Fossil Fuels and Renewable Energy: Mix or Match?*

Natalia Fabra
Universidad Carlos III and CEPR

Gerard Llobet
CEMFI and CEPR

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Abstract

A profound shift in the ownership structures of energy companies is currently underway, transitioning from diversified technology portfolios to a focus on either renewable energy or fossil fuels. This paper examines the competitive consequences of this transformation on the performance of oligopolistic electricity markets. Our analysis reveals that competition among diversified firms is more intense compared to specialized firms. However, the ranking in terms of productive efficiency tends to favor the specialized ownership structure. Overall, simulations using Spanish data and planned future investments in renewable energy show that the diversified structure is usually socially preferable. Methodologically, 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.

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1 Introduction

Renewable energy plays a central role in decarbonizing the power sector, contributing to reduced emissions in other polluting sectors through electrification. Achieving carbon-free electricity markets demands significant efforts, yet noteworthy milestones have already been attained. For instance, by 2022, nine European countries had already surpassed the halfway mark in generating electricity from renewable sources, and projections suggest this share will further increase to 75% by 2035 (Ember, 2023).

Investing in renewable energy entails substantial upfront costs, but once the infrastructure is in place, it allows the production of electricity at almost zero marginal costs. However, in oligopolistic markets, lower costs need not translate into lower prices due to incomplete cost pass-through rates (Weyl and Fabinger, 2013; Miravete et al., 2023). Understanding the price impact of renewable investments on electricity prices is of utmost importance as, beyond their impact on consumers' welfare, electricity prices influence the incentives for electrification and, with it, the success of the Energy Transition.

In this paper, we analyze the impact of renewable investments on electricity prices and productive efficiency, considering the strategic interaction among electricity producers and the coexistence of multiple generation technologies. Our primary focus is on the differential impact of firms' ownership structures, whether diversified or specialized in certain generation technologies.

The relevance of this question is underscored by the rapid transformation in the ownership structures of European energy companies as the Energy Transition moves forward (Jarvis, 2023). Notably, established utility companies are increasingly divesting from fossil-fueled generation to specialize on renewable energy sources.[1] For instance, in 2016, the German energy giant E.ON made a strategic decision to split its clean energy and fossil fuel operations, creating a new company, Uniper, to manage its thermal assets.[2]

[1] Several quotes from the media and the companies' websites illustrate this. For instance, in "Europe's utilities battle for survival in changing market place," Financial Times, February 28, 2019, it is claimed that: *"The traditional utilities are thinking again. For many, the answer is to specialise and build scale in one or two parts of the chain, such as renewables"* (last accessed: September 8, 2023) https://www.ft.com/content/21941afa-3416-11e9-bd3a-8b2a211d90d5. Similarly, the Danish utility Orsted claims in its website: *"We transformed from a coal-intensive utility to a green energy major in only a decade."* (last accessed: September 8, 2023) https://orsted.com/en/who-we-are/our-purpose/our-green-energy-transformation.

[2] "E.ON completes split of fossil fuel and renewable operations," The Guardian, January 4, 2016, (last accessed: September 8, 2023) https://www.theguardian.com/environment/2016/jan/04/eon-completes-split-of-fossil-fuel-and-renewable-operations.

RWE, another major player in the industry, followed a parallel path.[3] In the UK, Scottish Power completely divested from coal and gas generation, selling its fossil-fuel assets to a rival power supplier, Drax.[4] Simultaneously, new players have entered the power sector with a strong focus on renewable energy, including investment funds and big oil companies under pressure to invest in low-carbon assets. These corporate strategies are transforming the power sector from one characterized by companies with diversified portfolios to one where firms specializing in renewable energy or fossil fuels directly compete against one another.

This paper sheds light on the competitive implications of this corporate transformation. Our findings reveal a fundamental trade-off between the diversified and specialized ownership structures during the early stages of the Energy Transition. On the one hand, firms with diversified technology portfolios stimulate competition, which reduces electricity prices. On the other hand, firms specializing in specific technologies tend to enhance productive efficiency, resulting in lower production costs and reduced emissions. However, at later stages, once renewable energy investments have outgrowth existing fossil-fuel capacity, this trade-off disappears, as the specialized ownership can lead to substantial efficiency losses, making the diversified ownership structure socially preferable. These predictions are confirmed with highly-detailed simulations using Spanish data and planned future investments in renewable energy.

We develop a duopoly model where firms operate renewable and thermal energy plants that consume fossil fuels. Following Fabra and Llobet (2023), we consider two distinctive features of these two technologies. First, the marginal cost of renewable energy plants is (almost) zero, and their available capacity is random and private information. Second, thermal plants have positive marginal costs and (almost) perfectly known production capacities. Firms compete to dispatch their production through a uniform-price auction, similar to the one used in most electricity spot markets in practice. We allow firms to place different bids for each of their plants, giving rise to step-wise supply functions. Bids are limited by a price cap.

We consider two alternative ownership structures: firms are *specialized* when each

[3] "RWE approves plans to split and create green powerhouse," Business Green, December 11, 2015, (last accessed: September 8, 2023) https://www.businessgreen.com/news/2438976/rwe-approves-plans-to-split-and-create-green-powerhouse.

[4] "Drax to buy £700m of assets from Iberdrola," Financial Times, October 16, 2018, (last accessed: September 8, 2023) https://www.ft.com/content/c46b0acc-d110-11e8-a9f2-7574db66bcd5.

owns a single technology, or *diversified* when they own both. We illustrate the interaction between both technologies depending on the level of demand relative to renewable and thermal capacities. In turn, we identify two relevant scenarios depending on whether thermal power sources or renewable energy dominate. These scenarios reflect the early and late stages of the Energy Transition, respectively.

When thermal capacity dominates, the two ownership structures give rise to a trade-off. Specialization always leads to higher prices but also higher productive efficiency compared to diversification. The reason is as follows. Under specialization, the thermal producer, which has higher costs, is always outbid by the renewable producer. Since it faces the residual demand not covered by renewable power sources, the thermal producer has incentives to raise its bid up to the price cap. Because the merit order is preserved — i.e., the renewable producer is dispatched first — the specialized ownership structure leads to productive efficiency despite the high prices it engenders.

Diversification, in contrast, fosters within-technology competition by placing price-setting plants in the hands of competing firms. This force depresses prices. However, since firms own a portfolio of technologies, diversification entices them to escape competition by raising the bid of their renewable (and thermal) plant in order to jack up the market price. This strategy may jeopardize the dispatch of some low-cost renewable production, which engenders productive inefficiency.

However, when renewable capacity is sufficiently large compared to thermal power sources, the diversified ownership structure is unambiguously preferred. The reason is that specialization yields, as before, higher prices but might also give rise to greater productive inefficiencies. In particular, when demand can be fully covered with renewable energy, the renewable firm anticipates that offering a low bid would result in a low price. For this reason, it might prefer to bid above the thermal firm in order to push the market price up. Doing so implies serving the residual demand not covered by the competitor, creating a significant distortion in the merit order. In contrast, under diversification, each producer preserves the merit order within the firm, dispatching its renewable production first. Therefore, the distortion in productive efficiency affects, at most, one thermal plant rather than two.

Interestingly, in our model, diversified firms offer lower bids when their realized renewable capacity is larger. This finding is in contrast with what is commonly found in oligopoly models and the auction literature, where the higher the inframarginal production, the stronger the incentives to raise prices (Khezr and Cumpston, 2022; Ausubel et al., 2014). The source of this fundamental discrepancy has to be traced back to two modeling differences: in our setting, the residual demand faced by firms is step-wise instead of continuous, and there is private information on capacities instead of costs (or valuations). To understand the importance of these differences note that, in our setting, conditional on being the high bidder, a firm's residual demand is inelastic, while conditional on tying, it is perfectly elastic. In the first case, it is optimal to raise the price regardless of the firm's inframarginal capacity. In case of a tie, however, an infinitesimal price reduction allows the firm to increase its output. This quantity gain is stronger the larger the firm's capacity, for two reasons. First, the output gain from undercutting is larger; and second, the firm infers that, in case of a tie, its residual demand is also smaller as the rival's capacity is equally large. The combination of the above effects induces the firm to bid more competitively the larger its capacity. These incentives are absent in standard settings with continuously differentiable demand, cost, and strategy functions because the residual demand is always downward sloping, and firms' capacities are assumed to be known.

Our model also provides instances where joint bidding, understood as the decision of a firm to offer the same bid for both plants, is optimal (rather than assumed, as in Ausubel et al. (2014)). This occurs in situations where the price cap is high and demand is relatively small. In those cases, a firm might be willing to set a high price for the renewable production when a low capacity realization is expected to be marginal. The possibility to increase the price is limited by the bid of the thermal plant, making it optimal to equate both bids.

The stringency of the price cap regulation is a critical element in our analysis. Under both ownership structures, a high price cap gives rise to higher equilibrium prices. However, the specialized market structure is more vulnerable to this effect. The relationship between the price cap and productive efficiency is non-monotonic. When it is low, increasing the price cap induces firms to distort their production to raise prices. However, when it is high enough, firms can achieve prices at the price cap without engendering productive inefficiency.

To assess the theoretical predictions empirically, we run a series of simulations of equilibrium outcomes using actual market data. We consider two scenarios with more or less renewable and thermal installed capacity, and different price cap levels, under specialized or diversified ownership structures. Our simulations use data from the Spanish electricity market as of 2019, considering the existing volume of renewable energy at that date, versus the amount planned for 2030. Consistent with our theoretical predictions, the results reveal that the specialized ownership structure always delivers less competitive outcomes. In contrast, the specialized ownership structure tends not to distort the merit order (unless renewables are very abundant), and, as a result, it yields higher productive efficiency.

1.1 Related Literature

Recent literature has studied the price-depressing effect of renewable energy, often referred to as the "merit-order effect." However, this terminology implicitly assumes that the only impact of renewable energy is to shift the supply curve to the right, thus reducing the market price. By doing so, some of this literature often overlooks the impact of renewable energies on market power.

Acemoglu et al. (2017) were one of the first to analyze the price-depressing effect of renewable energy in the presence of market power, which they model *à la* Cournot. They show that Cournot competitors respond to increased renewable availability by withholding their thermal output. Hence, when all renewable capacity is in the hands of the strategic firms, the price-depressing effect of renewables is fully neutralized. Conversely, if all renewable capacity is in the hands of fringe players, the strategic firms can only partially mitigate their price-depressing effect.[5] Hence, Acemoglu et al. (2017) predict that strategic firms exert more market power when their portfolios are diversified, in stark contrast with our findings. Several modeling choices explain this difference. First, our setup captures important institutional features of electricity markets, where firms compete in a uniform-price auction by choosing prices for their plants rather than a single quantity. Second, they only consider cases in which renewable energy is insufficient to cover total demand, and is thus never marginal. Last but not least, in their setup, trans-

[5] 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. They find that prices were 24% higher when renewable plants are allocated to the largest firm relative to the fringe. Other related papers are Kakhbod et al. (2021), who extend Acemoglu et al. (2017) by allowing for correlation across renewable plants, and Genc and Reynolds (2019) who also highlight the relevance of the market structure in determining the strength of the merit-order effect.

ferring renewable capacity from the fringe to the strategic players enlarges the capacity of the latter, making it unclear whether their main prediction is driven by diversification or capacity asymmetries.

Fabra and Imelda (2023) also analyze the price-depressing effects of renewable energy, but their focus is on the distinctive impact of alternative support schemes. They find that the merit-order effect is stronger when renewable energy is paid at fixed prices (the so-called Feed-In-Tariffs) rather than exposed to market-price volatility (Feed-In-Premia).[6] Furthermore, the merit-order effect is never neutralized under fixed prices even when the strategic firms own all the renewable plants. Similarly to us, despite the different setups, Fabra and Imelda (2023) find that the ownership structure of renewable and thermal plants is a key determinant of the competitive effects of the alternative renewable support schemes.

Few papers have analyzed the case in which renewable energy might be abundant enough to cover total demand. As far as we know, Fabra and Llobet (2023) is the first paper to model competition in renewable-only markets. This paper shows that firms bid more aggressively when their available renewable capacity is larger, as the output gain from undercutting the rival is more significant. Unlike the papers cited above, this implies that renewable energy not only affects 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 remain above marginal costs unless there are large amounts of excess capacity. Somogy et al. (2023) characterize the equilibrium of a similar model under pay-as-bid pricing when total quantity is endogenous.

In this paper, we adopt a similar modeling approach as Fabra and Llobet (2023). In particular, we also assume that firms' available renewable capacity is private information. However, our analysis also applies to cases with high demand relative to renewable capacity by allowing firms to produce using fossil-fuel technologies. This assumption opens the possibility to analyze 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

[6]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 renewable energy is mainly owned by large firms, this effect is dominated by the fact that fixed prices weaken the large firms' market power.

model competition with private information, such as Holmberg and Wolak (2018) and Vives (2011), who assume private information on costs (rather than capacities). Fabra et al. (2006) and de Frutos and Fabra (2012) analyze more general situations at the cost of assuming complete information on costs and capacities.

Finally, our work contributes to the literature on multi-unit auctions where firms can offer multiple bids for units with (possibly) different costs or valuations. Following the pioneering work of Wilson (1979), early papers on multi-unit auctions assumed pure common values, so efficiency was not an issue. Subsequent work allowed for private values, concluding that uniform-price auctions are prone to differential bid shading that, in line with our findings, gives rise to inefficiencies (Ausubel et al., 2014; Noussair, 1995; Engelbrecht-Wiggans and Kahn, 1998). However, the existing literature has made limited progress in characterizing the bidding equilibria beyond specific examples. For instance, Ausubel et al. (2014) characterize the equilibria in uniform-price and pay-as-bid auctions with *flat demands*, such that two bidders with two equally-valued units compete for two indivisible units. Similarly, Noussair (1995) and Engelbrecht-Wiggans and Kahn (1998) assume that bidders compete in a uniform-price auction to buy two indivisible units, but allow for independent valuations across units. These papers find that the dominant strategy in uniform-price auctions is to bid the true valuation for the high-value unit and to shade the bid of the low-value unit – a finding that is akin to our results in the low-demand case, in which the renewable bid is payoff irrelevant and can thus be offered at marginal cost. However, the equilibria in Noussair (1995) and Engelbrecht-Wiggans and Kahn (1998) satisfy a separability property (i.e., the equilibrium bid of the second unit is independent of the valuation for the first unit) which naturally fails in our setup. The reason is that, in their setup, valuations are independent across units and their capacities are fixed, so the second unit's valuation and quantity sold do not depend on the private information regarding the first unit. In our setup, as discussed in Fabra and Llobet (2023), the fact that capacities (instead of costs or valuations) are private information gives rise to the non-separability of the bids of the thermal plants from the private information on the renewable plant's capacity. This non-separability is at the heart of our predictions on the price-depressing effect of renewables, which affect market prices through the thermal bids even when renewables are not marginal.

Although our analysis does not provide a general characterization of equilibria in uniform-price auctions, it constitutes a step forward in the literature, as it covers a broader range of cases regarding the relationship between demand and capacities and does not constrain the costs (or valuations) of the two units to be equal. Nevertheless, much work remains to be done regarding the equilibrium characterization in general multi-unit auction settings.

The remainder of the paper is structured as follows. In Section 2 we describe the model. In Sections 3 to 5, we assume that the size of renewable and thermal capacities coincide and characterize equilibrium bidding among specialized and diversified firms. In Section 6 we allow expected renewable availability to exceed thermal capacity, and show how the equilibrium outcomes differ compared to the baseline model. Section 7 discusses the competitive mechanisms that underpin the different theoretical predictions across ownership structures. Section 8 runs electricity market simulations with actual data and planned future investments under the alternative ownership structures. Section 9 concludes. All proofs are relegated to the Appendix.

2 The Model

Consider an electricity market in which thermal (or gas) and renewable plants coexist. There are two identical thermal plants which can produce electricity with marginal cost $c > 0$ up to their capacity $g > 0$. There are also two renewable energy plants, $m = 1, 2$. They can produce at zero marginal cost but their capacity is subject to *i.i.d.* and privately-known shocks. In particular, plant m's capacity, denoted as 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. Total demand θ is fixed and known. We assume there is always enough aggregate capacity to cover the market, i.e., $\theta < 2\underline{k} + 2g$.

We consider a duopoly model,[7] 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. To abstract from differences in bidding behaviour due to capacity asymmetries, in our

[7]The main results of the paper are robust to allowing for a generic number of firms n as long as there are n plants of each technology.

baseline model we assume $E(k) = g$. This implies that the two firms have symmetric expected capacities under both ownership structures. In Section 6, we show that the same results apply when $E(k) < g$ and we extend the analysis to allow for ex-ante higher renewable capacity, $E(k) > g$.

The market is organized as a uniform-price auction. Each firm submits two bids, one for each plant, specifying the minimum price at which it is willing to produce up to the plant's capacity. These bids are subject to a price cap $P > c$. 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. 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 cheapest plants 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. When two plants have equal prices we assume that the renewable plant is dispatched first.[8]

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.

Equilibrium bidding behaviour depends on the relationship between demand and plants' capacities. For this reason, in the following sections, we analyze three cases. The first looks at situations when demand is high, so both thermal plants are required to cover it. At the other extreme, the second case looks at situations where demand is low, so it can be covered by renewable energy without relying on thermal plants. The last case analyzes situations where demand is intermediate so that it can be met with renewable production and only one thermal plant.[9] In all cases we focus on equilibria sustained by weakly undominated pure strategies.

[8] This rationing rule is used solely to characterize a well-defined pure-strategy equilibrium in the standard Bertrand game with asymmetric costs.

[9] In between these cases are others in which either two, one, or no gas plants may be needed with a probability between zero and one. While these cases share properties with the ones we analyze, a complete characterization of equilibrium bidding in all these cases is beyond the scope of the paper.

3 High Demand

We first assume that demand is high, i.e., both thermal plants are required to cover it, $\theta > 2\overline{k} + g$. Hence, the competitive market price is equal to the thermal plants' marginal cost, c. Below we consider the case with specialized and diversified firms.

3.1 Specialized Firms

As shown in our first proposition, when demand is high, specialized firms can sustain the highest admissible market price in equilibrium without distorting productive efficiency.

Proposition 1. *When firms are specialized and $\theta > 2\overline{k} + g$, the equilibrium market price equals P. There always exists an equilibrium with efficient production.*

This equilibrium outcome arises from asymmetric equilibria where one producer (the *high bidder*) bids at P while the other one (the *low bidder*) chooses sufficiently low bids so that the rival finds unprofitable to undercut them.[10] The low bidder has no incentives to deviate as it sells its full capacity at P, while the high bidder maximizes its profits over the residual demand by setting the market price at P.

Regarding productive efficiency, there are two potential market outcomes. When the renewable firm is the low bidder, the market outcome is efficient given that its renewable capacity is fully utilized. This equilibrium always exists given that the renewable firm can offer its output at zero prices, which the thermal firm cannot profitably undercut. However, when P is sufficiently high, there exists another equilibrium where the thermal firm acts as the low bidder by offering its capacity at prices at or sufficiently close to c. If P is sufficiently high, the renewable firm is better off serving the residual demand at P, rather than undercutting c to dispatch at capacity. This equilibrium entails productive inefficiencies.[11]

[10] The bids chosen by the low bidder are payoff-irrelevant, as long as they are low enough, given that they never set the market price. Therefore, there exists a continuum of payoff-equivalent equilibria. In what follows, whenever the equilibria only differ in bids that are pay-off irrelevant, we will refer to them as being *unique*.

[11] In a version of this model without asymmetric information, Fabra et al. (2006) characterize a continuum of mixed-strategy equilibria in addition to the pure-strategy equilibria. They show that mixed-strategy equilibria are sustained by weakly dominated strategies.

3.2 Diversified Firms

Diversified firms are ex-ante symmetric. For this reason, we characterize the asymmetric as well as the symmetric equilibria of the game.

Proposition 2. *When firms are diversified and $\theta > 2\overline{k} + g$, there exist asymmetric Bayesian Nash Equilibria, in all of which the market price equals P and production is efficient. There also exists a unique symmetric Bayesian Nash equilibrium in which the market price is between c and P and production is efficient.*

The nature of the equilibrium bidding behaviour is very similar to the one characterized above. One firm acts as the low bidder by offering its plants at or close to marginal cost, while the other acts as the high bidder by setting the market price at P. The former sells at capacity, while the latter serves the residual demand, which exceeds the capacity of its renewable plant. Therefore, since renewable plants are always dispatched at full capacity, equilibrium production is efficient.

Since the low bidder is better off than the high bidder, each firm prefers to play the asymmetric equilibrium in which it acts as the low bidder. However, in a one-shot game like the one analyzed here, it is left unspecified how firms learn to coordinate on who will be the low or high bidder.

In contrast, the symmetric equilibrium that we characterize next is not subject to this concern. We start by establishing some monotonicity conditions that any symmetric equilibirum must satisfy.

Lemma 1. *When firms are diversified and $\theta > 2\overline{k} + g$, in any symmetric Bayesian Nash Equilibrium of the game, the bids of renewable plants are payoff irrelevant. Equilibrium 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 $b_i^R(k_i) \leq b_i^G(k_i)$, the market price is set by the thermal plant owned by the firm with the smallest realized renewable capacity.*

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 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 as Δq), and a profit loss due to the reduction in the market price (*price effect*). Regarding the quantity effect, if the thermal plant slightly undercuts its rival (an event that occurs when $k_j = k_i$, i.e., with probability $f(k_i)$), the firm moves from serving the expected residual demand, $\theta - E(k_j|k_j = k_i) - g = \theta - k_i - g$, to selling at capacity, $k_i + g$. Hence, the output gain, $\Delta q = 2k_i + 2g - \theta$, is increasing in k_i. Intuitively, when k_i is high, the production of its thermal plant is low unless it undercuts the rival, making the quantity effect stronger. On the contrary, contingent on setting the market price with its thermal bid, the firm always sells the expected residual demand. If the rival's bidding function is decreasing in capacity, the residual demand faced by the price-setter, $\theta - g - E(k_j|k_j > k_i)$, is smaller as k_i increases. This implies that the *price effect* is decreases in k_i. 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 for the thermal plant that is decreasing in k_i. Finally, standard Bertrand arguments allow us to rule out symmetric equilibria that contain flat segments.

The previous lemma allows us to characterize the symmetric equilibrium by assuming that firms choose the same bidding function for the thermal plant, $b^G(k)$, which is decreasing in their realized renewable plant's capacity, k. In equilibrium, since renewable plants are always dispatched at capacity, their bids are payoff irrelevant.

Using the Revelation Principle, we can transform the problem as follows: instead of choosing the bid for its thermal plant, each firm reports a renewable capacity k' knowing that its thermal bid will be derived from a decreasing function $b^G(k')$. In this transformed problem, the expected profits of firm i with realized capacity k_i that reports renewable capacity k', can be expressed as

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

The first term captures cases where firm i's reported capacity is above firm j's. Since the bidding function is decreasing, $b^G(k') < b^G(k_j)$, and firm i sells all its renewable and thermal capacity 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, and hence its bid is higher. 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 $k' = k_i$.

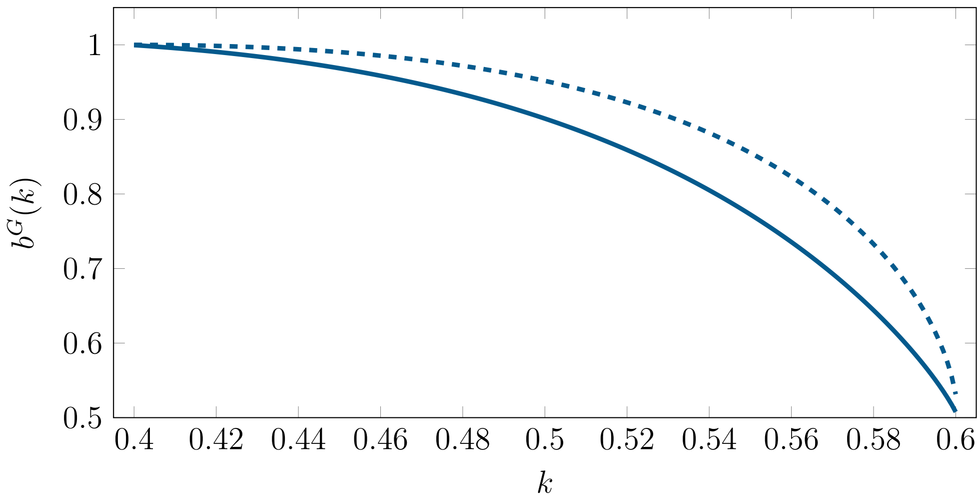

Figure 1: Equilibrium bid for thermal plants at the symmetric equilibrium with diversified firms (high demand)

Notes: The figure shows the equilibrium bids for the thermal plant when $k_i \sim U[0.4, 0.6]$, $c = 0.5$, $P = 1$, and $g = 0.5$ for demand values $\theta = 1.7$ (solid) and $\theta = 1.8$ (dashed).

The following proposition characterizes the unique symmetric equilibrium.

Proposition 3. *When firms are diversified and $\theta > 2\overline{k} + g$, in any symmetric Bayesian Nash equilibria of the game, each firm $i = 1, 2$ offers a sufficiently low price for its renewable plant. The unique 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, as shown in (2), 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 place a lower bid for their thermal plants when their realized renewable capacity is higher, 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, its bid always sets the market price. Therefore, it finds it optimal to bid at P. At the other extreme, when $k_i = \overline{k}$, firm i has the largest renewable capacity with probability one and, hence, never sets the market price. Therefore, it finds it optimal to offer its thermal production at c to dispatch it at capacity.

Figure 1 provides a numerical example of the equilibrium bidding function for different demand values, θ. For a given realization of the renewable capacity k_i, the optimal price offer increases as the demand raises. The reason is that the higher θ the larger the residual demand faced by the high bidder, making the quantity effect weaker and the price effect stronger. Both reasons relax competition, leading to higher bids.

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 in the asymmetric equilibria. Pareto dominance arguments cannot be used for equilibrium selection as firms' expected profits in the symmetric equilibrium are (strictly) in between those of the high and the low bidder in the asymmetric equilibrium. This result is in contrast with the model in which capacities are public information (Fabra et al., 2006) where the asymmetric equilibrium Pareto dominates the symmetric one.[12]

Specialized versus Diversified Firms. In the high-demand case, the comparison across equilibrium outcomes shows that prices are weakly lower when firms are diversified. In particular, the equilibrium market price is P under both ownership structures when diversified firms bid asymmetrically (Proposition 2). However, the price comparison is strict under the symmetric equilibrium (Proposition 3). In this case, diversification fosters competition among the price-setting thermal plants, while specialization shuts it down completely. Productive efficiency can be achieved in equilibrium under both ownership structures.

4 Low Demand

The previous section considered cases in which both thermal plants are always needed to meet demand. We now turn to the other extreme situation where they are never

[12]When capacities are privately known, 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.

required because demand is so low that renewable energy is always enough to cover it entirely, i.e., $\theta \leq 2\underline{k}$. Hence, the competitive market price is equal to the renewable plants' zero marginal cost. As in the earlier case, we characterize equilibrium bidding under the two alternative ownership structures.

4.1 Specialized Firms

Note that the assumption $E(k) = g$ implies $2g \geq 2\underline{k} \geq \theta$. As a result, both the thermal firm and the renewable firm have enough capacity to cover the whole market. Standard Bertrand arguments apply as firms always have incentives to undercut each other unless the price equals the marginal cost of the thermal firm. In equilibrium, the renewable firm serves the whole market, leading to productive efficiency.

Proposition 4. *When firms are specialized and $\theta \leq 2\underline{k}$, the equilibrium market price is c and production is efficient.*

4.2 Diversified Firms

Again, note that each firm always has enough capacity to cover the market on its own, even under the lowest renewable realization, $\underline{k} + g > 2\underline{k} \geq \theta$. Hence, Bertrand competition drives the equilibrium price offers for the thermal plants down to c. Still, firms compete to dispatch their renewable plants at capacity. The following proposition characterizes the equilibrium market outcome when firms bid asymmetrically, with the low bidder offering its renewable plant at or close to its marginal costs while the high bidder offers it at c, constrained by the rival's thermal bid.

Proposition 5. *When firms are diversified and $\theta \leq 2\underline{k}$, in all asymmetric Bayesian Nash Equilibrium the market price equals c and production is efficient. There also exists a unique symmetric Bayesian Nash Equilibrium in which the market price is between* 0 *and c and production is also efficient.*

We next characterize the symmetric equilibrium, which has to satisfy the following monotonicity properties.

Lemma 2. *When firms are diversified and $2\underline{k} \geq \theta$, in any symmetric Bayesian Nash Equilibrium of the game the bids of thermal plants are payoff irrelevant. Equilibrium bidding for renewable plants is in pure strategies and the function $b_i^R(k_i)$ must be strictly* *decreasing in the firm's renewable capacity, k_i. Since $b_i^R(k_i) \leq b_i^G(k_i)$, the market price is set by the renewable plant owned by the firm with the smallest realized renewable capacity.*

Again, the equilibrium bid function must be strictly decreasing because of the interplay between the quantity and the price effects. 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 capacity. This allows us to characterize the symmetric Bayesian Nash equilibrium, which is described in Proposition 6 and illustrated in Figure 2.

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

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

where

$$\omega^R(k_i) = \int_{\underline{k}}^{k_i} \frac{(2k-\theta)f(k)}{\int_k^{\overline{k}}(\theta - k_j)f(k_j)dk_j}dk. \qquad (4)$$

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

By bidding both of their plants at c, firms can obtain profits of at least $cE(\theta - k)$, which sets a lower bound to equilibrium profits. Indeed, these are the equilibrium profits of a firm with capacity $\underline{k}$ while, due to incentive compatibility, the profits for higher capacity realizations are strictly increasing in k_i.

The resulting equilibrium bidding function is as in Fabra and Llobet (2023).[13] That paper considers firms that only own a renewable plant and face a price ceiling that can be interpreted as the result of a competitive fringe of thermal producers bidding at marginal cost. Proposition 6 above extends these results and shows that the same equilibrium arises when firms are diversified and their thermal capacity is sufficiently large despite not being price-takers.

[13] The notation is slightly different but the same expressions arise replacing P with c and c with 0.

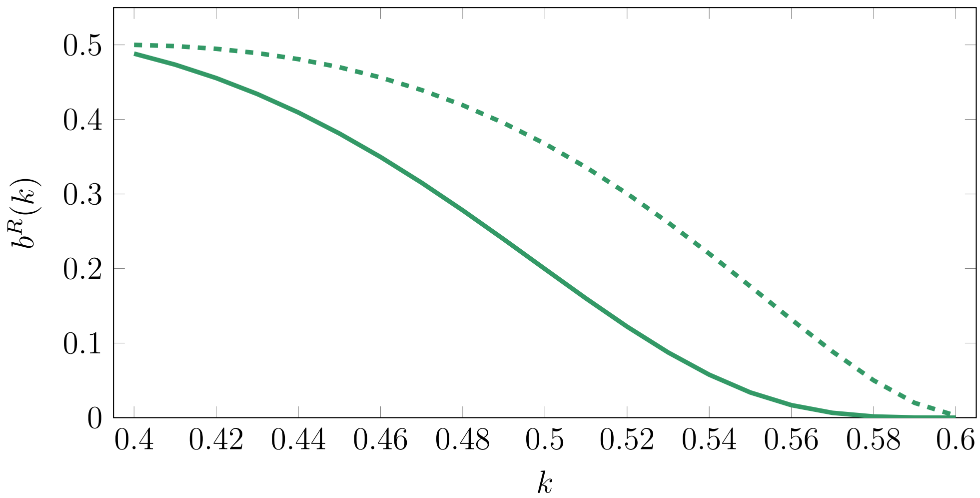

Figure 2: Equilibrium bid for the renewable plant with diversified firms (low demand, low price cap)

Notes: The figure shows the equilibrium bids for the renewable plant when $k_i \sim U[0.4, 0.6]$, $c = 0.5$, and $g = 0.5$ for demand values $\theta = 0.7$ (solid) and $\theta = 0.8$ (dashed).

Importantly, the equilibrium bidding function spans from c at $\underline{k}$ to zero at $\overline{k}$. Hence, since all the renewable capacity is offered at prices below c, it is never profitable to dispatch the thermal plants. As a result, production is efficient.

Specialized versus Diversified Firms. When demand is low, both ownership structures generate efficient outcomes as only the renewable power plants are dispatched in equilibrium. However, diversified ownership yields (weakly) lower prices, at c or below.

5 Intermediate Demand

In the previous cases, we assumed that the two thermal plants were needed to cover demand (high-demand case), or none was required (low-demand case). We now consider an intermediate situation in which demand is such that only one thermal plant is required, i.e., $2\overline{k} < \theta < 2\underline{k} + g$. As we will see, the resulting equilibria share some features with both previous cases.

5.1 Specialized Firms

The equilibrium in this case is identical to the one described in the high-demand case (Proposition 1). In particular, the equilibrium market price equals P. An equilibrium where the thermal firm bids both plants at P and serves the residual demand always exists and it results in productive efficiency.

5.2 Diversified Firms

As in previous cases, the asymmetric equilibria are characterized by one firm bidding sufficiently low while the rival sets the market price that maximizes its profits over the residual demand. Differently from those cases, however, is the fact that the profit-maximizing price of the high bidder might depend on its own capacity realization. More specifically, the high bidder maximizes its profits by bidding at P whenever selling the residual demand at that price is more profitable than selling the renewable capacity at c, i.e., if $PE(\theta - k - g) \geq ck_i$.[14] This means that high capacity realizations make firms willing to bid low as the increase in output compensates for the price reduction.

Thus, a necessary condition for an asymmetric equilibrium with price P to exist is that the price cap is high enough from the point of view of the price setter, firm i. That is, firm i will bid at P if it is above

$$\rho_I^d(k_i) \equiv c\frac{k_i}{E(\theta - k - g)}, \tag{5}$$

which is increasing in k_i.

When the price cap is above the highest of these thresholds, $\rho_I^d(\overline{k})$, the low bidder is certain that its rival's best response is to set the price at P. Hence, it does not have incentives to deviate. This equilibrium is inefficient given that the high bidder does not dispatch some of its renewable production.

In contrast, when the price cap is below the lowest of these thresholds, $\rho_I^d(\underline{k})$, the low bidder is certain that its rival's best response is to bid competitively, which is also the low bidder's best response. Hence, an asymmetric equilibrium does not exist in this case, and both firms bid competitively in the symmetric equilibrium.

In between these thresholds, an asymmetric equilibrium does not exist because firms' best responses may vary depending on their realized capacities, which are private information. The unique equilibrium is symmetric, with firms bidding their thermal plants at prices between c and P, giving rise to productive inefficiencies. We formally state these results below.

Proposition 7. *When firms are diversified and* $2\overline{k} < \theta < 2\underline{k} + g$*:*

[14] Note that prices in between c and P would never be profitable given that the firm could always increase the price to P without losing output.

(i) If $P \geq \rho_I^d(\overline{k})$, there exist asymmetric Bayesian Nash equilibria, in all of which the market price equals P and production is inefficient. There also exists a unique symmetric Bayesian Nash equilibrium with expected prices between c and P and inefficient production.

(ii) If $\rho_I^d(\underline{k}) < P < \rho_I^d(\overline{k})$, there exists a unique symmetric Bayesian Nash equilibrium with expected prices between c and P and inefficient production. No asymmetric equilibrium exists.

(iii) If $P \leq \rho_I^d(\underline{k})$, the equilibrium market price is c and production is efficient.

The previous result shows that a symmetric equilibrium exists in all cases. As mentioned before, when $P \leq \rho_I^d(\underline{k})$, in equilibrium firms bid their thermal plants at marginal cost (and their renewable plants at c or below). When $P > \rho_I^d(\underline{k})$, the equilibrium outcome features higher prices, as we show in our next Proposition. Beforehand, it is convenient to introduce the following piece of notation,

$$\rho_I^d(k_i|k) \equiv c\frac{(1-F(k))k_i}{\int_k^{\overline{k}}(\theta - k_j - g)f(k_j)dk_j}. \tag{6}$$

Note that (6) is increasing in k and it coincides with (5) when $k = \underline{k}$.

Proposition 8. *Assume $P > \rho_I^d(\underline{k}|\underline{k})$. When firms are diversified and $2\overline{k} < \theta < 2\underline{k} + g$, 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 $b^R(k_i) \leq b^G(k_i) = c$. 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 $b(\hat{k}) = \rho_I^d(\hat{k}|\hat{k}) \equiv \hat{\rho} > c$.

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 c and the renewable plant at or below c. This behaviour mimics the equilibrium in the low-demand case (Proposition 3), with the difference being that here the firm is guaranteed to sell its renewable plant at capacity and the bid for this plant is payoff irrelevant as long as it is at or below

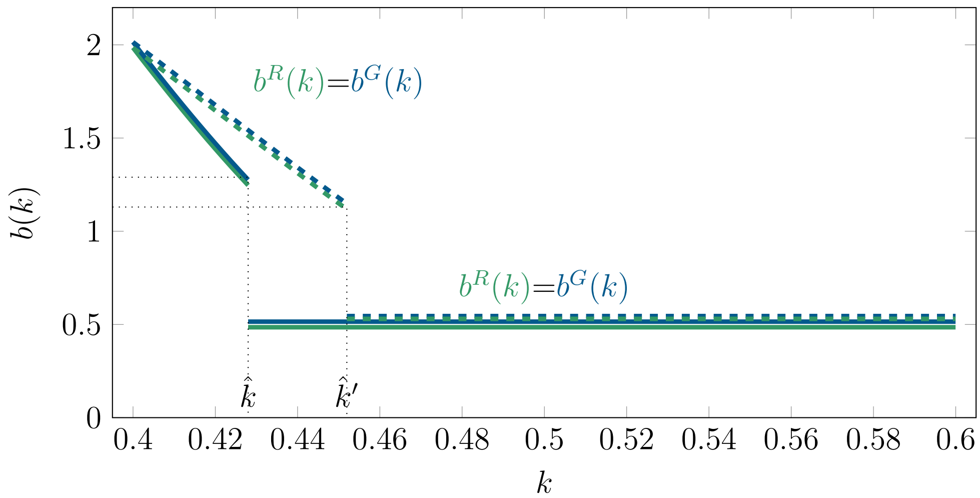

Figure 3: Equilibrium bids for the renewable and thermal plants with diversified firms (intermediate demand, high price cap)

Notes: The figure shows the equilibrium bids for the renewable (green) and thermal plants (blue) when $k_i \sim U[0.4, 0.6]$, $c = 0.5$, $P = 2$, $g = 0.5$, and $\theta = 1.2$ (solid) and $\theta = 1.3$ (dashed).

c. Instead, for smaller capacity realizations ($k \leq \hat{k}$), firm i makes a joint offer for its thermal and renewable capacity at a price strictly above c. This behaviour mimics the equilibrium in the high-demand case (Proposition 6), with the difference being that here the firm knows that if it is the high bidder it does not dispatch its thermal plant. Hence, its thermal bid is payoff irrelevant as long as it is at or above the renewable plant's.

Interestingly, for $k \leq \hat{k}$, the first two terms of the bidding function (7) coincide with the ones in the high-demand case (in Proposition 3, see equation (2)). The relevant marginal cost in that case was c since each firm was competing to serve their thermal capacity. Given that the firm is now competing to serve its total capacity, the relevant marginal cost is lower, in between the thermal marginal cost, c, and the renewable marginal cost, 0. This lower marginal cost is captured in the third term of the bidding function (7), which reduces the equilibrium bid below the one in (2). The larger the renewable capacity, the lower the relevant marginal cost, and the more likely it is that the firm serves all its renewable capacity. Hence, the third term increases in k_i.

Importantly, for small capacity realizations ($k \leq \hat{k}$), a firm cannot play the strategy prescribed by Proposition 6 because it is now dominated by bidding both plants at P. Indeed, under such a strategy, firm i's profits are ck_i. However, when $P > \rho_I^d(\underline{k})$, the firm would benefit from deviating to P, obtaining profits $PE(\theta - k - g)$. To offset this incentive to deviate, the bidding strategy in Proposition 8 calls for firms to offer both plants at higher prices, spanning from P, when renewable capacity is $\underline{k}$, to $\hat{\rho} > c$, when renewable capacity is $\hat{k}$.

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 renewable output from bidding at c rather than $\hat{\rho}$ exactly compensates the price reduction. Expression (6) derives from this indifference condition. The critical values $\hat{\rho}$ and $\hat{k}$ are determined jointly, affecting the whole bidding function and not just the discontinuity. As shown in Figure 3, increasing θ from $2\overline{k}$ to $2\underline{k} + g$ shrinks the region where the thermal's bid is flat at c, while more weight is placed on prices above c. This leads to less competitive bidding, higher market prices, and a greater likelihood of productive inefficiencies.

Specialized versus Diversified Firms. It follows that, if the price cap is not low enough, the comparison of market outcomes across ownership structures is now subject to a trade-off: only the specialized ownership structure guarantees productive efficiency, but it does so at the cost of higher prices. However, if the price cap is low, diversified ownership always attains productive efficiency and competitive pricing, unlike the specialized ownership structure.

6 Renewable Energy Dominates

So far, our analysis has focused on situations where firms have the same capacity ex-ante regardless of the ownership structure. This modeling assumption has helped isolate the effects of the ownership structure from those due to capacity asymmetries, which constitute a source of market power *per se*. However, asymmetries will inevitably arise along the Energy Transition as the weight of renewable energies increases relative to fossil fuels. The effect is particularly relevant under the specialized ownership structure, as differences in the importance of the two technologies also give rise to capacity asymmetries across the two firms.

To study the implications of this asymmetry, in this section we dispense with the assumption $E(k) = g$. Instead, for simplicity, we now assume $\theta - \overline{k} - g > 0$ so that diversified firms always face a positive residual demand.

It is simple to see that the results of the previous sections go through essentially unchanged if $E(k) < g$, i.e., when thermal capacity is relatively large compared to expected renewable capacity.[15] The irrelevance of making thermal capacity larger is in contrast with the effects of renewable energy becoming relatively more abundant, as it is expected to be the case along the Energy Transition. In particular, results change when $E(k) > g$ and demand is low, $\theta \leq 2\underline{k}$. While in the baseline case both the renewable firm and the thermal firm always had enough capacity to cover the whole market, the latter is no longer true when g is small. As we will see next, this has significant implications on equilibrium bidding under both ownership structures.

6.1 Specialized Firms

When demand is low, $\theta \leq 2\underline{k}$, the renewable producer always has enough capacity to serve the whole market. However, it might prefer to serve the residual demand, $\theta - 2g$, instead of total demand, θ, in order to increase the market price from c to P. Whether this is profitable or not depends on whether the price cap is above or below the critical threshold,[16]

$$\rho_H^s \equiv \frac{c\theta}{\theta - 2g}. \tag{8}$$

We formally state this result below.

Proposition 9. *When firms are specialized and $\theta \leq 2\underline{k}$:*

(i) If $P > \rho_H^s$, there exist Bayesian Nash equilibria, in all of which the market price equals P and production is inefficient.

(ii) If $P \leq \rho_H^s$, there exist asymmetric Bayesian Nash equilibria, in all of which the market price equals c and production is efficient.

When the price cap is higher than ρ_H^s, the renewable firm finds it optimal to serve the residual demand at P rather than total demand at c, giving rise to productive inefficiencies. In contrast, when the price cap is below ρ_H^s, the results of our baseline model apply,

[15] In the case of the specialized ownership structure, Proposition 1 applies with a small caveat. As thermal capacity gets relatively larger, the incentives of the renewable firm to act as the high bidder diminish. Eventually, when g is sufficiently large, i.e., if $2g > \theta$, the equilibrium in which the renewable firm bids P vanishes. As this inefficient equilibrium has been ignored throughout the analysis, this change is inconsequential for our results. In the case of the diversified ownership structure, enlarging the thermal capacity is also irrelevant. To the extent that the equilibrium configuration depends on whether zero, one, or two thermal plants are required, increases in g only change the case to be considered.

[16] Our result presupposes that $\theta > 2g$. When the opposite occurs, the threshold ρ_H^s becomes infinity and the equilibrium price is always equal to marginal cost.

delivering a market price of c. Therefore, increasing the price cap above ρ_H^s increases market prices but also reduces productive efficiency.

6.2 Diversified Firms

Diversified firms also face a trade-off between setting the market price at P or at c. However, the threshold value for the price cap that makes firms indifferent is now given by

$$\rho_H^d \equiv c\frac{E(\theta - k)}{E(\theta - k - g)}, \tag{9}$$

as they expect to serve the residual demand $E(\theta - k - g)$ when the market price is P versus $E(\theta - k)$ when it is c. This has implications for the equilibrium characterization.

Proposition 10. *When firms are diversified and $\theta \leq 2\underline{k}$:*

(i) If $P > \rho_H^d$, there exist asymmetric Bayesian Nash equilibria, in all of which the market price equals P and production is inefficient.

(ii) If $P \leq \rho_H^d$, there exist asymmetric Bayesian Nash equilibria, in all of which the market price equals c and production is efficient.

This equilibrium characterization is analogous to Proposition 9 but with a different threshold. In particular, a straightforward comparison of both thresholds, (8) and (9), shows that $\rho_H^s < \rho_H^d$. The reason is that the specialized renewable firm gains relatively more from increasing the price from c to P than the diversified firm, so a lower price cap is enough to induce firms to bid at P. This implies that the incidence of the seemingly collusive and inefficient market outcomes is greater under the specialized ownership. Furthermore, whenever the equilibrium price is P, the efficiency loss is greater under the specialized versus the diversified structure: both thermal plants operate at capacity under the former, and only one of them under the latter.

We now turn to the characterization of the symmetric equilibrium of the game. When the price cap is low, $P \leq \rho_H^d$, firms have no incentives to set a price above c, which means that the symmetric equilibrium is still characterized by Proposition 6. 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,

$$\rho_H^d(k) \equiv c\frac{\int_k^{\overline{k}} (\theta - k_j) f(k_j) dk_j}{\int_k^{\overline{k}} (\theta - k_j - g) f(k_j) dk_j} > c. \tag{10}$$

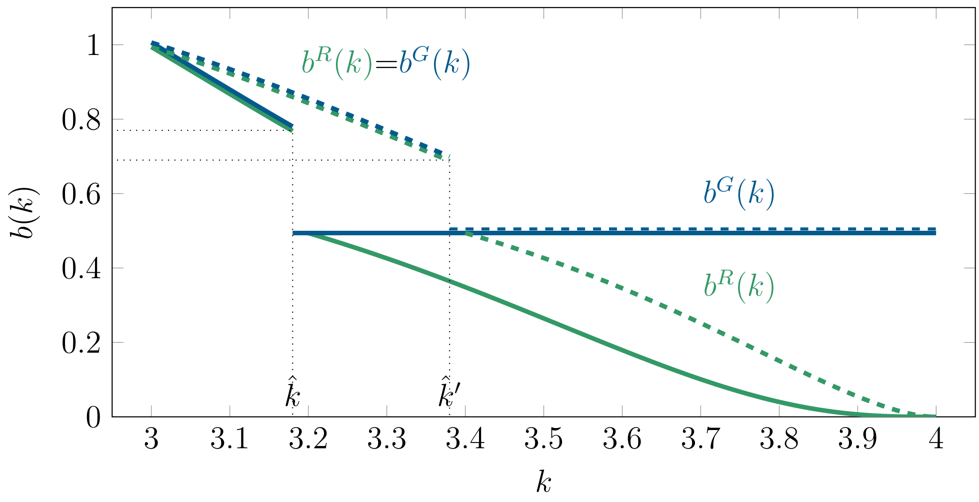

Figure 4: Equilibrium bids for the renewable and thermal plants with diversified firms (low demand, high price cap)

Notes: The figure shows the equilibrium bids for the renewable (green) and thermal plants (blue) when $k_i \sim U[3,4]$, $c = 0.5$, $P = 1 > \rho_H^d = 0.75$, $g = 0.5$, and $\theta = 5$ (solid) and $\theta = 5.5$ (dashed).

Note that this expression encompasses ρ_H^d as $\rho_H^d = \rho_H^d(\underline{k})$. Our next proposition characterizes the symmetric Bayesian Nash equilibrium in this case, and Figure 4 illustrates it.

Proposition 11. *Assume $P > \rho_H^d(\underline{k})$. 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 $k > \hat{k}$. When $k_i \leq \hat{k}$, firm i chooses the same bid for its renewable and thermal plants, $b^R(k_i) = b^G(k_i) = b(k_i)$, according to*

$$b(k_i) = c + (P - c)exp(-\omega^G(k_i)) - c\left[\gamma(k_i) - \gamma(\underline{k})\right] exp(-\omega^G(k_i)), \tag{11}$$

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 $b(\hat{k}) = \rho_H^d(\hat{k}) \equiv \hat{\rho}$.

There is a close analogy between this equilibrium and the one in the intermediate-demand case (Proposition 8). In both cases, for small renewable capacity realizations ($k \leq \hat{k}$), firms offer their two plants at the same price above c, while for large capacity realizations ($k > \hat{k}$) they offer their thermal plant at c. The difference between the two cases lays in the bidding behaviour of the renewable plant for large capacity realizations. In the low-demand case, since there is enough renewable energy to cover total demand, renewable plants compete to sell at capacity, similarly as under Proposition 6. In contrast, in the intermediate-demand case, the renewable bids were payoff irrelevant because it was necessary to dispatch one gas plant to cover total demand. Hence, in the low-demand case, when the realized capacities of both renewable plants is above $\hat{k}$, market prices fall below c, unlike the intermediate-demand case, where they remain at c.

Specialized versus Diversified Firms. In this case, diversified ownership is weakly preferred to specialized ownership, both regarding prices as well as efficiency. In contrast, recall that in the symmetric capacities case, the specialized ownership was always (weakly) superior in terms of efficiency. Hence, one can associate the greater inefficiencies that arise when the renewable firm withholds output to the greater capacity asymmetries that arise among specialized firms when renewable capacity exceeds thermal capacity.

7 Discussion: Impacts of the Ownership Structure

Two key results emerge from the previous analysis. First, regarding prices, the specialized ownership structure leads to (weakly) higher prices than the diversified structure. Second, regarding productive efficiency, the specialized ownership structure leads to (weakly) higher productive efficiency unless the expected renewable capacity is larger than the thermal capacity, in which case productive efficiency can be greater under the diversified structure.

These findings are mainly driven by two mechanisms. First, the ownership structure strongly impacts the nature of competition. Under specialization, there is limited competition among the price-setting plants. The firm that owns the thermal plants typically finds it unprofitable to undercut the more efficient renewable producer, opting for raising prices, which are only constrained by the price cap P. In contrast, under diversification, there is often competition among the price-setting plants as they are owned by competitors. This competition can take different forms depending on whether thermal plants are required to cover demand. When they are not, firms compete to dispatch all their renewable capacity. When both thermal plants are required, firms place a low bid for the renewable plant to dispatch its production first, as the price will be set by the marginal thermal plant. In both cases, production is efficient as the merit order is preserved. However, head-to-head competition between plants of the same technology no longer arises when only one thermal plant is required. A bid for the renewable plant above the rival's bids now engenders a trade-off. The firm does not dispatch all its renewable capacity, but it can now set the market price. Under the asymmetric equilibrium, this means that it can drive the market price to the cost of the thermal plant or the price cap. In the symmetric equilibrium, firms bid jointly for both their plants, strengthening competition and leading to prices below the price cap. The merit order is usually distorted, creating a loss in productive efficiency.

Second, the degree of market power also affects the extent to which firms need to distort productive efficiency to raise market prices. More specifically, specialized firms can exert market power and raise prices without distorting productive efficiency when renewable energy is not relatively abundant. However, when renewable energy is abundant, and the renewable firm can cover the whole market, its exercise of market power comes with a significant efficiency loss. In particular, for the renewable firm to increase market prices, it has to give up a large amount of renewable output for the two thermal plants to become inframarginal and dispatch at capacity.

On the contrary, under a diversified ownership structure, firms' sizes remain equal regardless of the weight of each technology. This implies that firms only rarely distort the competitive outcome, preventing a productive efficiency loss. Even when diversified firms can profitably exercise market power, the resulting productive efficiency loss is smaller than under specialization because, within each firm, the merit order is preserved. That is, at most one gas plant gets dispatched at full capacity before dispatching the rival's renewable plant.

While the price comparison across ownership structures is unambiguous, the ambiguity in the efficiency comparison makes it compelling to analyze real-market data, an issue to which we turn next. Working with actual data also implies relaxing the assumption of ex-ante symmetry between renewable and thermal firms under specialized ownership.

8 Simulations

In this section, we illustrate our theoretical results using actual market data. We perform a series of simulations of the equilibrium outcomes in the Spanish electricity market at the hourly level over a year (8,760 hours).

We rely on highly detailed data on key parameters, including the plants' characteristics (capacity, efficiency rate, emission rate), the evolution of hourly electricity demand, the hourly availability of renewable resources, and the price of fossil fuels, among others.[17] This information allows us to compute the marginal cost of each plant,[18] and thus construct the industry competitive supply curve at the hourly level (since renewables availability changes hourly). Matching market demand (assumed to be inelastic at the realized hourly level) and competitive supply gives the competitive hourly price and efficient output allocation.

The richness of our empirical analysis comes at a cost. In reality, there might be cases that we have not characterized in previous sections such as those where there is uncertainty on the number of gas plants that are needed to cover demand. By focusing on the case with known capacities, we avoid this issue and our numerical results approximate those of the case where the private information on renewable capacities is small. This is particularly the case when firms play the asymmetric equilibria, whose prices are, in expectation, the same with and without private information.

Computing the strategic equilibria. We simulate firms' strategic behavior by characterizing the asymmetric equilibria under the assumption that renewables' capacities are publicly known. These equilibria correspond to the ones characterized in the previous sections when private information on capacities vanishes. The results of the simulations provide an upper bound to the equilibrium prices and costs in cases with symmetric diversified firms, as in these cases lower-priced symmetric equilibria also exist.

In line with de Frutos and Fabra (2012), computing the asymmetric equilibria involves two steps: (i) to characterize the price that each firm would set as a price-setter, i.e., as a best response to all other firms bidding at marginal cost, and (ii) for each of the candidate price-setters, verify that all the other firms do not have incentives to deviate by setting a higher market price. In case of equilibrium multiplicity, we report the highest-price equilibrium; and in case of multiplicity among equilibria with equal prices, we report the most efficient one.

[17]The hourly demand data, the hourly renewables availability data, and the installed capacity of each technology are publicly available at the Spanish System Operator's websites, https://www.esios.ree.es/ and https://www.ree.es/en/datos/todate. The plants' characteristics are obtained from https://globalenergymonitor.org/. The price of gas is obtained from the website of the Spanish gas exchange, https://www.mibgas.es/en, and the price of CO2 EU allowances and coal from https://data.bloomberg.com/.

[18]The computation follows standard methods in the literature. See, for instance, Fabra and Imelda (2023) for details.

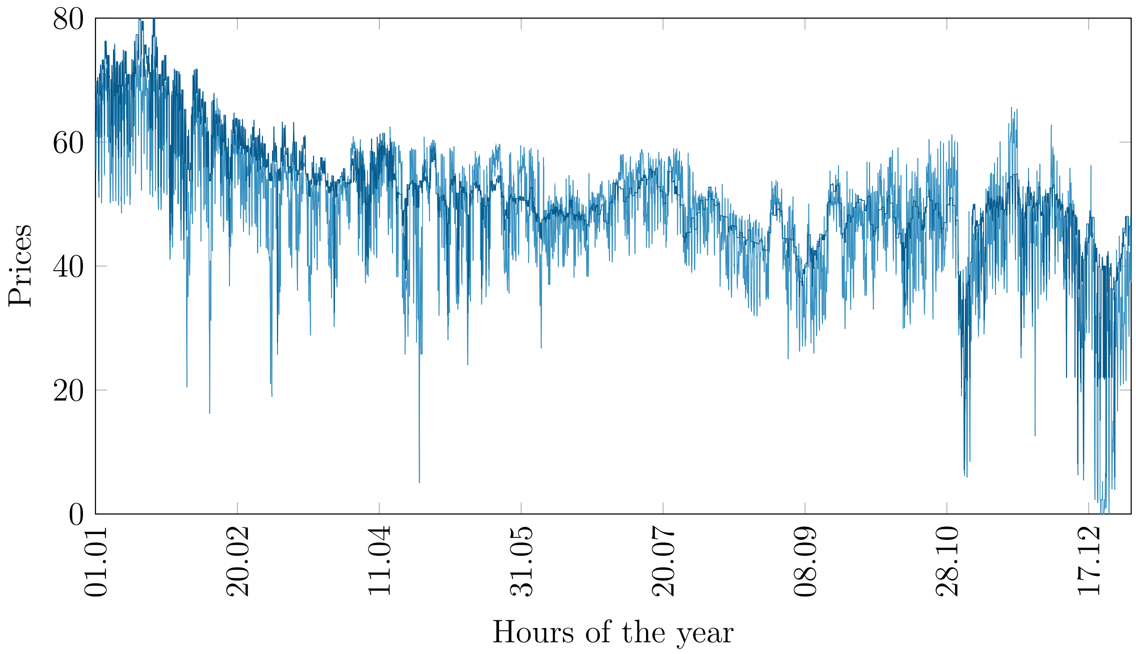

Figure 5: Real and simulated hourly electricity prices

Notes: This figure plots the real (light blue) simulated (dark blue) hourly prices during 2019 in the Spanish electricity market under the current market structure. The simulations allow for strategic behavior. The average hourly simulated and real prices are 51.6 €/MWh and 47.9 €/MWh, respectively, and the correlation between the two is 0.82.

As shown in Figure 5, simulations using the actual market structure reproduce well the observed hourly prices in the Spanish electricity market during 2019.

We next consider two scenarios that aim to capture two stages of the Energy Transition with a different importance of renewable power sources. In each scenario we compare the performance of the diversified and specialized ownership structured.

Renewable penetration. The two scenarios we consider differ in the volume of renewable and thermal capacity. The first one, meant to illustrate an *Early Stage* of the Energy Transition, replicates the Spanish electricity market as of 2019 when the total installed renewable capacity was 34.43 GW. The second scenario, which is meant to capture a *Late Stage* of the Energy Transition, adds 52.53 GW of new renewable energy capacity, as planned for 2030 in the Spanish National Energy and Climate Plan (NECP).[19] Also, by then, all coal and half of the nuclear capacity will be phased out. Table 1 summarizes the market structure under the two scenarios.

During the *Early Stage* of the Energy Transition, renewable energies are enough to

[19]See Ministerio para la Transición Energética y el Reto Demográfico (2020). The government increased the ambition of these objectives in June 2023. At the time of writing this paper the new objectives have not yet been approved by the European Commission.

Table 1: Installed capacity by technology and peak demand

	Early Stage		*Late Stage*	
	Capacity (GW)	% of total capacity	Capacity (GW)	% of total capacity
Solar capacity	8.749	10.5	39.181	32.7
Wind capacity	25.680	30.8	50.333	42.0
Nuclear capacity	7.397	8.9	3.670	3.0
Coal capacity	14.638	17.6	0	0.0
CCGT capacity	26.941	32.3	26.612	22.2
Peak demand	40.150	-	40.150	-

cover total demand only 3.9% of the time. Demand is lower at night, and wind stronger, so this average reaches a maximum of 13.1%. In contrast, during the *Late Stage*, renewable energy is enough to cover demand 55.2% of the time, achieving the highest value of 87.4% at noon. Hence, the scenarios we consider in the simulations encompass all the cases we have analyzed theoretically, with an increased incidence of the low-demand case as we move from the *Early* to the *Late* stages.

Ownership structures. We allocate all thermal and renewable plants to two firms, and the remaining assets (nuclear and hydropower plants) are assigned to a competitive fringe. Hence, nuclear plants are offered at marginal cost, and hydropower is allocated competitively, i.e., to shave the peaks of demand to flatten the residual demand that has to be met with thermal generation. For simplicity, we do not allow for imports/exports with neighboring countries.

We compare situations with specialized and diversified ownership structures,mimicking the analyses performed in previous sections. In the first one, we allocate all the thermal capacity (gas and coal) to one firm and all the renewable capacity to the other. In the second one, we assume that the two strategic firms have equal shares of all thermal and renewable power plants.

We also consider different levels of the price cap: 180 €/MWh (in place in 2019) and 500 €/MWh.[20]

[20]For robustness, we have also run simulations with price caps of 1,000 €/MWh, 2,000 €/MWh, and 3,000 €/MWh. We do not report the results as they provide insights similar to the analysis with 500 €/MWh. Results are available from the authors upon request.

8.1 Effects on prices

Figure 6 depicts hourly prices along the day, averaged across the year, under competitive pricing (dashed) and strategic pricing for the two ownership structures, specialized (dark solid) and diversified (light solid). It also shows the percentage of time during which, for each hour, demand is low, i.e., renewable power sources are enough to cover it entirely. The upper and lower figures show the results for the *Early* and *Late* stages of the Energy Transition, while the left and right figures show the results for values of the price cap 180€/MWh and 500€/MWh, respectively.

In all cases, prices are higher under specialized ownership. Quantitatively, the difference is substantial. For instance, with a price cap of 180€/MWh, equilibrium prices under specialization are 3.2 times higher than under diversification during the *Early Stage*, and 1.6 times higher during the *Late Stage*.

That prices under specialization are higher than under diversification also applies to every hour of the year, as shown in Table 2. During the *Early Stage*, specialized firms set prices almost always at the price cap (96.1% of the time), except for the night hours when demand is low relative to renewables. In contrast, competition among diversified firms drives prices closer to the competitive level when the price cap is low. Indeed, only 1.2% of the time is the price cap reached, and equilibrium prices are only 10% above the competitive level (Table 3). However, raising the price cap to 500 €/MWh weakens competition among diversified firms when renewables are scarce, pushing the price cost markup to 52%. In line with our theoretical predictions, an increase in the price cap shifts some equilibrium prices from the marginal cost of thermal generation to the price cap, as shown by the increase in the percentage time when the price cap is reached, 4.1%. Nevertheless, the market power impact of raising the price cap is even stronger under specialization, when prices are almost ten times higher than the competitive benchmark.

The price wedge across ownership structures narrows down considerably during the *Late Stage*. The main reason is that equilibrium prices under diversification now depart more from the competitive benchmark (indeed, relative to the *Early stage*, prices go up despite the fall in generation costs, leading to an increase in markups, as shown in Table 2). With the increase in renewable capacity and the reduction in thermal capacity, it now becomes more profitable to raise the price offers of the renewable plants even at the expense of losing output. The price wedge across ownership structures becomes

Table 2: Equilibrium prices, costs and profits

	Early Stage			
	$P = 180$		$P = 500$	
	Specialized	Diversified	Specialized	Diversified
Prices				
% hours at competitive prices	0.0	17.5	0.0	17.2
% hours at price cap	96.1	1.2	96.1	4.1
% hours when prices spec $\geq$ diver	100	-	100	-
Costs				
% hours productive efficiency	99.9	26.4	99.9	25.5
% hours when efficiency spec $\geq$ diver	73.7	-	74.8	-
Profits				
% hours at competitive profits	0.0	17.5	0.0	17.2
% hours when profits spec $\geq$ diver	100	-	98.8	-
	Late Stage			
Prices				
% hours at competitive price	0.0	10.3	0.0	6.8
% hours at price cap	47.9	13.9	58.4	25.0
% hours when prices spec $\geq$ diver	100	-	100	-
Costs				
% hours productive efficiency	97.0	22.7	88.0	17.5
% hours when efficiency spec $\geq$ diver	74.6	-	70.8	-
Profits				
% hours at competitive profits	0.0	10.3	0.0	6.8
% hours when profits spec $\geq$ diver	100	-	97.2	-

Notes: The table reports the percentage time at which equilibrium prices equal the competitive benchmark or the price cap. Regarding the price comparison across ownership structures, it also reports that prices under specialization are 100% of the time above prices under diversification. The table also reports the percentage time when the allocation achieves productive efficiency, and the percentage time when efficiency under specialization is greater than under diversification.

particularly narrow around noon, when solar production is abundant.

8.2 Effects on efficiency

Figure 7 depicts hourly per-unit generation costs, i.e., total generation costs over demand, averaged across hours of the year. Table 3 reports total annual costs relative to the competitive allocation, along with emissions and excess renewables. During the *Early Stage* of the Energy Transition, production is close to being fully efficient, particularly under specialization. In this case, firms exercise market power without incurring productive inefficiencies, as can be seen in the upper panels of Figure 7.

In contrast, firms sacrifice productive efficiency to increase prices during the *Late Stage*. This is particularly noticeable under specialization in the midday hours when

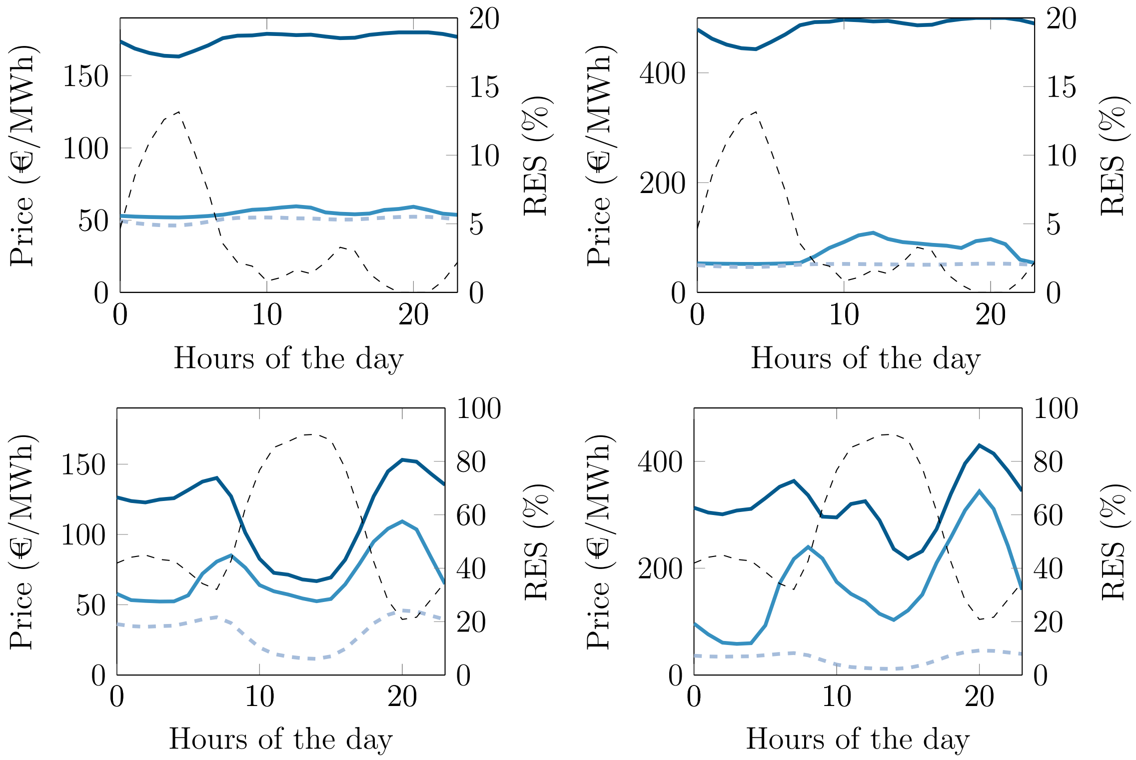

Figure 6: Average prices, ownership structures, and renewable energy penetration

Notes: These figures plot hourly prices during the day, averaged across the year. The dark and light blue lines represent prices under the specialized and diversified ownership structures, respectively. The dashed blue line represents the price in the competitive benchmark. The black dashed line indicates the percentage of hours during the year for which renewable energy could serve the whole demand (right axis). The figures on the left and the right correspond to a price cap of €180 and €500, respectively. The upper and lower figures correspond to the early and late stages of the Energy Transition, respectively.

solar production is abundant and the price cap is high. In this case, the renewable firm finds it profitable to withhold production to jack up the market price, which implies that thermal plants operate at capacity. As a consequence, carbon emissions increase and renewable capacity is wasted. Even though diversified firms face similar incentives, withholding by one firm means that only half of the thermal capacity gets dispatched, leading to a smaller inefficiency, and a weaker increase in emissions and excess renewables.

Overall, our simulations illustrate our theoretical findings. Mainly, diversified ownership gives rise to more competitive outcomes. However, the efficiency comparison can go either way. Whereas specialized ownership tends to result in higher productive efficiency, it can also give rise to significant efficiency losses when renewable power is abundant, and the price cap is high.

Table 3: Prices, costs, profits, emissions and excess renewables relative to the competitive benchmark (%)

	Early Stage			
	P = 180		$P = 500$	
	Specialized	Diversified	Specialized	Diversified
Market prices	348	110	961	152
Costs	100	101	100	102
Profits	523	116	1,570	188
Emissions	100	97	100	99
Excess RES	100	260	100	734
	Late Stage			
Market prices	371	235	1060	580
Costs	102	112	150	129
Profits	517	302	1,558	826
Emissions	103	121	192	156
Excess RES	103	129	193	159

Notes: This table reports the annual demand-weighted averages of market prices under strategic behaviour relative to the competitive benchmark, i.e., a value of (above) 100 % indicates that prices are equal to (above) the competitive price. The table also reports generation costs, firms' profits, carbon emissions and excess renewables relative to the competitive benchmark.

9 Concluding Remarks

In this paper, we have studied the performance of oligopolistic electricity markets in which renewable and thermal generation plants coexist. Not surprisingly, once we move away from the competitive paradigm, ownership of these plants matters for competition and productive efficiency. Furthermore, the implications of alternative ownership structures vary across the Energy Transition as the weight of renewable energies increases, also depending on the stringency of the price cap regulation.

Our results show that competition among diversified firms is more intense than among specialized firms. Hence, equilibrium prices tend to be lower under diversification. Yet, stronger competition does not always lead to improved productive efficiency. In particular, specialized firms can often exercise market power without distorting the efficient dispatch of the various generation technologies. The exception is when renewable energies are abundant relative to thermal capacity, and the price cap is high, in which case the renewable firm might find it profitable to give up production in order to increase prices. This behavior results in higher production costs, including emission costs, as thermal plants would inefficiently be dispatched at capacity.

A key difference in the competitive mechanisms across ownership structures underlies

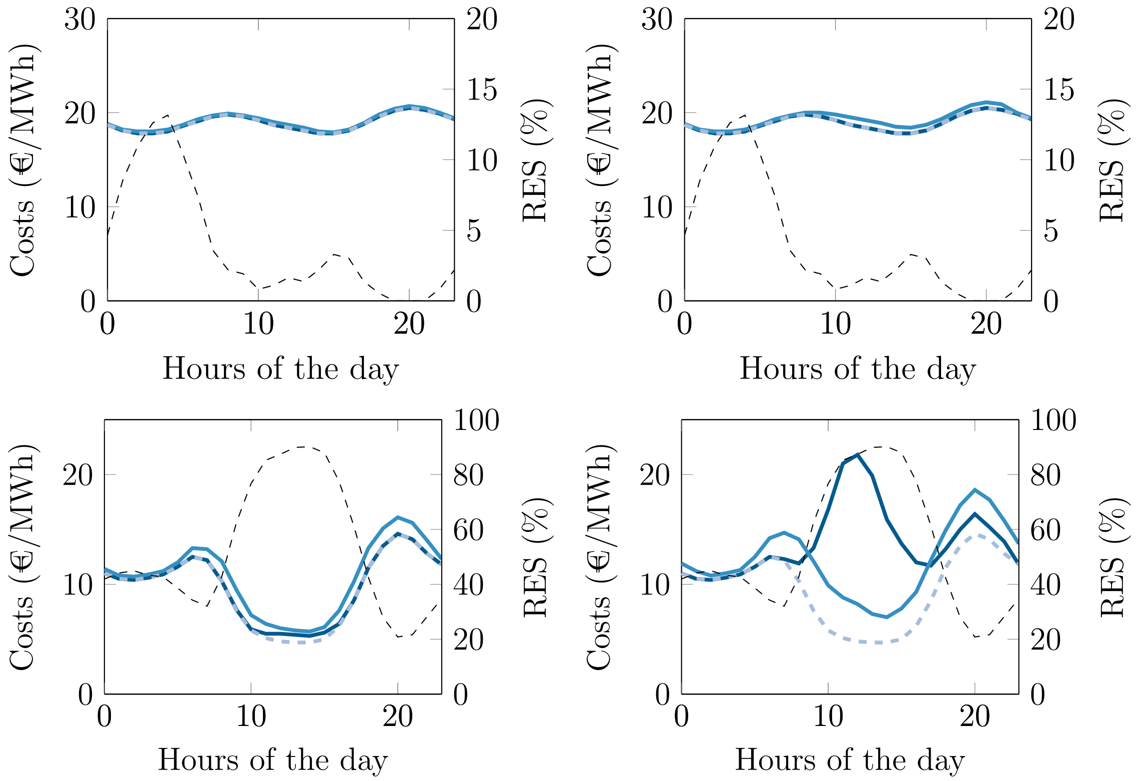

Figure 7: Generation costs, ownership structures, and renewable energy penetration

Notes: These figures plot hourly average generation costs (Generation costs/Generation) during the day, averaged across the year. The dark and light blue lines represent costs under the specialized and diversified ownership structures, respectively. The dashed blue line represents the cost in the competitive benchmark. The black dashed line indicates the percentage of hours during the year for which renewable energy could serve the whole demand (right axis). The figures on the left and the right correspond to a price cap of €180 and €500, respectively. The upper and lower figures correspond to the early and late stages of the Energy Transition, respectively.

these findings. Under specialized ownership, there is no competition between the price-setting plants, which can raise the price without distorting efficiency. In contrast, under the diversified structure, the price-setting plants exert competitive pressure on each other, leading to a competitive outcome or forcing them to escape such competitive pressure by giving up efficient production in exchange for increasing the market price. Early in the transition, this outcome entails higher productive inefficiency than under the specialized ownership.

We have simulated the Spanish electricity market at different stages of the Energy Transition and under counterfactual ownership structures to quantify the strength of each effect in a real-life context. Results confirm that the diversified structure always gives rise to lower prices than the specialized structure. And, while there are hours in which efficiency is higher among diversified versus specialized firms and vice-versa, average efficiency across the year tends to be higher under specialization. In line with the theoretical predictions, the efficiency comparison is reversed in favour of diversification during the Late Stage of the Energy Transition if the price cap is high.

Our theoretical analysis has focused on the duopoly case. Nevertheless, similar results would be obtained in a general oligopoly framework. In particular, the conclusion that diversification fosters competition compared to specialization is robust to the number of firms (keeping the number of existing plants constant). Although more firms make it more likely that the competitive equilibrium emerges under both ownership structures, whenever firms have market power (i.e., if one firm is pivotal), there will always be more competing plants under diversification than under specialization.

Finally, we have focused on three extreme cases when all the existing thermal capacity is necessary, only half of it or none. However, the model also spawns situations where these events occur with positive probability. Exploring the implications of the ownership structures in these situations might shed additional light on the mechanisms at work.

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A Proofs

The main results of the paper are proved here.

A.1 High Demand

The result under the **specialized** ownership structure is proved next.

Proof of Proposition 1: Candidate equilibria where firms' bids tie at a price above c can be ruled out by Bertrand arguments. Hence, candidate equilibria must have firms submitting different bids. Suppose that firm i has the highest bid. Since firm i will be serving the residual demand, conditional on being the high bidder, its unique best response is P. This rules out equilibria with prices below P.

First, consider a candidate equilibrium in which firm 2 is the high bidder and chooses $b_1^G \leq b_2^G = P$, while firm 1 chooses $b_1^R(k_1, k_2) = b_1^R(k_1, k_2) = 0$. Firm 2 cannot profitably undercut firm 1's bids and firm 1 obtains the highest possible profits, $P(k_1 + k_2)$. Hence, this is an equilibrium with efficient production.

Second, consider a candidate equilibrium in which firm 1 is the high bidder and chooses $b_1^R(k_1, k_2) \leq b_2^R(k_1, k_2) = P$, while firm 2 chooses $b_1^G = b_1^G = c$. Firm 2 obtains its highest possible profits, $(P - c)2g$, and never wants to deviate. For firm 1 not to be willing to undercut the bids of firm 2, it must be the case that its equilibrium profits are higher for all $k_1 + k_2$. Therefore, a necessary and sufficient condition for this equilibrium to exist is $P(\theta - 2g) \geq 2c\overline{k}$. Since some of firm 1's renewable capacity is not dispatched, the equilibrium entails productive inefficiency. □

For the **diversified** ownership structure we start by proving Lemma 1 and Proposition 3 which are instrumental to Proposition 2.

First notice that 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 $[\underline{b}(k_j), \overline{b}(k_j)]$. Profits for firm i

become

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

Notice that these profits are increasing in k_i, since

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

Furthermore, 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 weakly decreasing in k_i.

Suppose now that in a symmetric Nash Equilibrium a firm with capacity k_i randomizes between two different bids b_i^G and $\hat{b}_i^G$ 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 realization arises with probability 0, the previous result implies that 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. This allows us to conclude that all symmetric equilibria must be in pure strategies with $\hat{b}_i^G(k_i)$ decreasing in k_i. Lastly, Bertrand arguments rule out flat segments in the bidding function. This finalizes the **proof of Lemma 1**.

Taking the derivative of $\pi_i(k_i, k')$ in (1) we obtain

$$\frac{\partial \pi_i}{\partial k'} = (b^G(k') - c)(2g + k_i + k' - \theta) f(k') + b^{G'}(k') \int_{k'}^{\overline{k}} (\theta - k - g) f(k) dk.$$

Note that $\frac{\partial \pi_i}{\partial k' \partial k_i} = (b^G(k') - c) f(k') > 0$ and this implies that the optimal k' is increasing in k_i, satisfying a necessary condition for incentive compatibility.

In an equilibrium, $k' = k_i$ when $b^G(k_i)$ satisfies the previous first order condition,

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

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

$$b_i^{G'}(k_i) + a(k_i) b_i^G(k_i) = ca(k_i), \tag{12}$$

where

$$a(k_i) \equiv \frac{(2g + 2k_i - \theta) f(k)}{\int_k^{\overline{k}} (\theta - k - g) f(k) dk}. \tag{13}$$

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 $b_i^G(\underline{k}) = P$ as the firm with the lowest gas capacity will always sell the residual demand with its thermal plant, meaning that the highest price maximizes profits. This completes the **proof of Proposition 3.**

Consider now asymmetric equilibria. For similar reasons as in the proof of Proposition 1, the high bidder, firm j, optimally sets the market price at P by bidding $b_j^R(k_j) \leq b - j^G(k_j) = P$. The low bidder, firm i, obtains the maximum attainable profits, $Pk_i + (P-c)g$. The bids of firm i are in this case payoff irrelevant and, hence, we can set them at $b_i^R(k_i) = 0$ and $b_i^G(k_i) = c$. The best deviation of firm j would be to undercut firm i and choose $b_i^G \leq c$. This deviation is unprofitable as it yields profits lower or equal than $ck_j < Pk_j + (P-c)(\theta - E(k_i) - k_j - g)$. As renewable plants are always dispatched at capacity, the equilibrium attains productive efficiency. This result, combined with Proposition 3, finalizes the **proof of Proposition 2**.

A.2 Low Demand

For the **specialized** ownership structure, the **proof of Proposition 4** is an immediate application of standard Bertrand arguments.

For the **diversified** ownership structure, we start by proving Lemma 2 and Proposition 6, which are instrumental to Proposition 5.

The proofs of **Lemma 2 and Proposition 6** follow directly from Lemma 1 and Proposition 1 in Fabra and Llobet (2023) with a slight change in notation. We only need to show that both firms find it optimal to offer their gas plants at c. In equilibrium firms make no profits out of their gas plants. We can rule out deviations that only involve the gas bid as the thermal plant would never be profitably dispatched in any case. We can also rule out deviations where both plants are offered above 0 as the residual demand would be zero and profits would be 0.

Consider now asymmetric equilibria. Since the thermal plant with the highest price will never sell, Bertrand arguments imply $b_1^G(k_1) = b_2^G(k_2) = c$. The high bidder, firm j, sells the residual demand, $E(\theta - k)$, and optimally sets the market price at c by bidding $b_j^R(k_j) = c$. The low bidder, firm i, obtains the maximum attainable profits, ck_i. The renewable bid of firm i is in this case payoff irrelevant and, hence, we can set it at $b_i^R(k_i) = 0$, which firm j cannot profitably undercut. As thermal plants are never dispatched, the equilibrium attains productive efficiency. This concludes the proof of **Proposition 5**.

A.3 Intermediate Demand

Here we characterize equilibrium bidding under the diversified ownership structure in the symmetric equilibrium when $P > \rho_I^d(\underline{k})$. The remaining arguments are explained in the main text.

Consider the symmetric pure-strategy equilibrium described in Proposition 8 where both firms choose a decreasing and differentiable joint bid for its thermal and renewable capacity, $b^R(k_i) = b^G(k_i) = b(k_i)$ for $i = 1, 2$ for $k_i \leq \hat{k}$ and $b^R(k_i) = b^G(k_i) = b(k_i) = c$, otherwise. To characterize this equilibrium, we use the Revelation Principle, so that a firm with capacity k_i declares a capacity k' and obtains profits $\pi_z(k_i, k')$ for $z = L, H$. We denote $z = L$ and $z = H$ as situations where k' is lower and higher than $\hat{k}$, respectively. Notice that $\hat{k}$ is defined as $\pi_L(\hat{k}, \hat{k}) = \pi_H(\hat{k}, \hat{k})$.

Suppose first that $k_i \leq \hat{k}$ and consider deviations $k' \leq \hat{k}$. In that case, profits become

$$\pi_L(k_i, k') = \int_{\underline{k}}^{k'} \left[b(k_j)k_i + (b(k_j) - c)g\right] f(k_j)dk_j + \int_{k'}^{\overline{k}} b(k')(\theta - k_j - g)f(k_j)dk_j. \quad (14)$$

The first order condition of this problem results in

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

Note that $\frac{\partial \pi_L}{\partial k' \partial k_i} = b(k')f(k') > 0$ and this implies that the optimal k' is increasing in k_i, satisfying a necessary condition for incentive compatibility. In an equilibrium, $k' = k_i \leq \hat{k}$ when $b(k_i)$ satisfies the previous first-order condition for all $k_i \leq \hat{k}$. This expression can be rewritten as

$$\frac{b(k_i)(2k_i + 2g - \theta) - cg}{b'(k_i)} f(k_i) = -\int_{k_i}^{\overline{k}} (\theta - k_j - g)f(k_j)dk_j. \quad (15)$$

Note that we cannot have $\hat{k} = \overline{k}$, as the right-hand side of the previous expression would become zero, resulting in a bid

$$b(\overline{k}) = c\frac{g}{(2k_i + 2g - \theta)} < c,$$

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

$$\pi_H(k_i, k') = \int_{\underline{k}}^{\hat{k}} \left[b(k_j)k_i + (b(k_j) - c)g\right] f(k_j)dk_j + (1 - F(\hat{k}))ck_i,$$

and, trivially, since the previous expression does not depend on k', we have that $k' = k_i$ is optimal for all $k_i \geq \hat{k}$.

We now rule out deviations that imply choosing a k' outside the region where k_i lays. First, notice that $\pi_L(k_i, \hat{k}) - \pi_H(k_i, \hat{k})$ is strictly decreasing in k_i since

$$\pi_L(k_i, \hat{k}) - \pi_H(k_i, \hat{k}) = \int_{\hat{k}}^{\overline{k}} b(k')(\theta - k_j - g)f(k_j)dk_j - (1 - F(\hat{k}))ck_i,$$

and, by definition, $\pi_L(\hat{k}, \hat{k}) - \pi_H(\hat{k}, \hat{k}) = 0$. Thus, $\pi_L(k_i, \hat{k}) > \pi_H(k_i, \hat{k})$ if and only if $k_i < \hat{k}$.

Suppose that $k_i \leq \hat{k}$. Using the previous argument we have that $\pi_L(k_i, k_i) \geq \pi_L(k_i, \hat{k}) > \pi_H(k_i, \hat{k}) = \pi_H(k_i, k')$ for any $k' > \hat{k}$ and deviations are not profitable. Similarly, suppose now that $k_i \geq \hat{k}$. We have that $\pi_H(k_i, k_i) = \pi_H(k_i, \hat{k}) > \pi_L(k_i, \hat{k}) \geq \pi_L(k_i, k')$ for all $k_i \geq \hat{k}$, where the last term comes from $\frac{\partial \pi_L}{\partial k_i \partial k'} > 0$. Hence, deviations outside the region are not profitable.

Using the previous argument we can now characterize

$$\pi_L(\hat{k}, \hat{k}) = \int_{\underline{k}}^{\hat{k}} \left[b(k_j)k_i + (b(k_j) - c)g\right] f(k_j)dk_j + \int_{\hat{k}}^{\overline{k}} \hat{\rho}(\theta - k_j - g)f(k_j)dk_j$$
$$\pi_H(\hat{k}, \hat{k}) = \int_{\underline{k}}^{\hat{k}} \left[b(k_j)\hat{k} + (b(k_j) - c)g\right] f(k_j)dk_j + (1 - F(\hat{k}))c\hat{k},$$

where $\lim_{k \to \hat{k}^-} b(k) = \hat{\rho}$. Since $\pi_L(\hat{k}, \hat{k}) = \pi_H(\hat{k}, \hat{k})$, we can equate both expressions and obtain that

$$\hat{\rho} = \rho_I^d(\hat{k}|\hat{k}) \equiv c\frac{(1 - F(\hat{k}))\hat{k}}{\int_{\hat{k}}^{\overline{k}} (\theta - k_j - g)f(k_j)dk_j} > c. \tag{16}$$

The characterization of $\hat{\rho}$ and $\hat{k}$ relies on the fact that $b(k_i)$ is decreasing in k_i while $\rho_I^d(k_i|k_i)$ is increasing in k_i and, hence, they cross at most once. In particular,

$$\frac{\partial \hat{\rho}}{\partial \hat{k}} = c\frac{(1 - F(\hat{k})) + f(\hat{k})\hat{k}\left[(1 - F(\hat{k}))(\theta - \hat{k} - g) - \int_{\hat{k}}^{\overline{k}} (\theta - k_j - g)f(k_j)dk_j\right]}{\left[\int_{\hat{k}}^{\overline{k}} (\theta - k_j - g)f(k_j)dk_j\right]^2} > 0.$$

Furthermore, $\hat{k} \in (\underline{k}, \overline{k})$ since

$$b(\underline{k}) = P > \hat{\rho} \text{ and } b(\overline{k}) = c < \hat{\rho},$$

implying that the functions cross once and only once.

We next show that firm i cannot increase profits by choosing a different bid for the plants of the two technologies for any $k_i \leq \hat{k}$. Suppose, towards a contradiction that firm i chooses $b_i^R < b_i^G$ for some $k_i \leq \hat{k}$ where, obviously, $b_i^G \geq c$. Hence, we have three cases. First, $b_i^G < \hat{\rho}$. This strategy 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 $b_i^R \geq c$. In that case, the maximization problem of firm i can be written as

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

This profit 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 $b_i^R \leq c$. In that case, the maximization problem is similar,

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

but profits do not depend on b_i^R. This means that they are equivalent to $b_i^R = c$, which from previous arguments is also dominated.

Suppose that firm i has $k_i \geq \hat{k}$. We now show that firms do not have incentives to deviate from $b_i^R(k_i) = b_i^G(k_i) = c$. If $b_i^G(k_i) = c$ any $b_i^R(k_i) < c$ yields the same payoffs and it is equivalent to $b_i^R(k_i) = c$. If $b_i^G(k_i) \in (c, \hat{\rho})$ this thermal bid will never set the price and, therefore, it yields the same profits than $b_i^G(k_i) = c$. If $b_i^G(k_i) > \hat{\rho}$ the arguments for the case $k_i < \hat{k}$ apply in the sense that profits are decreasing in $b_i^G(k_i)$ and so $b_i^G(k_i) = b_i^R(k_i)$ is optimal. This shows that it is optimal to set $b_i^G(k_i) = c$ for $k_i > \hat{k}$.

We now turn to the differential equation determining the bid in expression (15) when $k_i \leq \hat{k}$, which 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 (12) where $a(k_i)$ is defined in (13), and it has an additional term,

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

Since

$$\frac{\partial}{\partial k_i}\left(e^{\int_{\underline{k}}^{k_i} a(k)dk}(b(k_i)-c)\right) = e^{\int_{\underline{k}}^{k_i} a(k)dk}\left(b'(k_i)+a(k_i)(b(k_i)-c)\right), \tag{17}$$

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 (17), 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 (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,

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

Finally, we also need to check that equilibrium profits exceed the minmax for all types, defined as the maximum between ck_i and $PE(\theta - k - g)$. Both profits can be achieved by offering both plants at c or at P, respectively, which we have just shown not to increase profits. Hence, equilibrium profits must be above the minmax. This step finalizes the **Proof of Propositions 7 and 8.**

A.4 Renewable Energy Dominates

Proof of Proposition 9: It follows from arguments similar to those used in the proof of Proposition 1 and described in the main text. □

Proof of Proposition 10: It follows from arguments similar to those used in the proof of Proposition 2 and described in the main text. □

Proof of Proposition 11: In many aspects, the proof of this proposition is common to that of Proposition 8.

Suppose that $P > \rho_I^d(\underline{k})$ and consider the symmetric pure-strategy equilibrium described in the proposition where both firms choose a decreasing and differentiable joint bid for its thermal and renewable capacity, $b^R(k_i) = b^G(k_i) = b(k_i)$ for $i = 1, 2$ and $k_i \leq \hat{k}$ with $b^G(k_i) = c$ and $b^R(k_i) < c$ decreasing in k_i. To characterize this equilibrium, we use the Revelation Principle, so that a firm with capacity k_i declares a capacity k' and obtains profits $\pi_z(k_i, k')$ for $z = L, H$. We denote $z = L$ and $z = H$ as situations where k' is lower and higher than $\hat{k}$, respectively. Notice that $\hat{k}$ is defined as $\pi_L(\hat{k}, \hat{k}) = \pi_H(\hat{k}, \hat{k})$.

When $k_i \leq \hat{k}$ the profit function

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

coincides with (14) meaning that $\hat{k} < \bar{k}$ and $b(k_i)$ is decreasing in k_i.

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

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

The first order condition becomes

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

As $\frac{\partial \pi_H}{\partial k' \partial k_i}(k_i, k') = b^R(k')f(k') > 0$ we have that k' is increasing in k_i, which is a necessary condition for incentives compatibility. This first order condition also implies that for $k' = k_i > \hat{k}$ we must have

$$\frac{b^R(k_i)(2k_i - \theta)}{b^{R'}(k_i)} f(k_i) = -\int_{k_i}^{\overline{k}} (\theta - k_j)f(k_j)dk_j. \tag{18}$$

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

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

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

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

where $\lim_{k->k_-} b^R(k) = \hat{\rho}$. Since $\pi_L(\hat{k},\hat{k}) = \pi_H(\hat{k},\hat{k})$ we can equate both expressions and obtain

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

The characterization of $\hat{\rho}$ and $\hat{k}$ goes as follows. The differential equation (11) 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 $\rho_H^d(\hat{k})$ is increasing in 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 $b^R(\overline{k}) < c$.

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, i.e. when $k_i \leq \hat{k}$. 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 $b_i^R \geq c$. In that case, the maximization problem of firm i can be written as

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

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 $b_i^R < c$. In that case, the problem is similar,

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

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

As shown earlier, the equilibrium bidding function when $k_i \leq \hat{k}$ arises from the same expression as in the case analyzed in Proposition 8 and the proof follows the proof in that case. □