Fossil Fuels and Renewable Energy: Mix or Match?*

Natalia Fabra
Universidad Carlos III and CEPR

Gerard Llobet
CEMFI and CEPR

February 28, 2023

VERY PRELIMINARY

Abstract

This paper investigates the impact of the ownership of electricity generation technologies, including fossil fuels and renewable energy sources, on the performance of electricity markets throughout the Energy Transition. Using a game-theoretical model, we examine how the ownership structure affects competition among the price-setting plants and the competitive pressure from the least-cost technologies. Our findings suggest that competition between firms with diversified technologies initially promotes competition among fossil-fuel price-setting plants, resulting in lower market prices. However, as renewable energy sources become more prevalent, the diversified ownership structure reduces competitive pressure on renewable energy plants, leading to inefficiencies in production, higher carbon emissions, and often higher prices. Furthermore, our analysis offers novel insights for the study of multi-unit auctions with cost heterogeneity and privately known capacities.

Keywords: multi-unit auctions, private information, electricity markets, renewable energies.
JEL Codes: L13, L94.

*Emails: natalia.fabra@uc3m.es and llobet@cemfi.es. This paper has benefited from comments by audiences at TSE and UIB and it has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No 772331). Support of the Regional Government of Madrid through grant H2019/HUM-5859 is also acknowledged.

1 Introduction

Worldwide, a growing consensus exists on the need to fight climate change. Under the Paris Agreement, most countries have already committed to reaching carbon neutrality by 2050 (e.g., Europe and the US), 2060 (e.g., China), or 2070 (e.g., India). They have also implemented policies to achieve those goals, with interim steps to align progress and objectives along the Energy Transition. For instance, by 2030, Europe is committed to reducing its greenhouse gas emissions by 55% compared to 1990 levels. It plans to do so by improving energy efficiency and increasing the weight of renewable energy to at least cover 30% of its final energy consumption (European Commission, 2021). The power sector has an important role to play in this transition. In several European countries, renewable energy already represents more than one-third of total electricity generation, and it is expected to become the primary source of electricity by 2030, reaching up to 80-90% by 2050. Given its unique ability to transform renewable energy into electricity, it can also help other polluting industries to reduce their carbon footprints through electrification.

Investments in renewable energy are costly, as they involve significant capital upfront costs, but once in place, they have almost zero marginal cost of production. While an increase in renewable generation will thus reduce the variable costs of producing electricity, will it also lead to lower electricity market prices? This paper shows that the effect depends on the ownership structure of the various generation technologies. Technology-diversified firms foster competition in the early stages of the Energy Transition, but they might lead to productive inefficiencies and less competitive prices when renewable plants become predominant.

Following Fabra and Llobet (2022), we consider two distinctive features of renewable energy sources: their marginal cost is (almost) zero, and their available capacity is random and private information. These features are in contrast with those of conventional technologies (which we generically refer to as *thermal*), with a positive marginal cost and (almost) perfectly known production capacities. However, whereas Fabra and Llobet (2022) analyze the performance of markets 100% renewable, this paper also pays attention to earlier stages of the energy transition, allowing for different ownership structures.

We develop a duopoly model where firms operate thermal and/or renewable energy plants. These firms compete to dispatch their energy through a uniform-price auction, similar to the one used in electricity spot markets in practice. We allow firms to place a different bid for each of the plants they own.

By studying different ownership structures of the two technologies, this paper uncovers a trade-off between competition among the plants that might be marginal and those that, while they might not operate in equilibrium, exert some external competitive pressure. The first kind of competition, which occurs *within technologies*, is fostered when price-setting plants are in the hands of different firms. The second kind of competition, which occurs *across technologies*, limits the market power of the marginal technologies to raise prices and cater the residual demand.

We consider two alternative ownership structures: firms are *specialized* when each owns a single technology, or *diversified* when they own both. Diversification promotes within technology competition, as it places price-setting plants in the hands of different firms. However, as it also implies that each firm owns a portfolio of technologies, it entices firms to individually raise the bids of their thermal plants to remove competitive pressure from the renewable plants. Doing so often allows the firm to profitably increase market prices, even at the expense of losing low-cost renewable production.

On the contrary, specialization promotes across-technology competition, encouraging the firm owning the thermal plants to bid competitively. This behaviour sets a ceiling on the degree of market power of the firm holding the renewable plants. In turn, this discourages the firm from offering its renewable production above the cost of thermal production, which prevents the loss of efficient renewable output. However, by placing all plants with similar costs in the hands of the same firm, specialization kills any competition among them.

We illustrate the interaction between these countervailing effects by focusing on two extreme stages of the Energy Transition. The first corresponds to its early stages, when renewable capacity is insufficient to cover the whole market and thermal plants are required. Competition among specialized firms is weak because the renewable firm can afford to bid below the costs of thermal plants. Consequently, facing no competition to serve the residual demand, the thermal firm sets a high market price. This result is in contrast with the outcome arising under a diversified ownership structure. Renewable plants are dispatched at capacity, and firms compete with their thermal plants. Competition among the price-setting plants pushes prices down, resulting in more competitive outcomes than under a specialized ownership structure.

At the other extreme, we also consider a later stage of the Energy Transition when renewable investments make it possible to cover the whole market without relying on thermal plants. In this case, the specialized market structure exerts downward pressure on prices. The firm owning the thermal plants offers its production at marginal costs, thus exerting competitive pressure on the firm holding the renewable plants. Again, this contrasts with the analysis of competition among diversified firms. In that case, each firm anticipates that bidding above the cost of thermal generation may allow it to increase its profits by selling the residual demand at a high price, even if that involves giving up some of its renewable production. As a consequence of this strategic behavior inefficiency in production might arise, with thermal plants displacing renewable production.

A critical element in this comparison is how stringent the regulation is in reducing the highest admissible price (or price cap). When it is high, diversified firms have stronger incentives to increase the bids offered for their renewable plants, which originates productive efficiencies and higher market prices. This outcome makes the specialized market structure socially preferred as fostering competition among the price-setting plants becomes more relevant in the absence of a stringent price cap regulation.

1.1 Related Literature

Recent literature has studied the price-depressing effect of renewables, often referred to as the "merit-order effect." However, this terminology implicitly assumes that renewables' only impact is to shift the supply curve to the right, thus causing a price reduction. By doing so, some of this literature often overlooks the impacts of renewable energies on market power. Acemoglu et al. (2017) is one of the first works to analyze the merit-order effect in the presence of market power, which they model *à la* Cournot. They show that the Cournot competitors respond to increased renewable availability by withholding their conventional output. Hence, if all renewable capacity is in the hands of the strategic firms, the merit-order effect is fully neutralized. The price-depressing effect of renewable energy becomes more relevant when it is in the hands of the fringe players. Bahn et al. (2021) empirically confirms this result by simulating renewable capacity transfers from the fringe to the large players in the Ontario electricity market. It finds that prices were 24% higher when renewable plants were allocated to the largest firm relative to the fringe.[1] Also allowing for market power, Fabra and Andrés-Cerezo (2023) analyze a model in which a conventional generation firm owns energy storage assets. They find that this ownership structure is detrimental to welfare. Our paper contributes to this literature by characterizing how different ownership structures affect productive efficiency along various stages of the Energy Transition. We do so under a setup that captures important institutional features of electricity, such as competition through uniform-price auctions.

Fabra and Imelda (2022) analyze the impact of renewable energy support schemes on the strength of the merit-order effect. They find that the merit-order effect is stronger when renewable energy is paid at fixed prices (through the so-called Feed-In-Tariffs) rather than being exposed to market price volatility (Feed-In-Premia).[2] Furthermore, the merit-order effect is never neutralized under fixed prices, even when large firms also own renewable plants. They find that the ownership structure of renewable and thermal plants is a key determinant of the competitive effects of those alternative support schemes.

Few papers have analyzed the case in which renewable energies might be abundant enough to cover total demand. As far as we know, Fabra and Llobet (2022) is the first paper to model competition among renewables in renewables-only markets. This paper shows that firms bid more aggressively when their available renewable capacity is larger, and the output gain from undercutting the rival is more significant. Unlike the papers cited above, this implies that renewables not only affect firms' bidding incentives through their inframarginal output but also because they compete at the margin. As a result, market prices tend to be lower when renewable capacity becomes more abundant, but they remain above marginal costs unless there are large amounts of excess capacity. Somogy et al. (2022) characterizes the equilibrium of a similar model where quantity is endogenous.

In this paper, we adopt a similar modeling approach as Fabra and Llobet (2022) and, in particular, we also assume that firms' available renewable capacities are private information. However, our analysis also applies to the early stages of the Energy Transition by allowing firms to produce using fossil fuel technologies. This case opens the door to

[1] Other related papers are Kakhbod et al. (2021), who extend Acemoglu et al. (2017) by allowing for correlation across renewable energies, and Genc and Reynolds (2019) who also highlight the relevance of the market structure in determining the strength of the merit-order effect.

[2] Paying renewable energy at fixed prices comes at the cost of reducing their incentives to arbitrage across sequential markets, as first shown in Ito and Reguant (2016). However, if renewables are mainly owned by the large firms, this effect is dominated by the fact that fixed prices weaken the large firms' market power.

analyzing the impact of renewable energy on bidding incentives when they are either marginal or inframarginal, which interacts with the ownership of the different technologies. From a methodological perspective, our analysis also relates to papers that model competition with private information, such as Holmberg and Wolak (2018) and Vives (2011), who assume private information on costs (instead of capacities).

Finally, our work contributes to the literature on multi-unit auctions where firms can offer multiple bids. The finding that the equilibrium outcome might be inefficient is related to results shown in Ausubel et al. (2014). However, our paper illustrates that this inefficiency is more likely to arise when bidders are more ex-ante similar. Compared to the extant literature that typically considers cases where agents have a demand for at most two discrete units (Noussair, 1995; Engelbrecht-Wiggans and Kahn, 1998; Khezr and Menezes, 2017), we provide a more general characterization of the equilibrium bidding behavior. The remainder of the paper is structured as follows. In Section 2, we describe the model. In Section 3, we compare the case of specialized and diversified firms in the early stages of the Energy Transition. Section 4 carries out the same analysis in later stages where thermal plants are not required. Section 5 concludes by discussing the implications of equilibrium bidding behavior along the energy transition. Most of the proofs are relegated to the Appendix.

2 The Model

Consider an electricity market in which thermal (or gas) plants and renewable plants coexist. There are two identical thermal plants, $m = 1, 2$, which can produce electricity with marginal cost $c > 0$ up to their capacities $g > 0$. There are also two renewable energy plants, $m = 1, 2$, whose capacities are subject to *i.i.d.* and privately known shocks. In particular, plant m's capacity, denoted k_m, is drawn from a distribution $F(k_m)$ in the range $[\underline{k}, \overline{k}]$, with a positive density $f(k_m)$. Plant m's realized capacity is only observed by its owner. All other information is public.

This paper assumes a duopoly model, with firms $i = 1, 2$ competing to supply electricity under two alternative ownership structures: firms are either *specialized* or *diversified.* In the first case, firm 1 owns the two renewable plants, while firm 2 owns the two thermal plants. In the second case, each firm owns one thermal and one renewable energy plant.

Firms submit their bids in a uniform-price auction to satisfy a fixed and known demand θ, subject to a price cap $P > c$. We assume there is always enough aggregate capacity to cover the market, i.e., $\theta < 2\underline{k} + 2g$.

Each firm submits two bids, one for each plant, specifying the minimum prices at which it is willing to produce up to the plants' capacity. When firms are specialized, firm 1 submits bids $b_1^R(k_1, k_2)$ and $b_2^R(k_1, k_2)$ for its renewable plants, while firm 2 submits bids b_1^G and b_2^G for its thermal plants. Instead, when firms are diversified, each firm submits bids $b_i^R(k_i)$ and $b_i^G(k_i)$, $i = 1, 2$.

The auctioneer ranks all bids in increasing price order, and calls the cheaper ones to produce until total demand is satisfied. All dispatched plants are paid at the market clearing price, equal to the bid of the highest-priced accepted plant. To simplify the discussion, we assume that the renewable plant is dispatched first when two plants have equal prices.[3] Finally, to simplify the number of cases we need to consider, we assume $\theta - \overline{k} - g > 0$, implying that under the diversified market structure, a single firm can never cover total demand.

For diversified firms, and without loss of generality, we restrict attention to bids satisfying $b_i^R(k) \leq b_i^G(k)$. Offering the production of the renewable plant at a price above the thermal plant's is never optimal, given that the firm could always increase profits by switching their bids for the two plants. By doing so, it would dispatch the same quantity at the same price but would reduce its production costs.

In the following sections, we analyze two cases. The first looks at early stages of the Energy Transition, when not enough renewable energy investments have yet occurred. More specifically, we assume that the two thermal plants are required to cover demand. The second case looks at late stages of the Energy Transition, when the amount of renewable capacity available in the market is sufficiently high to cover total demand without relying on thermal plants.

Our analysis uncovers two possible sources of inefficiencies. First and most important, productive inefficiency arises when thermal plants are dispatched without exhausting total renewable capacity. This would give rise to higher production costs and more carbon emissions. Second, different equilibria might yield different market prices. In our simplified framework, because we have assumed an inelastic demand, higher prices reduce consumer surplus but do not affect social welfare. To the extent that the welfare function

[3] The results are independent of the order in which plants of the same technology are dispatched whenever they make the same bid.

puts a higher weight on consumer surplus, or that our setup approximates a demand that exhibits some minimum price-elasticity, society would have a preference for lower prices. For this reason, among outcomes with equal productive efficiency, those resulting in lower prices will be considered socially preferred.

3 Early stages of the Energy Transition

In this case, we assume that both thermal plants are required to cover demand, i.e., $\theta - 2\overline{k} - g > 0$. We next analyze the cases with specialized and diversified firms.

3.1 Specialized Firms

The owner of the renewable plants, firm 1, has a lower marginal cost than firm 2. Hence, in equilibrium, it can offer its renewable capacity at prices that firm 2 cannot profitably undercut, forcing firm 2 to maximize its profits over the expected residual demand, $E[\theta - k_1 - k_2]$. As firm 2 faces no competition, it optimally sets the market price at the price cap by bidding at least one of its thermal plants at P.

Proposition 1. *When firms are specialized and $\theta - 2\overline{k} - g > 0$, in any Nash equilibrium of the game, the renewable firm chooses sufficiently low bids $b_1^R(k_1, k_2)$ and $b_2^R(k_1, k_2)$, while the thermal firm chooses bids $b_1^G \leq b_2^G = P$. The equilibrium market price is always P.*

This game exhibits a continuum of payoff equivalent equilibria. In particular, firm 1 should offer its renewable plants at sufficiently low prices so that firm 2 would not benefit from undercutting them despite the increase in output. Offering low prices is inconsequential to firm 1, given that its plants never set the market price.

The unique equilibrium outcome resulting from the previous continuum of equilibrium strategies satisfies two important properties. First, the market price is always the highest possible, P. Second, productive efficiency is always achieved given that the two renewable plants are dispatched at full capacity.

3.2 Diversified Firms

Diversified firms are ex-ante symmetric. For this reason, beyond characterizing the asymmetric equilibria of the game, we also characterize the symmetric one. We start with the former.

Proposition 2. *When firms are diversified and $\theta - 2\overline{k} - g > 0$, in any asymmetric Bayesian Nash Equilibrium of the game, firm $i = 1, 2$ chooses sufficiently low bids $b_i^R(k_i)$ and $b_i^G(k_i)$ while firm j chooses bids $b_j^R(k_j) \leq b_j^G(k_j) = P$ for all k_j, $i \neq j$. The equilibrium market price is always P.*

That firm i does not have incentives to deviate from this equilibrium is straightforward, given that it sells all its capacity at the price cap and, hence, it obtains the highest possible profits, $\Pi_i(k_i) = P(k_i + g) - cg$. Firm j sells all the capacity of its renewable plant and serves the remaining residual demand with its thermal plant, both at a price P. Its expected profits are

$$\Pi_j(k_j) = Pk_j + (P - c)(\theta - k_j - E(k_i) - g).$$

Alternatively, firm j could consider undercutting the rival's bids, which can be as low as $b_i^R(k_i) = 0 < b_i^G(k_i) = c$. In this case, the deviation would drive the market price to c, reducing its profits to $\Pi_j(k_j) = ck_j$.

Hence, all the asymmetric equilibria are price equivalent, resulting in a market price P. However, they are not payoff equivalent as whichever firm acts like the low-bidder obtains higher profits.

We now move to characterizing the symmetric equilibrium of the game. We start by providing some monotonicity conditions.

Lemma 1. *When firms are diversified and $\theta - 2\overline{k} - g > 0$, in any symmetric Bayesian Nash Equilibrium of the game, the bids for the renewable plants are payoff irrelevant. The bidding for thermal plants is in pure strategies and the function $b_i^G(k_i)$ must be strictly decreasing in the firm's renewable capacity, k_i. Since $b_i^R(k_i) \leq b_i^G(k_i)$, market prices are set by thermal plants.*

The optimal bid for a thermal plant must be decreasing in the firm's renewable capacity. To understand why, note that a marginal reduction in the firm i's thermal bid triggers two effects (given firm j's bids): a profit gain due to the increase in thermal output (*quantity effect*, denoted Δq), and a profit loss due to the reduction in the market price (*price effect*). Regarding the quantity effect, if the thermal plant bids slightly below its rival (an event that occurs with probability $f(k_i)$), the firm moves from serving the expected residual demand, $\theta - k_i - g$, to selling at capacity $k_i + g$. Hence, the output gain is $\Delta q = 2k_i + 2g - \theta$, increasing in k_i. Intuitively, when k_i is high, the production of its thermal plant is low unless it undercuts the rival. On the contrary, the *price effect* is decreasing in the firm's renewable capacity, as contingent on setting the market price with its thermal bid, the firm always sells the expected residual demand $\theta - g - E(k_j | k_j > k_i)$, which is smaller as k_i increases. Combining these two effects, the greater the firm's renewable capacity, the stronger its incentives to submit a low bid for the thermal plant, giving rise to an optimal bidding function that is decreasing in k_i.

Furthermore, standard Bertrand arguments allow us to rule out symmetric equilibria that contain flat segments. Since the two thermal plants are always required, firms could increase profits by either undercutting each other or by raising the market price to P rather than tying. It follows that the bids for the thermal plants must be strictly decreasing in the firms' realized renewable capacities.

Since renewable plants are always dispatched at capacity when $b_i^R(k_i) \leq c$, their bids are payoff irrelevant. For this reason, we turn our attention to the price offers of thermal plants.

Using the previous lemma, we characterize the symmetric equilibrium by assuming that firms choose the same bidding function $b^G(k)$, which is decreasing in their realized renewable plant's capacity, k. We use the Revelation Principle and transform the problem into the following one: instead of choosing the price for its thermal plant, each firm reports a renewable capacity k' knowing that its bid would be derived from a decreasing function $b^G(k')$. Under this transformed game, the profits a firm with actual capacity k_i that reports capacity k', can be expressed as

$$\begin{aligned}\pi_i(k_i, k') = &\int_{\underline{k}}^{k'} \left[b^G(k_j)k_i + (b^G(k_j) - c)g\right] f(k_j)dk_j \\ &+ \int_{k'}^{\overline{k}} \left[b^G(k')k_i + (b^G(k') - c)(\theta - k_i - k_j - g)\right] f(k_j)dk_j. \end{aligned} \tag{1}$$

The first term captures cases when firm i's reported capacity is above firm j's realized capacity. Since the bidding function is decreasing, we have that $b^G(k') < b^G(k_j)$ and, as a result, firm i sells all its renewable and thermal capacity, $k_i + g$, at a market price set by firm j's thermal bid, $b^G(k_j)$. In the second term, firm i's reported capacity is below k_j. Thus, it dispatches its renewable plant at capacity and serves any remaining demand with its thermal plant, both at its thermal bid, $b^G(k')$. As usual, the equilibrium bid function must make it optimal for firm i to report $k' = k_i$.

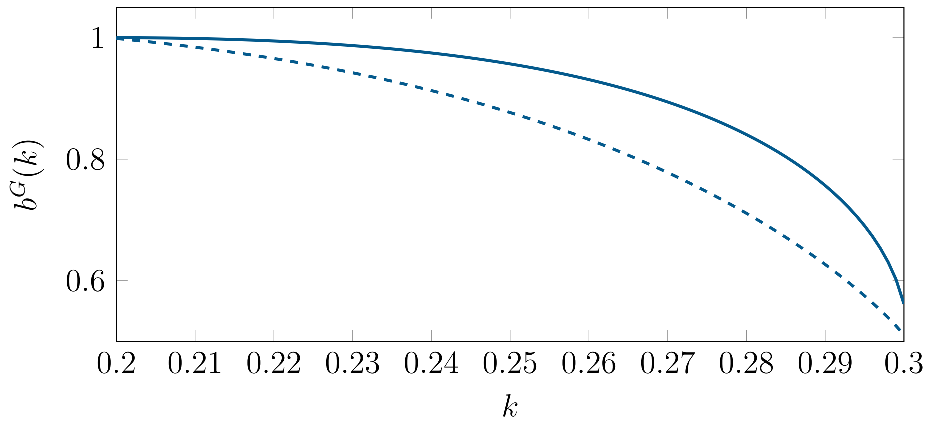

Figure 1: Equilibrium thermal bid when $k_i \sim U[0.2, 0.3]$, $\theta = 1$, $c = 0.5$ and for values of $g = 0.3$ (solid), $g = 0.4$ $g = 0.35$ (dashed).

The following proposition characterizes the symmetric equilibrium in this case.[4]

Proposition 3. *When firms are diversified and $\theta - 2\overline{k} - g > 0$, in any symmetric Bayesian Nash equilibria of the game, each firm $i = 1, 2$ offers a sufficiently low price for its renewable plant. The equilibrium price for its thermal plant is*

$$b^G(k_i) = c + (P - c)\exp(-\omega^G(k_i)), \tag{2}$$

where

$$\omega^G(k_i) = -\int_{\underline{k}}^{k_i} \frac{\theta - 2k - 2g}{\int_{k_i}^{\overline{k}}(\theta - k - g)f(k)dk} f(k)dk, \tag{3}$$

is decreasing in k_i, with $b_i^G(\underline{k}) = P$ and $b_i^G(\overline{k}) = c$.

In equilibrium, firms offer their thermal plant at its marginal cost c plus a markup reflecting the trade-off between the quantity effect, in the numerator of (3), and the price effect, in the denominator. As explained above, this trade-off implies that firms have stronger incentives to offer lower prices the larger their realized renewable capacities, making the equilibrium bidding function decreasing in k_i.

Equilibrium bids spawn all prices between the price cap P and the marginal cost of gas plants c. When $k_i = \underline{k}$, firm i has the smallest renewable capacity with probability one and, hence, always sets the market price. Therefore, it finds it optimal to bid at P. On the other extreme, when $k_i = \overline{k}$, firm i has the largest renewable capacity with

[4] As previously observed, there is a continuum of equilibrium bids for the renewable plant. However, since these bids do not affect the equilibrium allocation, all the symmetric equilibria are outcome equivalent.

probability one and hence never sets the market price. Therefore, it finds it optimal to offer its thermal production at c.

Figure 1 provides numerical examples of the equilibrium bidding function for different values of the gas plant's capacity, g. For a given realization of the renewable capacity k_i, the optimal price offer decreases as the thermal capacity increases. The reason is that the higher g, the smaller the residual demand faced by the high bidder, making the quantity effect stronger and the price effect weaker. Both reasons strengthen firms' incentives to bid more aggressively the larger is g.

Comparison of the asymmetric and symmetric equilibria (Propositions 2 and 3) shows that productive efficiency is achieved under both. However, equilibrium market prices are always higher under asymmetric equilibria. Pareto dominance arguments cannot be used for equilibrium selection as expected profits under the symmetric equilibrium are strictly in between those of the high and low bidders in the asymmetric equilibrium. This result is in contrast with the model in which capacities are public information (Fabra et al., 2006), in which the asymmetric equilibrium Pareto dominates the symmetric one.[5]

Specialized versus diversified firms. We are now ready to compare equilibrium outcomes with specialized versus diversified firms in the early stages of the Energy Transition. Under both ownership structures, productive efficiency is achieved because renewable plants always operate at capacity. However, equilibrium prices are weakly lower when firms are diversified. That is, the equilibrium market price is P under both market structures when diversified firms bid asymmetrically (Proposition 2). However, the price comparison is strict when they play the symmetric equilibrium (Proposition 3). In this case, diversification fosters competition among the price-setting thermal plants (intra-technology competition), while specialization shuts it down completely. The thermal firm anticipates that it cannot outcompete the renewable firm and, hence, it settles for the residual demand, facing no competition to raise the price up to P. In contrast, when firms are diversified, intra-technology competition among thermal plants to sell at capacity entices them to offer lower bids, leading to more competitive outcomes.

[5] In the asymmetric equilibrium, the low bidder gets the highest possible profits, which are trivially higher than the ones in the symmetric equilibrium. In contrast, the opposite occurs to the high bidder, who gets the same profits as the firm with the lowest capacity realization when the symmetric equilibrium is played. However, profits in the symmetric equilibrium exceed those of the high bidder in the asymmetric equilibrium because they are increasing in the firm's realized capacity.

Corollary 1. *When $\theta - 2\overline{k} - g > 0$, (i) productive efficiency is attained under the specialized and diversified ownership structures; however (ii) equilibrium market prices are weakly lower under a diversified ownership.*

4 Late stages of the Energy Transition

We now consider a situation where demand can be entirely covered with renewable energy plants without the need to dispatch thermal plants, i.e., $2\underline{k} \geq \theta$. As we did before, we characterize equilibrium bidding under the two alternative ownership structures.

4.1 Specialized Firms

As a renewable producer, firm 1 always has enough capacity to serve the whole market. Thus, the standard Bertrand outcome arises.

Proposition 4. *When firms are specialized and $2\underline{k} \geq \theta$, in any Nash equilibrium of the game, the renewable firm bids $b_1^R(k_1, k_2) \leq b_2^R(k_1, k_2) = c$, while the thermal firm bids $b_1^G = b_1^G = c$.*

As in the previous cases, there is a continuum of equilibrium strategies, even though they all result in the same equilibrium outcome. In particular, the firm that owns the renewable technology only needs to bid at c with one of the plants. Any lower bid for the inframarginal plant is irrelevant.

In this equilibrium, productive efficiency is achieved, since renewable plants are dispatched first, and the market price equals the marginal cost of thermal plants, c.

4.2 Diversified Firms

A key difference relative to the previous cases is that the equilibrium characterization now depends on whether the price cap is above or below a critical threshold,

$$\underline{\rho} \equiv c \frac{E(\theta - k)}{E(\theta - k - g)}. \tag{4}$$

Let us start by considering the asymmetric equilibria of the game.

Proposition 5. *When firms are diversified and $2\underline{k} \geq \theta$, at any asymmetric Nash equilibrium of the game, firm i bids $b_i^R(k_i) \leq b_i^G(k_i) = c$. The equilibrium bid of firm $j \neq i$ can take one of two forms:*

(i) If $P > \underline{\rho}$, then $b_j^R(k_j) = b_j^G(k_j) = P$, or

(ii) If $P \leq \underline{\rho}$, then $b_j^R(k_j) = b_j^G(k_j) = c$.

In an asymmetric equilibrium, the high bidder (firm j) faces a trade-off: either (i) to set the market price at P and serve the expected residual demand $E(\theta - k - g)$, or (ii) to reduce the market price to c while serving a higher residual demand $E(\theta - k)$. The comparison of the profits that arise under both prices delivers the threshold $\underline{\rho}$, defined in (4), that makes the firm indifferent.

The low bidder (firm i) cannot profitably deviate from the equilibria characterized in Proposition 5. Under (i), it sells at capacity at the highest possible price. Under (ii), it profits from selling its renewable capacity at c. The only potential deviation would be to raise the market price to P, but the assumption $P \leq \underline{\rho}$ makes it unprofitable.[6]

It follows that the equilibrium is characterized by a *tale of two states*.[7] When the price cap is low ($P \leq \underline{\rho}$), the market is cost-efficient (demand is fully served by renewable plants) and competitive (the market price is constrained by the cost of the least efficient technology). However, when the price cap is high ($P > \underline{\rho}$), the market is inefficient (the low bidder's thermal plant operates at capacity while the high bidder's renewable plant does not) and seemingly collusive (the market price is set at the highest admissible level).

These properties of the asymmetric equilibria extend to the symmetric equilibrium, which we characterize next. To simplify the exposition, we analyze the cases with either a low or a high price cap separately.

Proposition 6. *Assume $P \leq \underline{\rho}$. When firms are diversified and $2\underline{k} \geq \theta$, in the unique Bayesian Nash Equilibrium of the game, each firm offers $b^G(k_i) = c$ for its thermal plant. The equilibrium bid for its renewable plant is*

$$b^R(k_i) = c \exp(-\omega^R(k_i)),$$

[6] As shown by de Frutos and Fabra (2012), symmetric firms are always better off as non-price setters than as price setters. The reason is that conditionally on being the price setter, all firms would like to set the same market price (as in the current paper). Yet, as non-price setters, they would sell a higher quantity. Hence, deviating from being the non-price setter to being the price setter at the same price is never profitable for symmetric firms.

[7] We borrow this terminology from Fabra et al. (2006), who analyze a similar game as ours but with complete information. Interestingly, the asymmetric equilibria are invariant to whether firms have complete or incomplete information. Indeed, our equilibria correspond to theirs when firms' capacities are known to be equal to $E(k)$.

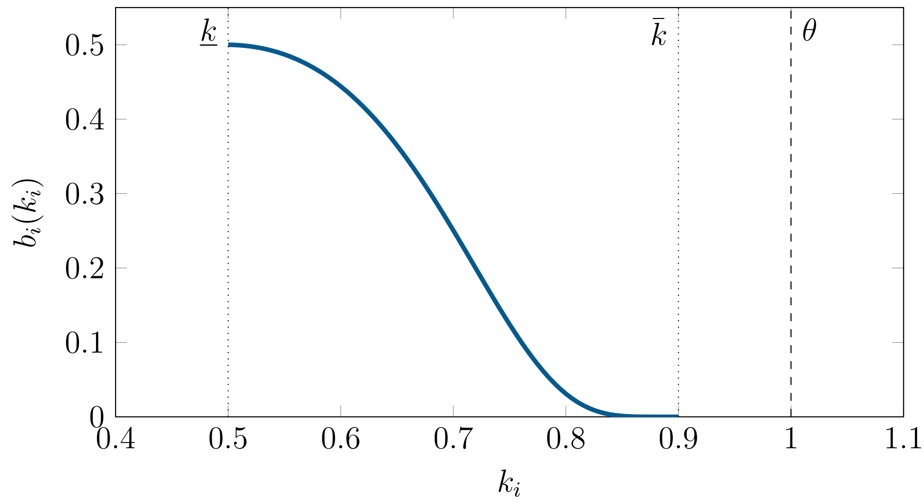

Figure 2: Equilibrium bid function when $P \leq \underline{\rho}$ as a function of k_i when $k_i \sim U[0.5, 0.9]$, with $\theta = 1$, $P = 0.5$, and $P \leq \underline{\rho}$.

where

$$\omega^R(k_i) = \int_{\underline{k}}^{k_i} \frac{(2k-\theta)f(k)}{\int_k^{\overline{k}}(\theta - k_j)f(k_j)dk_j} dk. \tag{5}$$

This bid is decreasing in k_i, with $b_i^R(\underline{k}) = c$ and $b_i^R(\overline{k}) = 0$.

Since all the renewable capacity is offered at prices below c, it is not profitable to dispatch the thermal plants. For the renewable plants, the interplay between the quantity and the price effects is similar to the one discussed above. At the margin, when firm i undercuts its rival (an event which occurs with probability $f(k_i)$), its output increases by $\Delta q = 2k_i - \theta$ (*quantity effect*). However, this also reduces the price at which it sells the residual demand in case it is the high bidder, $\theta - E(k_j|k_j > k_i)$ (*price effect*). As the quantity and price effects are increasing and decreasing in k_i, respectively, firms choose a lower bid the larger their realized renewable capacities. This gives rise to a decreasing bidding profile, from c at $\underline{k}$ to zero at $\overline{k}$. Figure 2 illustrates this equilibrium.

Firms can always guarantee profits $cE(\theta - k)$ by bidding their renewable plant at a price c (or equivalently, by reporting a capacity $\underline{k}$). Indeed, in equilibrium, firms make profits $cE(\theta - k)$ for $\underline{k}$, and their profits are strictly increasing in their realized renewable capacities (otherwise, they could pretend to have a smaller capacity). Importantly, this implies that, when $P \leq \underline{\rho}$, firms do not want to offer their production at P as the resulting profits, $PE(\theta - k - g)$, would fall below $cE(\theta - k)$, and hence below their equilibrium profits.

The bidding function for renewable plants we have just characterized is the same as in Fabra and Llobet (2022).[8] In that paper, the assumption was that renewable plants face a fringe of competitive thermal producers bidding at c and, for this reason, they cannot increase the market price above c. Proposition 6 above shows that the same equilibrium arises with diversified firms even if they could bid above c. The reason is that they do not find it profitable to do so as long as $P \leq \underline{\rho}$.

For higher values of the price cap, however, the previous result no longer applies. To show this, it is convenient to introduce the following piece of notation,

$$\rho(k) \equiv c \frac{\int_k^{\overline{k}} (\theta - k_j) f(k_j) dk_j}{\int_k^{\overline{k}} (\theta - k_j - g) f(k_j) dk_j} > c. \tag{6}$$

Note that $\underline{\rho}$ is encompassed by this expression as $\underline{\rho} = \rho(\underline{k})$. Our next proposition characterizes the symmetric Bayesian Nash equilibrium among diversified firms when the price cap is high.

Proposition 7. *Assume $P > \underline{\rho}$. When firms are diversified and $2\underline{k} \geq \theta > \overline{k}$, there exists a unique $\hat{k}$ such that, in the unique symmetric Bayesian Nash Equilibrium of the game, when $k_i > \hat{k}$ firm i bids as in Proposition 6, with $\omega^R(k)$ truncated at $k > \hat{k}$. Instead, when $k_i \leq \hat{k}$, firm i chooses the same bid for its renewable and thermal plants, $b(k_i) = b^R(k_i) = b^G(k_i)$, according to*

$$b(k_i) = c + (P - c) exp(-\omega^G(k_i)) - c\left[\gamma(k_i) - \gamma(\underline{k})\right] exp(-\omega^G(k_i)), \tag{7}$$

where $\omega^G(k_i)$ is defined in (3) and $\gamma(k_i)$ is an increasing function of k_i.

The equilibrium bid function $b(k_i)$ is decreasing in k_i, with $b(\underline{k}) = P$ and $b(\hat{k}) = \rho(\hat{k}) \equiv \hat{\rho}$.

The upper panel of Figure 3 illustrates this equilibrium. When a firm has a large renewable capacity realization ($k \geq \hat{k}$), it offers its thermal plant at marginal cost and competes by bidding its renewable plant below c, similarly as under Proposition 6. Instead, for smaller capacity realizations ($k \leq \hat{k}$), the firm offers both plants at the same price above c. Interestingly, the first two terms of the bidding function coincide with the one in Proposition 3 (see equation (2)), when both thermal plants are needed. Since firms

[8] The notation is different. The same expressions arise by setting $P = c$ and $c = 0$ in Fabra and Llobet (2022).

were competing to serve their thermal capacity, the relevant marginal cost in that case was c. Instead, they are now competing to serve their total capacity, with marginal cost is in between the thermal cost (c) and the renewable cost (zero). This lower marginal cost is captured in the last term of the bidding function. The larger the renewable capacity, the lower the relevant marginal cost, and the more likely that the firm will serve all its renewable capacity. Hence, the bid shading term increases in k_i.

For large capacity realizations, firms bid as if they competed with their renewable plants only (*within technology competition*). However, for small capacity realizations, they compete with their whole portfolio, knowing that whoever has the lower price will sell both plants at capacity (*across technologies competition*). This strategy is implemented by offering the same bid for both plants. We already know that offering the thermal plant at a price below the renewable plant is not profitable. Offering it at a higher price is not profitable either, as the gas plant will never set the market price: it is either inframarginal or the rival's plants displace it. Hence, offering renewable and thermal plants at the same price maximizes the chances of dispatching both at capacity.

Importantly, for small capacity realizations ($k \leq \hat{k}$), firms cannot play the strategy prescribed by Proposition 6 because it is now dominated by bidding both plants at P. Indeed, under such a strategy, firms' profits are close to $cE(\theta - k)$ for k close to $\underline{k}$. However, when $P > \underline{\rho}$, the firm would benefit from deviating to P to obtain profits $PE(\theta - k - g)$. To offset this deviation incentive, the bidding strategy in Proposition 7 calls firms to offer both plants at higher prices, from P for $\underline{k}$ to some critical price $\hat{\rho} \equiv \rho(\hat{k})$ for $\hat{k}$.

These two values, $\hat{\rho}$ and $\hat{k}$, are such that the firm is indifferent between bidding at $\hat{\rho}$ or c, as the increase in output, $\Delta q = g(1 - F(\hat{k}))$, would just compensate for the price reduction. This indifference condition gives rise to expression (6). As previously noted, the expression for $\hat{\rho}$ is the same as $\underline{\rho}$, with the distribution for k truncated at $k > \hat{k}$. Hence, as P approaches $\underline{\rho}$ the equilibrium approaches the one characterized in Proposition 6.

As it turns out, the indifference condition (6) is independent of k_i, which means that if the firm with capacity $\hat{k}$ is indifferent between bidding at $\hat{\rho}$ or c, the firm with a larger capacity would prefer to bid below c and maximize its chances of selling $k_i + g$. Instead, the firm with a smaller capacity would prefer to bid above $\hat{\rho}$ to sell its residual demand

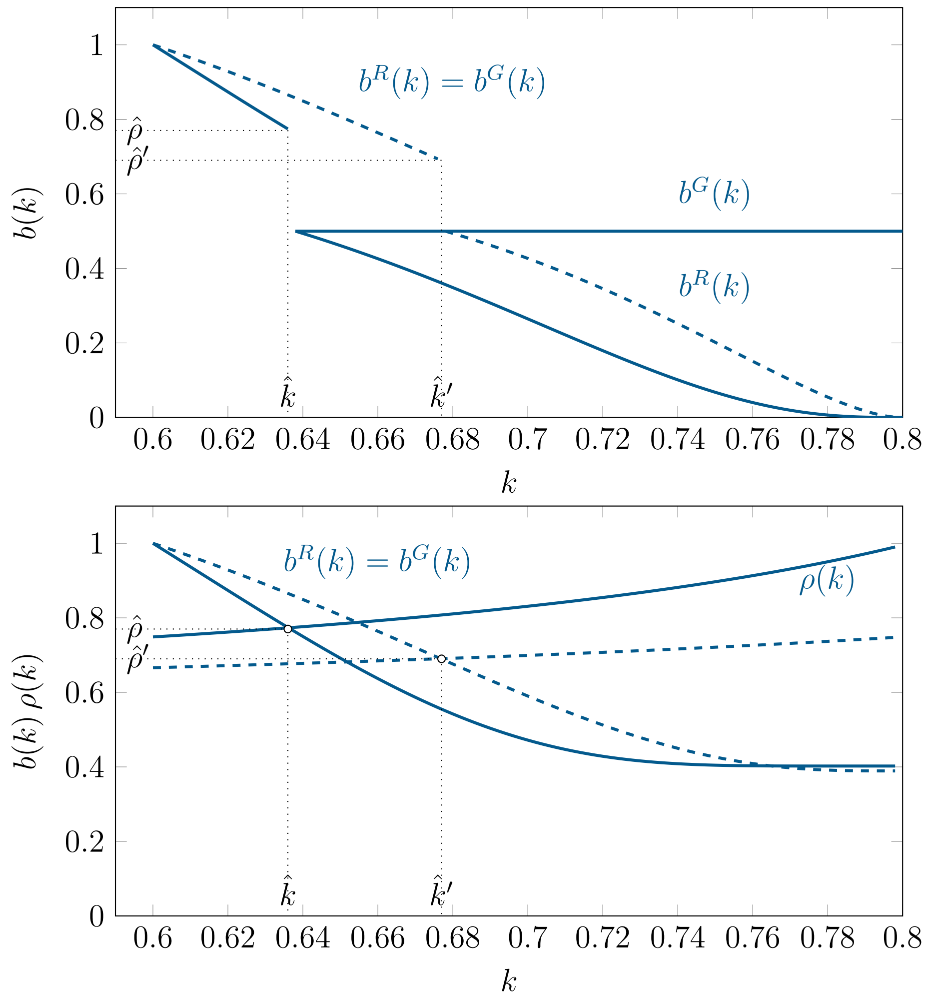

Figure 3: The upper panel illustrates the equilibrium bids when $k_i \sim U[0.6, 0.8]$, $g = 1$, $c = 0.5$ and for values of $\theta = 1$ (solid), $\theta = 1.1$ (dashed). In the lower panel, the equilibrium $\hat{k}$ is determined as the intersection of (7) and (6).

at a higher price.

The critical values $\hat{\rho}$ and $\hat{k}$ are determined jointly, affecting the whole bidding function and not just the discontinuity, as illustrated in the lower panel of Figure 3. On the one hand, the expression $\rho(k)$ increases in k given that a higher price is needed to make a bigger firm indifferent between bidding at c and bidding at such a price. Conversely, the bidding function $b(k)$ is decreasing in k, as shown in Proposition 7. In equilibrium, both schedules intersect at $\hat{\rho}$ and $\hat{k}$.

Changes in the parameters affecting the schedules $\rho(k)$ and $b(k)$ result in new equilibrium values for $\hat{\rho}$ and $\hat{k}$, ultimately shaping the equilibrium bidding function. The following result provides the comparative statics as a function of θ, P, and g.

Lemma 2. *(i) The bidding function shifts out with higher θ, higher P, and lower g,* *leading to higher market prices. (ii) The equilibrium capacity threshold $\hat{k}$ is increasing in θ and P, and decreasing in g, leading to a higher likelihood of productive inefficiency.*

The previous result indicates that, as expected, an increase in demand θ or the price cap P gives rise to less competitive bidding and higher market prices. A similar effect arises from a reduction in g, which makes the residual demand larger. In turn, these parameter changes shift $\hat{k}$ to the right, which enlarges the range of capacity realizations for which renewables bid above c, thus risking being underbid by the rival's thermal plant, which would result in productive inefficiency.

Putting together the results in Proposition 6 and 7, it follows that another *tale of two states* arises under the symmetric equilibrium, even though the price patterns are smoother than under the asymmetric equilibrium (Proposition 5). When the price cap is low ($P \leq \underline{\rho}$), the market is cost-efficient, and market prices never exceed the cost of thermal plants c. However, when the price cap is high ($P > \underline{\rho}$), the market is inefficient and market prices exceed c (unless *both* firms have capacities above $\hat{k}$, in which case the outcome is the same as under a low price cap). In both cases, the allocation is more efficient and prices are more competitive under the symmetric equilibrium relative to the asymmetric one.

Specialized versus diversified firms. The comparison between the specialized and the diversified ownership structure yields interesting insights. The equilibrium under the former structure is efficient, as demand is fully served by the renewable plants. The same result applies when diversified ownership and a low price cap ($P \leq \underline{\rho}$). However, the equilibrium price differs as it is c with specialized firms and weakly below that level when firms are diversified (the comparison is strict if firms play the symmetric equilibrium).

Results are substantially different with a high price cap ($P > \underline{\rho}$). Under diversified ownership, the asymmetric equilibrium always gives rise to productive inefficiencies, as the low bidder dispatches all its capacity. The equilibrium price is P, therefore higher than the one in the specialized ownership case, c. The symmetric equilibrium also exhibits inefficiencies in production but with a lower probability, given that the outcome is still efficient if both firms have large renewable capacities. In principle, the price comparison is ambiguous as, for small capacity realizations, diversified firms bid above the equilibrium price set by specialized firms, c, while the opposite is true for large capacity realizations.

Corollary 2. *When* $2\underline{k} \geq \theta$*:*

(i) If $P \leq \underline{\rho}$*, productive efficiency is achieved under the specialized and diversified ownership structures; however equilibrium market prices are weakly lower under a diversified ownership.*

(ii) If $P > \underline{\rho}$*, productive efficiency is achieved only under the specialized ownership structure; however (ii) the price comparison across the two ownership structures is ambiguous.*

5 Concluding Remarks

This paper studies how deploying renewable energy affects the performance of electricity markets. Not surprisingly, once we move away from the competitive paradigm, ownership of these plants matters. Furthermore, we show that the implications depend on the stage of the Energy Transition, which determines the weight of renewable energy in the market, as well as on the stringency of the price cap. A diversified ownership structure tends to foster competition in the initial stages of the Energy Transition, as firms compete to dispatch their thermal plants at capacity. Instead, if a single specialized firm owned all the thermal plants, there would be no competition among the price-setting plants, and market prices would be driven to the price cap.

In contrast, during later stages, when renewable plants have enough capacity to cover the market, a diversified market structure often yields higher market prices, and it is a source of productive inefficiency. That is, when firms own thermal and renewable plants and the price cap is high, market power might induce them to bid both plants at prices above the marginal cost of thermal generation. This implies that, with some probability, renewable plants might be displaced by gas plants despite their higher costs. In contrast, if one specialized firm owned all the renewable capacity, it would dispatch it all at the cost of gas-fired generation, thus avoiding productive inefficiencies and probably giving rise to lower prices.

Our analysis has focused on two extreme cases, when all existing thermal plants are necessary or when none are. However, the model also spawns some interesting intermediate situations that involve, for example, the case in which one thermal plant is always needed. In that case, it is immediate that under a specialized market structure, the renewable firm would also serve total demand at the cost of gas-fired generation. In that case, when the price cap is low, and firms are diversified, competition among renewable plants would give rise to more a competitive outcome.

The model is also amenable to the combination of these three cases. Exploring the implications of ownership structure in these situations might shed additional light on the mechanisms at work.

References

Acemoglu, Daron, Ali Kakhbod and Asuman Ozdaglar, "Competition in Electricity Markets with Renewable Energy Sources," *The Energy Journal*, 2017, *38*(IS), pp. 137–156.

Ausubel, Lawrence M., Peter Cramton, Marek Pycia, Marzena Rostek and Marek Weretka, "Demand Reduction and Inefficiency in Multi-Unit Auctions," *Review of Economic Studies*, 2014, *81*(4), pp. 1366–1400.

Bahn, O., M. Samano and P. Sarkis, "Market Power and Renewables: The Effects of Ownership Transfers," *The Energy Journal*, 2021, *42*(4), pp. 195–225.

de Frutos, María-Ángeles and Natalia Fabra, "How to allocate forward contracts: The case of electricity markets," *European Economic Review*, 2012, *56*(3), pp. 451–469.

Engelbrecht-Wiggans, Richard and Charles M. Kahn, "Multi-Unit Auctions with Uniform Prices," *Economic Theory*, 1998, *12*(2), pp. 227–258.

European Commission, "European Green Deal: Commission proposes transformation of EU economy and society to meet climate ambitions," Technical report, European Commission, 2021.

Fabra, Natalia and David Andrés-Cerezo, "Storing Power: Market Structure Matters," *RAND Journal of Economics*, 2023, pp. 1–51.

Fabra, Natalia, Nils-Henrik Fehr and David Harbord, "Designing Electricity Auctions," *RAND Journal of Economics*, March 2006, *37*(1), pp. 23–46.

Fabra, Natalia and Imelda, "Market Power and Price Exposure: Learning from Changes in Renewables Regulation," *American Economic Journal: Economic Policy*, 2022, *forthcoming*.

Fabra, Natalia and Gerard Llobet, "Understanding Competition among Renewables," *The Economic Journal*, 2022, *forthcoming*.

Genc, T. S. and S. S. Reynolds, “Who Should Own a Renewable Technology? Ownership Theory and an Application,” *International Journal of Industrial Organization*, 2019, *63*, pp. 213–238.

Holmberg, Pär and Frank A. Wolak, “Comparing auction designs where suppliers have uncertain costs and uncertain pivotal status,” *RAND Journal of Economics*, 2018, *49*(4), pp. 995–1027.

Ito, Koichiro and Mar Reguant, “Sequential Markets, Market Power, and Arbitrage,” *American Economic Review*, 2016, *106*(7), pp. 1921–57.

Kakhbod, Ali, Asuman Ozdaglar and Ian Schneider, “Selling Wind,” *Energy Journal*, 2021, *42*(1), pp. 1–38.

Khezr, Peyman and Flavio M. Menezes, “A new characterization of equilibrium in multiple-object uniform-price auctions,” *Economics Letters*, 2017, *157*, pp. 53–55.

Noussair, Charles, “Equilibria in a Multi-Object Uniform Price Sealed Bid Auction with Multi-Unit Demands,” *Economic Theory*, 1995, *5*(2), pp. 337–351.

Somogy, Robert, Wouter Vergote and Gabor Virag, “Price Competition with Capacity Uncertainty - Feasting on Leftovers,” 2022, mimeo.

Vives, Xavier, “Strategic Supply Function Competition With Private Information,” *Econometrica*, 2011, *79*(6), pp. 1919–1966.

A Proofs

The main results of the paper are proved here.

Proof of Proposition 1: Without loss of generality, we consider only cases where the bid of plant 1 is weakly lower than the plant of firm 2. When the thermal firm (firm 2) chooses bids $b_1^R \leq b_2^R = P$, it is clear that any lower bid would be the best response for firm 1, as it would obtain the highest possible profits, $P(k_1 + k_2)$. Suppose that among these prices, firm 1 chooses $b_1^R(k_1, k_2) = b_1^R(k_1, k_2) = \bar{b}$. The best deviation of firm 2 from P involves a bid slightly below $\bar{b}$. This deviation will not be profitable if $(P-c)E(\theta-2k) > 2(\bar{b}-c)g$. Hence, the proposed strategies will be part of an equilibrium as long as $\bar{b} \leq (P-c)\frac{E(\theta-2k)}{2g} + c$. The same equilibrium arises if $b_1^R(k_1, k_2) < b_1^R(k_1, k_2)$.

Finally, notice that any bid for firm $b_2^R < P$ would be dominated by choosing $b_2^R = P$. □

Proof of Proposition 2: Suppose that firm j is the high bidder and sells the residual demand, which includes all its renewable power as well as $\theta - k_i - k_j - g$ of gas production. As both thermal plants are always required, it follows that $b_j^G(k_j) = P$ maximizes profits. Given this price, the low bidder, firm i, obtains the maximum attainable profits, $Pk_i + (P-c)g$ and any $b_j^G(k_j) \geq c$ would be a (strict) best response.

Given $b_i^R(k_i) \leq b_i^G(k_i)$ the best deviation of firm j would be to undercut $\bar{b}$ with the gas plant (which would also involve a lower bid for the thermal plant). This deviation will not be profitable if $Pk_j + (P-c)(\theta - E(k_i) - k_j - g) > b_i^G(k_i)k_j + (b_i^G(k_i) - c)g$ or $b_i^G(k_i) \leq \frac{Pk_j+(P-c)(\theta-E(k_i)-k_j-g)}{k_j+g} + c$. As the right-hand side of this expression is decreasing in k_j a sufficient condition for this equilibrium would be that $b_i^G(k_i) \leq \bar{b} \equiv \frac{P\bar{k}+(P-c)(\theta-E(k_i)-\bar{k}-g)}{\bar{k}+g} + c$. □

Proof of Lemma 1: First, notice since renewable plants are always offered at a lower price than the thermal ones, they are always dispatched. Hence, we can assume without loss of generality that $b_i^R(k) \leq c$ for $i = 1, 2$.

We now focus on the bid by thermal plants. We start by showing that the equilibrium must be in pure strategies. Towards a contradiction, suppose that firm j chooses a bid according to a distribution $\Phi_j(b_j^G|k_j)$. Using standard arguments, this distribution must have a positive density in all its support, denoted as $[\underline{b}(k_j), \bar{b}(k_j)]$. Profits for firm i

become

$$v_i(b_i^G, k_i, \Phi_j) = \int_{\underline{k}}^{\overline{k}} \int_{\underline{b}(k_j)}^{\bar{b}(k_j)} \left\{ [bk_i + (b-c)g] \Pr(b_i^G \leq b) \right.$$
$$\left. + \left[b_i^G k_i + (b_i^G - c)(\theta - k_j - k_i - g) \right] \Pr(b_i^G < b) \right\} d\Phi_j(b|k_j) f(k_j) dk_j.$$

Notice that these profits are increasing in k_i, since

$$\frac{\partial v_i}{\partial k_i}(b_i^G, k_i, \Phi_j) = \int_{\underline{k}}^{\overline{k}} \int_{\underline{b}(k_j)}^{\bar{b}(k_j)} \left[c + (b-c) \Pr(b_i^G \leq b) \right] d\Phi_j(b|k_j) f(k_j) dk_j > 0.$$

This derivative is strictly decreasing in b_i^G and, thus, the function v_i is submodular in b_i^G and k_i, implying that the support of the best response set must be increasing in k_i.

Notice, however, that the previous result implies that each bid can be used by at most one capacity realization. That is, the bid support used for different capacity realizations do not overlap. Suppose now that in a symmetric Nash Equilibrium a firm with capacity k_i randomizes between two different bids b_i^G and $\hat{b}_i$ with $b_i^G < \hat{b}_i^G$. By Bertrand arguments, it has to be that case that all bids in between are also in the randomization support. However, since each capacity arises with probability 0, the firm will always prefer to choose the highest point in the support, $\hat{b}_i^G$, as the revenues increase but the probability of being outbid is essentially unchanged.

Hence, we conclude that the optimal thermal bid in the symmetric equilibrium is a strictly decreasing function of k_i. □

Proof of Proposition 3: Taking the derivative of $\pi_i(k_i, k')$ in 1 with respect to k' we have that choosing $k' = k_i$ would be optimal if

$$(b^G(k_i) - c)(2g + 2k_i - \theta) + b^{G\prime}(k_i) \int_{k_i}^{\overline{k}} (\theta - k - g) f(k) dk = 0.$$

The first term of the previous first order condition is negative and the second term is positive, taking the form

$$b_i^{G\prime}(k_i) + a(k_i) b_i^G(k_i) = ca(k_i), \tag{8}$$

where

$$a(k_i) \equiv \frac{(2g + 2k_i - \theta) f(k)}{\int_k^{\overline{k}} (\theta - k - g) f(k) dk}. \tag{9}$$

Solving for $b_i^R(k_i)$ we obtain

$$b_i^G(k_i) = c + Ae^{-\int_{\underline{k}}^{k_i} a(s)ds} = c + Ae^{-\omega(k_i)},$$

where $A \equiv b_i^G(\underline{k}) - c$ and $\omega(k_i) \equiv \int_{\underline{k}}^{k_i} a(s)ds$. Finally, notice that $b_i^R(\underline{k}) = P$ as the firm with the lowest renewable capacity will always sell the residual demand with its thermal plant, meaning that the highest price maximizes profits. □

Proof of Proposition 4: An immediate application of standard Betrand arguments. □

Proof of Proposition 5: Suppose that firm i is the low bidder. This means that we can start by assuming, without loss of generality, that $b_i^R = 0$ for all k_i so that all the renewable capacity is always dispatched, and that $b_i^G \geq c$. As a result, the best response of firm j can take two values. First, it can involve choosing $b_j^R = b_j^G = b_i^G$, obtaining profits $b_i^G E(\theta - k)$. Second, it can imply choosing $b_j^R = b_j^G = P$, with profits $PE(\theta - k - g)$. Notice that a combination of bids such that $b_j^R = b_i^G < b_j^G$ would always be dominated by the first option.

Under the high bid, firm i attains the highest possible profits and, therefore, any b_i^R and $b_i^G \geq c$ is optimal. Under the low bid, the best response of firm i for the thermal capacity is always to undercut firm j. This yields an equilibrium bid $b_i^G = c$, implying that any $b_i^R \leq c$ is optimal.

Finally, the previous comparisons allow us to conclude that a bid P for firm j will be optimal if and only if $PE(\theta - k - g) \geq cE(\theta - k)$. □

Proof of Proposition 6: Suppose that firm j uses the stated strategy. We first rule out the choice by firm i of bids higher than c. Such a bid only for the thermal power would be irrelevant, as the price would the plant would never be marginal or dispatched. If firm i chooses a higher bid for both the thermal and renewable production, it will serve the residual demand. As a result, it would be optimal to choose $b_i^G = b_i^R = P$. However, this strategy is dominated by choosing $b_i^R = c \leq b_i^G$. Hence, the minimax of firm i is $cE(\theta - k)$ and higher bids are irrelevant.

The rest of the proof follows Proposition 1 in Fabra and Llobet (2022). □

Proof of Proposition 7: Suppose that firm j chooses a bid as described in the text of the proposition. For a given k_i, we first characterize bidding functions that prevent local deviations around k_i. We later discuss the possibility that firms choose deviations k' below or above $\hat{k}$.

Suppose first that $k_i \le \hat{k}$. In that case, if firm i chooses $k' \le \hat{k}$ profits become

$$\pi_L(k_i, k') = \int_{\underline{k}}^{k'} \left[b^R(k_j)k_i + (b^R(k_j) - c)g\right] f(k_j)dk_j + \int_{k'}^{\overline{k}} b^R(k')(\theta - k_j - g)f(k_j)dk_j.$$

Define $W_L(k_i) = \max_{k' \le \hat{k}} \pi_L(k_i, k')$. The first order condition of this problem results in

$$\frac{\partial \pi_L}{\partial k'}(k_i, k') = \left(b^R(k')\left(k_i + k' + 2g - \theta\right) - cg\right) f(k') + \int_{k'}^{\overline{k}} b^{R'}(k')(\theta - k_j - g)f(k_j)dk_j = 0$$

Note that

$$\frac{\partial \pi_L}{\partial k' \partial k_i}(k_i, k') = b^R(k')f(k') > 0.$$

This implies that the optimal deviation k' is increasing in k_i. Hence, in an equilibrium, the FOC is equal to 0 when $k' = k_i \le \hat{k}$. Otherwise, if $k_i > \hat{k}$, the constrained solution should be $k' = \hat{k}$. Equivalently, $k' = \min\left\{k_i, \hat{k}\right\}$.

In the case of an interior solution, the FOC can be written as

$$\frac{b^R(k_i)(2k_i + 2g - \theta) - cg}{b^{R'}(k_i)} f(k_i) = -\int_{k_i}^{\overline{k}} (\theta - k_j - g)f(k_j)dk_j. \tag{10}$$

Note that we cannot have $\hat{k} = \overline{k}$. The RHS would be zero for $k_i = \hat{k}$, and hence the RHS would imply

$$b^R(k_i) = c\frac{g}{(2k_i + 2g - \theta)} < c$$

which cannot occur as the gas plant would then be offered at below marginal cost.

Suppose now that firm i has $k_i > \hat{k}$ and declares $k' > \hat{k}$. Profits become

$$\begin{aligned}\pi_H(k_i, k') = &\int_{\underline{k}}^{\hat{k}} \left[b^R(k_j)k_i + (b^R(k_j) - c)g\right] f(k_j)dk_j \\ &+ \int_{\hat{k}}^{k'} b^R(k_j)k_i f(k_j)dk_j + \int_{k'}^{\overline{k}} b^R(k')(\theta - k_j)f(k_j)dk_j.\end{aligned}$$

Define $W_H(k_i) = \max_{k' \le \hat{k}} \pi_H(k_i, k')$. The first order condition become

$$\frac{\partial \pi_H}{\partial k'}(k_i, k') = \left(b^R(k')\left(k_i + k' - \theta\right)\right) f(k') + \int_{k'}^{\overline{k}} b^{R'}(k')(\theta - k_j)f(k_j)dk_j = 0.$$

As before, we have that

$$\frac{\partial \pi_H}{\partial k' \partial k_i}(k_i, k') = b^R(k')f(k') > 0.$$

so that the optimal k' is increasing in k_i.

In an equilibrium we must have that $k' = k_i > \hat{k}$ and, as a result,

$$\frac{b^R(k_i)(2k_i - \theta)}{b^{R'}(k_i)} f(k_i) = -\int_{k_i}^{\overline{k}} (\theta - k_j) f(k_j) dk_j. \tag{11}$$

Otherwise, if $k_i < \hat{k}$, it implies $k' = \hat{k}$.

We now rule out deviations that imply choosing a k' outside the region of k_i. We do that in three steps. First notice that, by definition, we must have that $\pi_L(\hat{k}, \hat{k}) - \pi_H(\hat{k}, \hat{k}) = 0$ as the firm with capacity k_i should be indifferent between both bidding schedules.

Second, notice that $\pi_L(k_i, \hat{k}) - \pi_H(k_i, \hat{k})$ is independent of k_i. From the previous result, we know that the difference is 0 for $\hat{k}$. Thus, this also has to be true for any k_i and $\pi_L(k_i, \hat{k}) = \pi_H(k_i, \hat{k})$.

Third, suppose that $k_i \leq \hat{k}$. Using the previous arguments we have that

$$\pi_L(k_i, k_i) \geq \pi_L(k_i, \hat{k}) = \pi_H(k_i, \hat{k})$$

for any $k' > \hat{k}$ and, so, deviations are not profitable. The weak inequality is the result of the incentive compatibility constraints. A symmetric argument can be used for $k_i \geq \hat{k}$.

We now characterize the value $\hat{k}$. First notice that $\lim_{k->k_+} b^R(k) = c$. The argument is as follows. Suppose that $\lim_{k->k_+} b^R(k) < c$. By raising the bid, the renewable capacity of the firm would be dispatched with the same probability but the price would increase when $k_j > \hat{k}$.

Using the previous argument we can now characterize $\hat{k}$ using $\Pi_H(\hat{k}) = \pi_H(\hat{k}, \hat{k}) = \pi_L(\hat{k}, \hat{k}) = \Pi_L(\hat{k})$, where

$$\Pi_L(\hat{k}) = \int_{\underline{k}}^{\hat{k}} \left[b^R(k_j)k_i + (b^R(k_j) - c)g\right] f(k_j)dk_j + \int_{\hat{k}}^{\overline{k}} \hat{\rho}(\theta - k_j - g) f(k_j) dk_j$$
$$\Pi_H(\hat{k}) = \int_{\underline{k}}^{\hat{k}} \left[b^R(k_j)k_i + (b^R(k_j) - c)g\right] f(k_j)dk_j + \int_{\hat{k}}^{\overline{k}} c(\theta - k_j) f(k_j) dk_j,$$

where $\lim_{k->k_-} b^R(k) = \hat{\rho}$. Equating both expressions we obtain that

$$\hat{\rho} = c\frac{\int_{\hat{k}}^{\overline{k}} (\theta - k_j) f(k_j) dk_j}{\int_{\hat{k}}^{\overline{k}} (\theta - k_j - g) f(k_j) dk_j} > c.$$

Notice that this is a counterpart of $\hat{\rho}$ for the truncated distribution, $\hat{\rho}E(\theta - k | k > \hat{k}) = cE(\theta - k - g | k > \hat{k})$. Importantly, the threshold $\hat{\rho}$ is strictly increasing in $\hat{k}$.

The characterization of $\hat{\rho}$ and $\hat{k}$ goes as follows. The differential equation (7) is specified up to a constant, which can be pinned down from the boundary condition $b^R(\underline{k}) = P$. Hence, the equilibrium value of $\hat{k}$ can be defined from $b^R(\hat{k}) = \hat{\rho}$. Notice that this value is unique because $b^R(k)$ is decreasing in k and from the previous lemma, the right-hand-side of the expression is increasing in $\hat{k}$. Furthermore, $\hat{k} \in (\underline{k}, \overline{k})$ since

$$b^R(\underline{k}) = P > c\frac{\int_{\underline{k}}^{\overline{k}}(\theta - k_j)f(k_j)dk_j}{\int_{\underline{k}}^{\overline{k}}(\theta - k_j - g)f(k_j)dk_j},$$

and $b^R(\underline{k}) < c$.

We next show that firm i cannot improve upon joint bidding by choosing a different bid for the plants of the two technologies whenever the optimal bid b_i^R is above c. Suppose, towards a contradiction that firm i chooses $b_i^R < b_i^G$ for some $k_i \leq \hat{k}$. Obviously, $b_i^G \geq c$. Hence, we have three cases. First, $b_i^G < \hat{\rho}$. This case is dominated by $b_i^G = \hat{\rho}$, as this bid is only relevant when $k_j > \hat{k}$ and, in that case, increasing the bid does not affect the probability of winning.

Second, suppose that $b_i^G \geq \hat{\rho}$ and $b_i^G \geq c$. In that case, the maximization problem of firm i can be written as

$$\begin{aligned}\max_{b_i^G, b_i^R} &\int_{\underline{k}}^{b^{-1}(b_i^G)} \left[b(k_j)k_i + (b(k_j) - c)g\right] f(k_j)dk_j + \int_{b^{-1}(b_i^G)}^{b^{-1}(b_i^R)} b(k_j)k_i f(k_j)dk_j \\ &+ \int_{b^{-1}(b_i^R)}^{\overline{k}} b_i^R(\theta - k_j - g)f(k_j)dk_j.\end{aligned}$$

This function is decreasing in b_i^G, meaning that $b_i^R = b_i^G$ is optimal.

Third, suppose that $b_i^G \geq \hat{\rho}$ and $b_i^G < c$. In that case, the problem is similar,

$$\begin{aligned}\max_{b_i^G, b_i^R} &\int_{\underline{k}}^{b^{-1}(b_i^G)} \left[b(k_j)k_i + (b(k_j) - c)g\right] f(k_j)dk_j + \int_{b^{-1}(b_i^G)}^{b^{-1}(b_i^R)} b(k_j)k_i f(k_j)dk_j \\ &+ \int_{b^{-1}(b_i^R)}^{\overline{k}} b_i^R(\theta - k_j)f(k_j)dk_j,\end{aligned}$$

and we still find that it is optimal to set $b_i^R = b_i^G$.

The differential equation determining the bid in expression (10) when $k \leq \hat{k}$ can be rewritten as

$$b'(k_i) + a(k_i)b(k_i) = ca(k_i) - c\delta(k_i).$$

Note that this expression is the same as (8) where $a(k_i)$ is defined in (9), and it has an additional term, where

$$\delta(k_i) \equiv \frac{2k_i + g - \theta}{\int_{k_i}^{\overline{k}}(\theta - k_j - g)dk_j} f(k_i).$$

Notice that

$$\frac{\partial}{\partial k_i}\left(e^{\int_{\underline{k}}^{k_i} a(k)dk}(b(k_i)-c)\right) = e^{\int_{\underline{k}}^{k_i} a(k)dk}\left(b'(k_i)+a(k_i)(b(k_i)-c)\right). \tag{12}$$

Hence, we can write the differential equation as

$$e^{\int_{\underline{k}}^{k_i} a(k)dk}\left(b'(k_i)+a(k_i)(b(k_i)-c)\right) = -e^{\int_{\underline{k}}^{k_i} a(k)dk}\delta(k_i)c,$$

Integrating in both sides and using (12), we obtain

$$e^{\int_{\underline{k}}^{k_i} a(k)dk}(b(k_i)-c) = -c\int e^{\int_{\underline{k}}^{k_i} a(k)dk}\delta(k_i)dk_i + A.$$

Rearranging,

$$b(k_i) = c - e^{-\int_{\underline{k}}^{k_i} a(k)dk}c\int e^{\int_{\underline{k}}^{k_i} a(k)dk}\delta(k_i)dk_i + Ae^{-\int_{\underline{k}}^{k_i} a(k)dk}.$$

Using expression (3), we can now rewrite the previous expression as

$$b(k_i) = c - e^{\omega^G(k_i)}c\int e^{\omega^G(k_i)}\delta(k_i)dk_i + Ae^{\omega^G(k_i)}.$$

Since $b(\underline{k}) = P$ we can pin down $A = P - c + c\gamma(\underline{k})$ where $\gamma(k_i) \equiv \int e^{-\omega^G(k_i)}\delta(k_i)dk_i$. As a result,

$$b(k_i) = c + (P-c)exp(-\omega^G(k_i)) - c\left[\gamma(k_i)-\gamma(\underline{k})\right]exp(-\omega^G(k_i))$$

. □

Proof of Lemma 2: The comparative statics of $\rho(k)$, as defined in (6), are straight forward: it is decreasing in θ and increasing in g and c.

We now turn to the comparative statics of the bid function when $k \leq \hat{k}$. That the equilibrium bidding function (7) is increasing in P is immediate. To show that it is increasing in θ notice that $a(k_i)$ is decreasing in θ. This effect and the fact that $P > c$ guarantees that the second term in (7) is positive. Regarding the last term, notice that by the same reason, the last component $exp(-\omega^G(k_i))$ is increasing in θ. The term $[\gamma(k_i)-\gamma(\underline{k}))]$ is increasing in θ since its two components are increasing in θ. Last, we have that

$$\frac{\partial\gamma}{\partial k_i} = e^{\int_{\underline{k}}^{k_i} a(k)dk}\delta(k_i) > 0.$$

Hence, $[\gamma(k_i)-\gamma(\underline{k}))] > 0$.

The equilibrium comparative statics on $\hat{k}$ result from combining the comparative statics of $\rho(k)$ and $k \leq \hat{k}$. □