

Procurement auctions for an electricity system with increased wind technology

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PRELIMINARY AND INCOMPLETE

Abstract

Auctions are used in many countries as a policy measure to promote renewable energy. However, do auctions incentivise firms to invest in acquiring information regarding their own potential revenue? 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. Preliminary results show that both when each firm can cover the demand and when firms face residual demand, their choice can be steered towards acquiring information. This kind of information can be useful for the regulator, especially in the context of higher renewable penetration in the electricity system.

Keywords: Wind Energy, Auctions, Electricity, Information Acquisition

1 INTRODUCTION

Environmental policies in order to deploy renewable energy in the electricity sector are established in more than 120 countries around the world. Feed-in tariffs and premiums are still the most commonly used option (IEA et al., 2018), even though under these schemes, it is often difficult for regulators to identify the correct level of the policy measure. In an attempt to shift the burden of finding and revealing the right price from the regulator to firms, an increasing number of countries are implementing auctions of renewable energy capacity. Indeed, while only 8 countries had adopted them in 2004, auctions existed in 73 countries in 2017 (IEA et al., 2018).

Compared to the feed-in tariff structure, auctions can increase competition, since they lead to the price received by firms being closer to their costs, and to the information asymmetry between firms and the regulator being reduced (Myerson, 1981; Milgrom and Weber, 1982; Green and Laffont, 1977). However, for these results to hold, firms need to be informed about their own valuation of a potential investment site. It can be the case, though, that firms do not have information regarding their potential profits. The main focus of this paper is to examine under what conditions auctions incentivise firms to invest in acquiring information about their own potential revenue and reveal this information through their bids.

To answer this question I develop a stylised 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 as discriminatory, multi-unit, first-price sealed bid in a duopoly, with private values and the option of private information. Although this paper takes the example of wind farms, it could be applied

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to other variable renewable energies. Before participating in an auction, firms have the option to invest in acquiring information, receiving a perfectly informative signal regarding the production of potential wind farm sites. Wind profiles can be directly linked to the electricity production of a wind farm, hence this kind of information can allow firms to ask for a higher price per unit of electricity produced without procuring less quantity¹. Put differently, they can have a bidding strategy that will increase their produced quantity without necessarily compromising their revenues.

The main contribution of this paper is to investigate whether auctions affect the decision to invest in acquiring information about potential revenues, when implementing the mechanism at the stage of installing wind energy capacity. As such, it is connected to the literature on auctions, especially in the context of renewable energy. An extensive survey of the auction theory literature is provided by [Klemperer \(1999\)](#). Auctions within electricity markets have been extensively studied by [Green and Newbery \(1992\)](#) and [Green \(1996\)](#), among others. On the other hand, [Arozamena and Cantillon \(2004\)](#) looks into how the format of an auction changes a firm's decision to invest in cost reduction.

Furthermore, this paper also draws from research on information acquisition. 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. \(2013\)](#). 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 paper is organised as follows. In section 2, the model's components are presented. Section 3 presents and discusses the equilibrium outcomes divided in two main cases, depending on the assumptions made about the capacity available to firms. Section 4 concludes with a discussion on the implications of the model.

2 MODEL

A standard duopoly model is used, where two firms, $i = 1, 2$, bid in order to build wind capacity, $\theta > 0$, demanded by the regulator. Each firm has access to one site on which they can decide how much wind capacity, $\kappa_i \geq 0$, to install. Due to land availability and site topography, 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, $K_i > 0$, that each firm can install. It is assumed that the sites available to firms can cover the demanded capacity, that is $K_1 + K_2 \geq \theta$. Furthermore, each additional turbine has the same installation cost, $\beta > 0$, i.e. the marginal cost of installing capacity is constant and positive.

Electricity produced in wind farms is a stochastic variable, due to the stochastic nature of wind. In this model, each site has a different electricity production profile, meaning that the distribution of electric power produced by each wind turbine has different expected value, μ_i , and standard deviation². Assuming that firms are risk neutral, the only payoff-relevant part of the distribution is 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 $[\underline{\mu}, \bar{\mu}] \subset \mathbb{R}_{++}$

¹ A trade-off exists between increasing the probability of winning an auction and having lower profits from winning, see for example [Krishna \(2009\)](#) "An increase in the bid will increase the probability of winning while, at the same time reducing the gains from winning".

² Electricity production profiles are a result of the wind speed profile of a site. Wind speed is a random variable following 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. With a monotonic power curve, these two facts result in electric power being distributed along a different curve (see for example [The Swiss Wind Power Data Website \(2018\)](#)). The mean value of this distribution is the expected electric power per wind turbine, noted in this paper as μ_i for site i , $i = 1, 2$.

be the support of $f(\cdot)$, where μ_1 and μ_2 are i.i.d. For ease of calculations and exposition of results in the sections that follow, a uniform probability density function, i.e. $f(\mu_i) = \frac{1}{\bar{\mu} - \underline{\mu}}$, is chosen.

Each firm places a bid b_i which will be the price it will receive for its electricity production³. The regulator sets a price cap for the bids⁴, so $b_i \leq P$. It is assumed that P is set at a level high enough to incentivise firms to build capacity.

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

$$k_i = \begin{cases} \min\{\theta, K_i\}, & \text{if } b_i < b_{-i} \\ \max\{0, \theta - K_{-i}\}, & \text{if } b_i > b_{-i} \end{cases}$$

Without loss of generality, ties break in favour of firm $i = 1$; i.e. when $b_1 = b_2$, then $k_1 = \min\{\theta, K_1\}$ and $k_2 = \max\{0, \theta - K_1\}$.

Before the auction, each firm has the option to invest in information acquisition on its site's expected production. This investment costs $\gamma > 0$. Once firms pay γ , they observe a perfectly accurate signal, namely the realised value of their own expected production. Then, they decide on their bids. Note that in the setting of this paper, electricity production takes place within a given time duration, hence electric power and electricity production can be considered as the same quantities.

The timing of the game is as follows: Once the regulator announces θ and P , firms decide 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, 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.

When firm i does not invest in information acquisition, its expected profit is:

$$\mathbf{E}[\pi_i] = \begin{cases} (b_i \mu - \beta) \min\{\theta, K_i\}, & \text{if } b_i < b_{-i} \\ (b_i \mu - \beta) \max\{0, \theta - K_i\}, & \text{if } b_i > b_{-i} \end{cases}$$

where $\mu \equiv \int_{\underline{\mu}}^{\bar{\mu}} x f(x) dx = \frac{\bar{\mu} + \underline{\mu}}{2}$.

When $b_1 = b_2$, $\mathbf{E}[\pi_1] = (b_1 \mu - \beta) \min\{\theta, K_1\}$ and $\mathbf{E}[\pi_2] = (b_2 \mu - \beta) \max\{0, \theta - K_1\}$.

On the other hand, when firm i invests in information acquisition, it does not decide based on the prior probability density function $f(\cdot)$, but rather on the realization of μ_i , hence its profit reads:

$$\pi_i = \begin{cases} (b_i \mu_i - \beta) \min\{\theta, K_i\} - \gamma, & \text{if } b_i < b_{-i} \\ (b_i \mu_i - \beta) \max\{0, \theta - K_i\} - \gamma, & \text{if } b_i > b_{-i} \end{cases}$$

whereas in case of a tie, i.e. $b_1 = b_2$, firms with private information have the following expected profit:

$$\begin{aligned} \mathbf{E}[\pi_1] &= (b_1 \mu_1 - \beta) \min\{\theta, K_1\} - \gamma \\ \mathbf{E}[\pi_2] &= (b_2 \mu_2 - \beta) \max\{0, \theta - K_1\} - \gamma. \end{aligned}$$

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 $K_i \geq \theta$, $K_i < \theta$, or

³ Discriminatory auctions are the most common design for renewable energy capacity within the electricity sector (IRENA, 2015).

⁴ Auctions are commonly 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.

$K_i < \theta < K_{-i}$ 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 firm $-i$ cannot cover the whole demand θ that the regulator sets.

The remainder of this section focuses on symmetric firms in terms of capacity, meaning that either both or none of the firms are pivotal. In order to find the subgame perfect equilibrium of this auction, the equilibrium outcomes of all the subgames need to be considered. Equilibria are within symmetric pure strategies, and only when these do not exist, mixed and asymmetric strategies are considered.

3.1 Non-Pivotal Firms

When firms are non-pivotal, in other words when $K_i \geq \theta$, for $i = 1, 2$, firms never face residual demand, and capacity is auctioned similar to a single unit auction. Next, the analysis focuses on the firms' decision to invest in information acquisition and their respective profits.

3.1.1 None of the firms invests in information acquisition

When firms do not invest in information acquisition, firms decide in a common knowledge setting. Consequently, this case is similar to a Bertrand competition, since either firm can cover demand for capacity. [Proposition 1](#) describes the equilibrium bids and expected profits, when firms rely only on the prior expectation regarding their own and their opponents profits.

Proposition 1 *In equilibrium under a common knowledge regime, non-pivotal firms with a uniform prior probability density function $f(\mu_i) = \frac{1}{\bar{\mu} - \underline{\mu}}$ bid at*

$$b_i^* = \frac{2\beta}{\bar{\mu} + \underline{\mu}} \quad (1)$$

having an expected profit of

$$\mathbb{E}[\pi_i^*] = 0 \quad \forall i, \quad i = 1, 2. \quad (2)$$

Based on Bertrand competition reasoning, these bids are best responses. Furthermore, firms do not have profitable deviations. To prove that indeed this is the case consider whether a deviation of firm i can increase its expected profit. If firm i increases its bid by ϵ , with $\epsilon \rightarrow 0$, 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, $b_i^* = \frac{2\beta}{\bar{\mu} + \underline{\mu}}$, $i = 1, 2$, is an equilibrium.

3.1.2 Both firms invest in information acquisition

Let's turn to the case when firms have private information: firm i decides to pay the cost of information acquisition γ and therefore knows the realization of the expected production μ_i . However, firm i has only a belief on the expected production of firm $-i$, expressed through the prior probability density function $f(\mu_i) = \frac{1}{\bar{\mu} - \underline{\mu}}$. Firm i wins the auction and builds capacity θ when $b_i \leq b_{-i}$. Ex ante bid b_{-i} is unknown to firm i , due to μ_{-i} . Hence the expected profit of firm i is given by:

$$\mathbb{E}[\pi_i] = \Pr[b_i \leq b_{-i}] (b_i \mu_i - \beta) \theta - \gamma \quad (3)$$

Assuming bids are strictly decreasing in the observed μ_i , there is a function such that $b_i = B_i(\mu_i)$, $B_i'(\mu_i) < 0$. Firms are ex ante symmetric, consequently bidding strategies are too, i.e. $B_i(\cdot) = B_{-i}(\cdot) = B(\cdot)$. Expected profit can be rewritten as:

$$\mathbb{E}[\pi_i] = F\left(B^{-1}(b_i)\right) (b_i \mu_i - \beta) \theta - \gamma \quad (4)$$

where $B^{-1}(\cdot)$ is the inverse function of $B(\cdot)$ and the function $F(\cdot)$ is the cumulative distribution function corresponding to $f(\cdot)$.

Proposition 2 When a non-pivotal firm has private information regarding their expected production μ_i and a uniform prior probability density function, $f(\mu_i) = \frac{1}{\bar{\mu} - \underline{\mu}}$ regarding the expected production of their opponent, in a symmetric pure strategy equilibrium they bid according to

$$b_i^* = B^*(\mu_i) = \begin{cases} \beta/\underline{\mu}, & \text{if } \mu_i = \underline{\mu} \\ \frac{\beta (\ln \mu_i - \ln \underline{\mu})}{\mu_i - \underline{\mu}}, & \text{if } \underline{\mu} < \mu_i \leq \bar{\mu} \end{cases} \quad (5)$$

and have expected profit

$$E[\pi_i^*] = \begin{cases} -\gamma, & \text{if } \mu_i = \underline{\mu} \\ \frac{\beta}{\bar{\mu} - \underline{\mu}} (\mu_i (\ln \mu_i - \ln \underline{\mu}) - (\mu_i - \underline{\mu})) \theta - \gamma, & \text{if } \underline{\mu} < \mu_i \leq \bar{\mu}. \end{cases} \quad (6)$$

The bidding strategy described in proposition 2 is the result of maximising equation (4). Indeed, the uniform cumulative distribution function is logconcave and consequently, the objective function (4) is quasiconcave and maximised when

$$\begin{aligned} \frac{dF(B^{-1}(b_i))}{db_i} (b_i \mu_i - \beta) + F(B^{-1}(b_i)) \mu_i &= 0 \Leftrightarrow \\ F'(\mu_i) \frac{1}{B'(\mu_i)} (b_i \mu_i - \beta) + F(\mu_i) \mu_i &= 0 \Leftrightarrow \\ F'(\mu_i) (B(\mu_i) \mu_i - \beta) + F(\mu_i) B'(\mu_i) \mu_i &= 0 \Leftrightarrow \\ B'(\mu_i) (\mu_i - \underline{\mu}) \mu_i + B(\mu_i) \mu_i - \beta &= 0 \end{aligned} \quad (7)$$

The solution to this differential equation gives the bidding strategy of each firm after they have observed μ_i , $b_i^* = B^*(\mu_i)$, as in proposition 2 equation (5). It should be noted that the initial condition for $B^*(\mu_i)$ was chosen so that for every realization of μ_i there is a bid that does not tend to infinity and that $B^*(\mu_i)$ is a continuous function. Proving that $B^*(\mu_i)$ is indeed a decreasing function, as assumed, is straightforward from equation (5).

Regarding the firm's expected profit in equilibrium, given by equation (6), it can be seen that it is increasing in μ_i and always greater than $-\gamma$. Therefore, once a firm has paid the cost of information acquisition, it is optimal to participate in the auction, instead of choosing the outside option. It is worth noting that a higher realization of μ_i gives higher expected profit, a result that is rather intuitive. However, depending on the realization of μ_i and for given parameters β , $\bar{\mu}$, $\underline{\mu}$, θ and γ , expected profit can be either negative or positive.

3.1.3 Firm i invests in information acquisition, firm $-i$ does not invest

Let's now consider the case when firm 1 invests and firm 2 does not; their choices are overt. In this case, due to asymmetry in choice, firms cannot play symmetric strategies any more. In this setting, firm 1 maximises its actual profit, while firm 2 can only maximise its expected profit. Proposition 3 shows equilibrium bids and profits for the two firms.

Proposition 3 *In equilibrium when non-pivotal firm 1 has private information on its expected production μ_1 , whereas non-pivotal firm 2 does not have any private information, with a uniform prior possibility distribution function $f(\mu_2) = \frac{1}{\bar{\mu} - \underline{\mu}}$, their bidding strategies are given by*

$$b_1^* = B_1^*(\mu_1) = \begin{cases} \frac{\beta}{\mu_1}, & \text{if } \underline{\mu} \leq \mu_1 < \frac{\bar{\mu} + \underline{\mu}}{2} \\ \frac{2\beta}{\bar{\mu} + \underline{\mu}}, & \text{if } \frac{\bar{\mu} + \underline{\mu}}{2} \leq \mu_1 \leq \bar{\mu} \end{cases} \quad (8)$$

$$b_2^* = \frac{2\beta}{\bar{\mu} + \underline{\mu}}. \quad (9)$$

Their profits are respectively

$$\pi_1^* = \begin{cases} -\gamma, & \text{if } \underline{\mu} \leq \mu_1 < \frac{\bar{\mu} + \underline{\mu}}{2} \\ \frac{2\mu_1 - (\bar{\mu} + \underline{\mu})}{\bar{\mu} + \underline{\mu}} \beta \theta - \gamma, & \text{if } \frac{\bar{\mu} + \underline{\mu}}{2} \leq \mu_1 \leq \bar{\mu} \end{cases} \quad (10)$$

$$E[\pi_2^*] = 0. \quad (11)$$

For these strategies to be an equilibrium, firms should not have an incentive to deviate. Fixing the strategy for firm 2, when $\underline{\mu} \leq \mu_1 < \bar{\mu}$, firm 1 cannot bid lower than $\frac{\beta}{\mu_1}$ because this bid will result in negative profit, while bidding higher will not cause the firm to win the auction. When $\underline{\mu} \leq \mu_1 \leq \bar{\mu}$, firm 1 does not have an incentive to bid lower than $\frac{2\beta}{\bar{\mu} + \underline{\mu}}$, since this deviation will result to lower profit.

On the other hand, firm 2 only considers the prior probability density function $f(\mu_2)$, hence its bid has to be constant. Since both firms are non-pivotal, the optimal strategy for the uninformed firm 2 is to bid $\frac{2\beta}{\bar{\mu} + \underline{\mu}}$ and it cannot increase its profit by deviating. As a consequence, there is no profitable deviation for either firm and the aforementioned strategies constitute an equilibrium.

It is easy to confirm from equation (10) that once again, if firm 1 invests in information acquisition, profit is maximised when the firm participates in the auction and that profit of firm 1 increases with higher realizations of μ_1 . More specifically, when firm 1 observes μ_1 lower than the distribution's average, it has a profit of $-\gamma$, which is the same profit as choosing not to participate in the auction. When μ_1 is higher than the distribution's average, firm 1 bids at the level of b_2 , wins the auction and increases its profit. Turning to firm 2, it is uninformed, therefore it has always an expected profit of 0. This result is in accordance with the literature.

3.1.4 Discussion of non-pivotal case

Comparing the results of the three subgames, it can be seen that once a firm has invested in information acquisition, it is optimal to participate in the auction. Additionally, since firms are ex ante symmetric, the outcome in equilibrium has to be that either both firms invest in information acquisition or that neither does.

However, firms' choice is not clear under a uniform distribution function. More specifically, firms with private information regarding μ_i can end with positive or negative profits. Indeed, a threshold for the value of μ_i can be specified from equation (6) below which expected profit is negative and above which expected profit is positive. The value of this threshold, and whether eventually investing in information acquisition is the strategy in equilibrium, depends on the parameters, $\underline{\mu}$, $\bar{\mu}$, β , θ and γ .

If relative to $\frac{\bar{\mu} + \underline{\mu}}{2}$, the average of the prior pdf, cost of information acquisition γ is low, marginal capacity cost β is high, and demand for wind capacity θ is high, the threshold for positive profit is low, meaning that firms are more likely to realise positive profit and in expectation they are better off investing in information acquisition. Hence, an auction designer aiming at incentivising firms to invest in information acquisition, would need to consider the relative values of these parameters and

adjust the value of demanded capacity θ . Note that in the non-pivotal case, the value of the upper bound for the bids P is not relevant for equilibrium outcomes.

3.2 Pivotal Firms

Turning to the pivotal case, $K_i < \theta$, for $i = 1, 2$, firms now always build some capacity irrespective of their opponents bid. When winning the auction, firm i builds K_i , but it covers the residual capacity $\theta - K_{-i}$ in case it loses. In order to ensure that firms can always cover demand for wind capacity, let $\theta/2 < K_i < \theta$, for $i = 1, 2$.

3.2.1 None of the firms invests in information acquisition

Under common knowledge, symmetric firms have to bid at the same level, i.e. $b_1 = b_2$. Since ties break in favour of firm 1, firm 1 always wins and firm 2 always loses. Therefore, the expected profits that firms maximise read:

$$\mathbf{E}[\pi_1] = (b_1\mu - \beta)K_1 \quad (12)$$

$$\mathbf{E}[\pi_2] = (b_2\mu - \beta)(\theta - K_1) \quad (13)$$

where given a uniform prior pdf, $\mu = \frac{\bar{\mu} + \underline{\mu}}{2}$.

Profits are maximised when firms bid the maximum amount they can, that is when $b_1^* = b_2^* = P$, making these the equilibrium bids. Due to pivotality, firms now have positive profits and the upper bound for the bids, P , becomes a relevant parameter. Proposition 4 summarises the above and shows equilibrium expected profits.

Proposition 4 *In equilibrium, pivotal firms in a common knowledge setting with $f(\mu_i) = \frac{1}{\bar{\mu} - \underline{\mu}}$ bid at the upper bound:*

$$b_i^* = P, \quad i = 1, 2 \quad (14)$$

resulting in expected profits

$$\mathbf{E}[\pi_1^*] = \left(P \frac{\bar{\mu} + \underline{\mu}}{2} - \beta \right) K_1 \quad (15)$$

$$\mathbf{E}[\pi_2^*] = \left(P \frac{\bar{\mu} + \underline{\mu}}{2} - \beta \right) (\theta - K_1). \quad (16)$$

3.2.2 Both firms invest in information acquisition

Next, each firm i has private information on the realization of μ_i , while keeping the prior belief regarding the expected production of firm $-i$. Depending on the bids, firm i either wins the auction and builds its maximum capacity or loses and builds the residual. Formally, firms optimize the following objective function

$$\mathbf{E}[\pi_i] = \Pr[b_i \leq b_{-i}](b_i\mu_i - \beta)K_i + (1 - \Pr[b_i \leq b_{-i}])(b_i\mu_i - \beta)(\theta - K_{-i}) - \gamma \quad (17)$$

Similar to the non-pivotal case, let's assume that firms bid according to a decreasing function, $b_i = B_i(\mu_i)$, $B_i'(\mu_i) < 0$. Symmetric firms have symmetric bidding functions, that is $B_i(\cdot) = B_{-i}(\cdot) = B(\cdot)$, and expected profit becomes

$$\mathbf{E}[\pi_i] = F\left(B^{-1}(b_i)\right) (b_i\mu_i - \beta)(K_i + K_{-i} - \theta) + (b_i\mu_i - \beta)(\theta - K_{-i}) - \gamma \quad (18)$$

Note that the key difference compared to the non-pivotal case is that now firms always have some positive profit due to the residual demand.

Once again, the objective function is quasi-concave, since $F(\cdot)$ is a logconcave CDF. Hence, the first order condition reads

$$\begin{aligned} \frac{dF(B^{-1}(b_i))}{db_i} (b_i \mu_i - \beta) (K_i + K_{-i} - \theta) + F(B^{-1}(b_i)) \mu_i (K_i + K_{-i} - \theta) + \mu_i (\theta - K_{-i}) &= 0 \Leftrightarrow \\ F'(\mu_i) \frac{1}{B'(\mu_i)} (b_i \mu_i - \beta) (K_i + K_{-i} - \theta) + F(\mu_i) \mu_i (K_i + K_{-i} - \theta) + \mu_i (\theta - K_{-i}) &= 0 \Leftrightarrow \\ F'(\mu_i) (B(\mu_i) \mu_i - \beta) (K_i + K_{-i} - \theta) + F(\mu_i) B'(\mu_i) \mu_i (K_i + K_{-i} - \theta) + B'(\mu_i) \mu_i (\theta - K_{-i}) &= 0 \Leftrightarrow \\ B'(\mu_i) [(\mu_i - \underline{\mu})(K_i + K_{-i} - \theta) + (\bar{\mu} - \underline{\mu})(\theta - K_{-i})] \mu_i + B(\mu_i) \mu_i (K_i + K_{-i} - \theta) - \beta (K_i + K_{-i} - \theta) &= 0 \quad (19) \end{aligned}$$

The solution to this differential equation gives the equilibrium bid, $B^*(\mu_i)$. From there the equilibrium profit can be calculated.

Proposition 5 *Two pivotal firms investing in information acquisition with a uniform prior probability density function, $f(\mu_i) = \frac{1}{\bar{\mu} - \underline{\mu}}$, results in bidding*

$$b_i^* = B^*(\mu_i) = \frac{\beta \chi (\ln \mu_i - \ln \hat{\mu})}{K_i (\bar{\mu} - \underline{\mu}) - \chi (\bar{\mu} - \mu_i)} \quad (20)$$

where $\chi \equiv K_i + K_{-i} - \theta$, $\hat{\mu} \equiv \bar{\mu} - \frac{K_i}{\chi} (\bar{\mu} - \underline{\mu})$, and expected profit of

$$E[\pi_i^*] = (B^*(\mu_i) \mu_i - \beta) \left(K_i - \chi \frac{\bar{\mu} - \mu_i}{\bar{\mu} - \underline{\mu}} \right) - \gamma, \quad i = 1, 2. \quad (21)$$

Similar to the approach in the non-pivotal case, the initial condition for the differential equation (19) is such that the bidding function is continuous. It is easy to show that $\underline{\mu} > \hat{\mu}$ and therefore it always holds that $\mu_i > \hat{\mu}$ and bids are positive. Furthermore, from equation (20), it holds that $B^*(\mu_i)$ is decreasing in μ_i , as initially assumed.

Results on equilibrium expected profit remain similar as described in the non-pivotal case, in the sense that once a firm has paid the cost γ , it is optimal to participate in the auction, instead of choosing the outside option. However, it should be noted that different realizations of μ_i can result in firms having negative or positive profits. For $\mu_i \in [\underline{\mu}, \bar{\mu}]$, expected profit is an increasing function of μ_i , hence there exists a threshold, from equation (21), below which for a realization of μ_i profit is negative and above which it is positive.

3.2.3 Firm i invests in information acquisition, firm $-i$ does not invest

Last subgame of the pivotal case is the one where firms have asymmetric choices. The uninformed firm 2 needs to have a constant bid, while the informed firm 1 can condition its bid on the observed value of μ_i . As already discussed, firms always cover at least the residual demand. As a consequence, the uninformed firm is better off bidding the highest possible bid, leading both the uninformed and informed firm to bid the maximum they can. Proposition 6 shows this result.

Proposition 6 *For pivotal firms, where firm 1 has private information on the realization of μ_1 and firm 2 only relies on the uniform prior probability density function, $f(\mu_i) = \frac{1}{\bar{\mu} - \underline{\mu}}$, bidding in equilibrium is*

$$b_1^* = b_2^* = P \quad (22)$$

while profits read

$$\pi_1^* = (P \mu_1 - \beta) K_1 - \gamma \quad (23)$$

$$E[\pi_2^*] = (P \bar{\mu} - \beta) (\theta - K_1). \quad (24)$$

Indeed, in equilibrium neither firm can perform better by deviating. Additionally, participating in the auction is what the informed firm chooses to do, since its profit increases by $(P\mu_1 - \beta)K_1 > 0$.

3.2.4 Discussion of pivotal case

Ex ante symmetric firms will choose the same option regarding information acquisition, as described in sections 3.2.1 and 3.2.2. Informed firms participate in the auction once they have paid γ , but to conclude whether they invest in information acquisition or not, profits in propositions 4 and 5 need to be compared.

Proposition 4 suggests that there is a threshold for μ_i where profits turn from negative to positive. Information acquisition is the equilibrium with a uniform prior pdf, when this threshold value is low. This translates into low cost for information acquisition γ , high marginal cost to build wind capacity β , and high demand for wind capacity θ . Note however, the important difference between the non-pivotal and the pivotal case is the relevance of the bid cap P . When P is set high enough, then it is never optimal for firms to invest in information acquisition. In this case, the regulator bears costs for supporting wind energy that are higher than necessary.

4 CONCLUSION

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 mechanism to reduce the burden of regulators to specify the correct level of a feed-in tariff. This paper examines whether, under a specific auction scheme for wind capacity, investing in information acquisition regarding potential profits is the choice of firms. Different cases and equilibria emerge, depending on whether firms always cover residual demand for wind capacity or not. Through this analysis, a contribution is intended to the literature of auctioning renewable capacity in the electricity sector, combined with information acquisition.

Indeed, inducing information acquisition on the firms' side can be achieved through manipulating the amount of wind capacity and the cap on bids the regulator sets. However, especially in the case of pivotal firms, the upper limit on bids is crucial. Finding its correct level is information intensive and, when set too high, it can lead to increased costs for wind capacity deployment. Consequently, simply moving from a feed-in tariff to an auction scheme does not necessarily ensure that firms invest in and reveal their expected production; auctions need to be designed in an appropriate way to induce this choice.

The highly stylised 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, it is assumed that the expected production of a site is distributed uniformly within a range and that this range is the same for the two different sites that are available to firms.

Further work on this paper includes analysing the behaviour of firms for any prior probability density function. Additionally, the cases when firms are ex ante asymmetric in terms of pivotality still remains to be examined. An extension of this work will look into heterogeneous companies in terms of marginal capacity costs, i.e. $\beta_i < \beta_{-i}$, and how the investment decision changes when signals are not entirely accurate but rather with a higher γ , an increasingly accurate signal occurs.

Auctions are a powerful tool for environmental policy, however they do not come without limitations. In order for them to reduce the cost of supporting renewable energy and help regulators to transition into low carbon electricity system, they need to be carefully designed.

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