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SHIFTING THE BIDDING GAME: REFORM OF AUCTION DESIGN FOR PETROLEUM EXPLORATION AND PRODUCTION RIGHTS IN ARGENTINA

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Shifting the Bidding Game: Reform of Auction Design for Petroleum Exploration and Production Rights in Argentina.

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Abstract

This thesis examines the design of petroleum exploration and production (E&P) rights auctions in Argentina, emphasizing the theoretical and policy implications of President Milei's 2024 *Ley Bases* reform to Hydrocarbon Law 17,319, which introduced royalty bidding as an alternative to the prevailing investment-commitment framework. The study develops a Bayesian auction model in which firms, facing incomplete information, compete after receiving noisy private signals regarding the tract's underlying value. Two mechanisms are examined: (i) work-commitment bidding, where competition is based on the scale of exploration and production expenditures under a flat royalty; and (ii) royalty bidding, where firms bid a royalty rate rather than committing to a fixed investment level. The symmetric Bayesian Nash equilibrium is characterized by numerically solving coupled integro-differential equations, calibrated to the specific conditions of Argentina's hydrocarbon sector. The analysis reveals a key policy trade-off: royalty bidding enhances government rent capture but exposes the state to greater fiscal volatility, whereas work-commitment schemes provide more stable, though typically smaller, revenue flows, limiting the upside from high-quality tracts.

Keywords: Auction of Natural Resources; Bayesian Nash Equilibrium; Petroleum Contract Design; Oil and gas E&P rights; Fiscal Regimes in Extractives; Resource Rent Capture.

JEL Codes: D44; D82; H21; Q35; Q38; Q47; Q48.

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1 Introduction

The allocation of petroleum exploration and production (E&P) rights lies at the intersection of contract theory and public economics. At its core, this process involves the design of mechanisms capable of allocating resource access efficiently while ensuring a fair and sustainable distribution of rents between the state and private operators. This is particularly challenging in the extractive sector, where high sunk costs, informational asymmetries, and intertemporal fiscal trade-offs complicate the formulation of optimal contracts. Governments seek to maximize the value of public revenues derived from oil and gas resources through well-designed fiscal regimes (Van Meurs, 2008). This thesis focuses on a core element of that framework: the choice of bidding variable in first-price sealed-bid auctions for oil and gas exploration and production (E&P) rights. In particular, it examines the theoretical and empirical implications of shifting from investment-based to royalty-based bidding regimes, using Argentina as a case study. Sturzenegger (2008) noted that the complexity of designing oil contracts arises from the interplay between the need to implement a tax system that captures resource rents without significantly distorting investment and production incentives, the problem of time inconsistency that undermines the government's credibility, the asymmetric information between the state and private operators, and the agency issues inherent in state-owned production. In what follows, we analyze the legal framework governing Argentina's upstream sector to contextualize how these mechanisms operate within the country's institutional setting.

In an efficient market, competitive bidding can promote optimal resource allocation; however, one of its defining conditions is the availability of information. The exploration and production of natural resources are inherently uncertain, marked by numerous unknowns. When competition is limited, efficiency must therefore be embedded within the fiscal terms themselves (Johnston, 2003). Auction design typically hinges on two dimensions: the auction format (e.g., first-price sealed-bid, second-price sealed-bid, English, or Dutch) and the bidding parameter, which may involve a single or multiple variable. Focusing on the latter, Mead (1994) identifies four main schemes—work-program bidding, royalty bidding, profit-share bidding, and cash-bonus bidding. Against this broader backdrop of allocation mechanisms, our analysis turns to Argentina—a country with over a century of oil production—where we specifically examine two variants: royalty bidding and work-program bidding.

A concise review of the legal framework shaping auction design for the allocation of oil and gas exploration and production (E&P) rights in Argentina begins with the Mining Code of 1887, the country's first national legislation addressing hydrocarbon extraction. Law No. 12,161 subsequently introduced the first specific hydrocarbon regime, establishing a concessionary system based on royalties and setting a 12% rate for fluid hydrocarbons under Article 401. This framework was consolidated in 1967 by Law No. 17,319, which preserved the 12% royalty while allowing reductions to as low as 5% depending on well productivity, geographic location, and technical conditions. Critically, Article 47 incorporated competitive allocation criteria, requiring that E&P rights be awarded according to the size and timing of bidders' investment commitments. In 1992, Law No. 24,145 transferred jurisdiction over exploration and production to the provinces, a decentralization later entrenched by the 1994 Constitutional Reform, which—through Article 124—enshrined provincial ownership of natural resources. The process culminated in 2006 with Law No. 26,197 (the "Short Law"), which granted provinces full ownership and administrative authority over hydrocarbon deposits located within their territories and up to twelve nautical miles offshore, beyond which jurisdiction remains federal.

Most recently, Law No. 27,007, enacted in 2014 as an amendment to Law 17,319, reaffirmed the use of investment-based criteria for awarding E&P rights, stipulating that licenses be granted to bidders proposing the largest exploration commitments or investment programs, while preserving the option to reduce royalties to 5% for low-productivity areas. The reform also introduced a controversial provision for automatic concession extensions—an institutional feature beyond the scope of this analysis. A decade later, under President Javier Milei, Congress enacted Law No. 27,742 (*Ley de Bases y Puntos de Partida para la Libertad de los Argentinos*), which implemented substantial reforms to the national hydrocarbons regime. Article 125 of this law replaced Article 47 of Law 17,319, shifting the allocation criteria for E&P rights toward royalty-based bidding. Under the new framework, regulatory authorities may prioritize bids according to the royalty rate offered, with firms competing on a rate expressed as "15% + X," where X may be positive, zero, or even negative—permitting offers below the statutory base rate.

This statutory change prompts a fundamental design question in the context of petroleum lease auctions: does shifting the bid variable from ex ante investment commitments to ad valorem royalty rates increase the government's expected rent capture? The answer is theoretically ambiguous. Each mechanism embeds distinct incentive properties and allocative distortions, reflecting alternative policy objectives regarding E&P incentives.

What is the rationale for each allocation regime, and what are the implications of its adoption? Under the investment-commitment format, governments operate within a quasi-fixed royalty framework. Although legislation formally allows the rate to be set between 5% and 12%, in practice discretion is limited, since fiscal revenues scale directly with the chosen rate. Political economy considerations reinforce this constraint, creating a strong bias toward the upper bound—no governor is willing to forgo visible revenue. Assuming symmetric information between firms and the provincial regulator, this setting induces a strategic distortion. Firms anticipate that the government will overstate the expected value of marginal tracts, since it does not fully internalize the private investment risks faced by bidders. Two inefficiencies follow. For low-quality tracts, overestimation drives excessive bidding in work commitments, resulting in ex post projects whose realized productivity cannot justify the sunk investment—ultimately leading to abandonment and allocative inefficiency. For high-quality tracts, even accurate government assessments encounter an institutional revenue ceiling: the 12% cap restricts the fiscal take, leaving a share of the attainable rent uncaptured. By contrast, the rationale for royalty-based bidding rests on the premise that competition among firms endogenously reveals the fiscal rent available to the State. Because the auction format generates competitive pressure, the resulting equilibrium—absent collusion—tends toward allocative efficiency. Politically, the mechanism shields policymakers from the optics of setting low royalties ex ante, which could otherwise be portrayed as a concession of public wealth.

Instead, the royalty rate emerges as a market outcome, mitigating potential accusations of undervaluing high-potential tracts. Competition thus performs a sorting function: high-quality blocks, such as those in the Neuquén Basin, attract higher royalty bids that reflect their superior economic value, while marginal areas can clear at lower rates, preserving their viability. In this way, royalty bidding accommodates geological heterogeneity through the bidding process itself, eliminating the need for discretionary adjustments by the State.

If the royalty bidding regime offers clear advantages, why was it not adopted earlier? The underlying logic guiding policymakers prior to the enactment of the "Ley Bases" reform in 2024 appears to have been the following: bidding solely on the royalty rate could, in theory, yield more efficient allocations, as bids would more accurately reflect the value firms place on the resource. However, this mechanism entails a key drawback: without minimum investment commitments, firms retain the option to underexploit the field relative to the socially optimal extraction path. As a result, even when firms submit high royalty bids for high-quality reservoirs, fiscal revenue ultimately depends on actual extraction. If production does not occur—whether because the firm underinvests, delays development, or abandons the project—the government may receive little to no revenue, despite the apparently attractive royalty bid. To mitigate this risk, provincial governments tended to favor mechanisms that ensured greater fiscal certainty—such as minimum investment-commitment schemes—even at the expense of reduced allocative efficiency. This choice reflects a precautionary logic: securing a minimum level of investment and fiscal revenue, even at the expense of foregoing potential extraordinary rents. Although such reasoning may appear suboptimal from the perspective of dynamic efficiency, it was arguably rational for political actors primarily focused on short-term fiscal flows rather than on the intertemporal maximization of resource value. Moreover, both regimes are exposed to the winner's curse, but they differ in how risk is allocated. Under investment-commitment bidding, overestimating field value may lock the winner into excessive, loss-making investments. By contrast, under royalty bidding, fiscal obligations scale with actual production, shifting a greater share of the overestimation risk to the State while providing firms with greater ex post flexibility. An important aspect to evaluate is whether one bidding system generates more fiscal volatility than the other, and how this volatility changes when uncertainty about reservoir quality increases. In practice, this means examining how each mechanism translates noisy geological information into more or less variable government revenues.

The monetization of Vaca Muerta generated a major informational shift, sharply raising expectations about Argentina's hydrocarbon potential. The country now holds the world's fourth-largest stock of technically recoverable shale resources (Oil & Gas Journal, 2024), and production already exceeded 508,000 barrels per day by mid-2025 (Reuters, 2025a). Rystad Energy projects that output could surpass one million barrels per day by 2030 once midstream bottlenecks are resolved (Reuters, 2023). Under the current work–commitment framework with a 12% royalty, the NPV of Argentina's proven oil reserves (P1) is approximately USD 37.6 billion at a Brent price of USD 65/bbl, of which the government captures about 32.8%. For natural gas, proven reserves (P1) are valued at roughly USD 9.5 billion at USD 3.5/MMBtu, with a government take of 27.9%. When proven plus probable reserves (P2) are considered, NPVs rise to USD 58.5 billion for oil and USD 15.2 billion for gas. These figures assume full information and exclude contingent resources, which would further increase total valuations. Given the high economic value of the resource, even small gains in allocative efficiency can significantly increase provincial fiscal revenues. The upward revision of reserves, especially in the Neuquén Basin, has heightened interest in capturing a larger share of fiscal rents without discouraging investment. The central question is whether changing the auction's bidding variable can enhance the government's rent capture.

The remainder of this thesis is organized as follows. Section 2 reviews the theoretical and empirical literature on petroleum auction design and fiscal regimes, emphasizing the trade-offs between rent capture, efficiency, and risk allocation. Building on this foundation, Section 3 develops the formal model, detailing the Bayesian auction framework, the informational and cost structure, and the derivation of equilibrium bidding strategies under both royalty and work-commitment schemes. Section 4 then outlines the computational methodology and calibration procedure, which set the stage for Section 5, where the numerical results are presented and discussed, comparing government rent capture and revenue volatility across mechanisms. Finally, Section 6 concludes by summarizing the main findings, discussing their policy implications for Argentina's hydrocarbon sector, and suggesting avenues for future research.

2 Literature review

This thesis is situated at the intersection of several bodies of economic research. It draws on the common–value auction literature (Wilson 1977; Milgrom and Weber 1982), which studies bidding behavior when firms hold noisy private signals about a shared underlying value—an environment that closely describes hydrocarbon exploration. It also relates to the mechanism–design literature on public resource allocation (Laffont and Tirole 1993), where a regulator selects contractual forms under asymmetric information. A further foundation is the empirical and applied research on petroleum leasing (Capen, Clapp, and Campbell 1971; Reece 1978; Hendricks, Porter, and Wilson 2001), which documents winner's–curse dynamics, geological uncertainty, and the institutional features of offshore leasing systems.

The first relevant literature concerns common–value auctions, which analyze settings where bidders form private but imperfect estimates of a common payoff. Seminal contributions by Wilson (1967, 1977) and Milgrom and Weber (1982) characterize equilibrium strategies and show how information asymmetries create bid shading, participation thresholds, and the winner's curse. Experimental and theoretical work (Kagel and Levin 1986, 2002) further demonstrates that bidders internalize this risk and reduce bids as signal variance increases or competition intensifies. This framework fits naturally with oil and gas leasing, where firms infer tract value from imperfect geological information and uncertainty is resolved only after exploration. The modeling structure adopted in this thesis—lognormal tract values, Gaussian signals, and symmetric Bayesian–Nash strategies—directly follows this tradition.

A second line of work comes from mechanism design, which examines how a principal allocates rights under asymmetric information and selects mechanisms that satisfy incentive-compatibility and participation constraints. Foundational contributions (Laffont and Tirole 1993) show that the optimal mechanism depends on information structures, investment incentives, and risk allocation. In extractive industries, these insights explain why fiscal instruments differ in efficiency, since each mechanism induces a different mapping from private signals to bids and generates distinct fiscal outcomes.

The most applied body of research is the petroleum leasing literature. Early OCS studies (Capen, Clapp, and Campbell 1971) provided the first formal evidence of the winner's curse in hydrocarbon auctions. Crawford (1970) and Reece (1978) developed tract–valuation models under geological uncertainty, showing that multiplicative subsurface attributes imply approximately lognormal value distributions. Empirical research by Hendricks, Porter, and Wilson (1987, 1993, 2001) confirmed that bidding behavior in OCS auctions reflects common–value predictions: bidders shade bids as competition intensifies, condition participation on their private signals, and internalize the risk of overestimation. More recent evidence by Hendricks, Pinkse, and Porter (2003) reinforces this view by showing that OCS leases contain both private and common components, but that the common–value dimension is dominant, generating clear winner's–curse effects to which bidders respond strategically. Additional structural analyses by Li, Perrigne, and Vuong (2000) further highlight the importance of common–value uncertainty in wildcat tracts, documenting bid shading and participation patterns consistent with winner's–curse considerations. Complementing this, Porter (1995) shows that incumbents with superior geological information hold systematic advantages in OCS auctions, demonstrating how informational asymmetries shape bidding behavior and allocation outcomes.

The U.S. OCS institutional setting served as a natural laboratory for comparing allocation mechanisms. The 1978 Amendments to the OCS Lands Act prompted federal agencies to experiment with nine auction formats—from cash bonuses with fixed royalties to tapering royalties, sliding scales, profit–sharing schemes, and binding work commitments (U.S. Congress, 1978). This experimentation coincided with a wave of theoretical work analyzing how different bid variables perform under uncertainty. Reece (1978, 1979) developed the canonical bonus–bidding model and extended it to royalty and profit–sharing schemes, highlighting trade–offs between rent capture and investment incentives. Complementary studies (Leland 1978; Marsh 1980; Cox et al. 1983; Mead 1984) clarified how fiscal instruments allocate risk, shape participation, and affect revenue. Marsh (1980) emphasized the revenue advantages of bonuses with modest royalties; Cox, Isaac, and Smith (1983) focused on risk sharing and incentives; Mead and coauthors (1983, 1984) documented how participation, joint bidding, and geological selection affect tract performance; Moody (1994) reported that sliding–scale royalties did not expand competition; and Watkins and Kirkby (1981) showed that Alberta's upfront bidding system captured a large share of expected rents, whereas royalties alone failed to capture ex post windfalls.

Building on these foundations, a comparative literature examines how countries choose among fiscal regimes. Johnston (2003, 2010) surveys royalties, production-sharing contracts, and profit-based taxes, highlighting trade-offs between government take, investor risk, and administrative capacity. Tordo (2007) and Sunley, Baunsgaard, and Simard (2003) show that developing countries rely heavily on ad valorem royalties and signature bonuses, while mature producers increasingly adopt profit- or rent-based instruments. Political economy factors also matter: governments with short horizons or pressing fiscal needs tend to favor front-loaded revenues through bonuses or flat royalties (Robinson, Torvik, & Verdier 2006; Collier & Venables 2011), even when these instruments distort investment. More sophisticated regimes, such as profit taxes or production-sharing contracts, offer higher long-term rent capture but require strong monitoring capacity and patience (Daniel, Keen, & McPherson 2010; Osmundsen 2005). This helps explain the persistence of simple but distortionary mechanisms despite their efficiency costs.

Taken together, these contributions provide the foundation for evaluating alternative allocative mechanisms. By extending Reece's (1978) common–value framework to compare royalty and work–commitment bidding, this thesis examines how the choice of bid variable shapes government rent capture under geological uncertainty.

3 The model

Consider a one-shot, first-price sealed-bid auction in which $n \in N$ symmetric firms compete—absent collusion—for the exclusive exploration and production (E&P) rights to oil and gas within a delimited lease area. Each firm $i \in \{1, \ldots, n\}$ receives a private, noisy signal about the true value of the resource $v > 0$. Based on this information, the firm submits a bid aimed at maximizing its expected profit $E[\pi_i]$, conditional on incomplete knowledge of v. The n firms are symmetric, sharing identical risk preferences and homogeneous expectations. They participate in two distinct auction formats: royalty bidding and work-commitment bidding. Under a royalty bidding scheme, the lease is awarded to the firm that offers the highest fraction $b(s_i) \in [0, 1)$ of the gross wellhead value $v \cdot I(v)^{\alpha}$ of oil and gas as a payment to the government. In contrast, under a work-commitment bidding scheme, the concession is granted to the firm that commits to the highest level of investment $I(s_i, v) \geq 0$ in exploration and development activities. Due to the symmetry of the environment, the game admits a unique symmetric, continuously differentiable Bayesian Nash equilibrium in which all firms adopt identical bidding strategies $x(s_i)$, where $x(s_i)$ denotes either the royalty schedule $b(s_i)$ or the investment function $I(s_i, v)$, depending on the auction format. We make the following assumptions:

Assumption A1: The tract's true economic value v is a strictly positive random variable following a lognormal distribution:

$$v \sim \text{Lognormal}(\mu, \sigma^2), \quad v > 0,$$

where μ and σ^2 are, respectively, the mean and variance of $\log v$. This ensures v remains positive, consistent with the economic nature of the resource. Each firm $i \in \{1, \ldots, n\}$ receives a private, noisy signal

$$s_i = v \cdot \varepsilon_i,$$

where $\log \varepsilon_i \sim N(0, \sigma_s^2)$, independently across firms and conditional on v. Equivalently,

$$s_i \mid v \sim \text{Lognormal}(\log v, \sigma_s^2),$$

with conditional density $g(s_i \mid v)$. After the auction, the winning firm learns v with certainty. The value of an oil and gas lease is typically modeled as lognormal because it results from the product of several independent geological factors. As Reece (1978) notes, this assumption is supported by two observations: bids for petroleum tracts are empirically close to lognormal, and the multiplicative structure of subsurface uncertainty implies a lognormal distribution by the Central Limit Theorem in logs.

Assumption A2: Each participant faces an extraction function $\psi(I)$, where $I \geq 0$ represents sunk and non-contractible investment. We assume:

$$\psi(I) = I,$$

which is increasing and convex in I. The stochastic component of the payoff arises exclusively from the unknown v. The function $\psi(I)$ is common knowledge to all firms and to the government.

Assumption A3: The gross value of a tract is given by:

$$\Phi(v, I) = v \cdot I^{\alpha}, \quad 0 < \alpha < 1,$$

which is increasing and concave in I. For firm i, the net value of the lease after paying an ad valorem royalty b is:

$$NV_i = (1 - b)\big(v \cdot I^{\alpha} - I\big) - fc,$$

where $fc > 0$ denotes the fixed operating cost.

Assumption A4: Each firm's bidding strategy is a function of the following parameters of the game:

1. Auction format: royalty bidding or work-commitment bidding.
2. Private signal s_i about the true value v.
3. Investment cost function $\psi(I) = I$.
4. Parameters (μ, σ^2) of the distribution of v.
5. Signal-noise variance σ_s^2, capturing informational uncertainty about v.
6. Number of participating firms $n \in N$, affecting the probability of winning.
7. Output elasticity of investment α, governing returns to scale.

3.1 Royalty bidding formulation

We build on the framework of Reece (1979), introducing two main extensions. First, we specify the extraction cost through the function $\psi(I)$, which provides a more realistic representation of production cost structures than a simple fixed-cost specification. Second, we introduce the production function $\Phi(v, I)$, which jointly captures the tract's intrinsic value v and the level of investment I, thereby providing a more complete depiction of the extraction process. In the royalty bidding scheme, the strategic variable is the ad valorem royalty rate $b \in [0, 1)$, defined as the fraction of the gross value of production remitted to the government by the winning bidder. Given this setup, the firm's problem is to maximize the following expression:

$$\max_{b(s)} \int\int \Big[(1-b(s))\big(v\cdot I(v)^{\alpha}-I(v)\big)-fc\Big]\cdot F(b,v)\cdot g(s|v)\cdot h(v)\ \cdot ds\ \cdot dv \tag{1r}$$

where:

$F(b,v)$ denotes the probability of winning the auction with bid b when the tract's true value is v. Negative bids are not admissible; therefore, $F(b,v)=0$ for $b<0$;

$g(s\mid v)$ is the conditional probability density function of observing signal s given the true value v;

$h(v)$ is the prior probability density function of the true value v;

$fc>0$ is the fixed operating cost associated with production;

$I(v)$ is the endogenous investment function, representing the firm's optimal investment choice conditional on the resource value v, and derived from its profit-maximization problem.

At equilibrium, when all firms follow identical strategies, the probability $F(b,v)$ of winning with bid b equals the probability that all $n-1$ rivals receive less favorable signals than s (refer to subsection 7.3 for details). This is given by $G(s\mid v)^{n-1}$, where G is the cumulative distribution function associated with g. The firm's optimization problem is given by:

$$\max_{b(s_i)} \int\int \Big[(1-b(s_i))\big(v\cdot I(v)^{\alpha}-I(v)\big)-fc\Big]\cdot G(s_i|v)^{n-1}\cdot g(s_i|v)\cdot h(v)\ \cdot ds\ \cdot dv \tag{2r}$$

Proposition 1. *The symmetric Bayesian Nash equilibrium in the royalty-bidding framework is characterized by the following system of equations:*

$$\frac{db(s_i)}{ds_i}=\frac{\int_0^{\infty}\big(\big[(1-b_i(s_i))\big(v\cdot I(v)^{\alpha}-I(v)\big)-fc\big]\cdot(n-1)\cdot G(s_i\mid v)^{n-2}\cdot g(s_i\mid v)\big)\cdot r(v\mid s)\ \cdot dv}{\int_0^{\infty}\big((v\cdot I(v)^{\alpha}-I(v))\cdot G(s_i\mid v)^{n-1}\big)\cdot r(v\mid s)\ \cdot dv} \tag{7r}$$

$$I(v)=(\alpha\cdot v)^{\frac{1}{1-\alpha}} \tag{8r}$$

$$b_i(s_o)=0 \tag{9r}$$

where s_o satisfies:

$$\int_0^{\infty}((v\cdot I(v)^{\alpha})\ \ -I(v)-fc)\cdot G(s_o\mid v)^{n-1}\cdot r(v\mid s_o)\,dv=0$$

Proof in subsection 7.3

Solving equation (7r) subject to the initial condition (8r) yields the equilibrium bidding strategy $b_i(s)$, common to all firms in the symmetric Bayesian Nash equilibrium. Substituting this function into expression (1r) allows the computation of a firm's expected payoff under the derived strategy.

3.2 Work-Commitment bidding formulation

Under work-commitment bidding, leases are awarded to firms that commit to a specified program of exploration, development, production, transportation, and related activities deemed desirable by the leasing authority (Mead, 1994). In our model, this commitment is measured by the total dollar value of work units—a standardized metric encompassing all activities associated with resource exploration and production—and is operationalized as the firm's investment level I devoted to resource extraction.

$$\max_{I(s)} \int\int \Big[(1-b)\big(v \cdot I(s,v)^{\alpha} - I(s,v)\big) - fc\Big] \cdot F(I,v) \cdot g(s|v) \cdot h(v)\ \cdot ds\ \cdot dv \tag{1w}$$

where:

$F(I,v)$ denotes the probability of winning the auction with bid I when the tract's true value is v. Since negative bids are not admissible, $F(I,v) = 0$ for $I < 0$;

$I(s,v) = I(v) + I(s_i)$ denotes the firm's investment bid, expressed as the sum of:

1. the ex-ante component $I(v)$, obtained from the firm's internal maximization of investment given v, and
2. the incremental component $I(s_i)$, derived from the private signal s_i.

This separation into two components ensures that the bidding function is monotone increasing; relying solely on $I(s_i)$ undervalues the final investment, as it effectively imposes an artificial cap on the firm's commitment. By adding the ex-post component $I(v)$, the model guarantees that when the true value v exceeds the private signal s, the firm can optimally commit to a higher investment. The model assumes that, once the auction is awarded, both the winning firm and the government observe the true value v. Under this ex post information structure, the firm may increase its investment beyond the committed level, but never reduce it; the commitment thus functions as a binding minimum. We treat the committed investment as a fully contractible variable. In practice, enforcement may be imperfect, firms may default or underinvest, and governments rely on penalties to deter such behavior, but we abstract from these frictions and assume full compliance for analytical simplicity.

In this setting, the royalty rate b is fixed by the government and thus exogenous to the firm. With symmetric strategies, the probability of winning with investment I is $F(I,v) = G(s \mid v)^{n-1}$, the likelihood that all $n-1$ rivals receive lower signals. The work-commitment bidding problem is therefore:

$$\max_{I(s_i)} \int\int \Big[(1-b)\big(v \cdot I(s_i,v)^{\alpha} - I(s_i,v)\big) - fc\Big] \cdot G(s_i|v)^{n-1} \cdot g(s_i|v) \cdot h(v)\ \cdot ds\ \cdot dv \tag{2w}$$

Proposition 2. *The symmetric Bayesian Nash equilibrium in the work-commitment bidding framework is characterized by the following system of equations:*

$$\frac{dI(s_i)}{ds_i} = \frac{\int_0^\infty \Big[\Big[(1-b)\big(v \cdot I_i(s_i,v)^\alpha - I_i(s_i,v)\big) - fc\Big] \cdot (n-1) \cdot G(s_i \mid v)^{n-2} \cdot g(s_i \mid v)\Big] \cdot r(v \mid s) \cdot dv}{-\int_0^\infty \Big[\big((1-b) \cdot (v \cdot \alpha \cdot I_i(s_i,v)^{\alpha-1} - 1)\big) \cdot G(s_i \mid v)^{n-1}\Big] \cdot r(v \mid s) \cdot dv} \tag{7w}$$

$$I(s_i, v) = (\alpha \cdot v)^{\frac{1}{1-\alpha}} + I(s_i) \tag{8w}$$

$$I_i(s_o) = 0 \tag{9w}$$

where s_o satisfies:

$$\int_0^\infty ((v \cdot I(v)^\alpha) \ - I(v) - fc) \cdot G(s_o \mid v)^{n-1} \cdot r(v \mid s_o)\, dv = 0$$

Proof in subsection 7.4

Solving equation (7w) subject to the initial condition (8w) yields the equilibrium bidding function $I_i(s)$, common to all firms in the symmetric Bayesian Nash equilibrium. Substituting this function into expression (1w) allows the computation of the firm's expected payoff.

3.3 Government Rent Capture

As our objective is to compare the government rent capture achieved under each auction mechanism, we measure it as the ratio of actual government revenue to the maximum expected rent attainable if all economically viable tracts were developed and all uneconomic tracts avoided. In both cases, the denominator corresponds to the total expected rent inherent in the resource prior to extraction—defined as the gross value of the resource net of fixed costs across all tracts. This measure of government rent capture is particularly suitable for our setting because it isolates the fiscal performance of each auction mechanism from the underlying economic viability of the tracts. By normalizing actual government revenue by the maximum expected rent attainable in the absence of allocative distortions, the metric controls for differences in tract quality and for the endogenous investment responses embedded in the model. Moreover, given the mathematical complexity of solving the bidding functions numerically—where both $b(s)$ and $I(s)$ are obtained from nonlinear differential equations—this ratio provides a tractable and robust summary statistic. It circumvents the need to separately track firm-level decisions, cutoffs, and participation thresholds, all of which interact in non-linear ways within the equilibrium solution.

For the royalty-bidding case, the government rent capture G_r is obtained by substituting the equilibrium bidding function $b_i(s)$ from (1r) into the revenue expression. The resulting measure of maximum expected rent capture is:

$$G_r = \frac{n\displaystyle\int_0^{\infty}\int_0^{\infty} b(s)\cdot\big(v\cdot I(v)^{\alpha} - I(v)\big)\cdot G(s|v)^{n-1}\cdot g(s|v)\cdot h(v)\ \cdot ds\ \cdot dv}{\displaystyle\int_{I(v)+fc}^{\infty}\big((v\cdot I(v)^{\alpha} - I(v)) - fc\big)\cdot h(v)\ \cdot dv} \tag{9r}$$

For the work-commitment bidding case, the government rent capture G_w is obtained by substituting the equilibrium bidding function $I_i(s)$ from (1w) into the revenue expression. The resulting measure of maximum expected rent capture is:

$$G_w = \frac{n\displaystyle\int_0^{\infty}\int_0^{\infty} b\cdot\big((v\cdot I(s,v)^{\alpha} - I(s,v)\big)\cdot G(s|v)^{n-1}\cdot g(s|v)\cdot h(v)\ \cdot ds\ \cdot dv}{\displaystyle\int_{I(s,v)+fc}^{\infty}\int_0^{\infty}\big((v\cdot I(s,v)^{\alpha} - I(s,v)) - fc\big)\cdot g(s|v)\cdot h(v)\ \cdot ds\ \cdot dv} \tag{9w}$$

4 Numerical Solution

The auction environment is modeled as a Bayesian game with incomplete information. Each firm observes a private, noisy signal s regarding the tract's true economic value v. In a symmetric Bayesian Nash equilibrium, the optimal bidding strategies are governed by a system of coupled, nonlinear Euler–Lagrange differential equations of the form:

$$\frac{db(s)}{ds} = F\big(b(s), s; \theta\big), \qquad \frac{dI(s)}{ds} = F\big(I(s,v), s; \theta\big), \tag{7r and 7w}$$

where $\theta = (\alpha, fc, n, \sigma_v^2, \sigma_s^2)$ denotes the vector of structural parameters governing preferences, cost structure, competitive intensity, and informational uncertainty. Analytical characterization is hindered by two interrelated features of the problem. First, the equilibrium conditions are nonlinear and endogenous, as each firm's payoff involves fractional-polynomial interactions between its bid—either the royalty rate $b(s)$ or the investment commitment $I(s)$—and the estimated resource value, making the Euler–Lagrange equations depend on both the strategy and its derivative. Second, computing the optimal bid for any signal s requires expectations over the conditional distribution of v given s, yielding a coupled system of integro-differential equations in which each decision rule depends on the full joint distribution of signals and fundamentals. Given these complexities, we solve the model numerically by calibrating structural parameters to economically plausible values, discretizing the signal space on an adaptive grid, and applying numerical methods to approximate the equilibrium strategy trajectories.

4.1 Computational Framework

All numerical routines were implemented in `MATLAB` using a two-stage procedure. In the first stage, the equilibrium bidding strategies $b(s)$ and $I(s)$ are obtained by solving the nonlinear ODEs in (7r) and (7w) over an adaptive grid covering the signal domain. The boundary conditions $b(s_0) = 0$ and $I(s_0) = 0$ are set from the participation threshold s_0. The ODEs are solved with `ode45` under specified tolerance levels, where each step involves numerical integration over the conditional distribution of v given s. The discrete outputs are then interpolated with cubic splines to produce continuous strategy profiles. In the second stage, these strategies are substituted into the government rent capture expressions (9r) and (9w). The double integrals are computed via numerical quadrature on a tensor-product grid over s and v. The implementation incorporates bidder count, signal variance, fixed costs, and the participation constraint, ensuring that only economically viable tracts are included in the denominator of the rent capture ratio.

4.2 Parameters

Table 1 summarizes the baseline parameterization and the ranges explored in the sensitivity analysis, focusing on two auction fundamentals: the precision of bidders' private information(σ_s^2 and the intensity of competition (n). Uncertainty has two orthogonal sources: geological heterogeneity, governed by the prior variance $\sigma_v^2 = 0.5$; and information risk, given by the conditional variance $\sigma_s^2 \in \{0.75, 1.05, 1.35, 1.65, 1.95, 2.25\}$. The latter spans settings from highly informative signals (e.g., post-appraisal drilling) to low-precision environments (e.g., early-stage seismic data). The degree of competition is captured by the number of symmetric bidders $n \in [2, 15]$, enabling analysis of how equilibrium bidding functions and expected rent capture adjust as the market structure shifts from concentrated to highly competitive regimes. All variables are unit-free, as payoffs are expressed as shares of total revenue, rendering the model scale-invariant. The common-value component v follows a log-normal distribution, while each bidder observes a conditionally log-normal signal s that provides an unbiased yet noisy estimate of v.

Table 1: Model Parameters

Symbol	**Description**	**Baseline**
α	Elasticity of investment	0.50
fc	Fixed operating cost	0.10
μ_v	Mean of $\log v$	0
σ_v^2	Variance of $\log v$	0.50
σ_s^2	Variance of $\log s$	0.75, 1.05, 1.35, 1.65, 1.95, 2.25
n	Number of firms	2–15

The probabilistic structure underlying the model is specified and implemented through the following detailed definitions of distributions and associated functions:

Prior on resource value v: $\log v \sim \mathcal{N}(\mu_v, \sigma_v^2)$ with $\mu_v = 0$, $\sigma_v^2 = 0.50$.

Signal mean function $\mu_s(v)$: $\mu_s(v) = \log v$, so that $E[\log s \mid v] = \log v$.

Conditional CDF of signal $G(s \mid v)$: given v, $\log s \sim \mathcal{N}(\log v, \sigma_s^2)$.

Conditional PDF of signal $g(s \mid v)$: the derivative of $G(s \mid v)$.

4.3 Results

In the royalty-bidding framework, Figure 1 presents the numerical solutions to equation (7r), which define the equilibrium royalty schedule $b(s)$ in a symmetric Bayesian Nash equilibrium. Each panel depicts bidding functions for varying signal variances and numbers of competing firms.

Three robust patterns emerge. First, as the variance of private signals increases, the entire schedule shifts rightward and its participation threshold rises: under greater uncertainty, firms require a stronger signal before submitting a positive royalty rate, thereby mitigating the winner's-curse risk associated with overestimating tract value. Second, holding informational noise constant, intensifying competition (higher n) uniformly lowers and flattens the schedule. Analytically, the factor $G(s \mid v)^{n-2}$ in equation (7r) shrinks with each additional rival, reducing the marginal benefit of raising one's bid and inducing more conservative royalty shares. Third, signal precision governs curvature: when σ_s^2 is low, schedules are steep and tightly clustered—small improvements in s yield substantial increases in b; as σ_s^2 grows, curves fan out and flatten, reflecting the diminished informativeness of marginal signal changes. Together, these numerical regularities demonstrate how firms navigate the trade-off between extracting higher rents and preserving their probability of winning under different degrees of uncertainty and competition.

Figure 1: Royalty Bidding: Equilibrium bidding function $b(s)$ for different levels of σ_s^2

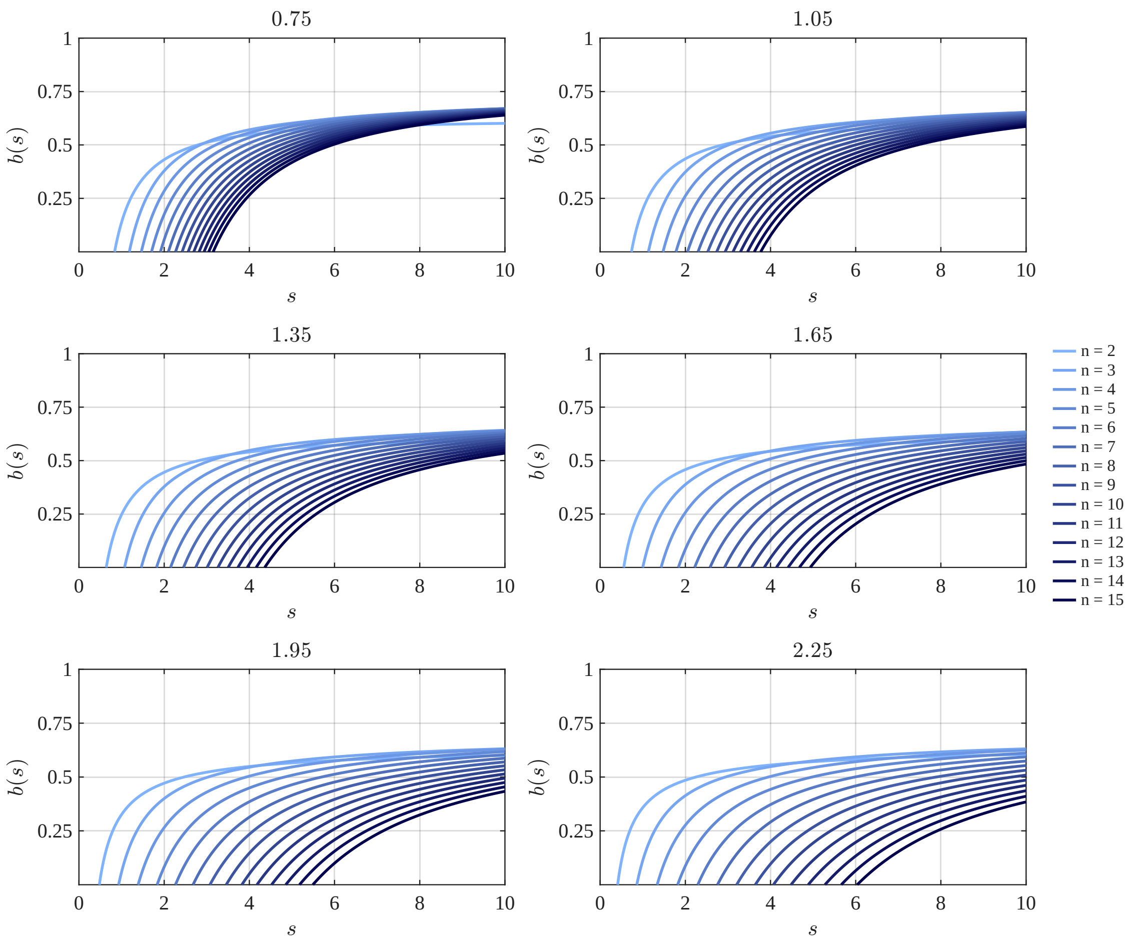
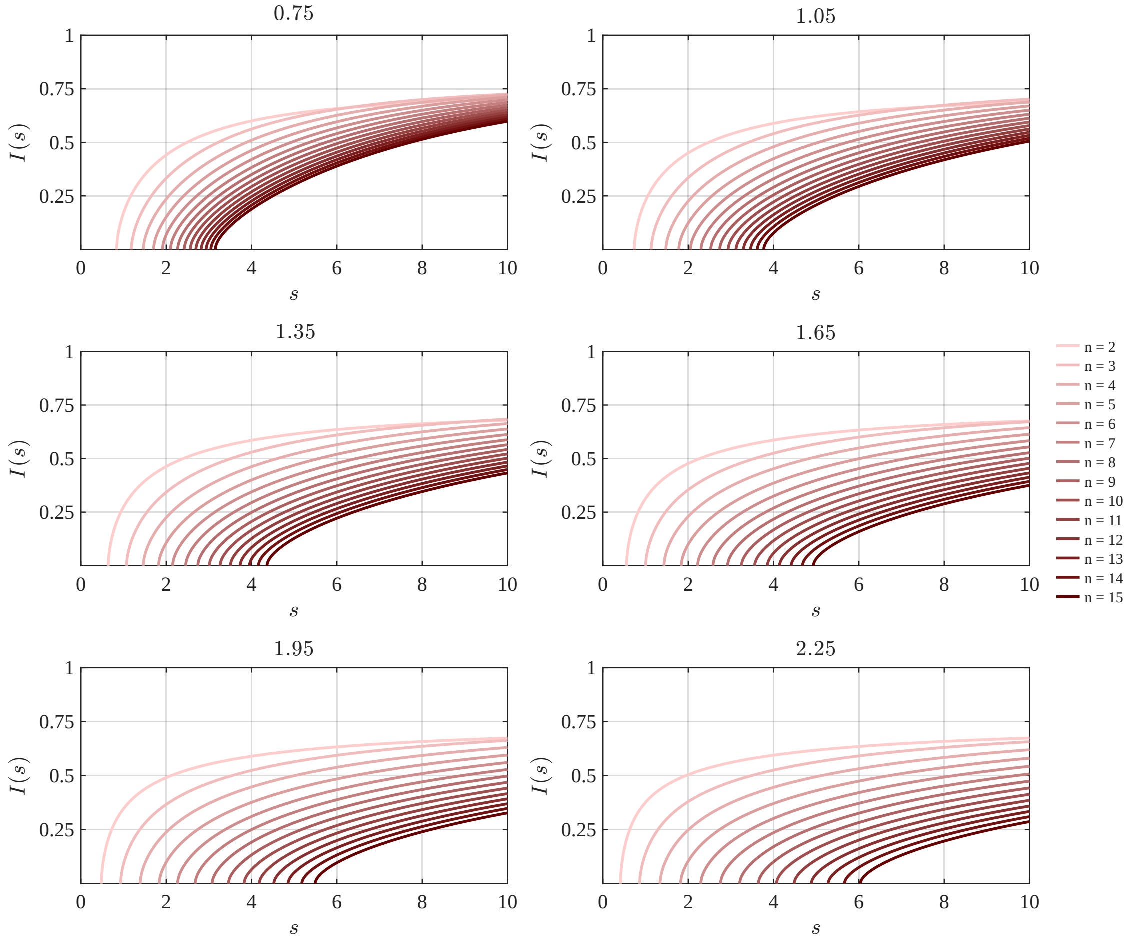


Figure 2 illustrates the equilibrium investment schedules $I(s)$ for the work-commitment bidding mechanism across the same levels of signal variance than royalty bidding. The general logic mirrors that of the royalty-bidding case, and three core regularities likewise emerge. First, as private-signal noise intensifies, the investment curves shift rightward and the participation threshold rises: under greater uncertainty, firms postpone positive investment until observing sufficiently strong signals, thereby guarding against overinvestment when values are overestimated. Second, for any fixed σ_s^2, elevating competition uniformly depresses and flattens the schedules: additional rivals reduce the marginal return to incremental investment, compelling more conservative commitments. Third, signal precision governs curvature: low σ_s^2 yields steep, closely clustered curves—small gains in s trigger substantial increases in $I(s)$—whereas high σ_s^2 produces flatter, more dispersed trajectories, reflecting the diminished informational value of marginal signal improvements.

Figure 2: Work Comitment Bidding: Equilibrium bidding function $I(s)$ for different levels of σ_s^2



In both mechanisms, as the number of competitors increases, the best response $b(s)$ becomes less aggressive. Although this may appear counterintuitive, it is partly explained by the way the solution code determines the initial signal value s_0. In practical terms, when the number of firms rises, the model requires a higher initial signal for bidders to participate in the auction. This shifts the participation threshold to the right and causes the optimal strategy to yield lower bids for comparable signal levels. Since this effect operates identically in both the work-commitment and the royalty bidding mechanisms, its impact is neutral and does not affect the comparison of total government rent captured under each scheme.

To quantify and compare government rent capture across auction formats, we implement the following procedure. First, for each combination of bidder count n and signal-noise variance σ_s^2, we numerically integrate the equilibrium ODEs (7r) and (7w) on a dense grid of private signals s. Next, we interpolate the derived functions $b(s)$ and $I(s)$ over a two-dimensional (v, s) grid and embed them into the tract-level revenue formulas (9r) and (9w). Finally, we compute the resulting double integrals over the joint density of true values v and signals s using a nonuniform trapezoidal rule, where each cell's weight equals the probability mass of its (v, s) bin. The outcome is a smooth revenue surface in (n, σ_s^2) space, which we subsequently analyze to assess and contrast the performance of each auction mechanism.

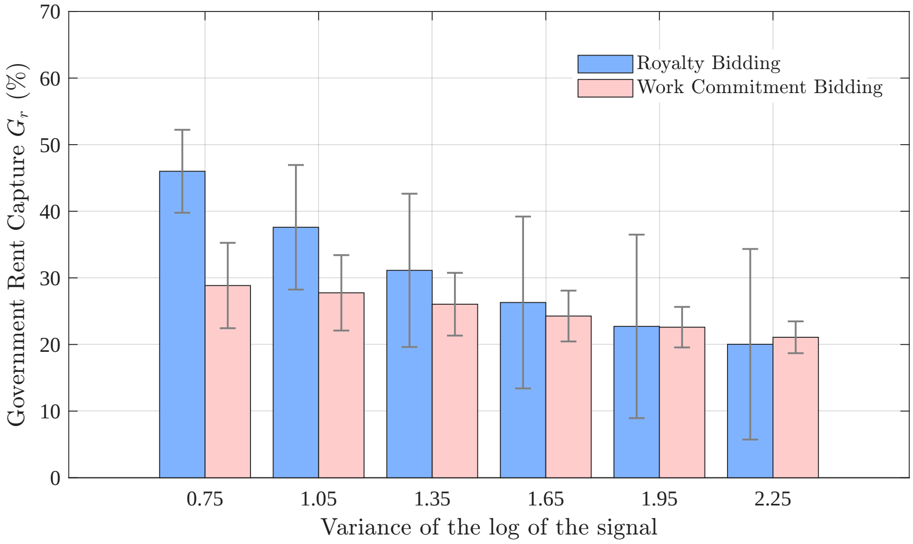
Table 2: Average and Standard Deviation of Rent Capture by Auction Mechanism

	RB		**WCB**	
Var[log S]	$\overline{G}$ (%)	SD (%)	$\overline{G}$ (%)	SD (%)
0.75	46.01	6.00	28.86	6.18
1.05	37.60	9.01	27.76	5.46
1.35	31.13	11.09	26.05	4.54
1.65	26.31	12.43	24.27	3.68
1.95	22.72	13.27	22.60	2.93
2.25	20.04	13.79	21.09	2.30
Average	**30.97**	–	**25.44**	–

Having constructed these revenue surfaces, we now examine their comparative implications. Since the policymaker's objective is to maximize expected total rent capture under each auction format, Table 2 reports, and Figure 3 illustrates, the average percentage of government rent capture. This measure is computed across all simulated combinations of bidder count n and private signal s, based on the symmetric Bayesian Nash equilibrium strategies $b(s)$ and $I(s)$. Results are presented for each signal variance σ_s^2, allowing for a direct comparison between the two auction formats. Absolute rent-capture levels are sensitive to model parameters so relative comparisons across auction formats yield more reliable insights than raw magnitudes. Each bar represents the mean rent capture at each variance level, with vertical whiskers indicating one standard deviation.

Several notable patterns emerge from Figure 3. First, both auction formats display a monotonic decline in mean rent capture as signal variance σ_s^2 increases, reflecting the greater difficulty of extracting surplus under less precise information. Second, royalty bidding achieves a higher average rent capture than work-commitment bidding across most variance levels, albeit with greater dispersion—its error bars are consistently wider, indicating more variability in equilibrium outcomes. For a low-uncertainty environment ($\sigma_s^2 = 0.75$), the government's average rent capture under Royalty Bidding is 46.01% (SD = 6.00%), suggesting that competitive intensity and signal realizations exert only a moderate effect on fiscal outcomes. In contrast, Work-Commitment Bidding yields 28.86% (SD = 6.18%), reflecting more conservative surplus appropriation with similar dispersion. In this regime, the superiority of royalty bidding is clear. As uncertainty rises to an intermediate level ($\sigma_s^2 = 1.05$), the average rent capture under Royalty Bidding drops to 37.60% (SD = 9.01%), while Work-Commitment Bidding delivers 27.76% (SD = 5.46%). The gap narrows, but

Figure 3: Average and Standard Deviation of Rent Capture by Auction Mechanism



royalty bidding retains an advantage. Under high uncertainty ($\sigma_s^2 = 1.65$), the decline is sharper: Royalty Bidding averages 28.15% (SD = 10.50%), compared to 25.34% (SD = 5.12%) for Work-Commitment Bidding, which remains more stable but still lags in expected revenues. At very high uncertainty ($\sigma_s^2 = 1.95$), the two formats converge further, with nearly identical mean captures, though Work-Commitment Bidding dominates by sustaining a lower standard deviation—offering comparable expected revenues with greater consistency.

The model developed in this thesis departs from the independent private values assumption that underpins the Revenue Equivalence Theorem. In petroleum lease auctions, the value of the tract is common to all firms, as it depends on the actual volume and quality of hydrocarbons in place and on future market conditions. Each bidder receives a private signal s_i that conveys imperfect information about the true value. Since all signals are drawn from a conditional distribution, they are correlated through the underlying resource value. This correlation creates a common-value environment in which information is interdependent rather than independent across bidders. In addition, under the work-commitment bidding framework, the assumption of costless participation does not hold, as firms must commit to a minimum investment level $I(s)$ before the true value of the tract is realized. This investment constitutes a sunk and non-recoverable expenditure required to participate and secure exploration rights. Consequently, participation becomes costly and endogenous, with only firms expecting non-negative net returns choosing to enter. The presence of such entry costs affects both the number of active bidders and their bidding strategies, relaxing another key condition of the Revenue Equivalence Theorem and amplifying differences in expected revenues across mechanisms.

The analysis highlights two central features of royalty bidding: its tendency to secure higher expected rent capture for the state, and its greater volatility relative to work-commitment schemes. Under this format, firms bid on the fraction of output to be remitted to the state, enabling them to offer larger rent shares as their private signal s increases—without immediately incurring additional fixed costs. In equilibrium, this yields more aggressive bidding schedules $b(s)$ relative to commitment-based schemes, ensuring that the government's claim on ex post surplus is systematically higher. Furthermore, because royalties are levied directly on realized production, any positive increase in the true field value v translates into proportionate additional revenue for the state, guaranteeing a constant marginal share of any upside. At the same time, the pronounced dispersion in government receipts stems from the fact that royalty revenues are linear in output and thus directly expose the state to fluctuations in both the private signal and the actual field value. As signal noise σ_s^2 increases, firms' extraction decisions and realized production volumes become more variable, and the royalty percentage $b(s)$ amplifies these swings in fiscal receipts. By contrast, work-commitment bids fix the investment ex ante, capping the state's exposure to output volatility and dampening the standard deviation of captured rent.

According to our estimates, under the current work-commitment bidding framework with a 12% royalty, at reference prices of 65 USD/bbl for Brent and 3.5 USD/MMBtu for natural gas, the NPV of oil reserves (P1) amounts to approximately 32.7 billion USD, with firms capturing 67.2% of the rent and the government 32.8%. For natural gas (P1), the NPV amounts to USD 7.6 billion, with a higher firm share of 72.1% and a lower government take of 27.9%. Looking specifically at the government's take, at a reference price of 65 USD/bbl, revenues amount to approximately 15.87 billion USD from non-conventional oil and 1.62 billion USD from conventional oil. At a reference price of 3.5 USD/MMBtu for natural gas, combining both conventional and non-conventional resources, the government's rent capture reaches about 3.25 billion USD. In sum, the government's total NPV from oil and gas amounts to approximately 20.74 billion USD. Therefore, according to our model, on average across all evaluated scenarios, the RB mechanism achieves a relative rent capture about 5% higher than the WCB framework (Table 2). This difference implies that a 5% improvement in rent capture would translate into an additional gain of approximately 1 billion USD for the government, not including the efficiency gains derived from improved allocative outcomes.

5 Conclusion

Four key insights emerge from this analysis. First, across most levels of informational variance, the royalty bidding (RB) mechanism allows the State to appropriate a larger share of resource rents, on average, than the work–commitment bidding (WCB) format. This result is robust across a wide range of parameter values and reflects the fact that royalty bids internalize ex post information about field productivity that work commitments cannot adjust to. Second, this fiscal advantage comes at the cost of greater dispersion: government revenues under the royalty system are more volatile, particularly as signal noise increases. By contrast, the work–commitment mechanism delivers lower average revenues but substantially greater stability, since the ex ante fixed investment requirement dampens variability arising from geological uncertainty and shocks to realized production outcomes. Third, given the evolution of Argentina's upstream sector, the informational environment has changed markedly. Both firms and the government now possess far more precise knowledge about reservoir quality—owing to decades of development in conventional basins and more than fifteen years of continuous learning in Vaca Muerta. With significantly lower uncertainty, the main justification for WCB weakens. In such a setting, the royalty mechanism is better aligned with current industry fundamentals, suggesting that the legacy investment–commitment system is no longer the efficient regulatory choice. Fourth, the analysis quantifies the economic value of the efficiency loss associated with the current work–commitment regime. Importantly, our model indicates that, on average across all evaluated scenarios, the royalty bidding mechanism yields a government rent capture roughly 5% higher than under the work–commitment framework. Quantitatively, this implies that the inefficiency of the current WCB system carries an economic cost of approximately 1 billion USD in foregone government revenue—excluding additional welfare gains that would arise from improved allocative efficiency under a more responsive royalty–based regime.

These aggregate results provide useful context for understanding the institutional sources of variation in rent capture. A key factor explaining the gap between regimes is the institutional ceiling on royalties within the WCB framework. In practice, the system operates within a quasi-fixed structure, where the 12% rate predominates as the de facto benchmark. This structural limit prevents fiscal capture from exceeding that threshold, even in highly productive fields. The results confirm this pattern: work-commitment bidding never reaches the average rent capture levels achieved by royalty bidding in low-variance environments, underscoring how the rule itself constrains the appropriation of extraordinary rents. In practice, if the authority were able to adjust the royalty rate without being constrained by a 12% ceiling or a 5% floor, the auction design would gain allocative efficiency. Assuming that the government observes an informative signal s about the tract's value v, a work–commitment auction would allow the auctioneer to announce a royalty rate b that depends on this signal. In other words, the seller could choose different levels of b according to the quality of its information, tailoring the fiscal burden to the expected characteristics of the resource. Under the current royalty–bidding system, such flexibility is prohibited; however, allowing it could represent an institutional improvement that enhances the mechanism's efficiency.

Our initial hypotheses regarding why the regime change did not occur earlier now appear to be understood in greater depth. First, the two mechanisms differ in the way they allocate the risk associated with the winner's curse. Under the work-commitment bidding format, overestimating the value of the field obliges the firm to undertake an excessive sunk investment, thereby shielding the government from additional losses but exposing the private operator to higher risks of negative profitability. By contrast, under the royalty bidding scheme, fiscal obligations scale proportionally with realized production, shifting part of the risk onto the government and making its revenues directly dependent on both signal variability and the true value of the resource. In this sense, the findings clearly highlight the trade-off between allocative efficiency and fiscal certainty. Second, we gain a clearer understanding of policymakers' preference for a lower certain payoff over a risky prospect with higher upside. Within this framework, the royalty bidding format emerges as more efficient in terms of allocation and rent capture, as it allows the auction to reveal the relative quality of each tract and enables the government to appropriate a larger share of rents in high-productivity areas. However, this efficiency comes at the cost of greater volatility in fiscal revenues. By contrast, work-commitment bidding forgoes part of the extraordinary rents but guarantees a minimum level of development, ensuring a more stable and predictable flow of resources to the public budget.

Overall, the findings indicate that the government's choice of bidding variable depends on the perceived level of uncertainty regarding the E&P rights associated with specific areas. Under high-uncertainty scenarios, a format that guarantees the effective development of the field becomes more attractive. In this respect, the work-commitment scheme with quasi-variable royalties provides the strongest guarantee, as it secures a minimum level of activity. The historical preference of provincial governments for ensuring a "minimum floor" of fiscal revenues is consistent with these results: work-commitment bidding exhibits lower dispersion than royalty bidding. While this implies foregoing part of the extraordinary rents in high-quality fields, it also reduces the risk of non-development. By contrast, when more information about resource quality is available—for instance, in areas such as Vaca Muerta, where geological certainty is high due to accumulated knowledge from adjacent blocks—the more efficient scheme is royalty bidding. In such contexts, firms can be expected to adjust their investment levels optimally, and it becomes more advantageous for the government to appropriate a larger share of the potential upside. An important implication of this observation is that provincial governments may exhibit a higher degree of impatience and risk aversion than private firms. This creates a natural extension of the framework: incorporating the government's objective explicitly into the mechanism-design problem. Rather than treating the government as a passive revenue collector, the analysis can be enriched by allowing the auctioneer to evaluate mechanisms according to the distribution of fiscal outcomes they generate. Under this perspective, the choice between royalty bidding and work–commitment bidding would depend not only on expected revenues but also on the variance and temporal profile of those revenues. In particular, a more risk-averse or impatient government may value the relative stability provided by the work–commitment regime, even if its expected revenue is lower, whereas a government placing greater weight on expected rent extraction would prefer the royalty mechanism. Incorporating these preferences yields a more complete and realistic characterization of mechanism choice in environments where fiscal stability and revenue smoothing are important policy considerations.

In terms of efficiency, the mechanisms are not neutral. Four aspects are particularly relevant. First, the investment–commitment requirement creates an implicit barrier that biases allocation toward larger firms or those with lower capital costs, reducing effective competition and potentially excluding firms that would be efficient under a scheme without upfront sunk costs. Second, an investment–commitment regime combined with a rigid royalty generates inefficiencies in lower–productivity fields: because the fiscal burden cannot adjust to geological heterogeneity, it may unnecessarily push marginal projects out of viability and discourage the development of resources that would be economic under a more flexible royalty structure. Third, both mechanisms affect the timing of investment, but the distortion is stronger under investment commitments: by requiring substantial upfront expenditures, the regime increases the value of wait, inducing firms to postpone development until conditions improve, thereby slowing exploration and production. Fourth, the mechanisms differ in their sensitivity to crude–price fluctuations. When prices fall, the investment–commitment regime becomes particularly problematic because sunk costs do not adjust to new market conditions, increasing the risk of unprofitable projects. In contrast, under a royalty system, payments to the government adjust automatically with price and production, preserving project viability and reducing the likelihood of allocative inefficiencies.

For future research, it would be interesting to relax the assumption of firm homogeneity. This would shed light on three key mechanisms. First, regarding the role of investment costs: investment-commitment regimes tend to favor large firms, which benefit from lower financing costs, stronger balance sheets, and greater access to capital markets. These advantages allow them to commit to higher levels of investment, often beyond the reach of smaller players. As a result, such regimes generate significant entry barriers for medium and small firms, discouraging their participation and reducing the degree of competition in the auction process. In the long run, this dynamic reinforces market concentration, consolidating the dominance of a few large actors and potentially limiting efficiency and innovation in the sector. Second, regarding the role of information: firms already operating in nearby areas are better positioned to anticipate the quality and potential productivity of a new field, as they benefit from accumulated geological knowledge, prior exploration data, and operational experience. This informational advantage reduces their uncertainty and risk perception relative to new entrants, enabling them to design more aggressive bidding strategies. Third, the possibility of extensions: the amendment to Law 17,319 introduced a provision for automatic concession renewals. This reform, widely debated for its implications on competition and fiscal outcomes, created an institutional mechanism that extends operators' control over resources beyond the original contractual horizon. Taken together, these elements help to better understand the position of Yacimientos Petrolíferos Fiscales S.A. (YPF, Argentina's national oil company), whose scale and extensive concessions make it a dominant player.

However, relaxing the assumption of bidder symmetry and introducing an asymmetric environment with a big firm and a set of smaller fringe firms would not overturn the main results of this paper; if anything, it would strengthen them. Under symmetry, the central finding is that the workcommitment mechanism is less efficient and yields lower government rent than royalty bidding. Once a dominant bidder with preferential access to financing and a lower cost of capital is incorporated, the gap between the two mechanisms would likely widen. The intuition is straightforward. First, the presence of a large player reduces effective competitive pressure. Smaller firms, anticipating a lower probability of winning against a dominant bidder, rationally shade their bids and choose less aggressive strategies. This further weakens competition under workcommitment bidding. Second, because the workcommitment mechanism requires sunk investment outlays before the true value of the resource is known, firms with higher financing costs are disproportionately penalized. This exacerbates the competitive asymmetry vis–à–vis a firm like YPF, making entry less attractive and depressing bidding intensity. By contrast, under royalty bidding the fiscal transfer to the government adjusts endogenously to the ex post value of the resource and does not require large up–front capital commitments. As a result, the competitive disadvantage of high–cost firms is mitigated and the presence of a dominant bidder is less distortionary.

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7 Appendix

7.1 NPV of oil reserves in Argentina

Argentina's oil reserves are officially reported by the National Secretariat of Energy. Table 3 summarizes reserves by category as cumulative estimates: P1 (proven) includes volumes recoverable with reasonable certainty under current conditions; P2 adds probable reserves with a recovery likelihood above 50%; P3 further incorporates possible reserves based on geological evidence but with lower certainty; and C1 (contingent resources) refers to volumes not currently considered commercially viable due to technical, economic, or regulatory constraints.

Table 3: Oil Reserves by province in Argentina (in Billion Barrels, cumulative categories)

	Conventional				Non-Conventional			
Province	P1	P2	P3	C1	P1	P2	P3	C1
Chubut	0.95	1.27	1.39	0.11	0.00	0.00	0.00	0.00
La Pampa	0.03	0.04	0.06	0.02	0.00	0.00	0.00	0.00
Mendoza	0.12	0.15	0.18	0.20	0.00	0.00	0.00	0.00
Neuquén	0.03	0.04	0.05	0.46	1.54	2.53	3.43	3.67
Río Negro	0.04	0.04	0.05	0.04	0.00	0.00	0.00	0.01
Santa Cruz	0.24	0.35	0.41	0.33	0.00	0.01	0.01	0.00
Rest	0.04	0.06	0.08	0.03	0.00	0.01	0.01	0.00
Total	1.45	1.92	2.16	1.19	1.55	2.54	3.45	3.69

Source: own elaboration based on data from the Secretariat of Energy, Oil and Gas Reserves.

Table 4 presents the aggregated net present value (NPV) results for firms and government under combined (conventional + non-conventional) oil reserve scenarios. Results indicate that projects remain profitable for firms across all oil price levels, with NPVs rising steadily as prices increase. In the base case (P1, oil price of 65 USD/bbl), the combined firm NPV amounts to 32.7 billion USD, while government revenues reach nearly 5 billion USD. Higher prices magnify results, especially in P2 and P3, where larger reserves boost both private and public returns. For further details on the estimation procedures, readers may refer to Subsection 7.1.1 for non-conventional oil and Subsection 7.1.2 for conventional oil.

Table 4: NPV and rent capture of total oil reserves

	NPV (bn USD)			**Rent Capture (%)**	
Oil Price (USD/bbl)	**P1**	**P2**	**P3**	**Firm**	**Gov**
50	3.09	4.64	5.88	28.0	72.0
55	12.96	20.48	27.11	51.0	49.0
60	22.82	36.34	48.38	61.2	38.8
65	32.68	52.19	69.56	67.2	32.8
70	42.55	68.02	90.75	71.0	29.0
75	52.42	83.89	112.02	74.0	26.0
80	62.28	99.73	133.25	75.9	24.1
Average	–	–	–	**61.2**	**38.8**

7.1.1 NPV of non-conventional oil reserves

The valuation of unconventional oil reserves is based on the aggregation of production profiles across all wells required to exploit the total recoverable reserves R. Given the estimated ultimate recovery per well (EUR), the number of wells N is:

$$N = \frac{R}{\text{EUR}}.$$

Each well's production is modeled using the hyperbolic decline function of Arps (1945):

$$q(t) = \frac{q_0}{(1 + bDt)^{1/b}},$$

where q_0 is the initial production rate (in bbl/d), D the initial decline rate, and b the curvature parameter. The annual production of a single well is given by

$$Q_{\text{well},t} = q(t) \times 365,$$

and the total annual production of the project is

$$Q_t = N \times Q_{\text{well},t}.$$

The total investment cost is determined by multiplying the CAPEX per well by the number of wells:

$$\text{CAPEX}_0 = N \cdot \text{CAPEX}_{\text{per well}}.$$

Operating expenditures are specified on a per-barrel basis. Let OPEX denote the unit cost of lifting and evacuation. Annual operating costs are then:

$$\text{Costs}_t = \text{OPEX} \cdot Q_t.$$

The government's revenue from royalties is modeled as a fixed *ad-valorem* rate roy applied directly to the gross value of production. Formally:

$$\text{Gov}_t = \text{roy} \cdot P \cdot Q_t,$$

where P denotes the international oil price and Q_t is the production level in period t. Unlike taxes on profits, royalties are levied on revenues before deducting either operating or capital costs. This implies that the government secures a share of production value regardless of the project's profitability, while firms bear the full risk of cost fluctuations.

The firm's net cash flow in year t is:

$$CF_t = \big[(1 - \text{roy}) \cdot P \cdot Q_t - \text{OPEX} \cdot Q_t\big].$$

Discounting at rate r, the present value of cash flows is:

$$PV(CF_t) = \frac{CF_t}{(1 + r)^t}.$$

The net present value (NPV) of the project is obtained by summing the discounted cash flows and subtracting the initial investment:

$$\text{NPV} = \sum_{t=1}^{T} \frac{CF_t}{(1+r)^t} - \text{CAPEX}_0.$$

This framework allows us to evaluate both the private NPV for investors and the fiscal take of the government under different oil price scenarios. The model was implemented in MATLAB, using the parameters reported in Table 5.

Table 5: Parameters and assumptions for non-conventional oil valuation

Parameter	**Value**
Estimated ultimate recovery per well (EUR)	500,000 bbl
CAPEX per well	USD 25 million
Initial production per well, q_0	1,200 bbl/d
Initial decline rate, D	70% per year
Hyperbolic parameter, b	0.60
Project horizon, T	25 years
Real discount rate, r	11%
OPEX (lifting + evacuation)	USD 5.00/bbl
Royalty, roy	12%

Table 6 presents the scale of the conventional oil project under three reserve scenarios (P1, P2, P3). Higher reserves translate into a larger number of wells and higher investment needs. In P1, 1.45 billion barrels require about 1,200 wells and a CAPEX of USD 3.6 billion, while in P3, 2.16 billion barrels imply 1,800 wells and USD 5.4 billion.

Table 6: Project scale under reserve scenarios for non-conventional oil valuation

Parameter	**P1**	**P2**	**P3**
Recoverable reserves, R	1.55 bn bbl	2.54 bn bbl	3.44 bn bbl
Number of wells, N	3,104	5,076	6,890
Total CAPEX	77.6 bn USD	126.9 bn USD	172.2 bn USD

Table 7 reports the NPV of non-conventional oil projects and the distribution of rent capture between firms and government under alternative reserve scenarios. As expected, both higher oil prices and larger reserve estimates substantially increase the project's value. In scenario P1, firm NPV rises from USD 1.7 billion at 50 USD/bbl to USD 55.5 billion at 80 USD/bbl, while government revenues (through a 12% royalty) increase from USD 0.2 billion to USD 6.7 billion. Similar upward trends are observed in P2 and P3, confirming the sensitivity of both private and fiscal returns to price and scale. The government captures most of the rent at low prices (87.5% at 50 USD/bbl), but its share declines to 26.1% at 80 USD/bbl as firms retain the upside. This reflects the fixed 12% royalty on gross revenues: at low prices royalties weigh more relative to compressed profits, while at high prices firms capture rising margins, reducing the fiscal take.

Table 7: NPV and rent capture of non-conventional oil reserves

Oil Price (USD/bbl)	**NPV (bn USD)**			**Rent Capture (%)**	
	P1	**P2**	**P3**	**Firm**	**Gov**
50	1.74	2.85	3.86	12.5	87.5
55	10.69	17.48	23.73	44.3	55.7
60	19.64	32.12	43.60	57.3	42.7
65	28.59	46.76	63.47	64.3	35.7
70	37.55	61.40	83.34	68.7	31.3
75	46.50	76.04	103.21	71.8	28.2
80	55.45	90.67	123.08	73.9	26.1
Average	–	–	–	**56.1**	**43.9**

7.1.2 NPV of conventional oil reserves

In the case of conventional oil reserves, the methodology applied follows the same modeling framework as for unconventional resources, relying on the estimation of the number of wells required ($N = R/EUR$), the use of Arps' (1945) decline function to model production, and the construction of discounted cash flows to derive both private NPV and government take. The main difference lies in the calibration of parameters to reflect the specific features of conventional fields, as reported in Table 8: higher EUR per well, lower drilling CAPEX, smaller initial production rates with smoother decline profiles, longer project horizons, and higher unit OPEX. These adjustments capture the distinct economic and geological characteristics of conventional oil, while maintaining methodological consistency with the unconventional case.

Table 8: Parameters and assumptions for conventional oil valuation

Parameter	**Value**
Estimated ultimate recovery per well (EUR)	1,200,000 bbl
CAPEX per well	USD 3 million
Initial production per well, q_0	100 bbl/d
Initial decline rate, D	10% per year
Hyperbolic parameter, b	0.30
Project horizon, T	30 years
Real discount rate, r	11%
OPEX (lifting + evacuation)	USD 20.00/bbl
Royalty, roy	12%

Table 9 summarizes the scale of the conventional oil project across three reserve scenarios. The results show that higher recoverable reserves imply a greater number of wells and larger investment requirements. In P1, 1.45 billion barrels require around 1,200 wells with a total CAPEX of USD 3.6 billion, while in P3, 2.16 billion barrels demand 1,800 wells and USD 5.4 billion. These figures provide the baseline for the subsequent NPV analysis.

Table 9: Project scale under reserve scenarios for conventional oil valuation

Parameter	**P1**	**P2**	**P3**
Recoverable reserves, R	1.45 bn bbl	1.92 bn bbl	2.16 bn bbl
Number of wells, N	1,208	1,602	1,800
Total CAPEX	3.6 bn USD	4.8 bn USD	5.4 bn USD

Table 10 presents the NPV results of conventional oil projects together with the distribution of rent between firms and government across alternative reserve scenarios. As expected, the firm's NPV rises with higher oil prices and larger reserves, ranging from USD 1.35 billion in P1 at 50 USD/bbl to USD 10.17 billion in P3 at 80 USD/bbl. The government's revenue, collected through a fixed 12% royalty on gross production value, also scales with price but remains relatively modest, reaching a maximum of USD 1.22 billion. In terms of rent distribution, the government captures a significant share at low prices (47.8% at 50 USD/bbl), but its relative take decreases as prices increase, averaging only 31.2% across scenarios.

Table 10: NPV and rent capture of conventional oil reserves

	NPV (bn USD)			**Rent Capture (%)**	
Oil Price (USD/bbl)	**P1**	**P2**	**P3**	**Firm**	**Gov**
50	1.35	1.79	2.02	52.2	47.8
55	2.27	3.00	3.38	62.5	37.5
60	3.18	4.22	4.73	67.9	32.1
65	4.09	5.43	6.09	71.6	28.4
70	5.00	6.64	7.45	74.2	25.8
75	5.92	7.85	8.81	76.0	24.0
80	6.83	9.06	10.17	77.4	22.6
Average	–	–	–	**68.8**	**31.2**

7.2 NPV of gas reserves in Argentina

As with oil, Argentina's natural gas reserves are reported by the National Secretariat of Energy. Table 11 summarizes them as cumulative categories: P1 (proven) includes volumes recoverable with reasonable certainty; P2 adds probable reserves with recovery likelihood above 50%; P3 incorporates possible reserves based on geological evidence but with lower certainty; and C1 (contingent resources) covers volumes not currently deemed commercially viable due to technical, economic, or regulatory constraints.

Table 11: Gas Reserves by province in Argentina (in Billion MMBtu, cumulative categories)

	Conventional				Non-Conventional			
Province	P1	P2	P3	C1	P1	P2	P3	C1
Chubut	0.88	1.11	1.19	0.05	0.00	0.00	0.00	0.00
La Pampa	0.03	0.04	0.05	0.04	0.00	0.00	0.00	0.00
Mendoza	0.03	0.04	0.04	0.24	0.00	0.00	0.00	0.00
Neuquén	0.80	1.01	1.26	1.03	12.28	18.26	23.19	27.91
Río Negro	0.10	0.14	0.15	0.08	0.10	0.11	0.11	0.47
Santa Cruz	0.48	0.71	0.85	2.45	0.22	0.26	0.28	0.00
Rest	2.77	5.12	6.61	0.74	0.00	0.00	0.00	0.00
Total	5.09	8.17	10.15	4.63	12.61	18.63	23.59	28.38

Source: own elaboration based on data from the Secretariat of Energy, Oil and Gas Reserves.

Table 12 presents the NPV and rent distribution of total gas reserves, combining conventional and non-conventional resources. At very low prices, projects yield negative NPVs for firms, though the government still collects royalties. In the base case (P1, 3.5 USD/MMBtu), firm NPV reaches USD 7.6 billion and government revenues about USD 1.9 billion. At higher prices (P3, 4.5 USD/MMBtu), firm NPV exceeds USD 27.7 billion, while government revenues remain above USD 5.5 billion. In terms of rent distribution, the government captures a larger share at low prices (42% at 3.0 USD/MMBtu), but its participation declines as profitability rises, averaging 28.2%.

Table 12: NPV and rent capture of total gas reserves

	NPV (bn USD)			**Rent Capture (%)**	
Gas Price (USD/MMBtu)	**P1**	**P2**	**P3**	**Firm**	**Gov**
2.0	-2.59	-3.73	-5.76	–	–
2.5	0.82	1.39	1.71	–	–
3.0	4.23	5.01	8.17	58.0	42.0
3.5	7.64	11.62	14.62	72.1	27.9
4.0	11.05	16.43	21.15	77.3	22.7
4.5	14.46	21.87	27.72	79.7	20.3
Average	–	–	–	**71.8**	**28.2**

7.2.1 NPV of non-conventional gas reserves

The methodology to value non-conventional gas reserves mirrors that of oil, aggregating production profiles across wells to compute the NPV of discounted cash flows net of investment and operating costs. Firm cash flows, government revenues, and project NPVs are calculated identically to the oil case, with differences mainly in units and parameter magnitudes. Gas reserves R and EUR per well are expressed in MMBtu, production rates in MMBtu/day with decline rates calibrated to gas dynamics, and prices in USD/MMBtu. Operating costs are lower on a per-unit basis, while CAPEX per well reflects drilling and completion costs for shale gas. These adjustments ensure the model captures the technical and economic specificities of non-conventional gas projects. The parameters used are summarized in Table 13.

Table 13: Parameters and assumptions for non-conventional gas valuation

Parameter	**Value**
Estimated ultimate recovery per well (EUR)	20,000,000 MMBtu
CAPEX per well	USD 15 million
Initial production per well, q_0	15,000 MMBtu/d
Initial decline rate, D	60% per year
Hyperbolic parameter, b	0.70
Project horizon, T	25 years
Real discount rate, r	11%
OPEX (variable)	USD 0.80/MMBtu
Royalty, roy	12%

Table 14 presents the project scale under alternative unconventional gas reserve scenarios. As expected, higher reserve estimates translate into larger project sizes, both in terms of the number of wells required and the associated capital expenditure. Moving from P1 to P3, the number of wells increases from 630 to 1,179, while total CAPEX rises from 9.5 to 17.7 billion USD, reflecting the scale sensitivity of unconventional developments to reserve assumptions.

Table 14: Project scale under reserve scenarios for non-conventional gas valuation

Parameter	**P1**	**P2**	**P3**
Recoverable reserves, R	12.61 bn MMBtu	18.63 bn MMBtu	23.59 bn MMBtu
Number of wells, N	630	932	1179
Total CAPEX	9.5 bn USD	14.0 bn USD	17.7 bn USD

Table 15 reports the NPV and rent distribution of non-conventional gas projects. At low prices (USD 2.0–2.5/MMBtu), firms record negative NPVs while the government still collects royalties, reflecting the ad-valorem nature of the regime. As prices rise, firm NPVs turn positive and expand sharply, especially under P2 and P3. Government revenues also grow in absolute terms, but their relative share falls from 51.6% at 3.0 USD/MMBtu to 24.6% at 4.5 USD/MMBtu. On average, firms capture 65.2% of the rent, showing how higher prices shift value toward private investors.

Table 15: NPV and rent capture of non-conventional gas reserves

	NPV (bn USD)			**Rent Capture (%)**	
Gas Price (USD/MMBtu)	**P1**	**P2**	**P3**	**Firm**	**Gov**
2.0	-3.41	-5.04	-6.39	-	-
2.5	-0.64	-0.95	-1.20	-	-
3.0	2.13	3.14	3.98	48.4	51.6
3.5	4.90	7.23	9.16	65.0	35.0
4.0	7.67	11.33	14.34	71.8	28.2
4.5	10.44	15.42	19.52	75.4	24.6
Average	–	–	–	**65.2**	**34.8**

7.2.2 NPV of conventional gas reserves

The valuation of conventional gas reserves follows the same framework as for non-conventional gas, with lower EUR per well, smaller initial production rates, and reduced CAPEX, reflecting the maturity of conventional fields. The parameters used are shown in Table 16.

Table 16: Parameters and assumptions for conventional gas valuation

Parameter	**Value**
Estimated ultimate recovery per well (EUR)	15,000,000 MMBtu
CAPEX per well	USD 3 million
Initial production per well, q_0	2,500 MMBtu/d
Initial decline rate, D	10% per year
Hyperbolic parameter, b	0.30
Project horizon, T	30 years
Real discount rate, r	11%
OPEX (variable)	USD 0.50/MMBtu
Royalty, roy	12%

Table 17 summarizes the project scale for conventional gas across reserve scenarios. Recoverable reserves increase from 5.09 to 10.15 billion MMBtu (P1–P3), raising the number of wells from 339 to 677 and total CAPEX from USD 1.0 to 2.0 billion. These results reflect the smaller scale and lower capital intensity of conventional gas relative to non-conventional projects.

Table 17: Project scale under reserve scenarios for conventional gas valuation

Parameter	**P1**	**P2**	**P3**
Recoverable reserves, R	5.09 bn MMBtu	8.17 bn MMBtu	10.15 bn MMBtu
Number of wells, N	339	544	677
Total CAPEX	1.0 bn USD	1.6 bn USD	2.0 bn USD

Table 18 shows the NPV and rent distribution of conventional gas. Projects remain profitable even at low prices (USD 2.0–2.5/MMBtu) due to lower costs. As prices rise, firm NPVs grow steadily, while the government's share averages 20.8%, highlighting greater resilience and fiscal stability compared to non-conventional gas.

Table 18: NPV and rent capture of conventional gas reserves

	NPV (bn USD)			**Rent Capture (%)**	
Gas Price (USD/MMBtu)	**P1**	**P2**	**P3**	**Firm**	**Gov**
2.0	0.82	1.31	1.63	70.0	30.0
2.5	1.46	2.34	2.91	77.0	23.0
3.0	2.10	3.37	4.19	80.1	19.9
3.5	2.74	4.39	5.46	81.8	18.2
4.0	3.38	5.42	6.74	82.8	17.2
4.5	4.02	6.45	8.02	83.6	16.4
Average	–	–	–	**79.2**	**20.8**

7.3 Proof of Proposition 1

Proof. We aim to find a bidding strategy function $b(s)$ that maximizes the objective function given by expression (2r). Before proceeding, we will reverse the order of integration in $(2r)$ to derive the following expression:

$$\int\int \Big[(1-b(s))\big(v \cdot I(v)^{\alpha} - I(v)\big) - fc\Big] \cdot F(b,v) \cdot r(v|s) \cdot dv \cdot p(s) \cdot ds \tag{3r}$$

Where $r(v|s)$ is the conditional distribution of true gross values v given the value estimate signal s. This distribution is obtained from $h(v)$ and $g(s|v)$ by Bayes' theorem. The unconditional probability density function for the value estimate signal received by a firm, $p(s)$ is:

$$p(s) = \int_0^{\infty} g(s|v) \cdot h(v) \cdot dv$$

The integral of two lognormal distributions remains a lognormal distribution. Therefore, $p(s)$ will be lognormal when $g(s|v)$ and $h(v)$ are lognormal. The problem is now reduced to maximizing the inner integral:

$$\int_0^{\infty} \Big[(1-b(s))\big(v \cdot I(v)^{\alpha} - I(v)\big) - fc\Big] \cdot F(b,v) \cdot r(v|s) \cdot dv \tag{4r}$$

Since all firms will adopt identical strategies, the probability $F(b,v)$ of winning the auction is, at equilibrium, the probability that all of the firm's competitors receive more pessimistic estimates of the true value v. To reach this expression, we will consider the maximization of a generic firm i. Thus, the probability of winning for firm i is:

$$F(b_i, v) = \Pr(b_j < b_i \, \forall\, j \neq i)$$

The symmetric equilibrium strategy is the one in which all participants use the same bidding strategy. Given that the function $\hat{b} = b(s)$ is increasing, then $s = b^{-1}(\hat{b})$.

$$F(b_i, v) = \Pr(b(s_j) < b_i \, \forall\, j \neq i)$$

$$F(b_i, v) = \Pr(s_j < b^{-1}(b_i) \, \forall\, j \neq i)$$

$$F(b_i, v) = G(b^{-1}(b_i)|v)^{n-1}$$

$$F(b_i, v) = G(s_i|v)^{n-1}$$

where $G(b^{-1}(b_i)|v)^{n-1}$ is the cumulative distribution function of the inverse bidding function (which maps the bid to the underlying value of the signal s), given a certain value of v. Substituting the function $F(b_i, v)$ with the new expression in Equation (4r), we obtain:

$$\int_0^{\infty} \Big[(1-b_i(s_i))\big(v \cdot I(v)^{\alpha} - I(v)\big) - fc\Big] \cdot G(b^{-1}(b_i)|v)^{n-1} \cdot r(v|s) \cdot dv \tag{5r}$$

Because the game is symmetric, an equilibrium strategy in this game is one that is optimal for each bidder if each other bidder uses it (Wilson 1977). We want to find an expression for $b_i(s)$ that, when substituted into Equation (1r), maximizes the expression. To find the optimal bidding strategy $b_i(s)$, we differentiate the objective function with respect to $b_i(s_i)$ and set it equal to zero:

$$\frac{d}{db_i(s_i)}\left[\int_0^\infty \Big[(1-b_i(s_i))\big(v\cdot I(v)^\alpha - I(v)\big) - fc\Big]\cdot G(b^{-1}(b_i)|v)^{n-1}\cdot r(v|s)\ \cdot dv\right] = 0$$

Since $b_i(s_i)$ appears both in the term $\Big[(1-b_i(s_i))(v\cdot I(v)^\alpha) - I(v) - fc\Big]$ and in $G(s_i|v)$, we must apply the product rule:

$$\int_0^\infty \frac{d}{db_i(s_i)}\Big[(1-b_i(s_i))\big(v\cdot I(v)^\alpha - I(v)\big) - fc\Big]\cdot G(b^{-1}(b_i)|v)^{n-1}\cdot r(v|s)\ \cdot dv$$

$$+\int_0^\infty \Big[(1-b_i(s_i))\big(v\cdot I(v)^\alpha - I(v)\big) - fc\Big]\cdot \frac{d}{db_i(s_i)}\left[G(b^{-1}(b_i)|v)^{n-1}\right]\cdot r(v|s)\ \cdot dv = 0$$

Derivative of the first term:

$$\frac{d}{db_i(s)}\Big[(1-b_i(s))\big(v\cdot I(v)^\alpha - I(v)\big) - fc\Big] = -(v\cdot I(v)^\alpha - I(v))$$

Derivative of the second term:

$$\frac{d}{db_i(s)}G(b^{-1}(b_i)|v)^{n-1} = (n-1)\cdot G(b^{-1}(b_i)|v)^{n-2}\cdot g(b^{-1}(b_i)|v)\cdot \frac{1}{b'(b^{-1}(b_i))}$$

$$\frac{d}{db_i(s)}G(s_i\mid v)^{n-1} = (n-1)\cdot G(s_i|v)^{n-2}\cdot g(s_i|v)\cdot\frac{1}{b'(s_i)}$$

where $g(\cdot)$ is the probability density function associated with $G(\cdot)$. We sum these terms and establish the first-order condition (FOC) to maximize the objective function:

$$\begin{aligned}\int_0^\infty \Bigg[& -(v\cdot I(v)^\alpha - I(v))\cdot G(s_i\mid v)^{n-1} \\ & + \Big[(1-b_i(s_i))\big(v\cdot I(v)^\alpha - I(v)\big) - fc\Big]\cdot(n-1) \\ & \cdot G(s_i\mid v)^{n-2}\cdot g(s_i\mid v)\cdot\frac{1}{b'(s_i)}\Bigg]\cdot r(v\mid s)\ \cdot dv = 0\end{aligned} \tag{6r}$$

We distribute the integral and take out the negative sign from the first term:

$$\begin{aligned} & -\int_0^\infty \left[(v\cdot I(v)^\alpha - I(v))\cdot G(s_i\mid v)^{n-1}\right]\cdot r(v\mid s)\ \cdot dv \\ & +\int_0^\infty \Bigg[\Big[(1-b_i(s_i))\big(v\cdot I(v)^\alpha - I(v)\big) - fc\Big]\cdot(n-1) \\ & \qquad \cdot G(s_i\mid v)^{n-2}\cdot g(s_i\mid v)\cdot\frac{1}{b'(s_i)}\Bigg]\cdot r(v\mid s)\ \cdot dv = 0\end{aligned}$$

Solving for:

$$\int_0^\infty \Bigg[\Big[(1-b_i(s_i))\big(v\cdot I(v)^\alpha - I(v)\big) - fc\Big]\cdot(n-1)$$
$$\cdot\, G(s_i\mid v)^{n-2}\cdot g(s_i\mid v)\cdot \frac{1}{b'(s_i)}\Bigg]\cdot r(v\mid s)\ \cdot dv$$
$$=\int_0^\infty \Big[(v\cdot I(v)^\alpha - I(v))\cdot G(s_i\mid v)^{n-1}\Big]\cdot r(v\mid s)\ \cdot dv$$

Take $\frac{1}{b'(s_i)}$ outside the integral on the left-hand side:

$$\frac{1}{b'(s_i)}\cdot \int_0^\infty \Bigg[\Big[(1-b_i(s_i))\big(v\cdot I(v)^\alpha - I(v)\big) - fc\Big]\cdot(n-1)$$
$$\cdot\, G(s_i\mid v)^{n-2}\cdot g(s_i\mid v)\Bigg]\cdot r(v\mid s)\ \cdot dv$$
$$=\int_0^\infty \Big[(v\cdot I(v)^\alpha - I(v))\cdot G(s_i\mid v)^{n-1}\Big]\cdot r(v\mid s)\, dv$$

We isolate $\frac{1}{b'(s_i)}$:

$$\frac{1}{b'(s_i)} = \frac{\displaystyle\int_0^\infty (v\cdot I(v)^\alpha - I(v))\cdot G(s_i\mid v)^{n-1}\cdot r(v\mid s)\ \cdot dv}{\displaystyle\int_0^\infty \Big(\big[(1-b_i(s_i))\big(v\cdot I(v)^\alpha - I(v)\big) - fc\big]\cdot(n-1)\cdot G(s_i\mid v)^{n-2}\cdot g(s_i\mid v)\Big)\cdot r(v\mid s)\ \cdot dv}$$

$$\frac{db(s_i)}{ds_i} = \frac{\displaystyle\int_0^\infty \Big(\big[(1-b_i(s_i))\big(v\cdot I(v)^\alpha - I(v)\big) - fc\big]\cdot(n-1)\cdot G(s_i\mid v)^{n-2}\cdot g(s_i\mid v)\Big)\cdot r(v\mid s)\ \cdot dv}{\displaystyle\int_0^\infty \Big((v\cdot I(v)^\alpha - I(v))\cdot G(s_i\mid v)^{n-1}\Big)\cdot r(v\mid s)\ \cdot dv} \tag{7r}$$

The investment function $I(v)$, which represents the optimal level of investment chosen by the firm, is endogenous to the model and is derived from the firm's profit maximization problem. The firm's profit function is given by:

$$\max_I \pi(I) = (1-b)\cdot\big(v\cdot I^\alpha - I\big)$$

The first-order condition:

$$\frac{\partial\pi(I)}{\partial I} = (1-b)\cdot\big(\alpha\cdot v\cdot I^{\alpha-1} - 1\big) = 0$$

Since $(1-b)\neq 0$, we can simplify by removing $(1-b)$ from the equation:

$$\alpha\cdot v\cdot I^{\alpha-1} - 1 = 0$$

Rearranging terms, we get:

$$\alpha\cdot v\cdot I^{\alpha-1} = 1$$

Now, isolating I, we solve for I:

$$I^{\alpha-1} = \frac{1}{\alpha \cdot v}$$

$$I = \left(\frac{1}{\alpha \cdot v}\right)^{\frac{1}{\alpha-1}}$$

Simplifying further, the optimal investment is:

$$I(v) = (\alpha \cdot v)^{\frac{1}{1-\alpha}} \tag{8r}$$

Equation (7r) and the expression for $I(v)$ define a unique equilibrium since an initial condition has been specified. The expected gross value of the tract, conditional on receiving the signal s, is given by the following expression. To solve the differential equation characterizing the firm's bidding strategy, a single initial condition is required. A firm will submit a strictly positive bid only if the expected net value of the tract is positive under two conditions: (1) the firm has received the signal s, and (2) the firm wins the auction, which occurs if and only if the other $n-1$ competing firms receive signals lower than s.

This conditions is:

$$b_i(s_o) = 0 \tag{9r}$$

where s_o satisfies:

$$\int_0^\infty ((v \cdot I(v)^\alpha) \ - I(v) - fc) \cdot G(s_o \mid v)^{n-1} \cdot r(v \mid s_o)\, dv = 0$$

□

7.4 Proof of Proposition 2

Proof. We want to find a investment strategy function $I(s,v)$ wich maximizes expresion $2w$. Before proceeding, we reverse the order of integration to obtain the following expression:

$$\int\int \Big[(1-b)\big(v\cdot I(s,v)^{\alpha} - I(s,v)\big) - fc\Big]\cdot F(I,v)\cdot r(v|s)\,dv\cdot p(s)\ \cdot ds \tag{3w}$$

Where $I(s,v) = I(v) + I(s_i)$ denotes the investment bid of the firm as the sum of the ex ante amount $I(v)$ and the additional component $I(s_i)$, derived from the private signal s_i. Here $r(v|s)$ is a proven lognormal distribution, demonstrated for the case of royalty bidding, and can be consulted in the Appendix. The unconditional probability density function for the value estimate signal received by a firm, $p(s)$ is:

$$p(s) = \int_0^{\infty} g(s|v)\cdot h(v)\ \cdot dv$$

Since $g(s|v)$ and $h(v)$ are lognormal, then $p(s)$ is also lognormal. Now the problem is to maximize the inner integral:

$$\int_0^{\infty} \Big[(1-b)\big(v\cdot I_i(s_i,v)^{\alpha} - I_i(s_i,v)\big) - fc\Big]\cdot F(I,v)\cdot r(v|s)\ \cdot dv \tag{4w}$$

Since all firms will adopt identical strategies, the probability $F(I,v)$ of winning the auction is, at equilibrium, the probability that all of the firm's competitors receive more pessimistic estimates of the true value v. Therefore, the probability of winning for firm i is given by the following expression:

$$F(I_i,v) = \Pr(I_j < I_i\,\forall\, j \neq i)$$

The symmetric equilibrium strategy is the one in which all participants use the same bidding strategy. Given that the function $\hat{I} = I(s)$ is increasing, then $s = I^{-1}(\hat{I})$.

$$F(I_i,v) = \Pr(I(s_j) < I_i\,\forall\, j \neq i)$$

$$F(I_i,v) = \Pr(s_j < I^{-1}(I_i)\,\forall\, j \neq i)$$

$$F(I_i,v) = G(I^{-1}(I_i)|v)^{n-1}$$

$$F(I_i,v) = G(s_i|v)^{n-1}$$

where $G(I^{-1}(I_i) \mid v)^{n-1}$ is the cumulative distribution function of the inverse of the bidding function (which maps the bid to the underlying signal value s), given a certain value of v. Substituting the function $F(b_i,v)$ with this new expression in Equation (4w), we obtain:

$$\int_0^{\infty} \Big[(1-b)\big(v \cdot I_i(s_i,v)^{\alpha} - I_i(s_i,v)\big) - fc\Big] \cdot G(s_i|v)^{n-1} \cdot r(v|s) \cdot dv \tag{5w}$$

Subject to:

$$\begin{aligned} &(1) \quad I(s,v) \geq 0 \quad \forall\, s \\ &(2) \quad (1-b) \cdot (v \cdot I(s,v)^{\alpha} - I(s,v)) - fc \geq 0 \quad \forall\, s \end{aligned}$$

We introduce these restrictions to ensure that the investment $I(s,v)$ adheres to the principles of optimal firm behavior in a competitive setting. The constraint $I(s,v) \geq 0$ guarantees that firms cannot engage in negative investment, which is neither practical nor economically rational. Additionally, the restriction that ensures positive expected profits, $(1-b)\big(v \cdot I(s,v)^{\alpha} - I(s,v)\big) - fc \geq 0$, ensures that firms will only undertake investments that generate nonnegative returns. Together, these conditions capture the rational profit-maximizing behavior of firms, ensuring that investments remain within economically viable bounds based on the project's cost-benefit structure. To find the optimal bidding strategy $I(s,v)$, we will consider the case of a particular firm, which will be $I_i(s_i,v)$. Consequently, the revised function incorporating the constraints is:

$$\begin{aligned} \mathcal{L}(I_i(s_i,v), \lambda_1(s_i), \lambda_2(s_i)) = \int_0^{\infty} &\Big\{\Big[(1-b)\big(v \cdot I_i(s_i,v)^{\alpha} - I_i(s_i,v)\big) - fc\Big] \cdot G(s_i|v)^{n-1} \cdot r(v|s)\, dv\Big\} \\ &+ \lambda_1(s_i) \cdot I_i(s_i) \\ &+ \lambda_2(s_i) \cdot ((1-b)\big(v \cdot I_i(s_i,v)^{\alpha} - I_i(s_i,v)\big) - fc) \end{aligned}$$

We differentiate the objective function with respect to $I_i(s)$,$\lambda_1(s)$ and $\lambda_2(s)$ and set it equal to zero:

$$\frac{\partial \mathcal{L}}{\partial I_i(s_i,v)} = 0 \tag{a}$$

$$\frac{\partial \mathcal{L}}{\partial \lambda_1(s_i)} = 0 \tag{b}$$

$$\frac{\partial \mathcal{L}}{\partial \lambda_2(s_i)} = 0 \tag{c}$$

First, we solve equation (a). The derivative has three terms. Derivative of the first part of the first term:

$$\frac{d}{dI_i(s_i,v)}\Big[(1-b)\big(v \cdot I_i(s_i,v)^{\alpha} - I_i(s_i,v)\big) - fc\Big] = (1-b) \cdot (v \cdot \alpha \cdot I_i(s_i,v)^{\alpha-1} - 1)$$

Derivative of the second part of the first term:

$$\frac{d}{dI_i(s_i,v)} \cdot G(s_i|v)^{n-1} = (n-1) \cdot G(s_i|v)^{n-2} \cdot g(s_i|v) \cdot \frac{1}{I'(s_i,v)}$$

Derivative of the second term:

$$\frac{d}{dI_i(s_i,v)}\left[\lambda_1(s) \cdot I_i(s_i,v)\right] = \lambda_1(s_i)$$

Derivative of the third term:

$$\frac{d}{dI_i(s_i,v)}\left[\lambda_2(s_i)\cdot\left[(1-b)\big(v\cdot I_i(s_i,v)^\alpha - I_i(s_i,v)\big)-fc\right]\right]=\lambda_2(s_i)\cdot(1-b)\cdot\left[v\cdot\alpha\cdot I_i(s_i,v)^{\alpha-1}-1\right]$$

We add the obtained derivatives to get the complete solution to equation (a):

$$\begin{aligned}\frac{d}{dI_i(s_i,v)} = \int_0^\infty \Bigg[& \big((1-b)\cdot(v\cdot\alpha\cdot I_i(s_i,v)^{\alpha-1}-1)\big)\cdot G(s_i\mid v)^{n-1} \\ & + \left[(1-b)\big(v\cdot I_i(s_i,v)^\alpha - I_i(s_i,v)\big)-fc\right]\cdot(n-1)\cdot G(s_i\mid v)^{n-2}\cdot g(s_i\mid v)\cdot\frac{1}{I'(s_i,v)} \\ & + \lambda_1(s)+\lambda_2(s)\cdot(1-b)\cdot\left[v\cdot\alpha\cdot I_i(s_i,v)^{\alpha-1}-1\right]\Bigg]\cdot r(v\mid s)\,\cdot dv = 0\end{aligned} \tag{as}$$

Next, we solve equation (b), the derivative with respect to $\lambda_1(s_i)$:

$$\frac{\partial\mathcal{L}}{\partial\lambda_1(s_i)} = I_i(s_i,v)=0 \tag{bs}$$

Finally, we solve equation (c), the derivative with respect to $\lambda_2(s_i)$:

$$\frac{\partial\mathcal{L}}{\partial\lambda_2(s_i)} = \left[v\cdot\alpha\cdot I_i(s_i,v)^{\alpha-1}-1\right]=0 \tag{cs}$$

The solution can be characterized by three mutually exclusive cases, depending on which constraints are active:

Case 1: Neither constraint is active. The firm chooses a strictly positive investment level: $I_i(s_i,v)>0$, and the expected profit condition holds strictly:

$$(1-b)\cdot(v\cdot I_i(s_i,v)^\alpha - I_i(s_i,v))-fc>0$$

Consequently, both Lagrange multipliers are zero: $\lambda_1(s_i)=0$ and $\lambda_2(s_i)=0$.

Case 2: Only the non-negativity constraint is active. In this corner solution, the firm does not invest: $I_i(s_i,v)=0$, which implies $\lambda_1(s_i,v)\geq 0$. Since the expected profit constraint is strictly satisfied, $\lambda_2(s_i,v)=0$. This case is only feasible when $fc\leq 0$, as otherwise it would contradict the assumption that fixed costs are strictly positive.

Case 3: Only the profitability constraint is binding. The firm invests a strictly positive amount $I_i(s_i,v)>0$, but expected profits exactly match the fixed cost:

$$(1-b)\cdot(v\cdot I_i(s_i,v)^\alpha - I_i(s_i,v))-fc=0$$

In this case, $\lambda_2(s_i)$ may be nonzero, while $\lambda_1(s_i)=0$, as the non-negativity constraint is not binding.

Among the three possible cases, case 1 is the most relevant for the analysis, as it corresponds to an interior solution in which neither constraint is binding. In this scenario, the optimal investment

$I_i(s_i, v)$ is strictly positive, and expected profits—net of both investment costs and fixed costs—are also positive. This configuration captures the economically meaningful setting in which firms actively participate in the auction and the government secures rent through actual production. Case 2, in contrast, assumes $I_i(s_i, v) = 0$, implying that the firm undertakes no investment. If all firms behave this way, no exploration or production occurs, and the government collects no rent. Such an outcome is inconsistent with the fundamental purpose of a competitive auction aimed at allocating resource rights. Furthermore, the condition for this case to arise—namely $fc \leq 0$—is not economically plausible in the context of oil and gas development, where fixed costs are inherently positive. Finally, Case 3, in which the profitability constraint binds exactly and expected net profit equals the fixed cost, is theoretically possible but redundant. Because the profitability constraint in the model may hold weakly, any solution that satisfies it with equality is subsumed by Case 1, making the resolution of Case 1 alone sufficient to fully characterize the firm's optimal bidding strategy.

Given its economic relevance and generality, we now proceed to characterize the firm's optimal strategy by solving the first-order condition associated with Case 1:

$$\frac{d}{dI_i(s_i, v)} = \int_0^\infty \Bigg[(1-b)\cdot\big(v\cdot\alpha\cdot I_i(s_i,v)^{\alpha-1} - 1\big)\cdot G(s_i \mid v)^{n-1} + \Big[(1-b)\big(v\cdot I_i(s_i,v)^{\alpha} - I_i(s_i,v)\big) - fc\Big]\cdot(n-1)\cdot G(s_i \mid v)^{n-2}\cdot g(s_i \mid v)\cdot\frac{1}{I'(s_i)}\Bigg]\cdot r(v \mid s)\cdot dv = 0$$

Isolate $\frac{1}{I'(s_i,v)}$:

$$-\int_0^\infty \Big[\big((1-b)\cdot(v\cdot\alpha\cdot I_i(s_i,v)^{\alpha-1} - 1)\big)\cdot G(s_i \mid v)^{n-1}\Big]\cdot r(v \mid s)\cdot dv = \int_0^\infty \Bigg[\Big[(1-b)\big(v\cdot I_i(s_i,v)^{\alpha} - I_i(s_i,v)\big) - fc\Big]\cdot(n-1)\cdot G(s_i \mid v)^{n-2}\cdot g(s_i \mid v)\cdot\frac{1}{I'(s_i,v)}\Bigg]\cdot r(v \mid s)\cdot dv$$

Rearranging terms:

$$\frac{-\int_0^\infty \Big[\big((1-b)\cdot(v\cdot\alpha\cdot I_i(s_i,v)^{\alpha-1} - 1)\big)\cdot G(s_i \mid v)^{n-1}\Big]\cdot r(v \mid s)\cdot dv}{\int_0^\infty \Big[\Big[(1-b)\big(v\cdot I_i(s_i,v)^{\alpha} - I_i(s_i,v)\big) - fc\Big]\cdot(n-1)\cdot G(s_i \mid v)^{n-2}\cdot g(s_i \mid v)\Big]\cdot r(v \mid s)\cdot dv} = \frac{1}{I'(s_i,v)}$$

Isolate $I'(s_i, v)$:

$$\frac{dI(s_i)}{ds_i} = \frac{\int_0^\infty \Big[\Big[(1-b)\big(v\cdot I_i(s_i,v)^{\alpha} - I_i(s_i,v)\big) - fc\Big]\cdot(n-1)\cdot G(s_i \mid v)^{n-2}\cdot g(s_i \mid v)\Big]\cdot r(v \mid s)\cdot dv}{-\int_0^\infty \Big[\big((1-b)\cdot(v\cdot\alpha\cdot I_i(s_i,v)^{\alpha-1} - 1)\big)\cdot G(s_i \mid v)^{n-1}\Big]\cdot r(v \mid s)\cdot dv} \tag{7w}$$

To obtain the numerical solution for $I_i(s_i, v)$, an initial condition must be specified. This condition is based on the expected gross-of-bid value of the tract, conditional on receiving signal s. A firm will choose a strictly positive investment only if the expected net value is positive under two events: (1) the firm has received signal s, and (2) it wins the auction—an outcome that occurs when all $n-1$ rival firms receive lower signals. These conditions jointly define the basis for the initial value required to solve the differential equation for $I_i(s)$. This conditions is:

$$I_i(s_o) = 0 \tag{8w}$$

where s_o satisfies:

$$\int_0^\infty ((v \cdot I(v)^\alpha) \ - I(v) - fc) \cdot G(s_o \mid v)^{n-1} \cdot r(v \mid s_o)\, dv = 0$$

$\square$