Production sharing agreements versus concession contracts

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Abstract

Governments choose among many contracts to delegate the exploration and the extraction of oil. The contractual form changes between and within countries but the most common contracts are concession contracts and production sharing agreement (PSA). This paper compares the tax revenue and the firm’s incentive to explore and extract under these two contracts. We also investigate the effect of information asymmetry on costs on the optimal contract. The concession contract is simplified to a royalty rate and the PSA to a two-variable contract, i.e., the share of the extraction allocated to the costs reimbursement and the one the firm receives after this reimbursement. We show that without information asymmetry, PSAs always generate higher tax revenue than concession contracts. A large share of the extraction should be allocated to the cost reimbursement to promote the exploration and to avoid any productive distortions. In fact, under PSA, the government is able to capture almost the entire revenue. However, if the government does not know the firm’s costs, the government only captures a small share of the revenue under PSAs since the cost recovery mechanism increases the firm’s incentive to overvalue its costs. Under a concession contract, only one unique contract, independent from the firm’s efficiency, can be implemented.

1 Introduction

In 2012, Exxon Mobil’s annual profit reached $44.9 billion, nevertheless, a large majority of countries where it has established refineries suffers from poor economic growth, low standards of living and inequality. Hydrocarbons generate substantial revenues; in producing countries, especially in developing countries, a large share of tax receipts comes from their production. For instance, in 2011, the five major integrated oil companies reported an income equivalent to 10% of U.S GDP. Furthermore, from 2000 to 2007, at least 70% of the government’s revenue in Algeria, Libya or Angola came from hydrocarbons. In the
The central objective in designing petroleum fiscal regimes is easily stated. It is to acquire for the state in whose legal territory the resources in question lie, a fair share of the wealth accruing from the extraction of that resource, whilst encouraging investors to ensure optimal economic recovery of the hydrocarbon resources. How to achieve this balance is a subject of enduring controversy.

Concession contracts used to be the rule to delegate the exploration and the extraction of hydrocarbons. However, following the independence of former colonies, they were more and more criticized. As a result, new agreements under which the government remains the owner of the resource emerged. Iran has experienced a wide variety of contractual regimes and perfectly illustrates how petroleum legislation is influenced by political and efficiency concerns. The first oil discoveries in the early 1900s were exploited through concession contracts which were very favorable to international oil companies. The first petroleum law was created 50 years later to attract investments, to increase the government’s revenue and to ensure its control on the operations. At this time, production sharing agreements (PSAs) and joint ventures with the government participation were introduced. However, shortly before, the Islamic revolution, the previous contracts were banned and only service contracts were permitted. Then, only pure service contracts such as buy-back agreements could be used. Nevertheless, in May 2013, to favor investments, Iran reintroduces PSAs for developing the offshore Farzad B gas field in the Farsi block in the Persian Gulf.

This paper deals with PSA, since starting from the 1960s, many developing countries have switched from concession contracts to PSA. In 1994, Russia signs its first PSA and has continued to use this contract so far. This contractual agreement emerged to fill the gap between concession contracts that give the resource sovereignty to the firm and the establishment of national oil companies that requires some technical knowledge. PSAs were first implemented in Indonesia and today, more than 10% of the oil and gas production is done through such agreements. Furthermore, nearly half of the countries with petroleum potential have a tax system based on PSAs. Under PSAs, the firm commits to undertake and finance at its own risk the exploration and the extraction activities. In compensation, it recovers its costs by appropriating a share, not exceeding a certain percentage of the production. The share of the production is valued using the oil price and this payment is called the cost oil whereas the maximum value that can be allocated to the cost is the cost stop. The costs not recoverable in a year are recovered the following years using the same principle. The remaining production is called the profit oil and is shared with the government according to a rule defined by the contract. Other instruments (bonuses and
royalties) common in concession contracts can be used. Despite their development, far too little attention has been paid to PSAs. Most studies on PSAs have been carried out in law literature and using economic approach, mainly simulation models have been developed. The existing literature highlights different facts.

First, there is a wide variety of PSAs as shown by Bindemann (1999) which studies 268 PSAs signed in 74 countries from 1966 to 1998. A large majority does not include royalties and the level at which the cost stop is set changes between and within countries. Furthermore, the way the profit oil is shared changes across the oil fields.

Then, the cost stop is recognized as an instrument to promote the investments (Ashong (2011) and Yusgiantoro and Hsiao (1993)) but the use of profit oil sliding scale is controversial. Allowing the government’s takes to increase in case of high prices or large discovery deters renegotiation (Merklein (2010), Isenunwa and Uzoalor (2011) and Hampson et al. (1991)). However, under price uncertainty, such mechanism may distort the investments (Blake and Roberts (2006)). According to Johnson (1981), the government should receive a low share of the profit oil to promote the exploration and compensate with a resource rent tax. As Pongsiri (2004) and Nurakhmet (1993), he also underlines the need for the government to have a priori knowledge on the field to define the optimal contract.

Finally, several papers show that the government’s take is the higher under PSAs than under concession contracts (Johnston (1994), Gaspar Ravagnani et al. (2012) and Dongkun and Na (2010)).

One major issue in the taxation theory is the information asymmetry between taxpayers’ and tax collectors, especially in developing countries (Gordon and Li (2009) and Laffont (1998)). This issue is even more relevant in the petroleum sector. Indeed, oil companies usually have more information on the size of the stock or on the technology used to foster and extract resources (Garnaut and Ross (1975), Boadway and Keen (2009), Daniel et al. (2010), Aghion and Quesada (2009)). Gaudet et al. (1995) and Osmundsen (1995) were the first to propose a theoretical model to investigate the effect of information asymmetry on costs between a government and an oil company. Both study a two period model with no exploration. While Gaudet et al. (1995) investigates the effect of the resource constraint on the optimal contracts, Osmundsen (1998) studies how the effect of the stock on the extraction costs affect the contracts. Hung et al. (2006) relaxe the two period assumptions and argue that asymmetric information increases the contract duration and decreases the scarcity rent.

In the present paper, we assume that the government cannot impose the extraction and the exploration to the firm. It only defines the taxation scheme and leave to the firm the exploration and extraction decisions. We compare in a theoretical model: concession contracts and PSAs. We use as a benchmark a contract were the government receives a fix
payment and imposes the exploration and extraction levels. We compare those contracts in terms of tax revenue and exploration and extraction levels. In this paper we have both a normative and a positive approach. Indeed, taking for granted the contract (fix payment, concession contract or PSA), we define the level of taxation that maximizes the tax revenue. Two scenarios are investigated: one where the information is symmetric and another one where the firm has private information on the extraction costs. The primer objective is to define the optimal level of taxation for each type of agreements and determine how information asymmetry affect the contract and the firm’s strategy. Our contribution is threefold, first we contribute to the literature on PSA by proposing a theoretical model. Indeed, most of the studies uses simulation to study this type of contract whereas we define the firm’s incentive to explore and extract under PSA. We also determine the level of production allocated to the cost reimbursement and the profit oil split that maximize the tax revenue. Then, we contribute to the contract theory literature by studying a PSA. More precisely, we study how the cost reimbursement mechanism included under PSA affects the firm’s incentive to reveal its information. Finally, we contribute to the literature on petroleum taxation with information asymmetries since we introduce new contractual forms and exploration. We also consider that the firm freely chooses the exploration and the extraction levels.

The present paper is structured as follows. Section 2 presents the general setting. Section 3 defines and compares the optimal PSAs and concession contracts under symmetric information. Section 4 repeats the exercise assuming information asymmetry on the firm’s extraction cost. The results are discussed in Section 5. The appendices are given at the end of the paper and include some simulations tables.

2 General settings

There is a stock of resources in ground and to exploit this resource, an exploration process is needed. Before exploration, the size of the resource in ground \( R \) is known. The exploration process can be successful or not and is simplified to a costly exploration effort \( e \). The exploration costs \( c_e(e) \) and the probability to discover \( \rho(e) \) increase with the exploration effort. Except from the resource in ground, there is no resources available, the extraction \( q < R \) only starts if a discovery occurs. The extraction costs \( c_p(q, \theta) \) increase with the quantity extracted and an efficiency parameter \( \theta \). In addition, the size of the discovery is assumed to be high enough for the extraction level to be unconstrained\(^1\). We also consider that the size of the discovery is independent from the exploration effort. Thus, the probability to discover is endogenous but size of the resource is exogenous. For convenience, the following specifications are used:

\(^{1}\)We relax this assumption in the appendices in the most simple scenario (symmetric information).
\[ e \in [0, +\infty], \quad \rho(e) = \frac{e}{1+e}, \quad \rho(0) = 0, \quad \rho'(e) > 0, \quad \rho''(e) < 0 \text{ and } \lim_{e \to +\infty} \rho(e) = 1; \]
\[ c_e(e) = e, \quad c'_e(e) > 0, \quad c_p(q, \theta) = \theta q + \frac{q^2}{2} \text{ with } \theta > 0, \quad c'_p(q, \theta) > 0, \quad c''_p(q, \theta) > 0. \]

We assume no fixed cost and we do not introduce the stock of resource in the extraction cost, indeed, since only one extraction period is considered, introducing the stock is not relevant. We use the same extraction cost function as in Gaudet et al. (1995). The extraction costs are convex since extracting high quantity means going deeper in ground. The probability to discover increases with the exploration effort but at a decreasing rate. Indeed, if the exploration costs are already high, increasing further the spending only slightly increases the probability to discover. The convexity of the extraction costs and the concavity of the probability function insure that the optimization problem is convex without taxation. Those specifications are used to keep things tractable, nevertheless, along the paper, we will discuss how these specifications affect our results.

\( \theta \), reflects the extraction efficiency, the lower \( \theta \) is, the more efficient the firm is. This parameter can be subject to information asymmetry and is such that \( \theta < p \) which implies that without taxation, the extraction is positive. In addition, the price of the resource \( p \) is not affected by the extraction level. As a particular oilfield is studied, this assumption seems reasonable. It is the oil market price; neither the government nor the firm can influence this price.

In this paper limited liability constraints are not introduced. However, the firm only accepts the contract if its expected payoff is greater than its outside opportunity which is normalized to zero.

### 3 Symmetric information

#### 3.1 No taxation

The firm chooses the exploration effort and the extraction level to maximize its payoff.

\[
\max_{q,e} U_{NT}^{F}(e, q) = -c_e(e) + \rho(e) [pq - c_p(q, \theta)]
\]  

Solving this problem gives \( q^*(p, \theta) \) and \( e^*(p, \theta) \). An increase in the oil price or an improvement in the extraction efficiency increase the exploration and the extraction. This benchmark allows to determine the inefficiencies induced by the taxation scheme (tax neutrality). Indeed, the revenue the firm gets without taxation is the maximum revenue that can be generated for a given field.

By proposing a contract that specifies the exploration, the extraction and a monetary transfer, the government is able to capture the entire revenue. This contract is such that
the firm receives the revenue net of costs and pays a fixed payment \((T)\) to the government. The government maximizes its payoff \((T)\) by setting the exploration and extraction levels to the same levels as without taxation: \(q^*(p, \theta)\) and \(e^*(p, \theta)\) and the monetary transfer \(T^*\) is set such that the firm gets an expected payoff equals to zero. If the government proposes a contract \(T^*\) and leaves to the firm the exploration and extraction decisions, the firm is indifferent between accepting and rejecting the contract. If the firm accepts the contract, it explores and extracts \(q^*(p, \theta)\) and \(e^*(p, \theta)\). The government capture the entire revenue and this gets the same payoff as an untaxed firm. Nevertheless, the present paper considers two other types of contracts where the exploration and the extraction is not imposed: a concession contract and a PSA. Indeed, these contracts are widely used in the gas and oil industry.

### 3.2 Concession contract:

The government proposes to the firm a concession contract simplified to a royalty rate \(\tau\). Depending on the royalty rate, the firm decides its exploration and extraction levels.

**Firm’s problem:**
The firm chooses the exploration and extraction levels that maximize its payoff:

\[
\max_{q, e} U_F^\tau(e, q, \tau) = -c_e(e) + \rho(e) [pq(1-\tau) - c_p(q, \theta)]
\]  

Solving this problem gives \(q^\tau(p, \theta, \tau)\) and \(e^\tau(p, \theta, \tau)\). The firm’s extraction and exploration levels are lower than without taxation. The royalty rate lowers the exploration and the extraction whereas the price and the efficiency increase them. The firm only accepts the contract if \(\tau < \tau^{\text{max}}(p, \theta)\).

**Government’s problem:**
Knowing the firm’s strategy, the government chooses the royalty rate \(\tau^*(p, \theta)\) that maximizes its payoff under the firm’s participation constraint \((PC_\tau)\). For simplicity, the arguments in the firm’s exploration and extraction strategy are dropped.

\[
\max_{\tau} U_G^\tau(\tau) = \rho(e^\tau) p \tau q^\tau
\]  

s.t \(\tau \leq \tau^{\text{max}}\) \((PC_\tau)\)

The government’s payoff strictly increases with the extraction and exploration levels. The government faces a trade off; by increasing the royalty rate it increases its share of the revenue but decreases the revenue itself and the probability it gets a revenue. An increase in the price or in the firm’s extraction efficiency increases the optimal royalty rate. Within our specifications, the government gets at most 50% of the revenue. The level of this
threshold depends on our specifications but it illustrates the fact when the government uses royalties it is unable to capture a high share of the revenue because of the distortions in the exploration and extraction levels.

3.3 Production sharing agreement:

The government proposes a PSA, if the firm accepts the contract, it chooses the exploration and extraction levels. The PSA is a two-variables contract \((\alpha, \beta)\).

\(\alpha \in [0, 1]\) is the share of the production that can be allocated to the costs reimbursement. The payment received for the cost reimbursement is the cost oil: \(CO = \text{Min} [\alpha pq, c_e(e) + c_p(q)]\) where \(\alpha pq\) is the cost stop (the maximum value that can be allocated to the cost reimbursement). The remaining revenue after the cost oil payment is the profit oil.

\(\beta \in [0, 1]\) is the share of profit oil left to the firm.

Depending on the contract and on the exploration and extraction levels induced by the contract itself, the costs may be entirely or partly reimbursed. We define:

\[
f(p, \theta, \alpha, e, q) = \alpha pq - c_e(e) - c_p(q, \theta)\quad (4)
\]

If \(f(\cdot)\geq 0\), the costs are lower than the cost stop, i.e, the costs are entirely reimbursed and this type of PSA is denoted \(PSA_1\). If \(f(\cdot) < 0\), the costs are higher than the cost stop, i.e, the costs are partly reimbursed and this type of PSA is denoted \(PSA_2\). If \(f(\cdot) = 0\), then the two types of PSA are similar. \(f(\cdot)\) defines the cost oil constraint (COC), depending on the sign of \(f(\cdot)\), one type of PSA applies.

For each type of PSAs, we define the firm’s exploration and extraction strategy. The government decides to entirely or partly reimbursed the costs depending on which optimal contract offers the highest tax revenue. This choice may depend on the exogenous parameters: \(p\) and \(\theta\).

Firm’s problem:

The firm receives if a discovery occurs the cost oil payment, i.e, the total cost or the cost stop and a share \(\beta\) of the remaining revenue (the profit oil).

\[
\max_{q,e} U^\text{psa}_F = - c_e(e) + \rho(e) [CO - c_p(q, \theta) + \beta (pq - CO)]
\]

with \(CO = \text{Min} [\alpha pq, c_e(e) + c_p(q, \theta)]\)

i) The costs are entirely reimbursed: \(PSA_1\)

If a discovery occurs, the firm gets its costs entirely reimbursed and receives a share \(\beta\) of the net revenue. This PSA is equivalent to a contract where firms pays a profit tax \(1 - \beta\)
and gets their exploration costs reimbursed if a discovery occurs.

\[
\max_{q,e} U_{\text{psa}}(e, q, \beta) = -c(e) + \rho(e) [c(e) + \beta(p - c(q, \theta) - c(e))]
\]

s.t \( f(p, \theta, \alpha, e, q) \geq 0 \) \quad (6)

Solving this problem gives \( q_{\text{psa}1}(p, \theta) = q^*(p, \theta) \) and \( e_{\text{psa}1}(p, \theta, \beta) \). The share of the profit oil left to the firm (\( \beta \)) has two effects on the exploration effort. On the one hand, the firm increases its exploration effort to increase the probability it gets a revenue (probability effect). On the other hand, the firm decreases the exploration effort and the exploration costs to increase the gain itself (costs effect). Within our specifications, the probability effect always dominates and an increase in the profit oil left to the firm increases the exploration effort.\(^2\)

The firm only accepts the contract if \( \beta > \beta_{\text{min}}(p, \theta) \). We define \( \alpha_{\text{min}}(p, \theta, \beta) \) such as \( f(p, \theta, \alpha_{\text{min}}, e_{\text{psa}1}, q_{\text{psa}1}) = 0 \), \( \alpha_{\text{min}} \) is the minimum share of the production that should be allocated to the cost reimbursement to ensure that the costs are fully reimbursed.

As compared to a simple profit tax, the extraction level is the same but the exploration effort is higher.

**Proposition 1** Under a PSA, if the costs are entirely reimbursed, the extraction level is the same as without taxation but the exploration effort is lower. Both the exploration and the extraction levels increase with the price and the firm’s efficiency. The firm increases its exploration effort as it receives a higher share of the profit oil (\( \beta \)). Except on the cost oil constraint, the share of the revenue allocated to the costs (\( \alpha \)) has no impact.

Considering that the government’s take is the royalty rate (\( \tau \)) under a concession contract and the share of the profit oil left to the government \( (1 - \beta) \) under a PSAs. For a given government’s take, we show in the appendices that:

**Lemma 1** For a given government’s take, the optimal exploration effort is higher under PSA than under concession contracts. The cost recovery mechanism promotes the exploration activities.

ii) The costs are party reimbursed: \( \text{PSA}_2 \)

The firm receives a share \( (\alpha + (1 - \alpha)\beta) \) of the revenue. Its payoff is:

\[
\max_{q,e} U_{\text{psa}2}(e, q, \alpha, \beta) = -c(e) + \rho(e) [(\alpha + (1 - \alpha)\beta)p - c_p(q, \theta)]
\]

s.t \( f(p, \theta, \alpha, e, q) < 0 \) \quad (8)

\(^2\)Using other specifications, the firm’s objective function may entail some convexity in \( e \) and may not be single peak. The exploration effort may be discontinuous in \( \beta \) and may increase in \( \beta \) (see appendices).
Solving this problem gives \( q_{psa2}(p, \theta, \beta, \alpha) \) and \( e_{psa2}(p, \theta, \beta, \alpha) \). The extraction level and the exploration effort increase with the share allocated to the costs (\( \alpha \)) and the share of the profit oil the firm receives (\( \beta \)). We define \( \alpha^{\text{max}}(p, \theta, \beta) \) such as \( f(p, \theta, \alpha, e_{psa2}, q_{psa2}) = 0 \), for \( \alpha < \alpha^{\text{max}}(p, \theta, \beta) \), the firm is able to choose \( q_{psa2}(p, \theta, \beta, \alpha) \) and \( e_{psa2}(p, \theta, \beta, \alpha) \). Comparing the two exploration and extraction strategies \((q_{psa1} = q^*, e_{psa1})\) and \((q_{psa2}, e_{psa2})\), we show in the appendices that:

**Lemma 2** *For a given contract \((\alpha, \beta)\), the firm can never choose between the two strategies: have its costs entirely reimbursed or partly reimbursed.*

iii) The costs stop equals to the total costs: \( PSA_3 \)

If \( \alpha \in [\alpha^{\text{max}}, \alpha^{\text{min}}] \), the firm cannot choose the two strategies previously defined. It thus produces and extracts such as the cost stop equals to the total costs.

\[
(5) \quad \Leftrightarrow \max_{q,e} U_F^{psa2}(e, q, \alpha, \beta) = -c_e(e) + \rho(e) [(\alpha + (1 - \alpha)\beta)p q - c_p(q, \theta)]
\]

\[
s.t \quad f(p, \theta, \alpha, e, q) = 0
\]

\[
f(p, \theta, \alpha, e, q) = 0 \quad \text{defines} \quad \tilde{c}(q) = \frac{q(2(\alpha p - \theta) - q)}{q} \quad \text{and thus the problem becomes:}
\]

\[
\max_{q} U_F^{psa3}(q, \alpha, \beta) = -c_e(\tilde{c}(q)) + \rho(\tilde{c}(q)) [(\alpha + (1 - \alpha)\beta)p q - c_p(q, \theta)]
\]

Solving this problem gives \( q_{psa3}(p, \theta, \beta, \alpha) \) and \( e_{psa3}(p, \theta, \beta, \alpha) \). It is important to highlight that:

\[
U_F^{psa3}(q_{psa3}, \alpha^{\text{min}}, \beta) = U_F^{psa1}(e_{psa1}, e_{psa1}, \beta)
\]

\[
U_F^{psa3}(q_{psa3}, \alpha^{\text{max}}, \beta) = U_F^{psa2}(e_{psa2}, q_{psa2}, \alpha^{\text{max}}, \beta)
\]

\[
U_F^{psa3}(q_{psa3}, \alpha, \beta) \leq U_F^{psa1}(e_{psa1}, e_{psa1}, \beta)
\]

\[
U_F^{psa3}(q_{psa3}, \alpha, \beta) \leq U_F^{psa2}(e_{psa2}, q_{psa2}, \alpha, \beta)
\]

In figure 1, we represent the firm’s payoff under the 3 types of PSA as the share allocated to the costs reimbursement varies.
The firm’s payoff increases with $\alpha$. For low value of $\alpha$, the firm gets $U_{F_{psa2}}$ since $f(p, \theta, \alpha, e_{psa2}, q_{psa2}) < 0$. As $\alpha$ increases the firm’s payoff increases and at $\alpha = \alpha^{max}$, $U_{F_{psa2}}$ is equivalent to $U_{F_{psa3}}$. If $\alpha \in [\alpha^{max}, \alpha^{min}]$, the firm gets $U_{F_{psa3}}$ and finally for $\alpha > \alpha^{min}$, the firm gets $U_{F_{psa1}}$. $U_{F_{psa1}}$ is independent from $\alpha$.

**Government’s problem:**

For each contract and taking into account the firm’s exploration and extraction strategies, the government defines the share allocated to the costs and the profit oil split that maximize its payoff. The optimal contracts should be such as the firm accepts the contract ($PC$) and the cost oil constraint is satisfied ($COC$). For simplicity, the argument in the firm’s exploration and extraction strategy are dropped.

$$
\max_{\alpha, \beta} U_{G}^{psa} (\alpha, \beta) = \begin{cases} 
U_{G}^{psa1} & \text{if } f(p, \theta, \alpha, e_{psa1}, q^*) \geq 0 \\
U_{G}^{psa2} & \text{if } f(p, \theta, \alpha, e_{psa2}, q_{psa2}) < 0 \\
U_{G}^{psa3} & \text{otherwise}
\end{cases}
$$

The government never proposes a contract where $\alpha \in [\alpha^{max}, \alpha^{min}]$, the government only chooses between $PSA_1$ and $PSA_2$.

i) $(\alpha, \beta)$ are such that $f(p, \theta, \alpha, e_{psa1}, q^*) \geq 0$

$$
\max_{\alpha, \beta} U_{G}^{psa1} (\alpha, \beta) = \rho(e_{psa1})(1 - \beta)[pq^* - c_p(q^*, \theta) - c_e(e_{psa1})] \quad \text{s.t} \quad (17)
\beta \geq \beta^{min}(p, \theta) \quad (PC_1)
\alpha \geq \alpha^{min}(p, \theta, \beta) \quad (COC_1)
$$

Solving this problem gives $\alpha_{psa1}^*(p, \theta)$ and $\beta_{psa1}^*(p, \theta)$. The optimal share of the profit oil the firm receives decreases as the price and the firm’s efficiency increases. Thus, efficient
firms should receive a low share of the profit oil and as the price increases the profit oil split should favour the government. The share of the extraction allocated to the costs should be above $\alpha^{min}(p, \theta, \beta_{psa}^{*})$ to ensure that the costs are entirely reimbursed.

The government gets the same payoff as under a profit tax except that the exploration strategy is different. For a given profit tax, the firm explores a higher level under a PSA. Nevertheless, under both contracts the exploration effort is lower than the one maximizing the government’s payoff. As a result a PSA where the cost are entirely reimbursed always generates higher expected tax revenue than a simple profit tax.

Within our specifications, $(1 - \beta_{psa}^{*}) \in ]\beta^{min}, 1[$ and at least half of the production should be allocated to the cost reimbursement ($\alpha^{min}_{psa} > 50\%$). These thresholds depend on the specifications but illustrate the fact the under a $PSA_1$, the government may capture a much higher share of the revenue than under a concession contract. Indeed, the extraction level is not affected by $\beta$.

As compared to concession contracts, the government does not want the highest exploration and extraction levels as it bears the costs jointly with the firm. At equilibrium, the exploration effort is lower than the one desired by the government, i.e, the one that maximizes the expected profit oil. As under a concession contract, the government faces a trade off. By decreasing $\beta$, it increases its share of the revenue but decreases the probability to get a revenue. Under a $PSA_1$ the extraction level is not affected by the taxation, as a consequence, the government sets the taxation level with less distortions and captures a high share of the revenue. Comparing the optimal $PSA_1$ and the optimal concession contract, we show in the appendices that:

**Proposition 2** (i) The government’s take is higher under a $PSA_1$ since the government can increase its take without decreasing the extraction level. (ii) The expected tax revenue under a $PSA_1$ is higher. (iii) The exploration effort and the sum of the government and the firm’s expected payoffs are higher under a $PSA_1$. (iv) Nevertheless, the firm’s expected payoff is higher under a concession contract.

ii) $(\alpha, \beta)$ are such that $f(p, \theta, \alpha, e_{psa2}, q_{psa2}) < 0$

\[
\max_{\alpha, \beta} U_{G}^{psa2}(\alpha, \beta) = \rho(e_{psa2})(1 - \alpha)(1 - \beta)p q_{psa2} \text{ s.t } \quad (18)
\]

\[
U_{F}^{psa2}(e, q, \alpha, \beta) \geq 0 \quad (PC_{2})
\]

$\alpha < \alpha^{max}(p, \theta, \beta) \quad (COC_{2})$

This second type of PSA is exactly the same as a concession contract, the optimal contract is such that: $\alpha^{*}_{psa2} + (1 - \alpha^{*}_{psa2})\beta^{*}_{psa2} = 1 - \tau^{*}$ with $\alpha < \alpha^{max}(p, \theta, \beta)$. 11
Multiple solutions \((\alpha_{psa2}^*, \beta_{psa2}^*)\) satisfy these two conditions.

**Proposition 3** If the costs are partly reimbursed, the PSA is exactly the same as a concession contract. The share of revenue allocated to the costs and the share of the profit oil left to the firm are substitute instruments. The payoffs, the extraction and the exploration levels are exactly the same as under a concession contract.

To summarize, the government may implement two types of PSAs. On the one hand, it may entirely reimburse the costs, then the extraction level is the same as without taxation but the exploration effort is lower. On the other hand, it may propose a PSA where the costs are only partly reimbursed and then it is optimal for the PSA to exactly replicate the optimal concession contract. Both contracts can always be implemented whatever the values of \(p\) and \(\theta\). Nevertheless, a \(PSA_1\) always generates higher tax revenue than a concession contract that is the same as \(PSA_2\). Hence, the government should always implement a \(PSA_1\). Using simulations, we can see that the payoff the government gets using \(PSA_1\) is really close to the one it gets using complete contract.

### 4 Asymmetric information

The firm’s extraction efficiency is private information. The government does not know the firm’s extraction cost and has prior belief about the firm’s type. The firm is efficient \((\bar{\theta})\) with the probability \(\nu\) and inefficient \((\bar{\bar{\theta}})\) with the complementary probability \(1 - \nu\). The size of the information asymmetry is given by \(\Delta\theta = \bar{\bar{\theta}} - \bar{\theta} = > 0\). The efficient and inefficient firm’s payoffs are respectively denoted by \(U_F\) and \(\bar{U}_F\). The stages of the game are as follows:

- The government proposes a (menu of) contract(s).
- The firm chooses one contract. If the contract is incomplete, it also chooses the exploration and extraction levels.
- The revenue is generated and shared according to the terms of the contract.

#### 4.1 Complete contract

The government sets the exploration and extraction levels and the monetary transfer it receives. It proposes one contract to each type of firms and it maximizes its payoff under the firm’s participation and incentive constraints.

The optimal complete contracts are defined in the appendices. The inefficient firm gets no rents and the efficient one is indifferent between lying and revealing its type and gets an informational rent \(q(\bar{\epsilon})q\Delta\theta\). The optimal separating contracts are such that, the efficient
firm’s exploration and extraction levels are set to the same levels as without taxation. On the opposite, the inefficient firm’s exploration and extraction levels are lower than under symmetric information. The government faces a trade-off between rent extraction and productive efficiency. As the inefficient firm’s extraction and exploration increase, the efficient firm has more incentive to lie. Thus, the government reduces the extraction and exploration levels required from the inefficient firm to reduce the informational rent left to the efficient firm.

If the information asymmetry is large and/or the probability to face an efficient firm is high, it is optimal for the government to exclude the inefficient type. \( \nu_C \) is the probability to face an efficient firm above which it is optimal to propose only the efficient firm’s first best contract. In this case, the government captures all the rent and the inefficient firm gets a negative payoff if it participates.

**Lemma 3** Asymmetric information lowers the expected tax revenue from complete contracts. The optimal separating contracts are such that the efficient firm explores and extracts the first best and gets an informational rent. On the opposite, the inefficient firm extracts and explores less than when the information is symmetric. If the size of the information asymmetry is high, the government may only propose the efficient firm’s first best contract.

### 4.2 Concession contract

The exploration and extraction strategies are the same as under symmetric information. Since the firm chooses the contract with the lowest royalty, the government can only propose one contract. It chooses the royalty rate that maximizes its payoff given the firm’s exploration and extraction strategies and under the constraint that each firm accepts the contracts. The inefficient firm only accepts the contract if the \( \tau \leq \tau^\text{max}(p, \theta) \), if so the efficient firm also accepts the contract.

We denote \( e^\tau = e^\tau(p, \theta, \tau), q^\tau = q^\tau(p, \theta, \tau), e^\tau = e^\tau(p, \theta, \tau), q^\tau = q^\tau(p, \theta, \tau) \).

The government maximizes the tax revenue under the inefficient firm’s participation constraint \((PC^*_a)\).

\[
\max_{\tau} U^\tau_{G_a} = \nu \rho(e^\tau) \tau p q^\tau + (1 - \nu) \rho(e^\tau) \tau p q^\tau \quad \text{s.t} \quad \tau \leq \tau^\text{max}(p, \theta) \quad (PC^*_a)
\]

Solving this problem defines \( \tau_p \) such that: \( \tau_p = \nu \tau^*_s(p, \theta) + (1 - \nu) \tau^*(p, \theta) \). \( \nu \) is such that for \( \nu = \nu_s \), \( \tau_p = \tau^\text{max}(p, \theta) \). \( \nu \) is the probability to face an efficient firm above which it is optimal to propose only the efficient firm’s first best contract. This threshold decreases as the size of the information asymmetry increases.
Proposition 4 If the probability the firm is efficient and the information asymmetry are relatively high, the government only offers the efficient firm’s first best contract and the inefficient one does not participate. Otherwise, the government proposes a pooling concession contract. As compared to the first best, the government’s payoff is lower, the inefficient firm gets a lower payoff and lowers its exploration and extraction levels. On the opposite, the efficient firm gets a higher payoff and increases its exploration and extraction levels.

4.3 Production sharing agreement

We study the case where the government proposes to each firm a PSA where the costs are entirely reimbursed (PSA$^1$). Indeed, if the costs are partly reimbursed (PSA$^2$), the contract is similar to a concession contract. However, three other cases may occur: the government may propose a PSA$^2$ to both types of firms or a PSA$^2$ to one type of firms and a PSA$^1$ to the other.

Introducing information asymmetry under PSAs is more tricky since the firm has several exploration and extraction strategies. If two PSA$^1$ are proposed, the firm of type $\theta$ may either choose the contract designed for its type and explores and extracts $e^*_{psa1}$ and $q^*$ or it may choose the contract $(\hat{\alpha}, \hat{\beta})$ designed for the other type $(\hat{\theta})$ and gets:

$$
\max_{q,e} U_{psa}^{F} = -c(e) + \rho(e) \left[ C\hat{O} - c_p(q, \theta) + \hat{\beta}(pq - C\hat{O}) \right]
$$

with $C\hat{O} = \min \left[ \alpha p q, c(e) + c_p(q, \hat{\theta}) \right]$.

To determine the optimal separating contracts, we define the payoff the firm gets when it lies to determine the firm’s outside opportunity. If the firm chooses the contract designed for the other type, it has two extraction and exploration strategies. It may explore and extract to maximize its payoff when the announced costs are lower (strategy 1) or higher (strategy 2) than the cost stop. If the contract designed for the other type is such that none of these strategies are possible, the firm may produce and explore such as the announced costs equals to the cost stop (strategy 3).

4.3.1 The firm’s strategy

The firm’s payoff when it lies ($U_{psa}^{F_L}$) has a similar form as under symmetric information. Nevertheless, the cost which determines the reimbursement is the announced one $c(e) + c_p(q, \hat{\theta})$ which is different from the one paid: $c(e) + c_p(q, \theta)$. A figure showing the firm’s payoff when it lies is given in Appendix B.3.1.

$$
U_{psa}^{F_L}(\hat{\alpha}, \hat{\beta}) = \begin{cases} 
U_{FS_1} & \text{if } f(p, \hat{\theta}, \hat{\alpha}, e_{S_1}, q_{S_1}) \geq 0 \\
U_{FS_2} & \text{if } f(p, \hat{\theta}, \hat{\alpha}, e_{S_2}, q_{S_2}) < 0 \\
U_{FS_3} & \text{otherwise}
\end{cases}
$$
Under the first strategy, the announced costs are entirely reimbursed. The strategy that maximizes $U_{FS_1}$ is denoted by $(e_{S_1}, q_{S_1})$. The efficient (inefficient) firm gets as a cost reimbursement a higher (lower) amount than what it actually paid. The efficient firm extracts more and explores more or less than without taxation. On the opposite, the inefficient firm explores and extracts less than without taxation. In addition, for a given contract, the efficient (inefficient) firm explores a higher (lower) level than when it reveals its type and gets its cost entirely reimbursed. The inefficient firm only chooses this contract if it receives a sufficiently large share of the profit oil when lying: $\beta \geq \beta_{min}^{S_1}$.

We denote $\hat{\alpha}_{min}^{S_1}$ the minimum share of the production allocated to the cost needed for $\theta$ to get its announced costs fully reimbursed. Note that $\hat{\alpha}_{min}^{S_1} > \alpha_{min}$ and $\hat{\alpha}_{min}^{S_1} < \alpha_{max}^{S_2}$. Hence, for a given contract, the efficient firm may choose $(q^*, e_{psa1})$ while $(e_{S_1}, q_{S_1})$ is not possible (COC is not satisfied).

Under the second strategy, the announced costs are partly reimbursed. The strategy that maximizes $U_{FS_2}$ is denoted by $(e_{S_2}, q_{S_2})$. For a given contract, the firm adopts exactly the same strategy as when its costs are partly reimbursed: $q_{S_2} = q_{psa2}(p, \theta, \hat{\alpha}, \hat{\beta})$ and $e_{S_2} = e_{psa2}(p, \theta, \hat{\alpha}, \hat{\beta})$; as a result $U_{FS_2}(e_{S_2}, q_{S_2}) = U_F^{psa2}(e_{psa2}, q_{psa2})$. Since the size of the information asymmetry only affects the cost oil constraint, it is straightforward that the efficient firm may only choose this strategy when the information asymmetry is large enough.

We denote $\hat{\alpha}_{max}^{S_2}$ the maximum share of the production allocated to the cost needed for $\theta$ to get its announced costs partly reimbursed. Note that $\hat{\alpha}_{max}^{S_2} > \alpha_{max}$ and $\hat{\alpha}_{max}^{S_2} < \alpha_{max}^{S_2}$. Hence, for a given contract, the efficient firm may only choose this strategy when the information asymmetry is large enough.

The strategy that maximizes $U_{FS_3}$ is denoted by $(e_{S_3}, q_{S_3})$. Under the third strategy, the announced costs equal to the cost stop. Since the third strategy, is more constrained, the payoff associated is lower than the one associated with the two other strategies. However, this strategy occurs when the first or the second strategy are impossible, i.e, when $\hat{\alpha} \in [\hat{\alpha}_{max}^{S_2}, \hat{\alpha}_{min}^{S_1}]$.

### 4.3.2 Separating contracts

The government implements PSAs where the costs are entirely reimbursed for each type of firms ($PSA_1$). The government maximizes its expected payoff under the constraints that the firm accepts the contract: $\beta > \beta_{min} (PC)$, the costs are entirely reimbursed: $\alpha > \alpha_{min} (COC)$ and the firm reveals its types (IC).

For each type, there are three incentive compatibility constraints. Each constraint states that the firm should get a higher payoff when it reveals its type $\theta$ than when it
announces being $\hat{\theta} \neq \theta$ and chooses the first, the second or the third strategy. Those three constraints are denoted by $IC_1$, $IC_2$ and $IC_3$ and are respectively relevant when $\hat{\alpha} > \hat{\alpha}_{\min}^{S_1}$, $\hat{\alpha} < \hat{\alpha}_{\max}^{S_2}$ and $\hat{\alpha} \in [\hat{\alpha}_{\max}^{S_2}, \hat{\alpha}_{\min}^{S_1}]$.

All the constraints are given in the appendices B.3.2. The problem is the following:

$$\max_{(\beta_{AI}, \alpha_{AI})} U_{G}^{psa_1} = \nu \rho(\xi_{psa_1})(1-\beta)[pq^* - c_p(q^*, \theta) - c_e(\xi_{psa_1})] + (1-\nu)\rho(\xi_{psa_1})(1-\beta)[pq^* - c_p(q^*, \theta) - c_e(\xi_{psa_1})]$$

(22)

s.t $PC, PC, COC, COC, IC_1, IC_2, IC_3, IC_1, IC_2, IC_3$ (23)

Solving this problem gives $(\beta_{AI}, \alpha_{AI})$ and $(\alpha_{AI}, \beta_{AI})$. We show in the appendices B.3.2 that the optimal separating contracts must satisfy: (i) $\beta_{AI} > \beta_{AI}$ and (ii) $\alpha_{AI} = \alpha_{\min}$. (ii) implies (iii): $IC_1$ can be ignored. Finally, (iv) for the efficient firm only $IC_1$ matters. Using (i)-(iv), the set of constraints (23) is simplified to:

$$PC, PC, COC, IC_2, IC_3, IC_1, IC_2, IC_3, \alpha_{AI} = \alpha_{\min}$$

(24)

We have to determine which incentive constraints bind. Since under the first best contracts, the efficient firm misrepresents its type, its incentive constraint always binds ($IC_2$ or $IC_3$). Nevertheless, it is not straightforward to determine if $IC_1$ binds at equilibrium. This depends on how large the informational rent left the efficient firm is. As this rent increases, things being equal, the efficient firm is more willing to lie.

First, the probability the firm is efficient $(\nu)$ determines which contract (the efficient or the inefficient’s one) the government is more willing to distort from the first best. If $\nu$ is large, the regulator is less willing to increase above the first best the efficient firm’s share of the profit oil and prefers to decrease the inefficient’s one.

Then, the size of the information asymmetry $(\Delta \theta)$ determines which of the efficient firm’s incentive constraint binds and so whether the inefficient firm’s incentive constraint binds.

Finally, $\nu$ and $\Delta \theta$ determine whether the government proposes separating contracts, excludes the inefficient firm or offers a pooling contract. If $\nu$ and $\Delta \theta$ are large, the government is more willing to exclude the inefficient firm. Indeed, a separating contract satisfies $\beta_{AI} > \beta_{AI}$, yet under the first best, the profit oil the firm receives decreases with its efficiency. Hence, separating firms might be highly costly. If $\Delta \theta$ is low, the government may choose to pool the firm.

If the information asymmetry is high, $IC_2$ binds, the efficient firm is indifferent between revealing its type and choosing the second strategy and the $IC_1$ is satisfied (see in the
appendices Figure 4). For a given size of information asymmetry, the optimal separating contracts depend on \( \nu \) and are such as:

\[
\text{Max} \left[ \beta_{AI}, \beta^*_{psa1} \right] < \text{Min} \left[ \beta_{AI}, \beta^*_{psa1} \right]
\]  \hspace{1cm} (25)

The efficient firm receives a higher share of the profit oil than under the first best and the inefficient one receives a lower share. Only the efficient firm gets an informational rent. Moreover, the efficient firm always receives a higher share of the profit oil than the inefficient one. Because \( \alpha_{min} > 50\% \), the efficient firm gets a high informational rent and \( \beta_{AI} \) is much higher than \( \beta^*_{psa1} \). At equilibrium, the efficient firm explores more than the first best and the inefficient one explores less. Both firms extract the first best level.

Under information asymmetry, the optimal separating contracts grant a really high share of the profit oil to the efficient firm whereas under the first best the government captures almost the entire profit oil. As a result, if the information asymmetry is large, separating contracts are only proposed if the probability to face an efficient firm is really small. If not, the government only offers the efficient firm’s first best contract. We define \( \nu_{psa1} \) the probability to face an efficient firm above which it is optimal to exclude the inefficient firm. Above this threshold, only the efficient firm’s first best contract \( \beta^*_{psa1} \) is proposed and the inefficient one does not participate.

For instance, for a given size of information asymmetry, the government excludes the inefficient firm under a PSA as long as the probability to face an efficient firm is higher than 8\%. Under a complete (concession) contract the inefficient firm would have been excluded only if the probability to face an efficient firm is higher than 27\% (14\%). Under a PSA, if the information asymmetry is high, the government may exclude the inefficient firm even if the probability to face this type of firm is relatively small.

**Proposition 5** If the information asymmetry is large, there are no countervailing incentives. If the probability to face an efficient firm is small, the government separates firms only. If so, as compared to the first best, the efficient firm receives a higher share of the profit oil and the inefficient one a lower share. If not, the government only proposes the efficient firm’s first best contract.

If the information asymmetry is small (IC\(_3\) binds) or if it is medium size (IC\(_2\) binds), the inefficient firm’s incentive constraint may not be satisfied. Thus at equilibrium, both incentive constraints bind. The contracts such as both incentive constraints bind is usually unique (see Figure 5). In this case the probability to face one type of firm has no impact on the optimal separating contracts. \( \nu \) only affects the types of contract the government implements: separating, pooling or exclusion.

Nevertheless, in the neighbourhood of the switching point from IC\(_2\) to IC\(_3\), both incentive constraints binds may bind for several contracts (see Figure 6). In this case the
government chooses the separating contract maximizing its tax revenue, and this choice depends on $\nu$. If both incentive constraints bind, the second best contracts satisfy:

$$
\beta^*_{psa} < \beta^*_{psa1} < \beta_{AI} < \beta_{AI}^1
$$

Both firms get a higher share of the profit oil than under the first best and thus they explore higher levels than under symmetric information. As in the previous case, both firms extract the first best level. Usually, as the size of information asymmetry decreases, separating firm is less costly. However, under a PSA, this induces countervailing incentives and thus separation is more costly.

We show in the appendices that this separating contracts is usually dominated by a pooling contract. Indeed, using this contract, the government collects low tax revenues since both firms receive an informational rent. Furthermore, countervailing incentives appear when the size of information asymmetry is low and this is precisely the conditions under which pooling is not too costly. As a consequence, this type of contract is only used when countervailing incentives appears and pooling is too costly (information asymmetry is medium sized).

Under a PSA, when the information asymmetry is low, both firms receive an informational rent. As a result, the government may exclude the inefficient firm under a PSA while it is never optimal under a concession contracts.

For instance, when the information asymmetry is low, the inefficient firm may be excluded under a PSA if the probability to face an efficient firm is higher than 51% whereas under a complete contract this threshold is 97%.

**Proposition 6** If the information asymmetry is small or if it is medium size, countervailing incentives appear and the optimal separating contracts are such as both firms receive a higher share of the profit oil than the first best. As a result, the exploration level is higher than under symmetric information. Nevertheless, if the probability to face an efficient firm is sufficiently large, the government only proposes the efficient firm first best contract.

To summarize, to induce truthful revelation, the efficient firm receives a higher share of the profit oil than under the first best. Furthermore, to lower the efficient firm’s gains from lying, the share of the revenue allocated to the cost reimbursement of an inefficient firm is set to its minimum level. Moreover, when the information asymmetry is low, the inefficient firm may also have the incentive to misrepresent its type. In this case, both firms receive an informational rent. However, separating firms is so costly that the government may exclude the inefficient firm by only proposing the efficient firm’s first best contract. This may occur even if the probability to face an efficient firm is low. A summary table is given at the end of the appendices to summarize the optimal contracts depending on the firm (efficient or inefficient) and on the information (asymmetric or symmetric).
Using simulation, we show that:

**Proposition 7** Under asymmetric information, complete contracts generate more tax revenue than incomplete contracts. PSA generates still higher tax revenue than concession contract. Nevertheless, the gap between them is really low especially when the information asymmetry is low and the probability to face an efficient firm is low. PSAs are now far from generating the same tax revenue as complete contracts.

### 4.3.3 "Pooling" contract

If separation is too costly, regulators usually propose the same contract to all types of agents (pooling) or at least the same contract to some types of agents (bunching). The cost of pooling the agents decreases with the size of the information asymmetry.

In our context, separation is costly when the size of the information asymmetry is low since in this case countervailing incentives appear and both firms receive an informational rent. Nevertheless, when the information asymmetry is low pooling is not too costly. As a result for low information asymmetry, a pooling contract should be implemented.

In the previous section, we know that proposing the same contract to both types of firm implies that the efficient firm lies whereas the inefficient one reveals its type.

The optimal "pooling" contract is such as $\alpha = \alpha^{\text{min}}$. Indeed, on the one hand, setting $\alpha$ to this value does not affect the inefficient firm strategy and thus the tax revenue the government gets from this firm. On the other hand, it decreases the payoff the efficient firm gets from lying and thus increases the government’s payoff. The "pooling" contract that maximizes the government payoff is given by:

$$
\max_{\beta > \beta^{\text{min}}} U^{\text{psa}}_G = \nu \rho(q_{s_3})(1 - \alpha^{\text{min}})(1 - \beta)pq_{s_3} + (1 - \nu)\rho(\tau_{psa})(1 - \beta)[p\bar{r} - c_p(q^*, \bar{r}) - c_e(\tau_{psa})]
$$

Solving this problem defines $\beta_P$. The share of the profit oil maximizing the first part of the government’s payoff is lower than $\beta^*$. The second part of the government’s payoff is maximized by $\beta^*$, hence, the higher $\nu$, the higher $\beta_P$.

For both types, the cost stop equals the total costs. The inefficient firm explores a lower level than under the first best ($\beta_P < \beta^*$) and extracts the same as under the first best. The efficient firm produces less than the first best and explores more or less.

**Proposition 8** If the information asymmetry is small, the government proposes the same contract to both types of firms. The efficient firm misrepresents its types and so receives as a cost reimbursement a higher amount than what it actually paid. The efficient firm increases its exploration and extraction levels until the cost stop is met. The inefficient firm extracts the first best and explores a lower level.
5 Discussion

Governments capture the entire surplus by using complete contracts with fixed payment and exploration and extraction quotas. Although, these contracts do not induce distortion, they are rarely used whereas incomplete contracts such as concession contracts or PSAs are common. Nevertheless, we show that their ability to raise tax revenue highly depends on the existence of information asymmetry. If the government has information on the oil companies, for instance if it has already done business with the firm or if the firm can be easily monitored (small firm), it should propose a PSA where the costs are entirely reimbursed. A high share of the revenue should be allocated to the costs to promote the exploration activities and to avoid any productive distortions. Under such contracts, the revenue generated is high and the government captures a high share of this revenue. Indeed, the extraction is the first best level (high revenue) and thus the government is able to raise its take (high share) with few distortions. Using PSAs, governments capture almost all the net revenue and the tax revenue is higher than under concession contracts. The tax revenue generated by PSAs is close to the one generated by complete contracts.

Nevertheless, if the government does not know exactly the firm’s extraction costs, PSAs generate much lower tax revenue than complete contracts. Indeed, the cost recovery mechanism gives strong incentive to the firm to undervalue its efficiency.

For instance, for a given price and efficiency, if the government does not know the firm’s cost it may only capture one quarter of the profit oil whereas on the first best, it captures almost the entire profit oil. The government’s take can be even higher under concession contracts than under PSAs.

As a consequence, when the asymmetric information is high, the government should exclude the inefficient firms even if the probability to face this type of firm is high. In other words, the government should only propose a really though contract (first best contract) that will only be chosen by high efficient firms rather than proposing the second best separating contracts that are too generous with firms.

When the information asymmetry is low, countervailing incentives appear and the government should propose the same contract to both types of firms. In this case the efficient firm overvalues its costs and explores and extract such as the the cost stop is met.

If there is asymmetric information on costs and the government wishes to implement a concession contracts, it can only propose a unique royalty rate to all types of firms. It may propose either a high royalty rate which excludes the less efficient firms or an average royalty rate that depends on its beliefs on the firm’s efficiency.

The large variety of PSAs can be explained by the information asymmetry on costs. Indeed, we show that if the government knows the firm’s cost, the optimal contract grants the government a really high share of the profit oil. This type of contracts is observed in Angola where the government gets at least 45% of the profit oil and up to 90% when the
production is large. On the opposite, China proposes a PSA where it gets at most 60% of the profit oil and only receives 10% of it when the production is low. Furthermore, in 2007, after its first oil discovery, Ghana has adopted a royalty tax system to govern the fiscal regime for its petroleum sector. Many commentators argue that Ghana would have obtained much more benefit under PSAs. However, the present paper argues that countries with a recent history of oil exploitation may find royalty tax system more profitable, since PSAs require some knowledge on the extraction costs. Ghana’s choice, may thus be justified by a lack of technical expertise. We argue in this paper that the large discrepancy in fiscal agreement cannot only be explained by a diversity in countries risk return but may well be explained by information asymmetry.

References


Appendices

We denote $p - \theta = X$ and assume $X \geq \sqrt{2}$. If not, the exploitation is not profitable without taxation.

A Symmetric information

A.1 No taxation and complete contract

$$q^* = X; \quad e^* = \frac{\sqrt{2}X - 2}{2}; \quad U_F^{NT*} = U_F^{NT}(e^*, q^*) = \frac{(X - \sqrt{2})(\sqrt{2}X - 2)}{2};$$

Under a complete contract the extraction levels and the exploration levels are the same as without taxation and the government captures the entire revenue.

A.2 Concession contract

$$e^\tau(p, \theta, \tau) = \sqrt{2} \left( \frac{X - \rho\tau}{2} \right) - \frac{2}{2}; \quad q^\tau(p, \theta, \tau) = X - \rho\tau; \quad \tau^{\max} = \frac{X - \sqrt{2}}{2}; \quad \tau^* = \frac{\sqrt{2}X - 2}{2};$$

$$\lim_{p \to +\infty} \tau^* = \frac{1}{2}; \quad e^\tau(p, \theta, \tau^*) = \frac{\sqrt{2}X - 2}{4} < e^*; \quad q^\tau(p, \theta, \tau^*) = \frac{\sqrt{2}X + 2}{4} < q^*;$$

$$U_G^{*} = U_G^{\tau}(\tau^*) = \frac{(\sqrt{2}X - 2)^2}{8}; \quad U_F^{*} = U_F^{\tau}(e^*, q^*, \tau^*) = \frac{(\sqrt{2}X - 2)^2}{16}; \quad U_F^{*} + U_G^{*} = \frac{3(\sqrt{2}X - 2)^2}{16} <$$

A.3 Production sharing agreement

Exploration strategy under $PSA_1$ in the general case:

Here, we just assume that $c_p(q, \theta)$ is convex and increasing in $\theta$ and that $\rho(e)$ is concave and increasing in $e$ where $\rho(0) = 0$ and $\lim_{e \to +\infty} \rho(e) = 1$.

Given $e_{psa_1}$ is given

$$\frac{\partial U_F^{psa_1}(e^*, q^*, \beta)}{\partial e} = \frac{\partial U_F^{psa_1}(e^*, q^*, \beta)}{\partial e} = A$$

$$= \frac{\partial U_F^{psa_1}(e^*, q^*, \beta)}{\partial e} = B$$

$$= \frac{\partial U_F^{psa_1}(e^*, q^*, \beta)}{\partial e} = 0$$

We define: $\hat{e} = \arg\min_e c_e(e)(1 - \rho(e))$, $e_g = \arg\max_e \rho(e)[pq^* - c_p(q^*) - c_e(e)]$, $p$ such that $e^*(p) = \hat{e}$ and $\beta_{conc(p)}$ such as $\frac{\partial U_F^{psa_1}(e^*, q^*, \beta)}{\partial e} = 0$. If $\lim_{\beta \to 1} e_{psa_1} = e^*$

Let’s denote $Y = \beta X^2 - 2(1 - \beta) > 0$
Proof of proposition 1

\[ e_{\text{psa}_1}(p, \theta, \beta) = \left( \frac{\sqrt{X + \beta}}{\sqrt{2}} \right)^2 - 1; \quad \frac{d e_{\text{psa}_1}(\cdot)}{d \beta} = \left( \sqrt{2Y \beta^2} \right)^{-1} > 0; \quad q_{\text{psa}_1}(p, \theta) = X; \quad \beta_{\text{min}} = \frac{2}{X^2}. \]

\[ \alpha_{\text{min}}(p, \theta, \beta) = \left( \sqrt{2Y \beta^2} \right)^{-1} [2 \beta \mu X]^{-1}; \quad \frac{d \alpha_{\text{min}}(\cdot)}{d \theta} = \sqrt{2Y \beta^2} \frac{(X^2 - 2 - 4(1 - \beta) Y)}{2 \sqrt{Y} \beta p X^2}. \]

\[ \frac{d \alpha_{\text{min}}(\cdot)}{d \theta} \] increases with \( \beta \) and \( \frac{d \alpha_{\text{min}}(\cdot)}{d \theta} |_{\beta = \beta_{\text{min}}} = 0, \) thus \( \alpha_{\text{min}}(\cdot) \) increases with \( \theta \)

Proof of Lemma 1

\[ e_{\text{psa}_1}(p, \theta, \beta) > 0 \iff \beta \theta^2 - 2 \beta p \theta + \beta p^2 - 2 > 0 \text{ and } e^\tau(\beta(\theta, 1 - \beta) = \left( \frac{\beta^p - \theta}{\sqrt{2}} \right) - 1 \iff \beta p - \theta > 0. \]

\[ e_{\text{psa}_1}(p, \theta, \beta) - e^\tau(\beta, \theta, 1 - \beta) = \left( \sqrt{\beta} \right)^X X^2 \xi - 2 (1 - \beta) \xi - \beta \xi (\beta p - \theta)^2 \]

\[ \text{positive if: } \sqrt{\beta} \left( \beta X^2 - 2 (1 - \beta) \right) \beta (\beta p - \theta) > 0 \iff \beta \left( \beta X^2 - 2 (1 - \beta) \right) \beta (\beta p - \theta)^2 = (1 - \beta) (\beta p - 2 \beta p + \beta^2 p^2 - 2) > 0 \iff \beta^2 p^2 - \beta \theta^2 > 0. \]

Yet \( \beta p - \theta > 0 \text{ and } \beta \in [0, 1]. \) Thus \( e_{\text{psa}_1}(\beta, \theta) > e^\tau(\beta, \theta, 1 - \beta) \)

Proof of Lemma 2

\[ \alpha_p q_a - c_p(q_a, \theta) > \alpha_p q_b - c_p(q_b, \theta), \forall \alpha_p - \theta < q_a < q_b. \text{ Yet, } \alpha_p - \theta < q_{\text{psa}_2} < q^* \text{ and } e_{\text{psa}_2} < e_{\text{psa}_1} \iff f(p, \theta, \alpha, e_{\text{psa}_1}, q^*) < f(p, \theta, \alpha, e_{\text{psa}_2}, q_{\text{psa}_2}) \]

The optimal contracts

It is straightforward that the government never proposes a contract such as \( \alpha \in [\alpha_{\text{max}}, \alpha_{\text{min}}]. \) A sufficient condition comes from the fact that \( U_{\text{psa}_3}^G \) maximized for \( \alpha = \alpha_{\text{min}}. \) Furthermore, for a given profit oil split \( \beta, \) two cases occur:

If \( U_{\text{psa}_1}^G(\beta) > U_{\text{psa}_2}^G(\beta, \alpha) \forall \alpha \) the government has the incentive to set \( \alpha \geq \alpha_{\text{min}}. \)

If \( U_{\text{psa}_1}^G(\beta) < U_{\text{psa}_2}^G(\beta, \alpha) \) for some value of \( \alpha, \) the government has the incentive to set \( \alpha = \alpha^* \) where \( \alpha^* \) maximizes \( U_{\text{psa}_2}^G. \)

The optimal \( PSA_1: \)

\[ \max_{\alpha, \beta} U_{\text{psa}_1}^G(\alpha, \beta) = (1 - \beta) \left( \sqrt{2 \beta - \sqrt{Y}} \right) \left( 2 \sqrt{Y} - \sqrt{2 \beta} \left( X^2 + 2 \right) \right) \left( 2^{-\frac{3}{2}} \beta Y \right)^{-\frac{1}{2}} \] \[ \text{s.t.} \]

\[ \beta \geq \beta_{\text{min}}(p, \theta) \]

\[ \alpha \geq \alpha_{\text{min}}(p, \theta, \beta) \]

\[ \frac{\partial U_{\text{psa}_1}^G(\cdot)}{\partial \beta} = \sqrt{2} \left( 1 + \beta - \beta^2 (X^2 + 2) (1 - Y) \right) \left( \beta Y \right)^{-\frac{1}{2}} - (X^2 + 4)^{-2} = 0 \]
\[
\frac{d(32)}{dX} = X \left( -\sqrt{2} \beta Y^\frac{3}{2} + 2 \beta^2 X^2 \left( Y + 2 \beta - 3 \right) - 2 \left( 1 - \beta \right) \left( 4 \beta^2 - 6 \beta + 3 \right) \right) \left( (2 \beta)^{-\frac{1}{2}} Y^{-\frac{3}{2}} \right)
\]
\[
\frac{d(32)}{dX} < 0 \quad \forall \beta > \beta^{\text{min}}, \forall X > \sqrt{2}
\]

Hence, \( \beta_{psa1}^* (p, \theta) \) increases with the price and the firm's efficiency.

**Proof of Proposition 2**

(i) \( 1 - \beta_{psa1}^* > \tau^* \) if \( (32) |_{\beta = A} < 0 \) where \( A < 1 - \tau^* \). Yet, \( 1 - \tau^* = \frac{\sqrt{2} (p+\theta)+2}{2^\frac{3}{2} p} > \frac{\sqrt{2} X - 2}{2^\frac{3}{2} X} \)

\[
(32) |_{\beta = \frac{\sqrt{2} X - 2}{2^\frac{3}{2} X}} = \frac{\sqrt{2} X^7 + 6 X^6 + 2^\frac{3}{2} X^5 + 4 X^4 + 2^\frac{3}{2} X^3 + 16}{2^\frac{3}{2} X^3} - \left( \frac{\sqrt{2} X + 2}{2^\frac{3}{2} X} \right)^\frac{3}{2} \left( X^3 + 2 X^2 - 2 X + 4 \right) \frac{16}{X^3} < 0, \forall X > \sqrt{2}.
\]

(ii) If \( U_{psa1}^G (\alpha_{psa2}^*, \beta_{psa2}^*) > U_{psa2}^G (\alpha_{psa2}^*, \beta_{psa2}^*) \), then \( U_{psa1}^G (\alpha_{psa1}^*, \beta_{psa1}^*) > U_{G}^G (\tau^*) = U_{psa2}^G (\alpha_{psa2}^*, \beta_{psa2}^*) \).

Multiple solutions \( (\alpha_{psa2}^*, \beta_{psa2}^*) \) maximizes \( U_{psa2}^G (\cdot) \) and we choose one particular solution \( (\tilde{\alpha}, \tilde{\beta}) \) defined by \( f(p, \theta, \alpha, e_{psa2}, q_{psa2}) = 0 \)

\[
\tilde{\alpha} = \sqrt{2} \left( 2 \beta^2 X^2 + (1 - \beta) \left( 2^\frac{3}{2} \beta X - 5 \beta - 3 \right) + 2 (\theta - \beta^2 p) + \sqrt{2} (1 - \beta) \right)
\]

\[
\tilde{\beta} = \frac{X^2 + 6}{3 X^2 + 2}.
\]

Hence, \( U_{psa1}^G (\tilde{\alpha}, \tilde{\beta}) > U_{psa2}^G (\tilde{\alpha}, \tilde{\beta}) = U_{psa2}^G (\tilde{\alpha}, \tilde{\beta}) = U_{psa2}^G (\alpha_{psa2}^*, \beta_{psa2}^*) = U_{G}^G (\tau^*) \)

\( \iff \ U_{psa1}^G (\alpha_{psa1}^*, \beta_{psa1}^*) > U_{psa2}^G (\alpha_{psa2}^*, \beta_{psa2}^*) \)

(iii) \( e_{psa1} (p, \tilde{\beta}, \theta, \theta) = e^* (p, \tau^*, \theta) \) with \( \tilde{\beta} = \frac{8}{3 X^2 - 2^\frac{3}{2} X + 6} \)

\[
(32) |_{\beta = \tilde{\beta}} > 0, \forall X > \sqrt{2} \iff \tilde{\beta} < \beta_{psa1}^* \text{ since } e_{psa1} (p, \beta, \theta) \text{ increases with } \beta:
\]

\[
e_{psa1} (p, \beta_{psa1}^*, \theta) > e_{psa1} (p, \tilde{\beta}, \theta) = e^* (p, \tau^*, \theta)
\]

Starting from \( U(e, q) \) defines in (1) we have \( U_F + U_G = U(e, q) \) which is maximized by \( (e^*, q^*) \). Hence \( U(e^*, q^*) = \max \{ U(e_{psa1}^*, q^*), U(e^{\tau^*}, q^{\tau^*}) \} \) since \( e^{\tau^*} < e_{psa1}^* < e^* \), then :

\[
U (e_{psa1}^*, q^*) > U (e^{\tau^*}, q^{\tau^*}) > U (e^{\tau^*}, q^*)
\]

(iv) \( U_{psa1}^G (e_{psa1}^*, q^*, \tilde{\beta}) = U_{F}^* \) with \( \tilde{\beta} = \frac{2^\frac{3}{2} \sqrt{X^6 - 2^\frac{3}{2} X^5 + 22 X^4 - 2^\frac{3}{2} X^3 + 44 X^2 - 2^\frac{3}{2} X^1 + 14 X^2 - 2^\frac{3}{2} X + 8}}{4 X^3} \)

and \( (32) |_{\beta = \beta} < 0, \forall X > \sqrt{2} \iff \beta > \beta_{psa1}^* \iff U_{psa1}^G (e_{psa1}^*, q^*, \tilde{\beta}) = U_{F}^* (\tau^*) > U_{psa1}^G (e_{psa1}^*, q^*, \beta_{psa1}^*) \)

**Proof of Lemma 3**

It is straightforward \( PSA_2 \) is similar to a concession contract where \( \tau = (1 - \alpha)(1 - \beta) \).

\( \alpha_{psa2}^* \) and \( \beta_{psa2}^* \) are substitute instruments.
The optimal contract is: 

\[(1 - \alpha_{psa}^*)(1 - \beta_{psa}^*) = \tau^* \text{ with } \alpha_{psa}^* (\beta_{psa}^*) = \frac{\sqrt{2}(\theta+p) - 2\beta p + 2}{2^{\frac{3}{2}} (1-\beta)p}\]

and \(\beta_{psa}^* \in \left[ \frac{X^2 + 6}{3X^2 + 2}, \frac{\sqrt{2}(\theta+p)+2}{2^{\frac{3}{2}} p} \right] \) to ensure that \(f(p, \theta, \alpha_{psa}^* (\beta_{psa}^*), e_{psa}, q_{psa}) < 0 \) and \(\alpha_{psa}^* > 0\).

### A.4 Low stock

If the stock is too low to extract \(q^*\) or \(\tau^*\), then:

**Without taxation:** 

\[e^* = \frac{\sqrt{2R(2X-R) - 2}}{2}; \quad U^* = \left(2 - \sqrt{2R(2X-R) + R(R-2X)}\right)\frac{2^{\frac{3}{2}}}{\sqrt{2R(2X-R)}}\]

Concession contract: \(R < \frac{X + \sqrt{3}}{2}\), 

\[e^R = \frac{\sqrt{2R(2(X-p\tau) - R)} - 2}{2} \quad \text{and } \tau_R \text{ is given by:} \]

\[pR - \frac{\sqrt{2Rp (2X - R - p\tau)}}{2(X - R - 2p\tau)^{\frac{3}{2}}} = 0 \quad (33)\]

\[\left(33\right)|_{\tau = \tau^*} = \frac{2^{\frac{3}{2}} (3X - 2R + \sqrt{3}) - 2\sqrt{R(\sqrt{3X - \sqrt{3}}R + 2)^{\frac{3}{2}}}}{2^{\frac{3}{2}}} \quad \forall \ R < \frac{X + \sqrt{3}}{2} \iff \tau_R > \tau^*\]

**PSA:** 

\[e^R_{psa} = \sqrt{2\beta (\beta R (2X-R) - 2(1-\beta)) - 2\beta} \quad \text{and } \beta_R \text{ is given by:} \]

\[-\sqrt{5} \beta^2 (R (2X - R) + 4) (\beta R (2X - R) - 2(1-\beta))^{\frac{3}{2}} + 4\beta^2 (R (2X - R) + 2) (\beta R (2X - R) + 2\beta - 3) + 4(\beta + 1) = 0 \quad (34)\]

\[\beta_R > \beta^*\]

### B Asymmetric information

Let’s denote \(X = p - \theta\) and \(\overline{X} = p - \overline{\theta}\)

#### B.1 Complete contract

The government sets the exploration and extraction levels and the monetary transfer it receives. It proposes two contracts, one designed for each type of firms and it maximizes its payoff under the firm’s participation (PC) and incentive constraints (IC). The contracts designed for the efficient and inefficient types are respectively denoted by \((e, q, T)\) and
(\tilde{\tau}, \tilde{q}, \tilde{T})$. This is a standard problem where (38) and (37) bind.

\[
\max_{(\epsilon, \tilde{q}, T)} U_{G_{ai}}^C = \nu T + (1 - \nu)\tilde{T} \quad \text{s.t.} \quad \begin{align*}
- c_e(\epsilon) + \rho(\epsilon)[pq - c_p(q, \tilde{\theta})] - \tilde{T} & \geq 0 \quad (35) \\
- c_e(\tilde{\tau}) + \rho(\tilde{\tau})pq - c_p(q, \tilde{\theta}) - T & \geq 0 \quad (36) \\
- c_e(\tilde{\tau}) + \rho(\tilde{\tau})pq - c_p(q, \tilde{\theta}) - \tilde{T} & \geq 0 \quad (37) \\
- c_e(\tilde{\tau}) + \rho(\tilde{\tau})pq - c_p(q, \tilde{\theta}) - \tilde{T} & \geq -c_e(\epsilon) + \rho(\epsilon)[pq - c_p(q, \tilde{\theta})] - T \quad (38) \\
- c_e(\tilde{\tau}) + \rho(\tilde{\tau})pq - c_p(q, \tilde{\theta}) - \tilde{T} & \geq -c_e(\epsilon) + \rho(\epsilon)[pq - c_p(q, \tilde{\theta})] - \tilde{T} \quad (39)
\end{align*}
\]

Solving the problem gives: $q_{ai}^C(p, \tilde{\theta}) = q^*(p, \tilde{\theta})$; $e_{ai}^C(p, \tilde{\theta}) = e^*(p, \tilde{\theta})$; $\nu_{ai}^C(p, \tilde{\theta}, \tilde{\theta}, \nu) = \tilde{q}^* - \nu \Delta \theta_{1\nu}$; $\nu^C = \frac{2 - \sqrt{2} \tilde{X}}{2 - \sqrt{2} \tilde{X}}$.

### B.2 Concession contract

Solving the problem gives: $\tau_p = \sqrt{2(\Delta \theta - \tilde{X}) - 2}$; $U_{G_{ai}}^{pool} = \frac{1}{8}(\sqrt{2(\nu \Delta \theta + \tilde{X} - 2)} - 2)^2$; $U_{G_{ai}}^{exclude} = \frac{1}{8}((\sqrt{2(\nu \Delta \theta + \tilde{X}) + 2})^2$; $\nu_{ai} = \frac{1}{16}(\sqrt{2(\Delta \theta - \tilde{X}) + 2)} - 2)^2 - \frac{1}{2\pi}$

### B.3 Production sharing agreement

#### B.3.1 The firm’s strategy

Let’s denote $\tilde{X} = p - \bar{\theta}$ where $\bar{\theta}$ is the announced type $\bar{\theta} = \{\tilde{\theta}, \tilde{\theta}\}$.

- **Strategy 1** $q_{ai}(p, \theta, \bar{\theta}, \bar{\beta})$ and $e_{ai}(p, \theta, \bar{\theta}, \bar{\beta})$ solves:

\[
\max_{e, q} U_{F_{ai}}(e, q, \bar{\beta}) = -c_e(e) + \rho(e) \left[c_e(e) + c_p(q, \bar{\theta}) - c_p(q, \bar{\theta}) + \bar{\beta}(pq - c_e(e) - c_p(q, \bar{\theta}))\right] \quad \text{s.t. } f(p, \bar{\theta}, \bar{\alpha}, e, q) \geq 0 \quad (40)
\]

\[
q_{ai}^* = \frac{\beta \tilde{X} + \tilde{\theta} - \bar{\theta}}{\beta} = q^*(\cdot) + (1-\beta)(\tilde{\theta} - \bar{\theta})\quad e_{ai}^* = \frac{\sqrt{(\beta \tilde{X} + \tilde{\theta} - \bar{\theta})^2 - 2(1-\beta)\beta}}{\sqrt{2} \beta} - 1;\quad q_{ai}^* > q^*(\cdot)
\]

and $q_{ai}^* > \bar{q}^*(\cdot)$ and $\frac{d q_{ai}^*}{d \beta} > 0$; $\frac{d e_{ai}^*}{d \beta} > 0$; $e_{ai}^* < \bar{e}_{psa1}^* < \bar{e}^*(\cdot)$ and $\bar{e}_{psa1}^* < e_{psa1}^*$. $\bar{\beta}$ only chooses the first strategy if: $\beta^{AI} > \beta^{minS_1} = \frac{\sqrt{2 \tilde{X} \Delta \theta + 1 + \tilde{X} \Delta \theta + 1}}{\tilde{X}^2}$; $e_{ai}^* > 0$ \lim_{\theta \to \bar{\theta}} q_{ai}^* = \bar{q}^*_{psa1}$ and \lim_{\theta \to \bar{\theta}} e_{ai}^* = \bar{e}^*_{psa1}
• **Strategy 2**

$q_{S_2}(p, \hat{\alpha}, \hat{\beta}, \theta)$ and $e_{S_2}(p, \hat{\alpha}, \hat{\beta}, \theta)$ solves:

$$
\begin{align*}
\max_{e, q} & \quad U_{F_{S_2}}(e, q, \hat{\alpha}, \hat{\beta}) = -c_e(e) + \rho(e) \bigl[ \hat{\alpha} + (1 - \hat{\alpha}) \hat{\beta} \bigr] p q - c_p(q, \theta) \\
\text{s.t} & \quad f(p, \hat{\theta}, \hat{\alpha}, e, q) < 0
\end{align*}
$$

\[(COC_{S_2})\]

The second strategy if the same as when the firm reveals its type and gets its cost partly reimbursed. Only the cost oil constraint changes, the cost stop is lower than the announced costs (≠ actual costs).

$$
\begin{align*}
f(p, \hat{\theta}, \hat{\alpha}, e, q) < 0 \\
\frac{\partial COC_{S_2}}{\partial \beta} = -[p (\overline{\alpha} + (1 - \overline{\alpha}) \overline{\beta}) - \bar{\theta}] < 0; \quad \frac{\partial COC_{S_2}}{\partial \theta} = -(1 - \overline{\alpha}) p \left( \Delta \theta + (1 - \overline{\alpha}), \overline{\beta} p - \frac{1}{\sqrt{2}} \right) < 0.
\end{align*}
$$

As $\overline{\theta}$ and $\overline{\beta}$ increase, $COC_{S_2}$ is more likely satisfied. Yet, assuming, that $IC_{S_1}$ is satisfied, $IC_{S_2}$ may bind if $\nu$ is sufficiently low. If the information asymmetry is small, $COC_{S_2}$ is never satisfied and $IC_{S_3}$ bind.

• **Strategy 3**

$e_{S_3}(p, \theta, \hat{\theta}, \hat{\beta}, \hat{\alpha})$ and $q_{S_3}(p, \theta, \hat{\theta}, \hat{\beta}, \hat{\alpha})$ solves:

$$
\begin{align*}
\max_{e, q} & \quad U_{F_{S_3}}(e, q, \hat{\alpha}, \hat{\beta}) = -c_e(e) + \rho(e) \bigl[ \hat{\alpha} + (1 - \hat{\alpha}) \hat{\beta} \bigr] p q - c_p(q, \theta) \\
\text{s.t} & \quad f(p, \hat{\theta}, \hat{\alpha}, e, q) = 0
\end{align*}
$$

\[(COC_{S_3})\]

$$
\begin{align*}
e_{S_3} = -\frac{2q_{S_3}^2 - 2q_{S_3}^4 + 2q_{S_3}^2}{2}, \quad \text{denoting } Z = \hat{\theta} - \hat{\alpha} p \quad \text{and } V = \hat{\theta} - \theta + (1 - \hat{\alpha}) \hat{\beta} p, \quad q_{S_3} \text{ is given by:}
q_{S_3}^4 V + 4 q_{S_3}^3 Z V + 2 q_{S_3}^2 (2 Z^2 - 3) V - 4 q_{S_3} (2 Z V - 1) + 4 Z = 0
\end{align*}
$$

This strategy appears only if the firm cannot choose the first or the second strategy, i.e, if the corresponding cost oil constraint is not satisfied. Indeed, under this strategy, the firm’s payoff is lower than under the two others.
Figure 2: Efficient firm’s payoff when it lies and reveals under PSA as $\alpha$ varies

Figure 3: Inefficient firm’s payoff when it lies and reveals under PSA as $\alpha$ varies
B.3.2 The optimal separating contracts

\[
\max_{(\beta, q), (\beta, \overline{\beta})} U^{psa_1}_G = \nu \rho(\epsilon_{psa_1})(1 - \overline{\beta})[pq^* - c_p(q^*, \overline{\theta}) - c_e(\epsilon_{psa_1})] \\
+ (1 - \nu) \rho(\epsilon_{psa_1})(1 - \overline{\beta})[pq^* - c_p(q^*, \overline{\theta}) - c_e(\epsilon_{psa_1})] \text{ s.t. (44)}
\]

\[
U^{psa_1}_F(\epsilon_{psa_1}, q^*, \overline{\beta}) \geq U_{F_S_1}(\epsilon_{S_1}, \overline{\epsilon}_{S_1}, \overline{\beta}) \quad \text{(IC1)}
\]

\[
U^{psa_1}_F(\epsilon_{psa_1}, q^*, \overline{\beta}) \geq U_{F_S_2}(\epsilon_{S_2}, \overline{\epsilon}_{S_2}, \overline{\alpha}, \overline{\beta}) \quad \text{(IC2)}
\]

\[
U^{psa_1}_F(\epsilon_{psa_1}, q^*, \overline{\beta}) \geq U_{F_S_3}(\epsilon_{S_3}, \overline{\epsilon}_{S_3}, \overline{\alpha}, \overline{\beta}) \quad \text{(IC3)}
\]

\[
f(p, \overline{\theta}, \overline{\alpha}, \epsilon_{psa_1}, q^*) \geq 0 \quad \text{(COC)}
\]

\[
f(p, \overline{\theta}, \alpha, \epsilon_{psa_1}, q^*) \geq 0 \quad \text{(COC)}
\]

\[
\overline{\beta} > \overline{\beta}_{min} \quad \text{(PC)}
\]

\[
\overline{\beta} > \beta_{min} \quad \text{(PC)}
\]

(IC1) is relevant if \(f(p, \overline{\theta}, \overline{\alpha}, \epsilon_{S_1}, q_{S_1}) \geq 0\), (IC2) is relevant if \(f(p, \overline{\theta}, \overline{\alpha}, \epsilon_{S_2}, q_{S_2}) < 0\) and (IC3) is relevant otherwise. (TC1) is relevant if \(f(p, \theta, \overline{\alpha}, \epsilon_{S_1}, q_{S_1}) \geq 0\), (TC2) is relevant if \(f(p, \theta, \alpha, \epsilon_{S_2}, q_{S_2}) < 0\) and (TC3) is relevant otherwise.

Proof of (i)-(iv)

(i) \(\overline{\beta}_{AI} > \overline{\beta}_{AI}\) is a necessary condition, a pooling contract cannot be implemented.
Indeed, for a given contract, the efficient firm always gets a higher payoff when it lies: \(U_{F_{S_1}} = U^{psa_1}_F + (1 - \beta)\Delta \theta q\). If the contract is such as the cost oil constraint \((COC_{S_1})\) is not satisfied, the efficient firm chooses the third strategy. It has the incentive to increase its cost until the cost stop is reached.

(ii) \(\overline{\sigma}_{AI} = \overline{\sigma}_{min}\)
It is straightforward that \(U_{F_{S_2}}\) increases with \(\overline{\sigma}\). \(U_{F_{S_3}}\) also increases with with \(\overline{\sigma}\). Indeed, the efficient firm only chooses the third strategy if the contract \((\overline{\alpha}, \overline{\beta})\) is such that \((COC_{S_1})\) is not satisfied. As \(\overline{\sigma}\) increases, the cost oil constraint is less strong and the firm’s payoff is closer to the one it gets in the first strategy. So decreasing \(\overline{\sigma}\) to its minimum level decreases the firm’s outside opportunity under strategy 1 and 3.
(iii) For the efficient firm only (IC2) and (IC3) matter since $f(p, \bar{\theta}, \alpha_{min}, \xi_{S1}, q_{S1}) < 0$.
Indeed, $\alpha p q_a - c_p(q_a, \theta) > \alpha p q_b - c_p(q_b, \theta), \forall \alpha p - \theta < q_a < q_b$. Yet, $\bar{\theta} - p - \theta < q^* < q_{S1}$ and $\xi_{psa} < \xi_{S1} \iff f(p, \bar{\theta}, \alpha_{min}, \xi_{S1}, q_{S1}) < f(p, \bar{\theta}, \alpha_{min}, \xi_{psa}, q^*) = 0$

(iv) For the inefficient firm only the incentive constraint (IC1) matters.

\[
f(p, \theta, \alpha_{min}, \xi_{psa}, q_{S1}) > 0 \iff f(p, \theta, \alpha, \xi_{psa}, q_{S1}) > 0, \forall \alpha \geq \alpha_{min}. \quad \text{Yet,}
\]
\[
f(p, \theta, \alpha_{min}, \xi_{psa}, q_{S1}) = \frac{\Delta \theta (XH + 2\beta) \sqrt{2\beta X^2 - 2(1 - \beta) H} + X^2 \sqrt{2\beta X^2 - 2(1 - \beta) H}}{2\beta X} \quad \text{(45)}
\]

with $H = \beta X - \Delta \theta > 0$
Since $\Delta \theta (XH + 2\beta) > 0$ and $2\beta X > 0$, a sufficient condition for (45) > 0 is:

\[
\sqrt{2\beta \sqrt{2\beta X^2 - 2(1 - \beta) H} + X^2 \sqrt{2\beta X^2 - 2(1 - \beta) H}} \Rightarrow 2\beta \beta X^2 - 2(1 - \beta) H^2 > 0.
\]

The inefficient firm may always choose the first strategy.

\[
f(p, \theta, \alpha_{min}, \xi_{psa}, q^*) > 0 \iff f(p, \bar{\theta}, \alpha, \xi_{psa}, q^*) > 0 \quad \text{(since } \alpha_{min} \text{ increases with } \theta) \\
\Rightarrow f(p, \bar{\theta}, \alpha, \xi_{psa}, q_{psa2}) > 0 \quad \text{(from lemma 2)} \iff f(p, \bar{\theta}, \alpha, \xi_{psa}, q_{psa}) > 0 \quad \text{(from } \theta < \bar{\theta})
\]

The inefficient firm may never choose the second strategy but it may always choose the first one. Since, the third strategy gives a lower payoff than the first one, only the incentive constraint (IC1) matters.

**The optimal contracts**

As under symmetric information, the optimal contracts can be obtained in two steps. First, from the binding constraint we obtain $\bar{\beta}(\beta)$ and we replace $\bar{\beta}$ by $\beta(\beta)$ in the government objective function. Then, we derive with respect to $\beta$. However, from the constraints we know that $\beta_{AI} > \text{Max } \beta_{AI}$ and $\beta_{psa1}$. In what follows, we report the binding constraints, illustrate the problem and finally give some simulations to illustrate the optimal separating contracts. This simulations allow to determine how large the contract distortion from the first best is. If both incentive constraints bind, the optimal contract is directly given by the binding constraints, only one solution $(\beta_{AI}, \beta_{AI})$ satisfies the constraints.
If for the efficient firm (IC3) binds, $U_{F_{psa1}}(\beta) = U_{FS3}(\pi^{min}(\beta), \bar{\beta})$ gives:

$$\beta(\bar{\beta}) = \left[2^{\frac{3}{2}} \left(U_{FS3}((U_{FS3} + 1)X^2 + 2U_{FS3})\right)^{\frac{1}{2}} + 2 \left(U_{FS3}(X^2 + 4) + X^2\right)\right] X^{-4}$$

(46)

where $U_{FS3} = q_{S3} \left(\frac{(1 - \pi^{min})}{\pi} p + \Delta \theta | q_{S3} - 1 \right) \left(2 \left(\bar{\beta} - \pi^{min} p\right) + q_{S3} \right) \left(q_{S3} (2q_{S3} (1 - \pi^{min} p)) - 2\right)^{-1}$

and $q_{S3}$ is given by (43) where

If for the efficient firm (IC2) binds, $U_{F_{psa1}}(\beta) = U_{FS2}(\pi^{min}(\beta), \bar{\beta})$ gives:

$$\beta(\bar{\beta}) = \left[2^{\frac{5}{2}} \left(U_{FS2}((U_{FS2} + 1)X^2 + 2U_{FS2})\right)^{\frac{1}{2}} + 2 \left(U_{FS2}(X^2 + 4) + X^2\right)\right] X^{-4}$$

(47)

where $U_{FS2} = \left(-\sqrt{2} \left((1 - \pi^{min}) (1 - \bar{\beta}) p - X\right) - 2\right) \left(X + (1 - \pi^{min}) (1 - \bar{\beta}) p - \sqrt{2}\right) 2^{-\frac{3}{2}}$

If for the inefficient firm (IC1) bind, $U_{F_{psa1}}(\bar{\beta}) = U_{FS1}(\bar{\beta})$ gives:

$$\bar{\beta}(\beta) = \left[2^{\frac{3}{2}} \left(U_{FS1}((U_{FS1} + 1)X^2 + 2U_{FS1})\right)^{\frac{1}{2}} + 2 \left(U_{FS1}(X^2 + 4) + X^2\right)\right] \bar{X}^{-4}$$

(48)

where $U_{FS1} = 2\beta - \sqrt{2} \sqrt{\left(\beta \bar{X} - \Delta \theta\right)^2 - 2 \left(1 - \beta\right) \bar{\beta} + \frac{(\beta \bar{X} - \Delta \theta)^2}{2^2}} - 1$

From the binding constraints, we can represent the firm incentive constraints. We can differentiate two cases depending on the size of the information asymmetry:

**High information asymmetry:**
Figure 4: Large $\Delta \theta$: the firms' incentive constraints

Figure 4 illustrates the firm's incentives constraints when the information asymmetry is large. The efficient firm's incentive constraint $IC_2$ is strictly above the inefficient firm's one $IC_1$. For the efficient firm, all the contracts below $IC_2$ are incentive compatible. On the opposite, for the inefficient firm, all the contract above $IC_1$ are incentive compatible. Hence, the set of incentive compatible contracts lie between the two constraints.

It is straightforward that the optimal separating contract is on $IC_2$. Indeed, for a given $\beta = \beta_{AI}$, if $IC_1$ binds, then the government has to offer to the efficient firm $\beta_1$. However, it can increase its payoff by decreasing $\beta$ and keeps $IC_1$ satisfied. At equilibrium, $IC_2$ binds since for a given $\beta$, binding this constraints minimizes the $\beta$ associated.

Low information asymmetry:
Figure 5: Small $\Delta \theta$: the firms’ incentive constraints

Figure 5 illustrates the firm’s incentives constraints when the information asymmetry is small. For low $\beta$, $\bar{\beta}$ (favourable contract for the government), the efficient firm’s incentive constraint $IC_3$ is below the inefficient firm’s one $TC_1$. Since the contracts above $IC_3$ and below $TC_1$ are not incentive compatible, the government cannot separate firm by proposing though contracts. The optimal contract is the one where $TC_1$ and $IC_3$ intersects ($\bar{\beta}_{AI}, \underline{\beta}_{AI}$).

The contracts above ($\bar{\beta}_{AI}, \underline{\beta}_{AI}$) are incentive compatible but since they are less favourable for the government (higher share of the profit oil left to the firm), they are not implemented.

Medium-sized information asymmetry:
Figure 6: Medium-sized $\Delta \theta$: the firms’ incentive constraints

For a small set of $\Delta \theta$, it is possible that both incentive constraints bind for two contracts. This case occurs to the neighbourhood of the switching point from $IC_3$ to $IC_2$. In this case, the government chooses among $(\bar{\beta}_{A1}, \bar{\beta}_{A1})$ and $(\bar{\beta}_{A2}, \bar{\beta}_{A2})$ the contract that maximizes the tax revenue.

C Simulations

For all this simulations we assume $p = 10$ and we let the firm’s efficiency vary.

<table>
<thead>
<tr>
<th>$\theta$</th>
<th>Complete</th>
<th>Concession</th>
<th>$PSA_1$</th>
</tr>
</thead>
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<tr>
<td>$e^*$</td>
<td>$T^*$</td>
<td>$e^*$</td>
<td>$q^*$</td>
</tr>
<tr>
<td>1</td>
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<td>5.4</td>
<td>37.9%</td>
</tr>
<tr>
<td>1.2</td>
<td>27.3</td>
<td>5.2</td>
<td>36.9%</td>
</tr>
<tr>
<td>3</td>
<td>15.6</td>
<td>4</td>
<td>27.9%</td>
</tr>
<tr>
<td>6.5</td>
<td>2.3</td>
<td>1.5</td>
<td>10.4%</td>
</tr>
</tbody>
</table>

Table 1: Optimal contracts and payoffs under symmetric information

Let’s recall that $e^* = \frac{1}{2} e^*; U^*_P = \frac{1}{2} U^*_G$ and that $q^* = q_{psa1} = p - \theta$.

The following tables report the outcome under asymmetric information. We assume $\theta = 1$ and $p = 10$ and we let the probability to face an efficient firm ($\nu$) and the size of the information asymmetry ($\Delta \theta$) vary.

35
\[ \Delta \theta = 5.5 \]
\[ \Delta \theta = 2 \]
\[ \Delta \theta = .2 \]

<table>
<thead>
<tr>
<th>( \nu^C )</th>
<th>( \nu^\tau )</th>
<th>( \nu^{\text{psa1}} )</th>
<th>( \nu^C )</th>
<th>( \nu^\tau )</th>
<th>( \nu^{\text{psa1}} )</th>
<th>( \nu^C )</th>
<th>( \nu^\tau )</th>
<th>( \nu^{\text{psa1}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>27.5%</td>
<td>14.4%</td>
<td>8%</td>
<td>73.6%</td>
<td>-</td>
<td>52%</td>
<td>97.4%</td>
<td>-</td>
<td>51%</td>
</tr>
</tbody>
</table>

Table 2: Exclusion threshold

For \( \nu > \nu^{\text{max}} = \{ \nu^C, \nu^\tau, \nu^{\text{psa1}} \} \), the government excludes the inefficient firm and the efficient firm gets the first best contract.

| \( \Delta \theta \) | \( \nu^C \) | \( \nu^\tau \) | \( \nu^{\text{psa1}} \) |
|---|---|---|
| 5.5 | \( \bar{T} \) | \( \bar{T} \) |
| 2 | \( \bar{T} \) | \( \bar{T} \) |
| 2 | \( \bar{T} \) | \( \bar{T} \) |

Table 3: Optimal complete contracts

<table>
<thead>
<tr>
<th>( \Delta \theta )</th>
<th>( \nu^C )</th>
<th>( \nu^\tau )</th>
<th>( \nu^{\text{psa1}} )</th>
<th>( \bar{T}_p )</th>
<th>( \bar{T}_g )</th>
<th>( \bar{T}_u )</th>
<th>( \bar{T}_e )</th>
<th>( \bar{T}_f )</th>
<th>( \bar{T}_p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.5</td>
<td>( \bar{T}_p )</td>
<td>( \bar{T}_g )</td>
<td>( \bar{T}_u )</td>
<td>( \bar{T}_e )</td>
<td>( \bar{T}_f )</td>
<td>( \bar{T}_p )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>( \bar{T}_p )</td>
<td>( \bar{T}_g )</td>
<td>( \bar{T}_u )</td>
<td>( \bar{T}_e )</td>
<td>( \bar{T}_f )</td>
<td>( \bar{T}_p )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>( \bar{T}_p )</td>
<td>( \bar{T}_g )</td>
<td>( \bar{T}_u )</td>
<td>( \bar{T}_e )</td>
<td>( \bar{T}_f )</td>
<td>( \bar{T}_p )</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4: Optimal concession contract
If $\Delta \theta = 5.5$, (IC3) binds and the inefficient firm incentive constraint is always satisfied at equilibrium. In the two other cases ($\Delta \theta = \{2, .2\}$), both incentive constraints (IC2) and (IC1) bind. If $\Delta \theta = 2$ ($\Delta \theta = .2$), the separating contract is such that the efficient firm gets 13.08 (14.7) whereas the inefficient one gets 2.3 (13.2).

<table>
<thead>
<tr>
<th>$\nu$</th>
<th>$1 - \beta^A$</th>
<th>$1 - \beta^A$</th>
<th>$U^A_G$</th>
<th>$1 - \beta^A$</th>
<th>$1 - \beta^A$</th>
<th>$U^A_G$</th>
<th>$1 - \beta^A$</th>
<th>$1 - \beta^A$</th>
<th>$U^A_G$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1%</td>
<td>25.9%</td>
<td>72.5%</td>
<td>1.8</td>
<td>53%</td>
<td>81%</td>
<td>13.3</td>
<td>46.6%</td>
<td>49%</td>
<td>13.8</td>
</tr>
<tr>
<td>10%</td>
<td>1 - $\beta^*$</td>
<td>-</td>
<td>2.8</td>
<td>53%</td>
<td>81%</td>
<td>13.5</td>
<td>46.6%</td>
<td>49%</td>
<td>13.8</td>
</tr>
<tr>
<td>25%</td>
<td>1 - $\beta^*$</td>
<td>-</td>
<td>6.9</td>
<td>53%</td>
<td>81%</td>
<td>13.9</td>
<td>46.6%</td>
<td>49%</td>
<td>13.8</td>
</tr>
<tr>
<td>50%</td>
<td>1 - $\beta^*$</td>
<td>-</td>
<td>13.7</td>
<td>53%</td>
<td>81%</td>
<td>14.5</td>
<td>46.6%</td>
<td>49%</td>
<td>13.8</td>
</tr>
<tr>
<td>70%</td>
<td>1 - $\beta^*$</td>
<td>-</td>
<td>19.2</td>
<td>1 - $\beta^*$</td>
<td>-</td>
<td>19.2</td>
<td>1 - $\beta^*$</td>
<td>-</td>
<td>19.2</td>
</tr>
<tr>
<td>90%</td>
<td>1 - $\beta^*$</td>
<td>-</td>
<td>24.7</td>
<td>1 - $\beta^*$</td>
<td>-</td>
<td>24.7</td>
<td>1 - $\beta^*$</td>
<td>-</td>
<td>24.7</td>
</tr>
</tbody>
</table>

Table 5: Optimal PSA

<table>
<thead>
<tr>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>low</th>
<th>high</th>
</tr>
</thead>
<tbody>
<tr>
<td>low</td>
<td>$\alpha+\theta$ (exclusion)</td>
<td>$\alpha+\theta$ (separation)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\alpha+\theta$</td>
<td>$\alpha+\theta$ (separation)</td>
<td></td>
</tr>
<tr>
<td>high</td>
<td>$\alpha+\theta$ (exclusion)</td>
<td>$\alpha+\theta$ (separation)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\alpha+\theta$</td>
<td>$\alpha+\theta$ (separation)</td>
<td></td>
</tr>
</tbody>
</table>

Table 6: Types of PSA$_1$ ($\alpha > 50\%$)