Auctioning wind farms

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PRELIMINARY AND INCOMPLETE

Abstract

This paper examines under what conditions auctions incentivize firms to invest in acquiring information regarding their own potential electricity production and revenue when building a wind farm. Auctions are used in many countries as a policy measure to promote variable renewable energy in electricity production, while allowing regulators to be better informed about firms' production levels and improve the planning of the electricity system. I use a first-price sealed bid auction model with two bidders to assess the effect of auctions on information acquisition, when procuring wind energy capacity demanded by the regulator. Results show that when each of the firms can cover the demand, their choice can be steered towards acquiring information through the demand for wind capacity, but not through the cap on bids. The regulator can then deduce this information from the bidding behaviour of the firms.

Keywords: Wind Energy, Auctions, Electricity, Information Acquisition

1 INTRODUCTION

Environmental policies in order to deploy renewable energy in the electricity sector are present in numerous countries around the world. While feed-in tariffs and premiums are still the most common option, auctions of renewable energy capacity are gaining ground to achieve an electricity production system with high share of renewables. Indeed, only 8 countries had adopted them in 2004, but, by contrast, auctions existed in 73 countries in 2017 (IEA et al., 2018).

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This shift from regulating the price to using quantity as an instrument is justified based on the model put forward by Weitzman (1974): when prices are uncertain then quantity should be fixed. An auction ensures a certain amount of renewable energy capacity will be added to the system, and at the same time, the regulator does not need to discover the correct price to remunerate producers. Firms are now the ones setting the price they will receive as a compensation. When deciding on a price for the electrical energy they produce, they can either rely on publicly available meteorological data or gather costly private information[1] about the climate conditions affecting their power plant. This private information can alter the price firms ask for, while allowing the regulator to deduce the information through the strategic behaviour of the firms. In the context of the current energy transition, this kind of information can prove useful in designing an electricity system where variable renewables play a major role. Considering these elements, the main focus of this paper is to examine under what conditions auction schemes incentivize firms to invest in acquiring information about their own electricity production and, by extension, potential revenue, and enable regulators to infer this information through the bids.

Variable renewables challenge the way electricity systems work, because of their lack of dispatchability and the uncertainty placed on the regulator regarding how much electricity will be available at any point in time. Investment in storage can address this issue, however, storing electricity is currently possible, but a very expensive technology. At the same time, electricity storage could also have some adverse effects in terms of reducing carbon emissions, due to improving the efficiency of thermal production (Lazkano et al., 2017). Consequently, policies need to be employed to reduce uncertainty due to variability and secure electricity supply.

A firm's electricity production from variable renewables is directly linked to the climate conditions at their plant's site. If the regulator is to steer a firm towards receiving more accurate information about their electricity production, a suitable regulatory framework is required. Market regulation, and auction design in particular, has to be adapted in answer to these challenges and designed so as to offer the ground for firms to bear the costs of such an investment in private information. A direct consequence of this modification is that it would allow the regulator to anticipate electricity from variable sources — for a review on how the European electricity market could be reformed to accommodate increased renewables see Newbery et al. (2018). Given this need and the high shares of variable renewables, what is the decisive factor in order to set the appropriate incentives to invest in acquiring private information?

To answer this question I develop a stylized model of procurement auctions in the spirit of Fabra et al. (2006) and Fabra and Llobet (2019). Similar to their approach, I model procurement auctions of wind farms[2] as discriminatory, multi-unit, first-price sealed bid in a duopoly, with private values and the option of private information. This model, however, focuses on the capacity stage; this results in the private value being multiplied with the bid, rather than with the bid less the marginal cost. The auction is designed by the regulator, who publicly announces

[1] Although capital costs are the most expensive part of a renewable energy plant, estimating energy yields is complicated and expensive. For a discussion on the topic and cost breakdown for the case of wind farms, see Wind power monthly (2015) and IRENA (2018), respectively.

[2] Although this paper takes the example of wind farms, it could be applied to other variable renewable energies.

the amount of wind capacity to be built, as well as the upper bound on the bids firms can place. Before participating in the auction, firms can decide to invest in acquiring information, thus receiving a perfectly informative signal regarding the wind profile and electricity production of their potential wind farm site. This kind of information can allow firms to adjust their strategic behaviour and respond accordingly to the central trade-off between increasing the probability of winning an auction and having lower profits from winning — a trade-off described for instance in Krishna (2009) "An increase in the bid will increase the probability of winning while, at the same time reducing the gains from winning". Put differently, having private information about how much electricity a site can produce, alters the way firms decide to bid in the auction.

The results of the model indicate that indeed the regulator has the means to influence the strategic decision of whether firms decide to acquire information or not. Focusing on the case when firms are big enough to cover the whole demand for wind farms set by the regulator, a higher auctioned volume motivates firms to pay the extra cost of information acquisition. More specifically, demand for wind capacity has a strategic effect, i.e. the level of demand changes the strategic decision of firms to acquire information or not. Additionally, there is strategic complementarity in the bidding behaviour of the firms, in the sense that acquiring private information from one firm's side has the same strategic effect on the bids of both firms. On the other hand, modifying the upper bound on bids does not affect the firms' behaviour, provided that the cap is set at a level high enough to ensure firms build capacity, even in case their site's production is expected to be low. The policy implications of these findings are relevant for real world auction design, since countries are in the process of defining the most suitable auction setting (IRENA, 2015).

The scope of this paper connects it to the literature on auctions and information acquisition; research on both these topics is extensive. Klemperer (1999) provides a comprehensive survey of the auction theory literature. How auctions can reduce information asymmetry between firms and the regulator is dealt with in early work in the field, e.g. by Myerson (1981), Milgrom and Weber (1982), or Green and Laffont (1977). Arozamena and Cantillon (2004) looks into how the format of a procurement auction changes a firm's decision to invest in cost reduction, while Fehr and Harbord (1993), Green and Newbery (1992) and Green (1996), among others, study auctions in the spot electricity market in the UK. Acemoglu et al. (2017) explores the concept of incomplete information in terms of how much available renewable energy there is on the opponent's side and the effect this has on prices. Although this paper looks at procurement auctions from a theoretical perspective, there is also recent empirical work on the effectiveness of these auctions using data from OECD, as well as emerging and developing countries (Matthäus, 2020).

However, for the aforementioned result to hold, firms need to be informed about their own valuation of a potential investment site. Yet it can be the case that firms are not completely informed regarding their valuation and potential profits. Information asymmetry and acquiring information regarding own valuations among bidders in different auction settings has been the main focus of numerous papers, such as Engelbrecht-Wiggans et al. (1983); Bennouri and Falconieri (2006); Bergemann et al. (2013). Bergemann et al. (2009) examine auctions with costly information acquisition about one's type, but with valuations that are interdependent. In Shi

(2012), a seller chooses the auction design in order to affect the decision of a buyer to invest in a more precise signal regarding her private valuation. Miettinen (2013) also discusses the equilibrium behaviour of bidders who can invest in information acquisition regarding their own valuations, however the setting in that analysis is a decreasing price auction. The scope of Persico (2000) is the value of information, and demonstrating how auction formats can influence bidders' incentives to acquire information about the object for sale.

The main contribution of this paper is to investigate what are the attributes of procurement auctions that affect the decision to invest in acquiring information about potential revenues. Most of the literature is so far focused on assessing the effects of auctions when implementing the mechanism at the dispatch stage. By contrast, this paper focuses on the stage of installing wind energy capacity, and combines the auction with a perfectly accurate information acquisition mechanism, which allows to draw useful insights regarding the regulatory framework, namely the decisive role of wind capacity demand and its strategic effects, and the strategic complementarity of bidding strategies.

The rest of the paper is organized as follows. In Section 2, the model's components are presented. Section 3 presents and discusses the equilibrium outcomes based on the assumptions about the firms' size compared to the demand for wind capacity. Section 4 concludes with a discussion on the implications of the model.

2 MODEL SETUP

A standard duopoly model is used, where two risk-neutral firms, $i = 1, 2$, bid in order to win an auction and build wind capacity in MW, $\theta > 0$, demanded by the regulator. Each firm has access to one site on which they can decide how much wind capacity, $k_i \geqslant 0$, to install. Land availability, site topography and regulations for land use pose restrictions on firms in case of both on- and off-shore wind farms. Hence there is a maximum number of wind turbines that can be installed at each site; assuming that every wind turbine available to firms has the same nominal capacity, there is a maximum capacity in MW, $K_i > 0$, that each firm can install. The sites available to firms can cover the demanded capacity, that is $K_1 + K_2 \geqslant \theta$. Furthermore, each additional turbine has the same installation cost, $\beta > 0$ in €/MW, i.e. the marginal cost of installing capacity is constant and positive. Before the auction, each firm has the option to invest in information acquisition regarding its site's expected production; the investment cost is $\gamma > 0$ in €. Once a firm pays γ, it observes a perfectly accurate signal, relative to its own production. Then, the firm decides on its bid b_i.

The goal of the regulator is to be able to infer information regarding the electricity production of wind farms. If the firms have acquired this information, the regulator can deduce it through the bidding of firms. Therefore, the regulator aims at designing the auction so as to incentivize firms to invest in information acquisition.

Each firm places a bid b_i which will be the price received for its electricity production in €/MWh. Discriminatory auctions are chosen because it is the most common design for renewable energy capacity within the electricity sector (IRENA, 2015). Additionally, the regulator sets a price cap for the bids, so $b_i \leqslant P$, where P is set at a level high enough to incentivize firms to build capacity, for every level of production. Auctions are in most countries used after a feed-in tariff scheme is established, therefore the upper bound for bids is often the level of the former feed-in tariff.

Electricity produced in wind farms is a random variable, due to the nature of wind. Wind speed is a stochastic variable approximated by a Weibull distribution. For every level of wind speed, a specific wind turbine produces a different level of electric power according to its power curve, see for example The Swiss Wind Power Data Website (2018). Wind turbines have monotonic and increasing power curves, meaning that the higher the wind speed, the higher the electric power produced. These two facts, the Weibull distribution and the monotonic power curve shown in Figures 1a and 1b, cause the electric power to follow its own distribution, as presented in Figure 1c. The mean of this distribution is the expected electric power produced per installed MW, noted in this paper as μ_i for each site[3]. Assuming risk neutral firms, the mean μ_i is the only payoff-relevant part of the distribution.

Each site has a different electricity production profile, in other words, the distribution of electric power produced by each wind turbine has different expected value, μ_i. Ex ante this parameter is unknown to both firms and the regulator. However, all agents have a common belief on what its value is. Let $f(\mu_i)$ denote the prior probability density function of μ_i and $[\underline{\mu}, \overline{\mu}] \subset R_{++}$ be the support of $f(.)$, where μ_1 and μ_2 are i.i.d. In the sections and results that follow, the probability density function is kept in a general form, however whenever the results are visualised the example of a uniform probability density function, i.e. $f(\mu_i) = \dfrac{1}{\overline{\mu} - \underline{\mu}}$, is chosen.

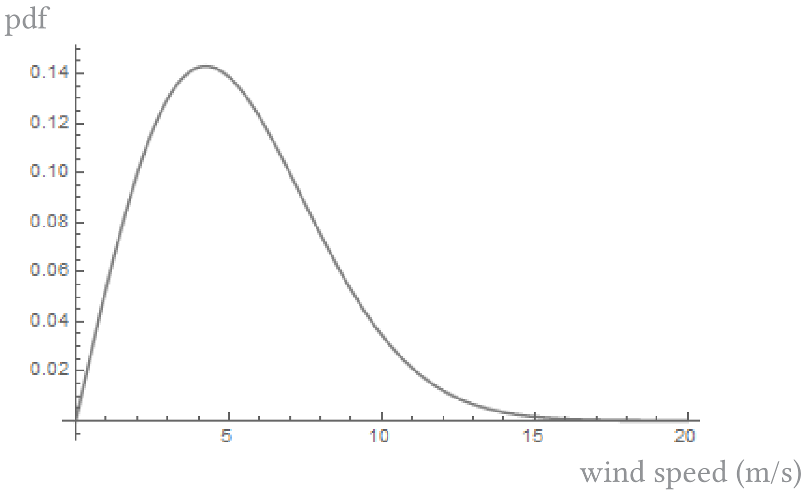
The wind capacity each firm builds depends on the bids they place, according to:

$$k_i = \begin{cases} \min\{\theta, K_i\}, & \text{if } b_i < b_j \\ \\ \max\{0, \theta - K_j\}, & \text{if } b_i > b_j. \end{cases}$$

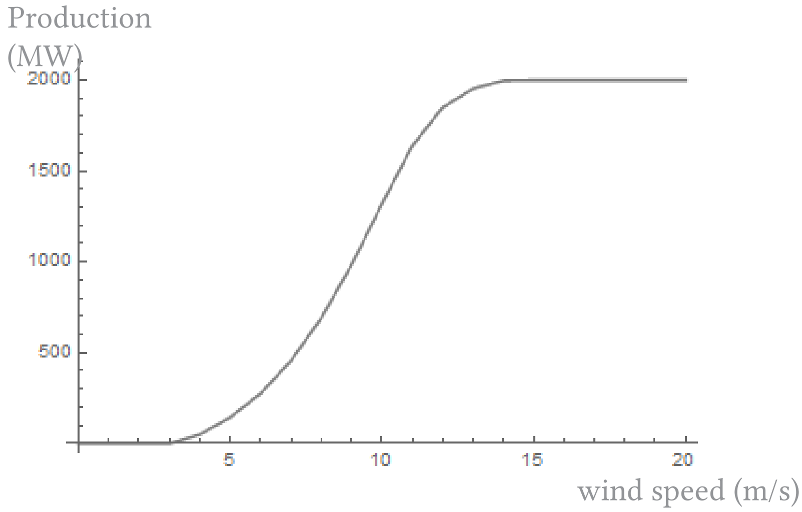
When $b_i = b_j$ and firms are both either informed or uninformed, each firm has a probability 0.5 of winning the auction and building $\min\{\theta, K_i\}$, and 0.5 probability of losing and building $\max\{0, \theta - K_j\}$. On the other hand, when $b_i = b_j$ and only one firm has invested in information acquisition, ties break in favour of the informed firm.

The timing of the game is as follows: Once the regulator announces θ and P, firms decide simultaneously and overtly to invest in information acquisition or not. After firms potentially receive additional information about the site characteristics, i.e. the expected electricity production μ_i, they bid for the price per unit of electricity produced, b_i, and, after bids are revealed,

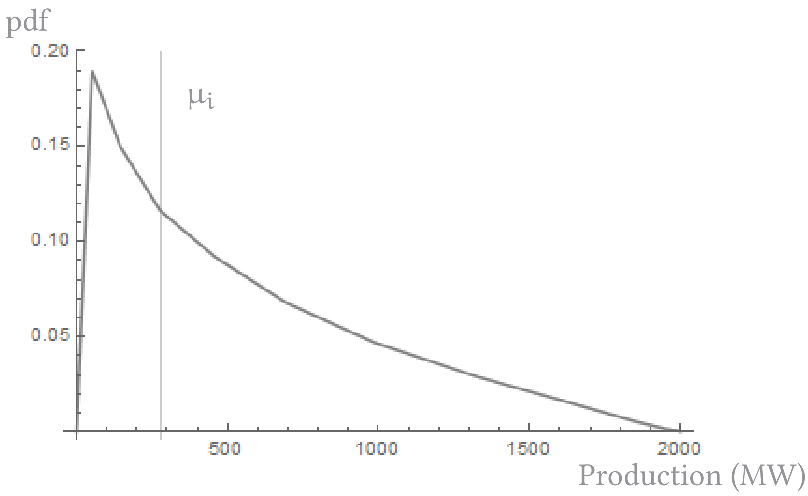
[3] In the context of this model, electricity production and capacity are used interchangeably.



(a) Weibull distribution, mean wind speed 5.3 m/s



(b) Power curve for the Dewind D8/80-2MW wind turbine



(c) Distribution of power production for the Dewind D8/80-2MW wind turbine, mean capacity production 276.4MW

Figure 1: Derivation of electric power distribution

they build k_i. There is the outside option of not participating in the auction; in that case firms do not build any capacity, but they bear the information acquisition costs if they decide to invest.

Irrespective of firm j, when firm i does not invest in information acquisition and wins the auction, it receives $b_i\tilde{\mu} - \beta$ per installed MW, where $\tilde{\mu}$ is the average of μ_i, i.e. assuming a uniform distribution $\tilde{\mu} \equiv \int_{\underline{\mu}}^{\overline{\mu}} \mu f(\mu) d\mu = (\overline{\mu} + \underline{\mu})/2$. When firm i invests and wins the auction, it receives $b_i\mu_i - \beta$ per installed MW. Notice that for an informed firm, the profit per MW depends on the realization on μ_i, rather than on the mean of its distribution.

In terms of notation, $x_i \in \{0, 1\}$ is the decision regarding information acquisition, where $x_i = 0$ means that firm i does not invest, while $x_i = 1$ indicates that it does. The bidding and profit functions are denoted by $b_i(x_i, x_j)$ and $\pi_i(x_i, x_j)$, respectively, when firm i decides to follow strategy x_i and its opponent follows x_j.

In the next Section, the best responses of firms, the strategic effects of acquiring information, as well as the equilibrium outcomes, in different subgames are analyzed. These will determine the attributes an auction needs to have in order for the regulator to achieve its objective.

3 BIDDING IN EQUILIBRIUM

The results of the analysis differ depending on the maximum capacity each firm is endowed with. More specifically, firms have a different bidding strategy in equilibrium when $K_i \geqslant \theta$, $K_i < \theta$, or $K_i < \theta < K_j$ for $i = 1, 2$. In order to make the results clearer, I will use the term of pivotality, as defined in Fabra and Llobet (2019): "a firm is pivotal if it faces a positive residual demand regardless of the bid of its rival". According to this definition, firm i is pivotal when it is essential in order to build the whole demand the regulator sets, or in other words, when firm j cannot cover θ.

The remainder of this Section focuses on symmetric, non-pivotal firms, where the actions of firms regarding investment in information acquisition are observable. When firms are non-pivotal, i.e. $K_i \geqslant \theta$, for $i = 1, 2$, firms never face residual demand, and capacity is auctioned similar to a single unit auction. Observability of actions is important in order to discuss the strategic substitutability or complementarity of bids. This framework allows to draw some key conclusions regarding the firms' strategic behaviour and the incentives to invest in information acquisition. Equilibria are within symmetric pure strategies, and only when these do not exist, mixed and asymmetric strategies are considered. In order to find the subgame perfect equilibrium of this auction, each subgame and its outcomes are studied.

3.1 None of the firms invests in information acquisition

When firms do not invest in information acquisition, they behave in a common knowledge setting. Essentially, this is a case of Bertrand competition, since either firm can cover demand for capacity and have the same beliefs on the value of the item in auction. Proposition 1 describes the equilibrium bids $b^*(0,0)$ and expected profits $\pi^*(0,0)$, when two non-pivotal firms rely only on the prior expectation regarding their own and their opponents' expected production.

Proposition 1. *In equilibrium under a common knowledge regime, non-pivotal firms with a prior probability density function* $f(\mu_i)$ *bid at*

$$b^*(0,0) = \frac{\beta}{\tilde{\mu}} \tag{1}$$

where $\tilde{\mu} \equiv \int_{\underline{\mu}}^{\overline{\mu}} \mu f(\mu) d\mu$ *having an expected profit of*

$$\pi^*(0,0) = 0 \qquad \forall i, \qquad i = 1,2. \tag{2}$$

Proof. Based on Bertrand competition reasoning, these bids are the equilibrium ones, as firms do not have profitable deviations. If firm i increases its bid by ϵ, with $\epsilon \to 0$, it will lose the auction resulting in zero expected profit. On the other hand, if firm i decreases its bid by ϵ, it will win the auction, but it will have negative expected profit. Therefore, $b^*(0,0) = \frac{\beta}{\tilde{\mu}}$ is the bid in equilibrium. □

This subgame reproduces the competitive outcome, since firms bid at their marginal cost and have no profit in expectation.

3.2 Both firms invest in information acquisition

Let's turn to the case when firms have private information: firms decide to pay the cost of information acquisition γ and therefore are perfectly informed regarding the expected production μ_i. However, firm i has only a belief on the expected production of firm j, expressed through the prior probability density function $f(\mu_j)$. Firm i wins the auction and builds capacity θ when $b_i \leqslant b_j$. Ex ante bid b_j is unknown to firm i, due to the stochastic nature of the opponent's expected production. Firm i, therefore, maximizes $\pi_i(1,1,b_i,\mu_i)$

$$\pi_i(1,1,b_i,\mu_i) = \Pr[b_i \leqslant b_j(\mu_j)]\,(b_i\mu_i - \beta)\,\theta - \gamma \tag{3}$$

Having private information about its expected production, firm i can now condition its bid on the observed value of μ_i. A higher level of μ_i induces a lower bid b_i, that reduces the price received when winning but at the same time increases the probability of winning the auction. This happens because, as μ_i increases, the production of wind energy when winning, $\mu_i\theta$, increases, too. Yet the increase in probability of winning due to a lower bid is not affected by the realized value of μ_i. Consequently, when a firm sees a higher level of μ_i, it will bid at a lower level[4].

[4] The monotonicity of the bidding function is further discussed in Appendix A.

Since bids are strictly decreasing in the observed μ_i, there is a bidding function such that $b_i(\mu_i)$, $b_i'(\mu_i) < 0$. Firms are ex ante symmetric, consequently bidding strategies are too, i.e. $b_i(.) = b_j(.) = b(.)$. Profit can then be rewritten as:

$$\pi(1, 1, b_i, \mu_i) = F\left(b^{-1}(b_i)\right)(b_i\mu_i - \beta)\,\theta - \gamma \tag{4}$$

where $b^{-1}(.)$ is the inverse function of $b(.)$ and the function $F(.)$ is the cumulative distribution function corresponding to $f(.)$. The results of the optimization process for firm i are summarized in Proposition 2.

Proposition 2. *When a non-pivotal firm has private information regarding its expected production μ_i and a prior probability density function, $f(.)$ regarding the expected production, in a symmetric pure strategy equilibrium they bid according to*

$$b^*(1, 1, \mu_i) = \beta\, E\left[\frac{1}{\mu}\,\middle|\, \mu \leqslant \mu_i\right] \tag{5}$$

The ex ante profit of firm i reads

$$\pi^*(1, 1) = \beta\theta \int_{\underline{\mu}}^{\overline{\mu}} F(\mu_i)\left(\mu_i\, E\left[\frac{1}{\mu}\,\middle|\, \mu \leqslant \mu_i\right] - 1\right) f(\mu_i)d\mu_i - \gamma \tag{6}$$

Proof. The bidding strategy described in Proposition 2 is the result of maximising Equation (3). Indeed, the first order condition of the problem is,

$$\begin{aligned}
\frac{dPr[b_i \leqslant b_j(\mu_j)]}{db_i}(b_i\mu_i - \beta) + Pr[b_i \leqslant b_j(\mu_j)]\mu_i = 0 \Leftrightarrow \\
\frac{b_i\mu_i - \beta}{\mu_i} = -Pr[b_i \leqslant b_j(\mu_j)]\left(\frac{dPr[b_i \leqslant b_j(\mu_j)]}{db_i}\right)^{-1}
\end{aligned} \tag{7}$$

Again, making use of the monotonicity of the bidding function $b(\mu_i)$, the first order condition can be transformed into

$$\begin{aligned}
\frac{dF\left(b^{-1}(b_i)\right)}{db_i}(b_i\mu_i - \beta) + F\left(b^{-1}(b_i)\right)\mu_i &= 0 \Leftrightarrow \\
F'(\mu_i)\frac{1}{b'(\mu_i)}(b(\mu_i)\mu_i - \beta) + F(\mu_i)\mu_i &= 0 \Leftrightarrow \\
F'(\mu_i)(b(\mu_i)\mu_i - \beta) + F(\mu_i)b'(\mu_i)\mu_i &= 0 \Leftrightarrow \\
b(\mu_i) = \beta\frac{1}{F(\mu_i)}\int_{\underline{\mu}}^{\mu_i}\frac{F'(\mu)}{\mu}d\mu = \beta\, E\left[\frac{1}{\mu}\,\middle|\, \mu \leqslant \mu_i\right]
\end{aligned} \tag{8}$$

The proof that the second order condition is satisfied can be found in Appendix B. □

The trade-off each firm faces becomes even clearer by assuming the bids of firm j follow a distribution with cdf $H(.)$ with $b_j \in [\beta/\overline{\mu}, P]$. The first order condition of the optimization problem for firm i (7) then is

$$b_i - \frac{\beta}{\mu_i} = \frac{1 - H(b_i)}{H'(b_i)}. \tag{9}$$

Increasing the bid increases the revenue when winning the auction while simultaneously decreasing the Mill's ratio, or equivalently there is a trade-off between the revenue when winning and the probability of winning adjusted by the density of the winning probability.

Turning to the bidding function as specified in (8), for any distribution $F(.)$, the optimal bid has a markup on top of the marginal cost β, which becomes lower for higher values of μ_i. The demand for wind capacity θ does not enter the bidding function of firm i, so it does not affect the strategic behaviour of the firm within the subgame. Moreover, the lowest realization of μ_i results in a bid equal to $\beta/\underline{\mu}$, which is less than the upper bound on bids set by the regulator P, making this restriction non-binding. For a uniform distribution of expected production, the bids follow the function depicted in Figure 2, with functional form:

$$b^*(1,1,\mu_i) = \begin{cases} \beta/\underline{\mu}, & \text{if } \mu_i = \underline{\mu} \\ \dfrac{\beta\,(\ln\mu_i - \ln\underline{\mu})}{\mu_i - \underline{\mu}}, & \text{if } \underline{\mu} < \mu_i \leqslant \overline{\mu} \end{cases} \tag{10}$$

In this subgame, firms bid higher than the competitive level. From Equation (6), it can be seen that it is increasing in μ_i and always greater than $-\gamma$; once a firm has paid the cost of information acquisition, it is optimal to participate in the auction, instead of choosing the outside option. Demand for wind capacity θ enters the profit function in a linear way, determining whether the ex ante profit is positive or negative. This highlights how the regulator can shape the firm's profit, as there is a threshold θ_1 for the value of θ, below which the ex ante profit is negative and above which it is positive. This threshold can be derived from Equation (6) as

$$\theta_1 \equiv \frac{\gamma}{\beta} \frac{1}{\int_{\underline{\mu}}^{\overline{\mu}} F(\mu_i)\left(\mu_i \,E\!\left[\frac{1}{\mu} \,\middle|\, \mu \leqslant \mu_i\right] - 1\right) f(\mu_i)d\mu_i} \tag{11}$$

Taking the example of a uniform distribution for expected production $f(\mu_i) = \dfrac{1}{\overline{\mu} - \underline{\mu}}$ transforms Equation (6) into

$$\begin{aligned} \pi^*(1,1) &= \int_{\underline{\mu}}^{\overline{\mu}} \left[\frac{\beta}{\overline{\mu} - \underline{\mu}} \left(\mu_i(\ln\mu_i - \ln\underline{\mu}) - (\mu_i - \underline{\mu})\right)\theta - \gamma\right] \frac{1}{\overline{\mu} - \underline{\mu}} d\mu_i \\ &= \frac{\beta\theta}{2(\overline{\mu} - \underline{\mu})^2}\left[(\ln\overline{\mu} - \ln\underline{\mu})\overline{\mu}^2 - \frac{(\overline{\mu} - \underline{\mu})(3\overline{\mu} - \underline{\mu})}{2}\right] - \gamma \end{aligned} \tag{12}$$

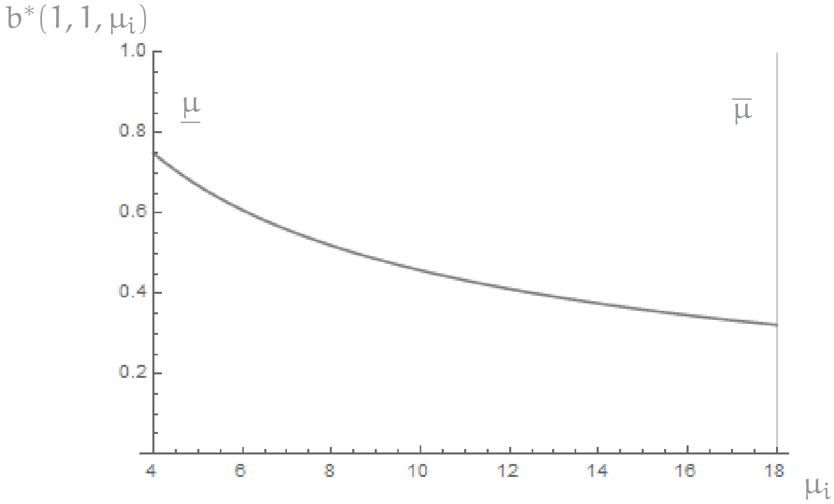


Figure 2: Bidding function under private information, $\mu_i \sim U[4, 18]$, $P = 1$, $\beta = 3$

and the threshold θ_1 becomes

$$\theta_1 = \frac{4\gamma(\overline{\mu} - \underline{\mu})^2}{\beta\left[2\overline{\mu}^2(\ln\overline{\mu} - \ln\underline{\mu}) - (3\overline{\mu} - \underline{\mu})(\overline{\mu} - \underline{\mu})\right]}. \tag{13}$$

3.3 Firm i invests in information acquisition, firm j does not invest

Let's now consider the case when firm i invests and firm j does not; their choices are overt. In this case, due to asymmetry in choice, firms do not play symmetric strategies any more. In this setting, firm i maximizes its profit knowing its actual expected production, while firm j optimizes based only on its prior beliefs. Ties break in favour of the informed firm i. Proposition 3 shows equilibrium bids and profits for the two firms.

Proposition 3. *In equilibrium when non-pivotal firm i has private information on its expected production μ_i, whereas non-pivotal firm j does not have any private information, with a prior possibility distribution function $f(.)$, their bidding strategies are given by*

$$b^*(0,1) = b \tag{14}$$

$$b^*(1,0,\mu_i) = \begin{cases} \dfrac{\beta}{\mu_i}, & \textit{if} \quad \underline{\mu} \leqslant \mu_i < \dfrac{\beta}{b} \\[2ex] b, & \textit{if} \quad \dfrac{\beta}{b} \leqslant \mu_i \leqslant \overline{\mu} \end{cases} \tag{15}$$

The ex ante profits are respectively

$$\pi^*(0,1) = F\left(\frac{\beta}{b}\right)(b\tilde{\mu} - \beta)\theta \tag{16}$$

$$\pi^*(1,0) = \theta\int_{\beta/b}^{\overline{\mu}} (b\mu_i - \beta)\, f(\mu_i)d\mu_i - \gamma \tag{17}$$

where $\tilde{\mu} \equiv \int_{\underline{\mu}}^{\overline{\mu}} \mu f(\mu) d\mu$.

Proof. The uninformed firm j only considers the prior probability density function, hence its bid has to be constant, let it be denoted by b. Firm i bids b_i and always loses the auction when $b_i > b$; in that case, it is a weakly dominant strategy to bid at $\frac{\beta}{\mu_i}$. Indeed, below a specific value of μ_i, firm i is weakly better off bidding at $\frac{\beta}{\mu_i} > b$ and earns a profit of $-\gamma$, due to the cost of acquiring information. Therefore, firm i always loses if $\mu_i < \frac{\beta}{b}$. On the other hand, firm i bids at $b_i = b$ for $\mu_i > \frac{\beta}{b}$, and being the informed firm, it always wins.

The level of b is found by solving the optimization problem of the uninformed firm j

$$\begin{aligned} &\max_b \Pr[b < b_i](b\tilde{\mu} - \beta)\theta \quad \Leftrightarrow \\ &\max_b F\left(\frac{\beta}{b}\right)(b\tilde{\mu} - \beta)\theta \end{aligned} \tag{18}$$

The first order condition is

$$\begin{aligned} &f\left(\frac{\beta}{b}\right)\left(-\frac{\beta}{b^2}\right)(b\tilde{\mu} - \beta) + F\left(\frac{\beta}{b}\right)\tilde{\mu} = 0 \quad \Leftrightarrow \\ &\underbrace{f\left(\frac{\beta}{b}\right)\left(-\frac{\beta}{b}\right)\left(\tilde{\mu} - \frac{\beta}{b}\right)}_{<0} + \underbrace{F\left(\frac{\beta}{b}\right)\tilde{\mu}}_{>0} = 0 \end{aligned} \tag{19}$$

and shows that there exists a $b > \frac{\beta}{\tilde{\mu}}$ such that the condition is satisfied. The ex ante profits of the firms can then are calculated and are presented in Proposition 3. □

The uniform pdf is used also in this case to visualize the results. The bidding functions become

$$b^*(0,1) = \frac{\beta}{\sqrt{\tilde{\mu}\underline{\mu}}} b^*(1,0,\mu_i) = \begin{cases} \dfrac{\beta}{\mu_i}, & \text{if} \quad \underline{\mu} \leqslant \mu_i < \sqrt{\tilde{\mu}\underline{\mu}} \\[2ex] \dfrac{\beta}{\sqrt{\tilde{\mu}\underline{\mu}}}, & \text{if} \quad \sqrt{\tilde{\mu}\underline{\mu}} \leqslant \mu_i \leqslant \overline{\mu} \end{cases} \tag{20}$$

and are shown in Figure 3.

The profit of the uninformed firm is now positive, in contrast to the standard result from Engelbrecht-Wiggans et al. (1983) of the uninformed firm having a zero expected profit in equilibrium. Despite the fact that firm j does not pay to acquire information, it benefits from the observable choice of firm i to invest in information. Firm j knows that firm i will lose the auction for certain realizations, allowing the firm to increase its bid compared to the case where both firms are uninformed.

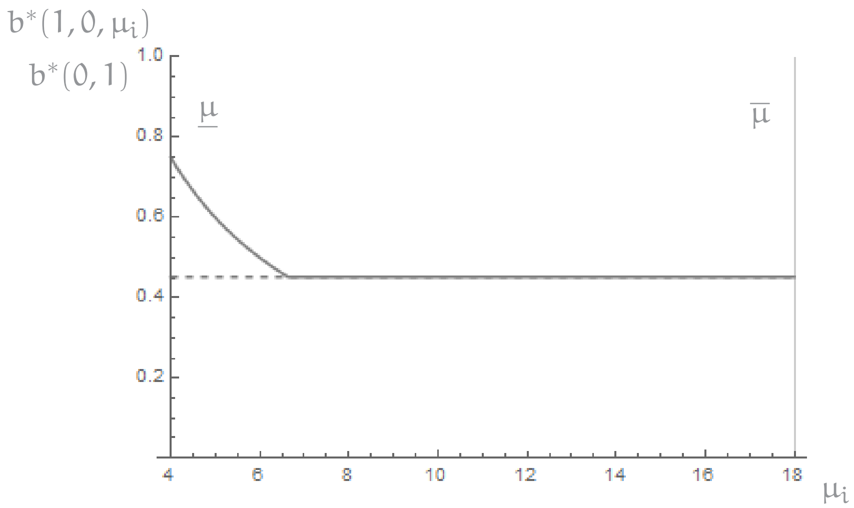


Figure 3: Bidding function for informed firm i (solid line), $\mu_i \sim U[4, 18]$, $P = 1$, $\beta = 3$, and uninformed firm j (dashed line)

It is easy to confirm from Equation (17) that once again, if firm i invests in information acquisition, profit is maximized when the firm participates in the auction. Demand for wind capacity from the regulator affects the ex ante profit in a linear way. The regulator can determine whether informed firm's i ex ante profit is positive or negative, effectively by choosing θ above or below threshold θ_2, defined from Equation (17)

$$\theta_2 \equiv \frac{\gamma}{\beta} \frac{1}{\int_{\beta/b}^{\overline{\mu}} \left(\frac{b}{\beta}\mu_i - 1\right) f(\mu_i) d\mu_i} \tag{21}$$

For the uniform pdf case, the profits of the two firms are

$$\pi^*(0,1) = \beta\theta \frac{\left(\sqrt{\tilde{\mu}} - \sqrt{\underline{\mu}}\right)^2}{\overline{\mu} - \underline{\mu}} > 0 \tag{22}$$

$$\pi^*(1,0) = \beta\theta \int_{\sqrt{\tilde{\mu}\underline{\mu}}}^{\overline{\mu}} \left(\frac{\mu_i}{\sqrt{\tilde{\mu}\underline{\mu}}} - 1\right) \frac{1}{\overline{\mu} - \underline{\mu}} d\mu_i - \gamma = \frac{\beta\theta \left(\overline{\mu} - \sqrt{\tilde{\mu}\underline{\mu}}\right)^2}{2(\overline{\mu} - \underline{\mu})\sqrt{\tilde{\mu}\underline{\mu}}} - \gamma \tag{23}$$

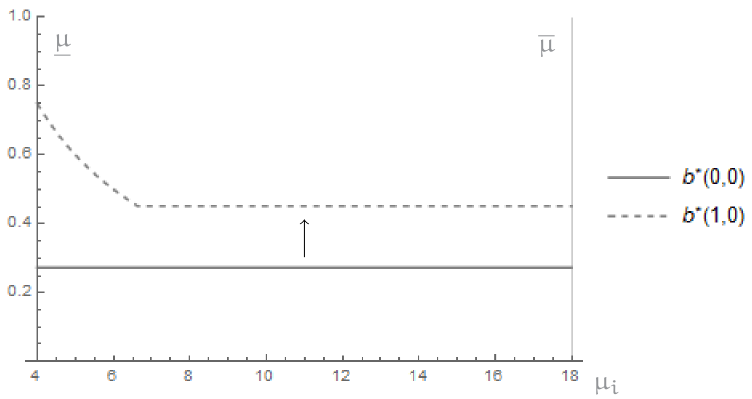
and the threshold θ_2 given by

$$\theta_2 = \frac{2\gamma(\overline{\mu} - \underline{\mu})\sqrt{\tilde{\mu}\underline{\mu}}}{\beta(\overline{\mu} - \sqrt{\tilde{\mu}\underline{\mu}})^2}. \tag{24}$$

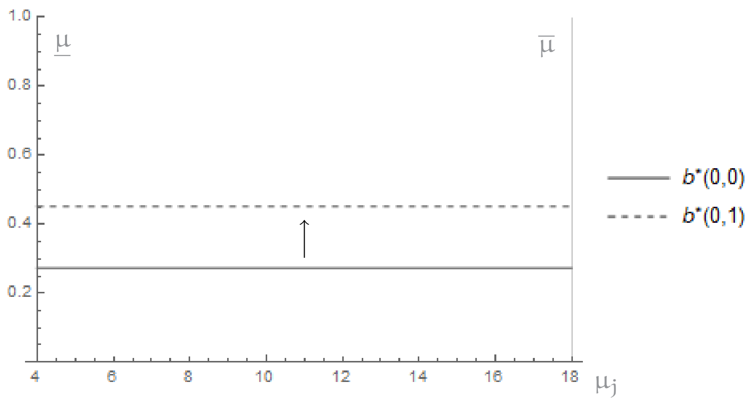
3.4 Discussion of non-pivotal case

Strategic complementarity or substitutability is an important feature of this game; it shows what are the strategic effects due to the interplay between a firm's actions and the decisions of its opponent. In order to assess whether an observable investment in information acquisition from a firm causes the opponent to bid more (less) aggressively, i.e. submit a lower (higher) bid, there needs to be an assessment of how the bidding function of a firm changes, when changing its own investment decision, and what is the opponent's best response to this change. Let's first look at the case when neither of the firms invests in information acquisition and one of them decides to change its decision, under observable actions.

Firstly, this change affects firm's i own bidding function. Keeping the opponent's j strategy constant, i.e. firm j remains uninformed, investing in information acquisition results in firm i bidding at a higher level for every realization of μ_i that is revealed, or in other words, less aggressively. Firm i takes advantage of the fact that it is informed, while firm j is uninformed, thus optimally bidding on a higher level. On the other hand, taking the perspective of firm j, its bid increases due to the fact that its opponent, firm i, is now informed and will inevitably lose for certain realizations of μ_i. Firm j responds to a less aggressive behaviour by firm i in the same manner; consequently this market structure results in a situation of strategic complementarity. These strategic effects are depicted through the bid functions under a uniform probability density function for expected production in Figure 4.



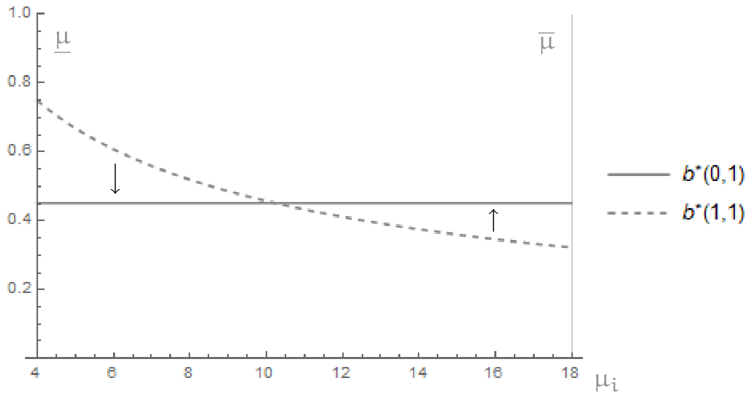
(a) Change in bidding function of firm i due to change in information investment from firm i



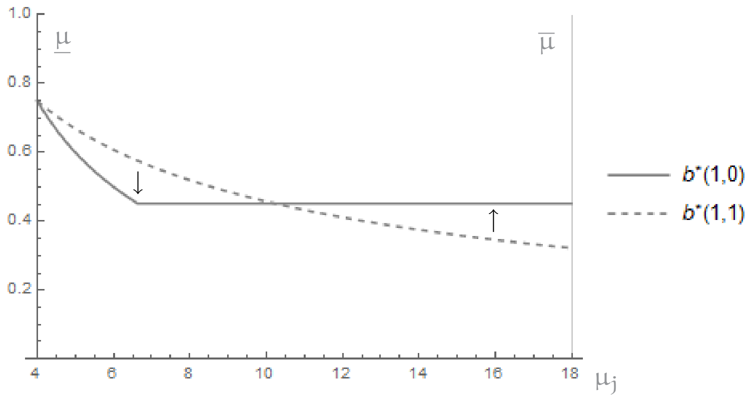
(b) Change in bidding function of firm j due to change in information investment from firm i

Figure 4: Strategic effects of changing i's decision on information acquisition investment (j uninformed)

Turning to the case when firms start from both investing in information acquisition, a similar reasoning can be applied. If firm i decides to switch its choice from investing to not investing, while firm j is still privately informed, firm i cannot condition its bid on μ_i anymore resulting in a constant bid b_i. This means that for values of μ_i below (above) $\frac{\beta}{b}$, b_i is more (less) aggressive. Firm j responds in the same form as firm i; its bids become more and less aggressive for the same range of values μ_j, see Figure 5 for an illustration of the uniform pdf case. The fact that their behaviours change for the exact same range of values of expected productivity is due to the flat region of $b^*(1, 0, \mu_i)$ being equal to $b^*(0, 1)$. The conclusion of strategic complementarity holds also in this case.



(a) Change in bidding function of firm i due to change in information investment from firm i



(b) Change in bidding function of firm j due to change in information investment from firm i

Figure 5: Strategic effects of changing i's decision on information acquisition investment (j informed)

Let's now focus on what the equilibrium outcome of this game will be and how the regulator can steer the players towards the preferred behaviour of information acquisition. Table 1 shows the normal-form game of this non-pivotal case. The two different strategic decisions for each firm is to either invest in information acquisition or not, with each combination of strategies resulting in different payoffs. Looking at Propositions 1, 2 and 3, it is evident that the value of wind capacity θ, a parameter set by the regulator, is the factor determining the ranking of the subgames' payoffs, given that the cap on bids induces building capacity for every level of expected production. The main policy implication is that the regulator dictates the equilibrium outcome. In what follows, I illustrate what is the range of values for θ to get different outcomes.

		firm j	
		yes	no
firm i	yes	$\pi^*(1,1), \pi^*(1,1)$	$\pi^*(1,0), \pi^*(0,1)$
	no	$\pi^*(0,1), \pi^*(1,0)$	$\pi^*(0,0), \pi^*(0,0)$

Table 1: Normal-form game of the non-pivotal case

The thresholds θ_1 and θ_2 are defined and specified for the example of a uniform probability density function in Sections 3.2 and 3.3, respectively.

For the regulator to induce an equilibrium where none of the firms invests in information acquisition, meaning that there is no profitable deviation from the decision $(0,0)$, it has to be that

$$\pi^*(0,0) \geqslant \pi^*(1,0) \Leftrightarrow \theta \leqslant \theta_2.$$

On the other hand, for the asymmetric choice, $(0,1), (1,0)$, to be the equilibrium it has to be that

$$\begin{aligned} \pi^*(0,0) < \pi^*(1,0) \quad &\text{and} \quad \pi^*(0,1) > \pi^*(1,1) \Leftrightarrow \\ \theta_2 < \quad &\theta \quad < \theta_1. \end{aligned}$$

Finally, the equilibrium $(1,1)$ arises if and only if

$$\pi^*(1,1) \geqslant \pi^*(0,1) \Leftrightarrow \theta \geqslant \theta_1.$$

If the regulator sets the demand lower than θ_2, none of the firms has the incentive to invest in information acquisition. However, once the demand surpasses the threshold of θ_2, while still lower than θ_1, asymmetric choice regarding information acquisition becomes the subgame perfect equilibrium. If θ is set higher than θ_1, then the regulator achieves the goal of inducing information acquisition on the firms' side as a subgame perfect equilibrium.

Increasing the level of θ has a size effect, meaning that firms' higher profits are a consequence of building a larger wind farm, but it also has a strategic effect. Indeed, the demand for wind capacity enters all payoffs linearly, causing profits to increase within a specific subgame; however increasing the level of wind capacity demanded beyond the thresholds described above, also alters the strategic behaviour of the firms. For instance, once $\theta > \theta_1$, both firms acquire information, and they change their bidding and profit function; although they could instead keep the same bidding and profit functional forms as when uninformed, and reduce their profit by the cost of information acquisition γ.

Finally, comparing auctioning wind capacity to feed-in tariffs, which is the support scheme most frequently used, shows that auctions result in lower prices and capacities. Under a feed-in tariff, the price paid to firms is equal to P and the installed capacity is the maximum firms can build, i.e. $K_1 + K_2$. In all subgames, bids are always lower than P and the installed capacity is lower than what the firms can build, since $\theta < K_1 + K_2$. Therefore, the built capacity is exactly equal to what the regulator asks, in other words there is no over-investment.

4 CONCLUSION

As the energy transition is in progress, many countries implement environmental policies to promote the investment in renewable energy in the electricity sector. Among the available options, auctions serve also as a framework to help regulators anticipate the electricity production from variable renewables and adapt to the new challenges. This paper examines the conditions such that investing in information acquisition regarding potential profits can be chosen by firms in equilibrium, under the most common auction design for wind capacity. Different cases and equilibria emerge, depending on how much capacity the regulator decides to auction. The strategic complementarity of bids is also discussed, as part of the effect information acquisition has in the behaviour of firms. Through this analysis, a contribution is intended to the literature of using auctions to build renewable energy capacity in the electricity sector, combined with information acquisition.

Indeed, inducing information acquisition on the firms' side can be achieved through setting the amount of wind capacity the regulator sets. This implies that, when firms are big enough to cover the demand, the regulator has an interest to organize an auction for the whole capacity that has to be built, rather than many, smaller ones. On the other hand, the upper limit on bids is not crucial, when set at a level that would always induce a wind farm to be constructed, as done under many feed-in tariff structures. Since finding its correct level is information intensive, moving from a feed-in tariff to an auction scheme would ensure that firms ask for a lower price. However, investing in and revealing their expected production is not certain; auctions need to be designed in an appropriate way to induce this choice.

The stylized model presented in this paper is of course limited by some key assumptions. For instance, the analysis is based on the fact that the signal received by firms when they have private information is completely accurate. Additionally, all agents have the same priors regarding expected production of the sites available to firms. What is more, it could be that the two sites have productions that are correlated; this can have important implications on the bids that firms place.

Further work on this paper includes relaxing the aforementioned assumptions, as well as a welfare analysis in order to determine whether auctions can replicate the solution planner optimum. The cases when firms are ex ante both pivotal, and asymmetric in terms of pivotality still remain to be examined. An extension of this work will look into heterogeneous companies in terms of marginal capacity costs, i.e. $\beta_i < \beta_j$, and how the regulator can then assign building capacity to the cost-minimizing firm.

Auctions are increasing part of environmental policy, hence their implications and limitations need to be thoroughly understood, in order for them to help countries transition into low carbon electricity system.

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APPENDIX

A PROOF OF DECREASING BIDS IN THE SITE EXPECTED PRODUCTION, NON-PIVOTAL CASE

In this Section, I show that under private information, if firm i has a higher realization of μ_i and the cumulative distribution function of firm i having a lower bid than firm j is steep enough, then firm i bids at a lower level. When firms pay the cost of information acquisition γ, they are perfectly informed about the expected production of their site μ_i. The profit function when each firm has private information about its expected production reads

$$\pi_i(1,1,b_i,\mu_i) = \int_{\underline{\mu}}^{\overline{\mu}} \Pr[b_i \leqslant b_j(\mu_j)]\,(b_i\mu_i - \beta)\,\theta f(\mu_j)d\mu_j - \gamma \tag{25}$$

The cross-derivative of the profit function with respect to μ_i and b_i is

$$\begin{aligned} \frac{\partial^2 \pi_i(1,1,b_i,\mu_i)}{\partial\mu_i \partial b_i} &= \frac{\partial^2}{\partial\mu_i\partial b_i}\left[\int_{\underline{\mu}}^{\overline{\mu}} \Pr[b_i \leqslant b_j(\mu_j)]\,(b_i\mu_i - \beta)\,\theta f(\mu_j)d\mu_j - \gamma\right] \\ &= \frac{\partial}{\partial b_i}\int_{\underline{\mu}}^{\overline{\mu}} \Pr[b_i \leqslant b_j(\mu_j)] b_i \theta f(\mu_j)d\mu_j \\ &= \int_{\underline{\mu}}^{\overline{\mu}} \left[\Pr[b_i \leqslant b_j(\mu_j)] + \frac{\partial \Pr[b_i \leqslant b_j(\mu_j)]}{\partial b_i} b_i\right] \theta f(\mu_j)d\mu_j \end{aligned} \tag{26}$$

The probability of firm i having the lower bid and winning the auction, $\Pr[b_i \leqslant b_j(\mu_j)]$, is decreasing in b_i. If the density of this probability is high enough, the cross-derivative is negative, denoting that when firm i receives information of a higher expected production, then it bids a lower bid.

B SECOND ORDER CONDITION IN OPTIZIMATION, NON-PIVOTAL CASE

In order for the profit function to be maximized by the bid specified in Proposition 2, the second order condition needs to be satisfied. Indeed, it is straightforward to calculate that

$$\begin{aligned} \frac{\partial^2 \pi_i(1,1,b_i,\mu_i)}{\partial b_i^2} &= \frac{F'(\mu_i)}{b'(\mu_i)}\left[2\mu_i - \frac{b''(\mu_i)}{(b'(\mu_i))^2}\,(b(\mu_i)\mu_i - \beta)\right] \Leftrightarrow \\ &= \frac{F'(\mu_i)\beta^2}{(b'(\mu_i))^3\,\mu_i^2(\mu_i - \underline{\mu})^2}\left[\mu_i(\ln\mu_i - \ln\underline{\mu}) - (\mu_i - \underline{\mu})\right] < 0 \end{aligned} \tag{27}$$

and that the solution to the optimization problem maximizes the objective function.