* - m, 0)\right] < 0 \tag{39}$$

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

(i) Check with (22) that

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

Further, $\Delta(N^*, N^*/2) < 0$ holds by optimality (15) so that there is a solution to (26) with $m < N^*/2$. By $\partial_m \Delta < 0$ this solution is unique.

(ii) The definition (22) of N_0 implies that $\Delta(N^*, N^* - n_P^*) > 0$ if and only if $N^* \in (N_0, 2n_P^*]$ and the claim follows with $\Delta(N_0, N_0 - n_P^*) = 0$ and (39).

(iii) $V^*(n_C^*, N^* - n_C^*, 0) > V^*(n_C^*, N^* - n_C^*, B)$ and (26) imply

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

By the concavity of u_t^* (14) and $m < N^*/2$ this shows the statement.

(iv) Compute

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

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. (14). Thus, with (39) the derivative

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

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 $\lim_{N^* \to 0} \Delta(N^*, 0) = 0$ and (iv). ■

Proof of Proposition 3. The proof consists of two parts: Part (i) shows that any belief system μ that satisfies $\mu(n_P^e) = \pi$ and A(iii) - A(v) sustains the strategies (37) as part of the SPBE in pure strategies. This shows existence. Part (ii) shows that any SPBE in pure strategies with μ satisfying A(i) - A(v) includes the strategies (37).

Part (i). Check **E(iii)**. The decision rule (25) grants W's individual optimality and, by construction of n_P^e via (24), induces $a_1^e(n_P^e) = 0$.

Check **E(ii)**. A(i) is void under (37) and $\mu(n_P^e) = \pi$ grants Bayesian updating. Notice also that A(iii) is void since its condition does not hold by (29) and (30).

Check **E(i)**. Optimality of n_P^e for O_H. Assume O_H deviates to $\tilde{n} < n_P^e$ so that W's optimal off-equilibrium strategy induces $\tilde{b} \in \{0, B\}$. In either case

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

holds by $\tilde{n} < n_P^e < \bar{N}/2$ and (14). Such a deviation $\tilde{n}$ cannot be optimal. If, instead, O_H deviates to $\tilde{n} \in (n_P^e, \bar{N} - n_P^*]$, condition (29) implies $n_P^e < \tilde{n} < \bar{N}/2$ and (30), (36), and A(iv) lead to $\mu(\tilde{n}) = \pi$. Hence, by $n_P^e < \tilde{n}$ and (24), $a_1^e(\tilde{n}) = A$ holds. But $n_P^e \in (m(\bar{N}), M(\bar{N}))$ from (36) implies

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

If, finally, O_H deviates to $\tilde{n} > \bar{N} - n_P^*$ (25) implies $a_1^e(\tilde{n}) = A$ for any $\mu \in [0,1]$, implying $\tilde{b} = B$. This implies

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

(the last inequality follows by (29) and (36)). Hence, O_H optimally plays $n_{1,H}^* = n_P^e$.

Optimality of n_P^e for O_L. If O_L deviates to $\tilde{n} \in (n_P^e, \bar{N} - n_P^*]$, condition (29) implies $n_P^e < \tilde{n} < \bar{N}/2$ and (30), (36), and A(iv) lead to $\mu(\tilde{n}) = \pi$ so that, finally, (24) is violated and W plays $a_1^e(\tilde{n}) = A$. If, instead, O_L deviates to $\tilde{n} > \bar{N} - n_P^*$ W's optimal strategy is $a_1^e(\tilde{n}) = A$ regardless of its beliefs. Thus, any deviation $\tilde{n} > n_P^e$ implies $\tilde{b} = B$, while

$$V^*(\tilde{n}, \xi\bar{N} - \tilde{n}, B) \leq V^*(n_{1,L}^*, \xi\bar{N} - n_{1,L}^*, b_{2,L}^*) < V^*(n_P^e, \xi\bar{N} - n_P^e, 0) \tag{40}$$

holds. The second inequality holds since either $b_{2,L}^* = B$ and $m(\xi\bar{N}) < m(\bar{N}) < n_P^e$ by Claim 1 (iv) and condition (36), or else $b_{2,L}^* = 0$ and (33) and (35) imply $n_P^e > \xi\bar{N} - n_P^*$ while (29), (33), and (34) imply $n_P^e < \bar{N} - n_P^* < n_P^*$.

Next, if O_L deviates to $\tilde{n} < n_P^e$ with $\left|\xi\bar{N}/2 - \tilde{n}\right| < \left|\xi\bar{N}/2 - n_P^e\right|$, then $\tilde{n} < n_P^e < \bar{N}/2$ and A(v) imply $\mu(\tilde{n}) = 0$. Thus, (40) applies again. Finally, if O_L deviates to $\tilde{n} < n_P^e$ with $\left|\xi\bar{N}/2 - \tilde{n}\right| \geq \left|\xi\bar{N}/2 - n_P^e\right|$ O_L's total utility decreases under the deviation. Hence, O_L optimal strategy is $n_{1,L}^* = n_P^e$.

Part (ii). Assume there is an equilibrium with $n_{1,H}^e \neq n_P^e$. If $a_1^e\left(n_{1,H}^e\right) = A$ in this equilibrium then

$$V\left(n_P^e, \bar{N} - n_P^e, 0\right) > V\left(n_{1,H}^e, \bar{N} - n_{1,H}^e, B\right)$$

by (36). Thus, A(iv) implies that $a_1^e\left(n_P^e\right) = 0$ and O's deviation to $\tilde{n} = n_P^e$ increases its payoff.

Hence, $a_1^e\left(n_{1,H}^e\right) = 0$ must prevail. In this case $n_{1,H}^e > \bar{N} - n_P^*$ can be ruled out since (24) would be violated. Also, $n_{1,H}^e < n_{1,P}^e$ can be ruled out since (14) and $n_{1,P}^e < \bar{N}/2$ imply

$$V\left(n_P^e, \bar{N} - n_P^e, 0\right) > V\left(n_{1,H}^e, \bar{N} - n_{1,H}^e, 0\right)$$

so that A(iv) applies and a deviation to $\tilde{n} = n_P^e$ would increase O's payoff. Hence, $n_{1,H}^e \in (n_P^e, \bar{N} - n_P^*)$ must hold. It is straight forward to check that in this case

$$V\left(n_{1,H}^e, \bar{N} - n_{1,H}^e, 0\right) > V\left(n_{1,L}^*, \bar{N} - n_{1,L}^*, b_{1,L}^*\right)$$

holds so that O_L pools to O_H's strategy $n_{1,H}^e$. By A(ii) this implies $\mu(n_{1,H}^e) = \pi$ and (24) is violated. This shows that $n_{1,H}^e = n_P^e$. As in Part (i) this implies that $n_{1,P}^e = n_P^e$ and proves the claim. ■

References

Almoguera, P. A. and A. M. Herrera (2007): "Testing for the Cartel in OPEC:. Noncooperative Collusion or Just Noncooperative?," *mimeo* Michigan State University.

Arrow, K.J. and S. Chang (1982): "Optimal Pricing, Use, and Exploration of Uncertain Natural Resource Stocks," *Journal of Environmental Economics and Management*, 9(1), 1–10.

Barrett, S. (2006): "Climate Treaties and "Breakthrough" Technologies," *American Economic Review*, 96(2), 23–25.

Bentley, R. W. (2002): "Global Oil and Gas Depletion: an Overview," *Energy Policy*, 30, 189–205.

Cho, I.-K. and D. Kreps (1987): "Signaling Games and Stable Equilibria," *Quarterly Journal of Economics*, Vol. 102 (2), 179–221.

Burt, O. R. and R. G. Cummings (1970): "Production and Investment in Natural Resource Industries," *American Economic Review*, 60(4), 576–590.

Campbell, C. J. and Jean H. Laherrère (1998): "The End of Cheap Oil?," *Scientific American*, March, 60–65.

Cuddington, J. T. and D. L. Moss (2001): "Technological Change, Depletion, and the U.S. Petroleum Industry," *American Economic Review*, 91(4), 1135–1148.

Dasgupta, P. and Heal, G. (1974): "The Optimal Depletion of Exhaustible Resources." *The Review of Economic Studies, symposium on the economics of exhaustible resources*, 3–28.

Davidson, R. (1978): "Optimal Depletion of an Exhaustible Resource with Research and Development towards an Alternative Technology," *Review of Economic Studies*, 45(2), 355–367.

Deshmukh, S. D. and Pliska S. R. (1983): "Optimal Consumption of a Nonrenewable Resource with Stochastic Discoveries and a Random Environment," *Review of Economic Studies*, 50(3), 543–554.

EWG (2007): "Crude Oil, the Supply Outlook", *The Energy Watch Group*, http://www.energywatchgroup.de/

Gaudet G., P. Lasserre, and N. Van Long (1995): "Optimal Resource Royalties with Unknown and Temporally Independent Extraction Cost Structures," *International Economic Review*, 36(3), 715–749.

GAUDET G. AND M. MOREAUX (1990): "Price versus Quantity Rules in Dynamic Competition: The Case of Nonrenewable Natural Resources," *International Economic Review*, 31(3), 639–650.

GERLAGH, R. AND M. LISKI (2007): "Strategic Oil Dependence," HECER discussion paper no. 165.

GRIFFIN J. M. (1985): "OPEC Behavior: A Test of Alternative Hypotheses," *American Economic Review*, 75(5), 954–963.

GRYGLEWICZ, S. (2009): "Signaling in a Stochastic Environment with an Application to Dynamic Limit Pricing," mimeo, Tilburg University

HELPMAN, E. AND P. KRUGMAN (1989): "Trade Policy and Market Structure," Cambridge, MA, MIT Press, 1989.

HOTELLING, H. (1931): "The Economics of Exhaustible Resources," *Journal of Political Economy*, 39, 137–175.

IEA (2005): "World Energy Outlook, Middle East and North Africa Insights" *International Energy Agency*, Paris, France.

IMF (2003): "World Economic Outlook, September 2003," *International Monetary Fund*, Washington, D.C.

ITPOES (2008): "The Oil Crunch, Securing the UK's energy future" *UK Industry Taskforce on Peak Oil and Energy Security*, October 29, 2008.

KAYA, A. (2009): "Repeated Signaling Games," *Games and Economic Behavior*, (forthcoming)

LIN, C.-Y. C. (2007): "An Empirical Dynamic Model of OPEC and Non-OPEC," *Working paper. University of California at Davis.*

LOVINS, A. B., E. K. DATTA, O.-E. BUSTNES, J. G. KOOMEY, AND N. J. GLASGOW (2005): "Winning the Oil End Game," *Rocky Mountain Institute, Colorado, USA.*

LYNCH, M. C. (2002): "Forecasting oil supply: theory and practice," *Quarterly Review of Economics and Finance*, 42, 373–389.

NEWELL, R, A. JAFFE, AND R. STAVINS (1999): "The Induced Innovation Hypothesis and Energy-Saving Technological Change," *Quarterly Journal of Economics*, 114, 907–940.

OSMUNDSEN, P. (1998): "Dynamic Taxation of Non-Renewable Natural Resources under Asymmetric informationabout reserves," *Canadian Journal of Economics*, 31(4), 933–951.

PINDYCK, R. S. (1978): "Gains to Producers from the Cartelization of Exhaustible Resources," *Review of Economics and Statistics*, 60(2), 238–251.

POPP, D. (2002): "Induced Innovation and Energy Prices," *American Economic Review*, 92(1), 160–180.

QUYEN, N. V. (1988): "The Optimal Depletion and Exploration of a Nonrenewable Resource," *Econometrica*, 56(6), 1467–1471.

SALANT, S. W. (1976): "Exhaustible Resources and Industrial Structure: A Nash-Counot Approach to the World Oil Market," *Journal of Political Economy*, 84(5), 1079–1094.

SMITH, J. L. (2003): "Inscrutable OPEC? Behavioral Tests of the Cartel Hypothesis," *mimeo*, Southern Methodist University.

SPENCE, M. (1973): "Job Market Signaling," *Quarterly Journal of Economics*, Vol. 87 (3), 355–374.

STIGLITZ, J. E. (1976): "Monopoly and the Rate of Extraction of Exhaustible Resources," *American Economic Review*, 66(4), 655–661.

TAHVONEN, O. AND S. SALO (2001): "Economic growth and transitions between renewable and nonrenewable energy resources," *European Economic Review*, 45, 1379–1398.

THE ECONOMIST: "Steady as She Goes," April 20, 2006.

THE WALL STREET JOURNAL: "Fear of Thighter Oil Supply May Further Rattle Market," May 22, 2008.

TSUR, Y. AND A. ZEMEL (2003): "Optimal transition to backstop substitutes for nonrenewable resources" *Journal of Economic Dynamics and Control*, 27, 551–572.

ULPH, A. M. AND G. M. FOLIE (1980): "Exhaustible Resources and Cartels: An Intertemporal Nash-Cournot Model" *Canadian Journal of Economics*, 13(4), 645–658.

WORKING, H. (1949): "The Theory of Price of Storage" *American Economic Review*, 39(6), 1254–1262.

Swiss National Bank Working Papers published since 2004:

2004-1 Samuel Reynard: Financial Market Participation and the Apparent Instability of Money Demand

2004-2 Urs W. Birchler and Diana Hancock: What Does the Yield on Subordinated Bank Debt Measure?

2005-1 Hasan Bakhshi, Hashmat Khan and Barbara Rudolf: The Phillips curve under state-dependent pricing

2005-2 Andreas M. Fischer: On the Inadequacy of Newswire Reports for Empirical Research on Foreign Exchange Interventions

2006-1 Andreas M. Fischer: Measuring Income Elasticity for Swiss Money Demand: What do the Cantons say about Financial Innovation?

2006-2 Charlotte Christiansen and Angelo Ranaldo: Realized Bond-Stock Correlation: Macroeconomic Announcement Effects

2006-3 Martin Brown and Christian Zehnder: Credit Reporting, Relationship Banking, and Loan Repayment

2006-4 Hansjörg Lehmann and Michael Manz: The Exposure of Swiss Banks to Macroeconomic Shocks – an Empirical Investigation

2006-5 Katrin Assenmacher-Wesche and Stefan Gerlach: Money Growth, Output Gaps and Inflation at Low and High Frequency: Spectral Estimates for Switzerland

2006-6 Marlene Amstad and Andreas M. Fischer: Time-Varying Pass-Through from Import Prices to Consumer Prices: Evidence from an Event Study with Real-Time Data

2006-7 Samuel Reynard: Money and the Great Disinflation

2006-8 Urs W. Birchler and Matteo Facchinetti: Can bank supervisors rely on market data? A critical assessment from a Swiss perspective

2006-9 Petra Gerlach-Kristen: A Two-Pillar Phillips Curve for Switzerland

2006-10 Kevin J. Fox and Mathias Zurlinden: On Understanding Sources of Growth and Output Gaps for Switzerland

2006-11 Angelo Ranaldo: Intraday Market Dynamics Around Public Information Arrivals

2007-1 Andreas M. Fischer, Gulzina Isakova and Ulan Termechikov: Do FX traders in Bishkek have similar perceptions to their London colleagues? Survey evidence of market practitioners' views

2007-2 Ibrahim Chowdhury and Andreas Schabert: Federal Reserve Policy viewed through a Money Supply Lens

2007-3 Angelo Ranaldo: Segmentation and Time-of-Day Patterns in Foreign Exchange Markets

2007-4 Jürg M. Blum: Why 'Basel II' May Need a Leverage Ratio Restriction

2007-5 Samuel Reynard: Maintaining Low Inflation: Money, Interest Rates, and Policy Stance

2007-6 Rina Rosenblatt-Wisch: Loss Aversion in Aggregate Macroeconomic Time Series

2007-7 Martin Brown, Maria Rueda Maurer, Tamara Pak and Nurlanbek Tynaev: Banking Sector Reform and Interest Rates in Transition Economies: Bank-Level Evidence from Kyrgyzstan

2007-8 Hans-Jürg Büttler: An Orthogonal Polynomial Approach to Estimate the Term Structure of Interest Rates

2007-9 Raphael Auer: The Colonial Origins Of Comparative Development: Comment. A Solution to the Settler Mortality Debate

2007-10 Franziska Bignasca and Enzo Rossi: Applying the Hirose-Kamada filter to Swiss data: Output gap and exchange rate pass-through estimates

2007-11 Angelo Ranaldo and Enzo Rossi: The reaction of asset markets to Swiss National Bank communication

2007-12 Lukas Burkhard and Andreas M. Fischer: Communicating Policy Options at the Zero Bound

2007-13 Katrin Assenmacher-Wesche, Stefan Gerlach, and Toshitaka Sekine: Monetary Factors and Inflation in Japan

2007-14 Jean-Marc Natal and Nicolas Stoffels: Globalization, markups and the natural rate of interest

2007-15 Martin Brown, Tullio Jappelli and Marco Pagano: Information Sharing and Credit: Firm-Level Evidence from Transition Countries

2007-16 Andreas M. Fischer, Matthias Lutz and Manuel Wälti: Who Prices Locally? Survey Evidence of Swiss Exporters

2007-17 Angelo Ranaldo and Paul Söderlind: Safe Haven Currencies

2008-1 Martin Brown and Christian Zehnder: The Emergence of Information Sharing in Credit Markets

2008-2 Yvan Lengwiler and Carlos Lenz: Intelligible Factors for the Yield Curve

2008-3 Katrin Assenmacher-Wesche and M. Hashem Pesaran: Forecasting the Swiss Economy Using VECX* Models: An Exercise in Forecast Combination Across Models and Observation Windows

2008-4 Maria Clara Rueda Maurer: Foreign bank entry, institutional development and credit access: firm-level evidence from 22 transition countries

2008-5 Marlene Amstad and Andreas M. Fischer: Are Weekly Inflation Forecasts Informative?

2008-6 Raphael Auer and Thomas Chaney: Cost Pass Through in a Competitive Model of Pricing-to-Market

2008-7 Martin Brown, Armin Falk and Ernst Fehr: Competition and Relational Contracts: The Role of Unemployment as a Disciplinary Device

2008-8 Raphael Auer: The Colonial and Geographic Origins of Comparative Development

2008-9 Andreas M. Fischer and Angelo Ranaldo: Does FOMC News Increase Global FX Trading?

2008-10 Charlotte Christiansen and Angelo Ranaldo: Extreme Coexceedances in New EU Member States’ Stock Markets

2008-11 Barbara Rudolf and Mathias Zurlinden: Measuring capital stocks and capital services in Switzerland

2008-12 Philip Sauré: How to Use Industrial Policy to Sustain Trade Agreements

2008-13 Thomas Bolli and Mathias Zurlinden: Measuring growth of labour quality and the quality-adjusted unemployment rate in Switzerland

2008-14 Samuel Reynard: What Drives the Swiss Franc?

2008-15 Daniel Kaufmann: Price-Setting Behaviour in Switzerland – Evidence from CPI Micro Data

2008-16 Katrin Assenmacher-Wesche and Stefan Gerlach: Financial Structure and the Impact of Monetary Policy on Asset Prices

2008-17 Ernst Fehr, Martin Brown and Christian Zehnder: On Reputation: A Microfoundation of Contract Enforcement and Price Rigidity

2008-18 Raphael Auer and Andreas M. Fischer: The Effect of Low-Wage Import Competition on U.S. Inflationary Pressure

2008-19 Christian Beer, Steven Ongena and Marcel Peter: Borrowing in Foreign Currency: Austrian Households as Carry Traders

2009-1 Thomas Bolli and Mathias Zurlinden: Measurement of labor quality growth caused by unobservable characteristics

2009-2 Martin Brown, Steven Ongena and Pinar Yeşin: Foreign Currency Borrowing by Small Firms

2009-3 Matteo Bonato, Massimiliano Caporin and Angelo Ranaldo: Forecasting realized (co)variances with a block structure Wishart autoregressive model

2009-4 Paul Söderlind: Inflation Risk Premia and Survey Evidence on Macroeconomic Uncertainty

2009-5 Christian Hott: Explaining House Price Fluctuations

2009-6 Sarah M. Lein and Eva Köberl: Capacity Utilisation, Constraints and Price Adjustments under the Microscope

2009-7 Philipp Haene and Andy Sturm: Optimal Central Counterparty Risk Management

2009-8 Christian Hott: Banks and Real Estate Prices

2009-9 Terhi Jokipii and Alistair Milne: Bank Capital Buffer and Risk Adjustment Decisions

2009-10 Philip Sauré: Bounded Love of Variety and Patterns of Trade

2009-11 Nicole Allenspach: Banking and Transparency: Is More Information Always Better?

2009-12 Philip Sauré and Hosny Zoabi: Effects of Trade on Female Labor Force Participation

2009-13 Barbara Rudolf and Mathias Zurlinden: Productivity and economic growth in Switzerland 1991-2005

2009-14 Sébastien Kraenzlin and Martin Schlegel: Bidding Behavior in the SNB's Repo Auctions

2009-15 Martin Schlegel and Sébastien Kraenzlin: Demand for Reserves and the Central Bank's Management of Interest Rates

2009-16 Carlos Lenz and Marcel Savioz: Monetary determinants of the Swiss franc

2010-1 Charlotte Christiansen, Angelo Ranaldo and Paul Söderlind: The Time-Varying Systematic Risk of Carry Trade Strategies

2010-2 Daniel Kaufmann: The Timing of Price Changes and the Role of Heterogeneity

2010-3 Loriano Mancini, Angelo Ranaldo and Jan Wrampelmeyer: Liquidity in the Foreign Exchange Market: Measurement, Commonality, and Risk Premiums

2010-4 Samuel Reynard and Andreas Schabert: Modeling Monetary Policy

2010-5 Pierre Monnin and Terhi Jokipii: The Impact of Banking Sector Stability on the Real Economy

2010-6 Sébastien Kraenzlin and Thomas Nellen: Daytime is money

2010-7 Philip Sauré: Overreporting Oil Reserves

Swiss National Bank Working Papers are also available at www.snb.ch, section Publications/Research
Subscriptions or individual issues can be ordered at Swiss National Bank, Fraumünsterstrasse 8, CH-8022 Zurich,
fax +41 44 631 81 14, E-mail library@snb.ch