Fossil Fuels and Renewable Energy: Mix or Match?*

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Abstract

This paper investigates the influence of technological ownership structures on pricing strategies and productive efficiency in oligopoly. Our motivation comes from the evolving landscape of electricity markets where firms are transitioning from diversified to specialized technology portfolios, focusing either on renewable energy or fossil fuels. Our theoretical model demonstrates that diversified firms compete more vigorously than their specialized counterparts. Conversely, specialized firms exhibit higher productive efficiency but only when thermal power sources dominate. The magnitude of our theoretical predictions is assessed through simulations using data from the Spanish electricity market. Methodologically, our analysis offers novel insights for studying multi-unit auctions with cost heterogeneity and privately known capacities.

Keywords: multi-unit auctions, private information, electricity markets, renewable energies.

JEL Codes: L13, L94.

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1 Introduction

Concentration measures, such as the Herfindahl-Hirschman Index (HHI), have traditionally been used to assess the strength of competition in oligopolistic markets. They have also been linked to the recent global trend of increasing mark-ups (De Loecker et al., 2020). While these indices account for the number of firms and the size asymmetries among them, they overlook a crucial factor: the composition of the firms' technological portfolio. Controlling for firms' size, the similarity or dissimilarity of their technologies can significantly determine the intensity of competition, an issue particularly salient when evaluating the effects of horizontal mergers and the impact of remedies such as divestitures. This paper aims to shed some light on this question by analyzing how different technological ownership structures affect prices and efficiency in oligopolistic markets.

The power sector provides a natural setting to explore these issues. Conventional technologies employing fossil fuels, such as coal and gas, are characterized by significant marginal costs, whereas the marginal costs of renewable energy sources, like solar and wind, are close to zero. As the expansion of renewable energy accelerates to meet environmental targets, these cost asymmetries are becoming increasingly relevant.[1] In this context, it is important to understand the competitive implications of the ownership structure, and in particular, the consequences of firms holding diversified versus specialized technological portfolios.

Alongside the surge in renewable investments, the ownership structure of energy companies is undergoing a rapid transformation (Jarvis, 2023). Europe exemplifies this trend, with utilities increasingly divesting from fossil-fueled generation to specialize in renewable energy sources.[2] 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.[3] RWE, another major player in the industry, fol-

[1]Other sectors have gone through similar technological transitions (see Collard-Wexler and De Loecker (2015) for the case of steel manufacturing).

[2]Several quotes from the media and the companies' websites illustrate this trend. 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 specialize 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 on 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.

[3]"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.

lowed a similar path.[4] In the UK, Scottish Power completely divested from coal and gas generation, selling its fossil-fuel assets to a rival power supplier, Drax.[5] 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 engage in direct competition with one another.

Against this background, our paper reveals a fundamental trade-off between diversified and specialized ownership structures. Although competition among diversified firms is more intense, productive efficiency is typically higher among specialized firms. However, this trade-off vanishes if investments in renewable energy outgrow the existing conventional capacity and price caps are high. In such scenario, the specialized ownership structure can lead to significant efficiency losses, rendering the diversified ownership structure socially preferable economically and environmentally.

To uncover these effects, we develop a duopoly model where firms operate a limited production capacity that uses thermal and/or renewable energy, with positive or zero marginal costs, respectively. In line with previous literature on competition in electricity markets (e.g., von der Fehr and Harbord (1993), Fabra et al. (2006), de Frutos and Fabra (2012), Holmberg and Wolak (2018), or Fabra and Llobet (2023)) we assume that firms compete to dispatch their production through a uniform-price auction, similar to the one actually used in most electricity spot markets.[6] 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.[7]

We provide a complete characterization of the pure-strategy equilibria for all possible capacity allocations across firms. In this respect, our results extend those of Fabra et al. (2006), who analyze the case where each firm owns a single technology. We show that, under certain conditions, multiple equilibria might exist, making it important to understand which ownership structures give rise to equilibria with high prices and/or low efficiency. Importantly, the discreteness of firms' bid functions prevents the emergence

[4]"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.

[5]"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.

[6]An alternative strand of the literature has focused on firms offering continuously differentiable supply functions (Klemperer and Meyer (1989), Vives (2011)). However, electricity market rules usually require electricity companies to submit a finite number of price-quantity pairs.

[7]The marginal cost of a competitive fringe would play a similar role as the price cap.

of collusive-like equilibria *à la* Back and Zender (2001), which rely on firms submitting sufficiently steep bid functions to deter undercutting at the margin.

As special cases of our general characterization, we further explore the competitive implications of two alternative ownership structures: the case of *specialized* firms, where each firm owns all the existing capacity of a single technology, or the case of *diversified* firms, where they own equal shares of both technologies. We identify two relevant scenarios depending on the relative size of the renewable and thermal capacity, which evolve along the Energy Transition.

During the early stages, when thermal capacity predominates, the two ownership structures give rise to a trade-off. Specialization always leads to higher prices but also higher productive efficiency than 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 all the way to the price cap. Because the cost ranking is preserved — i.e., the renewable production is dispatched first — the specialized ownership structure leads to productive efficiency despite engendering higher prices.

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) capacity to jack up the market price. This strategy jeopardizes the dispatch of some low-cost renewable capacity, which engenders productive inefficiencies.

The diversified ownership structure is unambiguously preferred in the late stages of the Energy Transition, when renewable capacity is sufficiently large compared to thermal power sources. As before, specialization yields higher prices, but it also gives 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 and elevate the market price. Doing so implies serving the residual demand not covered by the competitor, significantly distorting the cost ranking across technologies. 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, the thermal capacity of one firm rather than both.

Our equilibrium is characterized by asymmetric bidding among diversified firms, despite them being symmetric. However, we show that adding private information on firms' capacities — a common feature of electricity markets — gives rise to a unique symmetric pure-strategy equilibrium characterized by lower prices and higher efficiency than the asymmetric one. In line with Fabra and Llobet (2023), the equilibrium bids offered by diversified firms are decreasing in their realized renewable capacity. This finding stands in contrast with what is commonly found in oligopoly models and in the auction literature, where the higher the inframarginal production, the stronger the incentives to raise prices (Khezr and Cumpston, 2022; Ausubel et al., 2014).

Two theoretical papers analyze the impact of the ownership structure on competition in electricity markets.[8] Under Cournot competition, Acemoglu et al. (2017) examine the effect of symmetrically distributing renewable capacity among strategic firms versus transferring it to a competitive fringe. They find the latter to be pro-competitive as it prevents strategic firms from withholding thermal output when the available renewable energy increases. While this conclusion might seem to contradict our findings on the pro-competitive effects of diversification, it does not. In their model, transferring renewable capacity to the fringe reduces the size of Cournot competitors, thereby engendering the seemingly pro-competitive effect of specialization. More recently, Fioretti et al. (2024) use a supply-function equilibrium model to show that the effects of diversification on prices might be ambiguous and provide evidence using data from thermal and hydroelectric plants in Colombia. However, in their model, asset transfers also involve changes in firm relative sizes, making it difficult to disentangle the technological composition from the concentration effects.

To empirically assess the importance of the ownership of production assets, we run a series of simulations of equilibrium outcomes where we compare the specialized and diversified ownership structures studied in the theoretical analysis. We use data from the Spanish electricity market, where we account for existing assets in 2019 and also the expansion of renewable capacity planned for 2030. Consistent with our theoretical predictions, in the 2019 scenario, the results reveal that the specialized ownership structure delivers a significantly less competitive outcome, while the efficiency gains turn out to

[8]There are also some empirical papers. Using data from the Ontario electricity market, Bahn et al. (2021) find that prices were 24% higher when renewable plants were allocated to the largest firm compared to the fringe. Likewise, Genc and Reynolds (2019) emphasize the importance of market structure in determining the price-depressing effects of renewable energy. Kim (2023) analyzes the coal phase-out as gas-fired plants increase their output, showing that the ownership structure of the new plants is a key determinant of the competitive impacts of such a technological shift.

be modest. In contrast, in the 2030 scenario, the difference in prices is reduced, but the specialized structure becomes substantially less efficient, especially when the price cap is high.

Although endogenizing the ownership structure is beyond the scope of this paper, our work provides important insights for merger policy. With few exceptions, most of the literature has focused on the competitive effects of mergers and divestitures that affect the distribution of firms' size or product portfolios (Compte et al. (2002), Tenn and Yun (2011)). Other papers have analyzed the impact of mergers that affect firms' costs through synergies (Perry and Porter (1985), Nocke and Rhodes (2024)). Our results arise even when keeping the distribution of firms' size unchanged and in the absence of any cost synergies, showing that the technological composition of firms is a key strategic factor. Therefore, policies that take into account the technological composition of firms can be more effective in curbing market power than those solely focused on firm size.

In electricity markets, the observed trend toward firm specialization is consistent with our model predictions, indicating that it allows firms to mitigate competition and thus raise profits. Competition authorities should thus assess this trend with caution, as it might be detrimental to consumers and, in the late stages of the Energy Transition, give rise to higher productive inefficiencies and increase carbon emissions.

The rest of the paper proceeds as follows. In Section 2 we present the model and characterize the pure-strategy equilibria for a generic market structure. In Section 3, we compare the competitive effects of specialized and diversified ownership structures. Section 4 introduces private information on firms' capacities. Section 5 summarizes the qualitative implications of the model along the Energy Transition, which are then quantified in Section 6 using Spanish data. Section 7 concludes.

2 The Model

We consider a duopoly model, where firms $i = 1, 2$ compete to supply electricity in a wholesale market. There are two generation technologies: renewable and thermal. The marginal cost of renewable and thermal plants is 0 and $c > 0$, respectively.[9]

Firm i's renewable and thermal capacities are k_i and g_i, respectively. Therefore, firm i's marginal cost function can be written as

$$c_i(q) = \begin{cases} 0 & \text{if } q \leq k_i \\ c & \text{if } q \in (k_i, k_i + g_i]. \end{cases}$$

[9]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.

In our baseline model, we assume that firms' costs and capacities are publicly known.[10]

The market is organized as a uniform-price auction. Each firm submits a finite number of price-quantity pairs for each plant, specifying the minimum price at which it is willing to produce the corresponding quantity up to the plant's capacity. Therefore, firms compete by choosing step-wise supply functions. Bids cannot exceed the market's price cap, $P > c$.[11]

The auctioneer ranks all bids in increasing price order and calls the cheapest plants to produce until total demand, denoted as θ, is satisfied. We assume that this demand is higher than the capacity of a single renewable plant, $\theta > k_i$ for $i = 1, 2$, but there is always enough total capacity to cover the whole market, $\theta \leq \sum_{i=1}^{2}(k_i + g_i)$. Demand is price inelastic and known at the time of bidding.[12]

All dispatched output is paid at the market-clearing price p^*, equal to the highest accepted bid. When there is a price tie at the margin, we assume that renewable output is dispatched first; if two renewable plants tie at the margin, they split the residual demand equally.[13]

It will become useful to define the following concept:

Definition 1. *For an arbitrary bid profile, firm i is referred to as marginal if it dispatches at least part of a plant's capacity offered at the market-clearing price.*

2.1 Equilibrium Characterization

We start by characterizing two important properties that every pure-strategy equilibrium must satisfy. As it is common in the analysis of uniform-price auctions, we refine the equilibrium set by restricting attention to strategies that are not weakly dominated. In particular, this rules out below marginal cost bidding.[14]

[10]Note that a critical difference with Fabra et al. (2006) is that each firm can own both technologies and not just one.

[11]Price caps are present in almost all electricity markets, and its justification on efficiency grounds is well known (Joskow and Tirole, 2007). In markets for other products where price caps do not exist, our framework applies if there is a maximum willingness to pay or if, for example, there exists a fringe that introduces a competitive constraint on the strategic firms. Finally, Fabra and Llobet (2023) and Somogy et al. (2023) show that in the context of a unique technology, our results can be extended to a downward-slopping demand for the uniform and discriminatory auction, respectively.

[12]When firms bid in the day-ahead auction, they have precise demand estimates put forward by the regulator. This issue is well recognized in the literature, which has labeled the cases with or without demand uncertainty as *long-lived* versus *short-lived*, stressing the fact that demand is known when bidding takes place close to real-time (Fabra et al., 2006; Garcia-Diaz and Marin, 2003).

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

[14]Intuitively, bidding at marginal costs versus bidding below avoids being dispatched at times when the firm would make a loss. For a formal proof, see de Frutos and Fabra (2012)'s proof of Lemma 1.

Lemma 1. *At any pure-strategy Nash Equilibrium where firm i is marginal at the market price p^*:*

(i) Firm j fully dispatches all its plant(s) with marginal costs strictly below p^*.

(ii) The equilibrium market price p^* maximizes firm i's profits over its residual demand, constructed by subtracting firm j's competitive supply from total demand.

The intuition behind Lemma 1 (i) follows from standard Bertrand's arguments. Argue by contradiction and suppose that firm j had some undispatched plant(s) with costs strictly below p^*. Since firm i is marginal, i.e., it dispatches some output at p^*, firm j could choose a bid for such plant(s) slightly below p^* and sell a higher production at (almost) the same price, making higher profits. Hence, firm j must dispatch all its plant(s) with costs strictly below p^*. Key to this result is the fact that firms submit step-wise bid functions, implying that a positive output mass always exists at the margin. Hence, when firm j slightly undercuts p^*, the quantity gain always outweighs the price reduction, which can be arbitrarily small.

Since firm j behaves as a price taker, e.g., by offering its plants at a marginal cost $c_j(q)$,[15] firm i prefers to offer at least some of its output at the price that maximizes its profits over the residual demand. In particular, define $\pi_i(p; c_j(\cdot))$ as the profits of firm i when it submits a flat bid at p, and the rival firm bids at marginal cost. The equilibrium market price is defined as

$$p^* \in \arg\max_p \pi_i(p; c_j(\cdot)).$$

Using this definition, we can characterize the candidate pure-strategy equilibria as follows:

Proposition 1. *At any pure-strategy equilibrium, prices are either P or c. In particular,*

(i) An equilibrium where firm i is marginal at P exists if and only if $\pi_i(P; c_j(\cdot)) \geq \pi_i(c; c_j(\cdot))$.

(ii) An equilibrium where firm j is marginal at c exists if and only if $\pi_j(c; c_i(\cdot)) \geq \pi_j(P; c_i(\cdot))$ and $\pi_i(c_i(\cdot); c) \geq \pi_i(P; c_j(\cdot))$.

Importantly, it follows that a pure strategy equilibrium always exists.

Corollary 1. *There always exists a pure-strategy equilibrium.*

[15] Given that all dispatched plants receive the market-clearing price, there are multiple outcome-equivalent bid profiles consistent with Lemma 1.

Clearly, the equilibrium market price p^* must be either c or P given that firm i's residual demand is inelastic at prices other than c or P. If firm i is better off at P rather than c, an equilibrium exists where firm i sets the market price at P. If firm i faces a positive residual demand at P, i.e., $\theta - k_j - g_j > 0$, and since $\pi_i(P; c_j(\cdot))$ increases in P, it follows that there exists a threshold, $\underline{p}_i$, such that condition in part (i) of the Proposition is satisfied if and only if $P \geq \underline{p}_i$. Note that in this equilibrium, firm j obtains the highest possible profits; hence, it has no profitable deviation.

A necessary condition for the existence of an equilibrium where firm j is marginal at c is the first condition in part (ii) of the Proposition, which is equivalent to $P < \underline{p}_j$. However, one also needs to ensure that the second condition is satisfied, i.e., firm i must be better off acting as the price-taker than bidding at P, a deviation that would increase the market price at the expense of decreasing the firm's output. It follows that a threshold exists, $\overline{p}_i$, such that firm i does not prefer to deviate to P if and only if $P \leq \overline{p}_i$. Conditional on the market price being c, firm i is better off when the rival sets the market price, as it gets to sell more than when it sets the market price, i.e., $\pi_i(c_i(\cdot); c) \geq \pi_i(c; c_j(\cdot))$. This implies $\underline{p}_i \leq \overline{p}_i$.

The combination of the previous thresholds allows us to completely characterize the pure-strategy equilibria of this game. In particular, since an equilibrium is fully determined by the identity of the marginal bidder and its profit-maximizing price, there are four potential equilibrium outcomes, with either firm setting the market price at c or P. The following result provides conditions under which each candidate equilibrium can be sustained (i.e., whether it satisfies the conditions stated in Proposition 1). Note that market prices and/or efficiency might differ across the equilibria.

Proposition 2. *Given $\underline{p}_i \leq \overline{p}_i$ for $i = 1, 2$ and $j \neq i$,*

(i) (Low-price equilibria) If $P < \underline{p}_i$ and $P < \underline{p}_j$, there exist pure-strategy equilibria where either firm i and/or j are marginal at the market price c.

(ii) (Low-price and high-price equilibria) If $P < \underline{p}_i$ and $\underline{p}_j \leq P < \overline{p}_j$, there exists one pure-strategy equilibrium where firm i is marginal at the market price c and another one where firm j is marginal at the market price P.

(iii) (High-price equilibrium) If $P < \underline{p}_i$ and $P \geq \overline{p}_j$, there exist a unique pure-strategy equilibrium where firm j is marginal at the market price P.

(iv) (High-price equilibria) If $P \geq \underline{p}_i$ and $P \geq \underline{p}_j$ there exist two pure-strategy equilibria where either firm i or j are marginal at the market price P.

If $\theta - k_j - g_j \leq 0$ *then* $\underline{p}_i = \infty$ *for* $i \neq j$.

The previous result spawns three different situations. When both firms have a positive residual demand — that is, when $\theta - k_j - g_j > 0$ for $j = 1, 2$ —, the equilibria that may arise depend on whether firm i wants to deviate from an equilibrium where it sets the market price at P, $\underline{p}_i$, or the rival sets the market price at c, $\overline{p}_i$. As pointed out before, if a firm faces a zero residual demand at P, it cannot be marginal at P. In that case, the previous thresholds stop being relevant for that firm. As expected, when neither firm has a positive residual demand at P, i.e., each of them can cover the whole market, the equilibrium price is always c.[16]

In all situations where two pure-strategy equilibria exist, except for case (ii) in Proposition 2, prices are the same. However, firms are not indifferent regarding the equilibrium that emerges. Each firm prefers to be the price-taker as it sells more than the marginal bidder. Moreover, even when the equilibria are price equivalent, equilibrium selection matters for efficiency. As we show next, this situation will likely arise when one of the firms is larger than the other.

Example 1. *Suppose that firm* 1 *and* 2 *have the same renewable capacity* $k_1 = k_2 = k$. *Firm* 1 *owns more thermal capacity than firm* 2, $g_1 > g_2$, *but* g_1 *is not too large, and* g_2 *is not too small so that* $2k + g_2 > \theta > g_1 + k$.

An equilibrium where firm i *is marginal at* P *exists if and only if*

$$P(\theta - k - g_j) > c(\theta - k),$$

for $j \neq i$. *When* $P > \underline{p}_2 > \underline{p}_1$, *we are in case (iv) of the previous proposition where two price-equivalent equilibria simultaneously exist. However, both equilibria differ in terms of efficiency. Since* $g_1 > g_2$, *the equilibrium in which firm* 2 *is marginal is more inefficient because* g_1 *is fully dispatched while firm* 2 *partially dispatches its renewable capacity,* $k > \theta - k - g_1$.

Only in case (ii) in Proposition 2, equilibria with different prices coexist. This situation arises when firms have asymmetric technological portfolios, i.e., typically when one firm has a large proportion of the renewable capacity, and the rival has a large proportion of the gas capacity. This situation is illustrated in the following example.

Example 2. *Suppose that firm* 1 *and* 2 *have capacities* (k_1, g_1) *and* (k_2, g_2), *respectively. Assume that* g_1 *is large,* g_2 *is small, and renewable capacity is enough to satisfy total demand, i.e.,* $k_1 + k_2 > \theta$.

[16] Remember that our assumptions rule out the case where each firm can cover the market using only its renewable capacity, which would result in an equilibrium price of 0.

An equilibrium where firm 1 is marginal at P exists for g_2 sufficiently small so that $P(\theta - k_2 - g_2) \geq c(\theta - k_2)$. Firm 2 never wants to deviate because it is already selling all its capacity at the highest possible price.

An equilibrium where firm 2 is marginal at c exists when k_1 is sufficiently large so that

$$ck_1 \geq P(\theta - k_2 - g_2), \tag{1}$$

$$c(\theta - k_1) \geq P(\theta - k_1 - g_1), \tag{2}$$

where the two conditions guarantee that firm 1 and 2 do not want to deviate by setting the market price at P, respectively.

When $P < \underline{p}_2$ and $\overline{p}_1 > P \geq \underline{p}_1 = c$, we are in case (ii) in Proposition 2, and equilibria with prices P and c coexist.

In the example, firm 1 prefers to set a high price, P, over a low one, c, since g_2 being small implies that the price increase more than compensates for the small reduction in the residual demand. The opposite occurs for firm 2 as, if it bid its renewable capacity at P, residual demand would be significantly reduced when k_1 is large.

This example also illustrates the effect of changing size asymmetries. Suppose that some thermal capacity is transferred from firm 1 to firm 2, so that g_1 diminishes and g_2 grows. Suppose that k_1 is relatively small so that condition (1) in Example 2 is barely satisfied. In that case, an increase in g_2 results in a unique equilibrium with price P. Suppose now that k_1 is large and the equilibrium at P is the one for which the condition is barely satisfied. In that case, an increase in g_2 will lead to a unique equilibrium price at c. The first situation arises when firm 1 is small and the thermal capacity transfer exacerbates the difference in firm size, leading to higher prices. In the second situation, firm 1 is large, and the transfer makes firms more similar, increasing competition and lowering prices.

3 Specialized versus Diversified Ownership Structures

The relative likelihood of the equilibrium candidates listed in Proposition 2 depends on the ownership structure of the production plants. To shed light on this, we now compare two polar cases, keeping the total capacity of each technology fixed. Under a specialized structure, the two firms have asymmetric portfolios that contain only one technology. Under the diversified structure, the two firms have equal shares of the two technologies. This means that we can summarize the specialized and diversified market structures as an allocation of the capacity of the renewable and thermal technology for firm 1 and 2 of $\{(2k,0),(0,2g)\}$ and $\{(k,g),(k,g)\}$, respectively.

We first analyze the specialized ownership structure.

Lemma 2. *Under the specialized ownership, $\{(2k,0)\,(0,2g)\}$, the equilibrium thresholds can be obtained as follows:*

(i) For the renewable producer, firm 1,

$$\underline{p}_1 = \overline{p}_1 = c\frac{\min\{\theta, 2k\}}{\max\{\theta - 2g, 0\}}.$$

(ii) For the thermal producer, firm 2, $\underline{p}_2 = \overline{p}_2 = c$ *if* $2k \leq \theta$ *and* $\underline{p}_2 = \overline{p}_2 = \infty$ *otherwise.*

From this result, case (*ii*) in Proposition 2 cannot arise since, as reflected in equation (1), it requires that the firm that owns the gas capacity also owns a positive share of the renewable-energy capacity. Hence, the relevant cases in Proposition 2 are (*i*), (*iii*), and (*iv*), which give rise to the following equilibrium outcomes:

Proposition 3 (Specialized)**.** *Consider the specialized ownership, $\{(2k,0),(0,2g)\}$. Equilibrium outcomes are characterized as follows:*

(i) (Prices) The equilibrium price is P if and only if $k < \frac{\theta}{2}$ or $k \geq \frac{\theta}{2}$ and $g < \frac{P-c}{P}\frac{\theta}{2}$. Otherwise, the equilibrium price is c.

(ii) (Efficiency) When the equilibrium price is c, the outcome is always efficient. When $k > \theta/2$ and $g < \frac{P-c}{P}\frac{\theta}{2}$, the only equilibrium is inefficient because the renewable firm is marginal. Otherwise, if $k < \frac{\theta}{2}$ and $g < \frac{\theta}{2} - \frac{c}{P}k$, there exist two pure strategy equilibria depending on whether the renewable or the thermal firm is marginal. The former is inefficient, and the latter is efficient.

The left panels of Figures 1 and 2 illustrate the previous result for prices and efficiency, respectively. In quadrant II of Figure 1, renewable and thermal capacities are large compared to demand. Naturally, the equilibrium price is c. Beyond this region, unless renewable capacity is enough to satisfy total demand, there is no equilibrium at a price c because the thermal firm is always better off raising the price to P, as in quadrants I and IV.

When the equilibrium price is c, production is efficient as the renewable firm always prefers to undercut the rival. When the equilibrium price is P, production might still be efficient if the thermal firm is marginal and all renewable capacity is dispatched. However, another equilibrium might exist where the renewable producer sets the price at P. This is the most inefficient outcome because all the thermal capacity, $2g$, is dispatched before the renewable production. This is the unique equilibrium outcome when renewable capacity is large enough to cover the entire market, and P is sufficiently high (as in the lower region of quadrant III).

We now turn to considering the diversified ownership structure.

Lemma 3. *Under the diversified ownership, $\{(k,g),(k,g)\}$, the equilibrium threshold is unique, and it corresponds to*

$$\underline{p}_1 = \underline{p}_2 = \overline{p}_1 = \overline{p}_2 = \begin{cases} c\frac{\max\{k,\theta-k-g\}}{\max\{0,\theta-k-g\}} & \text{if } k \leq \frac{\theta}{2}, \\ c\frac{\theta-k}{\max\{0,\theta-k-g\}} & \text{if } k > \frac{\theta}{2}. \end{cases} \tag{3}$$

From this result, the two relevant cases in Proposition 2 are (i) and (iv), leading to the following equilibrium outcomes:

Proposition 4 (Diversified)**.** *Consider the diversified ownership, $\{(k,g),(k,g)\}$.*

(i) [Prices] The equilibrium price is P if and only if

$$g \leq \begin{cases} \theta - \frac{P+c}{P}k & \text{if } k < \frac{\theta}{2}, \\ \frac{P-c}{P}(\theta - k) & \text{if } k \geq \frac{\theta}{2}. \end{cases}$$

Otherwise, the equilibrium price is c.

(ii) [Efficiency] When the equilibrium price is c, the outcome is efficient. When the equilibrium price is P, the outcome is efficient if and only if $g < \theta - 2k$.

The right panels of Figures 1 and 2 illustrate prices and efficiency in this case. As under specialized ownership, the equilibrium price is c when capacity is abundant (quadrant II). A necessary condition for an equilibrium with a price P to exist is that the marginal bidder faces a positive residual demand, $\theta - g - k > 0$. This is not sufficient, however, as a high enough price cap is also required to compensate the marginal bidder for the output loss when the price jumps from c to P.

The equilibrium is efficient not only when the equilibrium price is c but also when it is P and the renewable capacity is sufficiently small so that the high bidder can dispatch it all.

We are now ready to compare prices and efficiency across the specialized and diversified ownership structures.

Corollary 2. *The equilibrium price is always (weakly) higher under the specialized ownership structure. The diversified ownership structure is (weakly) more efficient when $k > \frac{\theta}{2} > g$, and the specialized structure is (weakly) more efficient when $k < \frac{\theta}{2} < g$.*

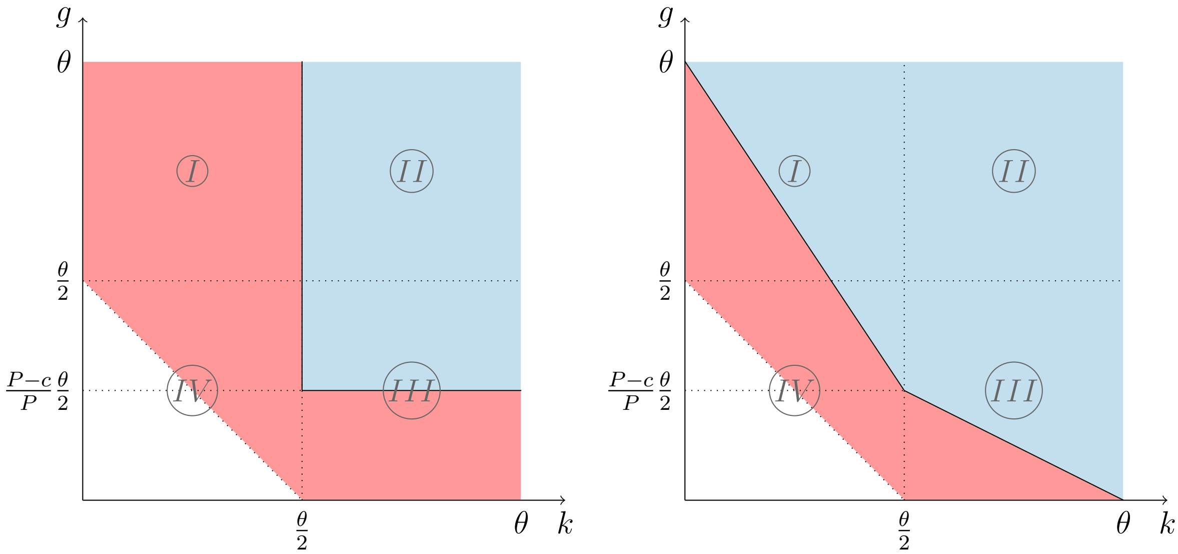

Figure 1: Equilibrium prices under the Specialized and Diversified Ownership Structures

Notes: Parameter regions where the equilibrium price is P (in red) and c (in blue) for the specialized (left) and diversified (right) market structure. One can see that for all combinations of k and g, equilibrium prices are (weakly) lower under the diversified structure. The left triangle is ruled out due to the no-blackout assumption $2k + 2g > \theta$.

Our model provides a clear-cut prediction regarding the price comparison: equilibrium prices are (weakly) higher under the specialized ownership structure. However, the efficiency comparison depends on parameter values. Furthermore, when the renewable and thermal capacities are small — the dark region in Figure 2 — the comparison depends on equilibrium selection, given that the two equilibria in the specialized case are not welfare equivalent. The specialized market structure is more efficient if the equilibrium where the thermal firm is marginal is selected. Instead, a trade-off between prices and efficiency arises if firms play the equilibrium where the renewable firm is marginal.

The regions where the diversified and the specialized ownership structures are inefficient do not coincide. However, when they do, the diversified ownership structure is always superior because one thermal plant is dispatched at most. In contrast, two gas plants are dispatched under the specialized ownership structure.

Despite the ambiguity in the efficiency ranking, a policy-relevant conclusion emerges from the previous analysis. In situations where thermal production dominates (quadrant I), only the specialized ownership is efficient. In contrast, when renewable production is relatively more abundant (quadrant III), the diversified structure delivers both lower prices and higher efficiency.

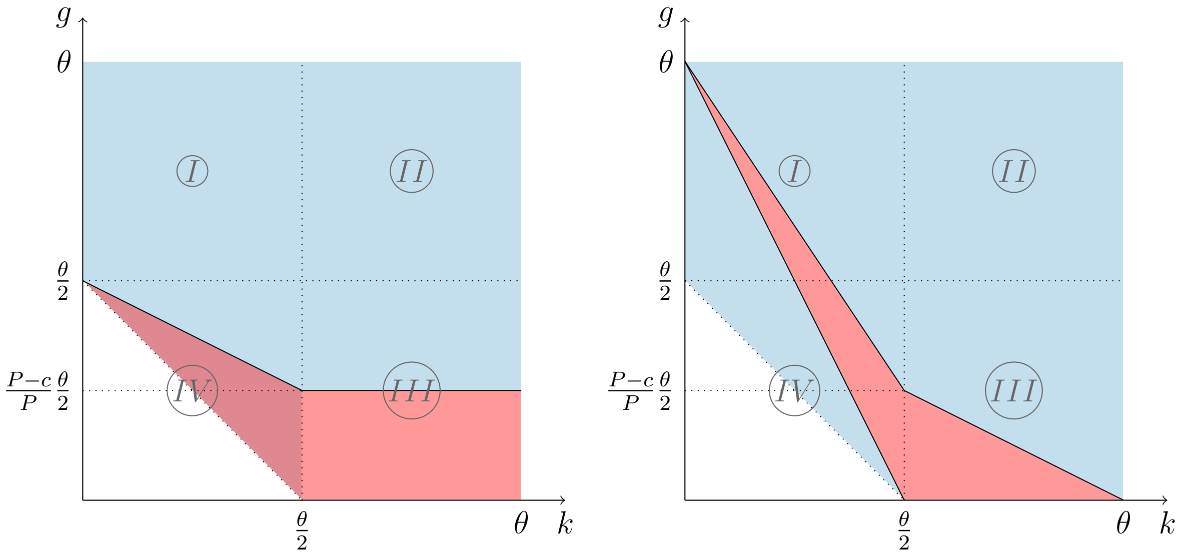

Figure 2: Efficiency under the Specialized and Diversified Ownership Structures

Notes: Parameter regions where the equilibrium outcome is inefficient (in red) and efficient (in blue) for the specialized (left) and diversified (right) market structure. In the purple area in the specialized case, there exists an efficient and an inefficient equilibrium. Unlike the price comparison, the efficiency comparison is ambiguous as there are combinations of k and g for which efficiency is lower under the diversified structure, and others for which the reverse holds. This ambiguity applies beyond the region in which the specialized structure has one efficient and one inefficient equilibrium. The left triangle is ruled out due to the no-blackout assumption $2k + 2g > \theta$.

4 Asymmetric versus Symmetric Equilibria

In the previous section, the pure-strategy equilibria under diversified ownership involved asymmetric bidding despite firms being symmetric. Firms have conflicting interests as they prefer to play the equilibrium where the rival firm is marginal. This situation does not arise under specialized ownership, as one would not expect asymmetric firms to bid symmetrically.

In this section, we rely on Fabra and Llobet (2023) to characterize the symmetric equilibrium that arises when renewable capacities are private information — a common feature of electricity markets.

In particular, we now assume that the renewable capacity of each firm is subject to an *i.i.d.* and privately known shock, i.e., the capacity of firm i, k_i, is drawn from a distribution $F(k_i)$ with a positive density $f(k_i)$ in the range $[\underline{k}, \overline{k}]$. As in the baseline model, we assume there is always enough aggregate capacity to cover the market, i.e., $\theta < 2\underline{k} + 2g$. Also, to preserve symmetry, we assume that, in expected terms, both technologies are equally sized, i.e., $E(k) = g$.

Bids are now contingent on each firm's private information. For simplicity, we restrict the strategy space so that firms can only choose two bids, one for their renewable and one for their gas plants.[17] Accordingly, given the renewable capacity realization k_i, we denote firm i's bids as $b_i^R(k_i)$ and $b_i^G(k_i)$, respectively.

We consider two extreme cases, where either demand can always be covered with renewable energy, i.e., $\theta \leq 2\underline{k}$ (low demand), or where the production of both thermal plants is always required to cover it, i.e., $\theta > 2\overline{k} + g$ (high demand). They illustrate the nature of the symmetric equilibria that also arise in the intermediate cases, e.g., where only the thermal capacity of one firm is needed, i.e., $2\overline{k} < \theta < 2\underline{k} + g$.[18]

First, the case where demand can always be covered with renewable energy, i.e., $\theta \leq 2\underline{k}$, highlights the trade-offs that arise in the symmetric equilibrium. Since each firm has enough capacity to cover the market on its own, i.e., $k+g \geq 2\underline{k} > \theta$, Bertrand competition drives the equilibrium thermal bids down to c. Still, firms compete to dispatch their renewable capacity.

Following Fabra and Llobet (2023), equilibrium bidding for the renewable capacity is in pure strategies, and the function $b_i^R(k_i)$ must be strictly decreasing in k_i due to the interplay between quantity and price effects.[19] Suppose both firms have the same renewable capacity, and they offer the same price. If firm i undercuts its rival (an event which occurs with probability $f(k_i)$), its output increases by $\Delta q = 2k_i - \theta$, i.e., the *quantity effect*. Doing so, however, also reduces the price at which it sells the residual demand in case it is the high bidder, $\theta - E(k_j|k_j > k_i)$, i.e., the *price effect*. When k_i increases, the positive quantity effect becomes stronger while the negative price effect becomes weaker. Hence, firms choose a lower bid when the realized renewable capacity increases.

The analysis in Fabra and Llobet (2023) provides the equilibrium characterization in this case.

Proposition 5. *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 capacity. The unique equilibrium bid for its renewable capacity is*

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

where

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

[17] In the baseline model without asymmetric information, limiting the strategy space in this fashion has no impact on the equilibrium. See Fabra et al. (2006).

[18] The characterization of the equilibrium in this intermediate case is available from the authors upon request.

[19] See also Lemma 4 in the Appendix.

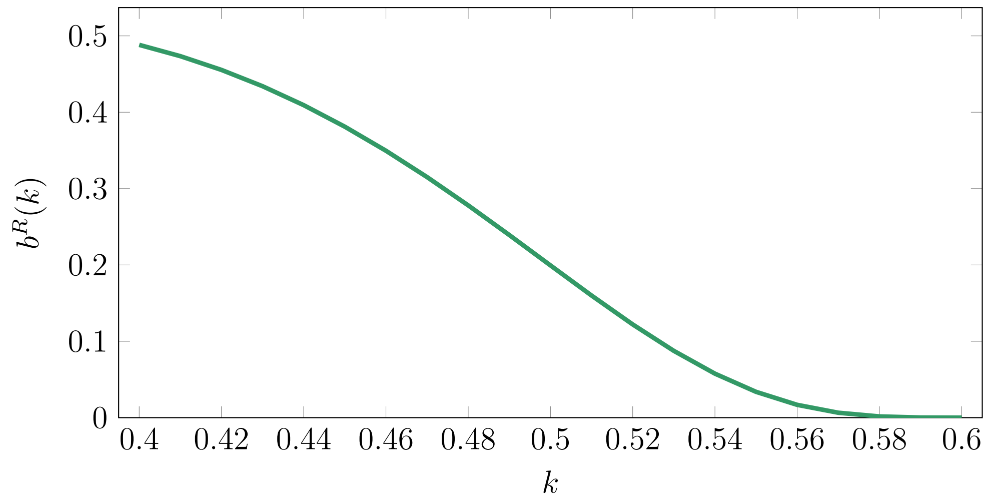

Figure 3: Equilibrium bid for the renewable plant with diversified firms (low demand, low price cap)

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 $\theta = 0.7$.

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

Figure 3 illustrates this equilibrium. Notably, the equilibrium bidding function spans prices from c to zero when capacity is $\underline{k}$ and $\overline{k}$, respectively. Hence, since all the renewable capacity is offered at prices below c, it is never profitable to dispatch the thermal plants, and production is always efficient. Furthermore, expected market prices are below c, and they are hence lower than those under the asymmetric pure strategy equilibria.

The same analysis can be extended to the case of high demand. Since demand can never be covered only with renewable energy plants, in equilibrium, their bids are price irrelevant. Hence, firms compete through the bids of their gas plants, which are decreasing in their realized renewable capacities. The following proposition characterizes the unique symmetric equilibrium in this case.

Proposition 6. *When firms are diversified and $\theta > 2\overline{k} + g$, in any symmetric Bayesian Nash Equilibrium of the game, the bids of the renewable plants are price irrelevant. The unique equilibrium price for its thermal plant is*

$$b^G(k_i) = c + (P - c)\exp(-\omega^G(k_i)), \tag{5}$$

where

$$\omega^G(k_i) = -\int_{\underline{k}}^{k_i} \frac{\theta - 2k - 2g}{\int_{k_i}^{\overline{k}} (\theta - k_j - g) f(k_j) dk_j} f(k) dk, \tag{6}$$

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

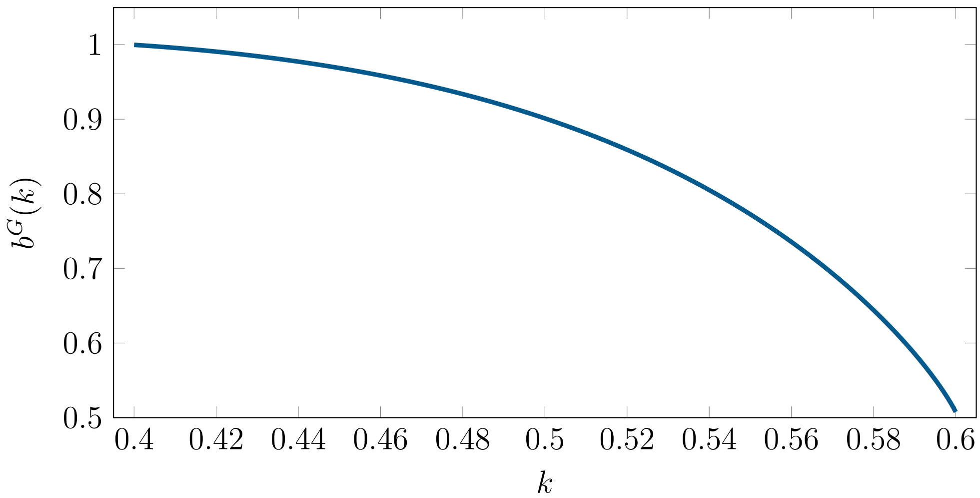

Figure 4: Equilibrium bid for thermal plants at the symmetric equilibrium with diversified firms (high demand)

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 a demand $\theta = 1.7$.

As shown in (5), 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 (6), and the price effect, in the denominator. The equilibrium bid is a decreasing function of k_i and spans 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, so its bid is always set at the cap P. At the other extreme, when $k_i = \overline{k}$, firm i has the largest renewable capacity with probability one and never sets the market price. Therefore, it finds it optimal to offer its thermal production at c to dispatch it at capacity. Figure 4 illustrates this equilibrium with a numerical example.

To conclude, the comparison of the asymmetric equilibria versus the symmetric equilibrium in the two cases considered shows that the symmetric equilibrium results in (weakly) lower prices and the same productive efficiency.

5 Competition along the Energy Transition

As shown in previous sections, the properties of the equilibrium outcomes depend on the relationship between demand and plants' capacities. Accordingly, the nature of competition will evolve along the Energy Transition as more renewable capacity becomes available. Taking stock of our previous results, we can now summarize the differential impact of the ownership structures on competition along this transition.

We envision the *Early Stages* of the Energy Transition as those where renewable energy is relatively scarce, making high-demand cases more likely. In contrast, during the *Late Stages*, renewable energy is relatively abundant, making low-demand cases more prevalent.

Consider the *Early Stages* first. Figure 1 and 2 illustrate the equilibria in this case under complete information for values of $k < \frac{\theta}{2}$ (quadrants I and IV). Corollary 2 applies, indicating that prices are (weakly) lower under the diversified ownership structure. In quadrant I, adding private information on capacity widens this difference, as the equilibrium price under the diversified structure falls below P (Proposition 5) while the equilibrium price under the specialized structure remains at P.[20] The corresponding equilibria imply a price-efficiency trade-off as the specialized structure is (weakly) more efficient and yet gives rise to (weakly) higher prices.

The comparison is more challenging for values in quadrant IV, as multiple equilibria might arise under both ownership structures. As a result, the comparison depends on equilibrium selection, both when capacities are publicly or privately known. As already discussed, with known capacities, prices are (weakly) lower under the diversified structure, but the efficiency ranking typically depends on the equilibrium selected in the specialized case. Introducing asymmetric information under diversified ownership yields lower prices and no changes in efficiency (Proposition 5). Under specialized ownership, however, asymmetric information might also yield lower prices at the cost of productive inefficiencies. In particular, if firms randomize their bids (i.e., the renewable firm's bid is a function of its realized capacity, while the thermal firm plays a mixed strategy), prices will be below P. Still, there is a positive probability that the thermal firm will be dispatched first without exhausting the renewable firm's capacity. This is the case when capacities are known. As shown in (Fabra et al., 2006), there exists a continuum of mixed-strategy equilibria that differ in two aspects: the identity of the firm that plays a mass point at P and the size of this mass. The equilibria engender outcomes that range from the most efficient one — where the thermal firm plays P with probability 1 – to the most inefficient one — where the renewable firm plays P with probability 1 (Proposition 3). The comparison between equilibrium prices and ownership structures remains ambiguous in this region.

However, this ambiguity disappears in the *Late Stages* of the Energy Transition when renewable energy is abundant ($k > \frac{\theta}{2}$, quadrants II and III). Under specialized ownership, a unique equilibrium emerges regardless of whether capacities are publicly or privately

[20] While these propositions assume $E(k) = g$, the same results apply when $E(k) < g$.

known. In this equilibrium, the renewable firm strategically allows the thermal firm to sell both of its plants at full capacity to monopolize the residual demand. This enables the renewable firm to maximize its profits by raising the market price to the price cap, even at the expense of losing output. This strategy results in significant inefficiencies, as renewable power is curtailed while thermal plants operate at full capacity. By contrast, such inefficiencies do not arise under diversification, as each firm at most allows the rival's thermal plant to operate at full capacity.

Therefore, with complete information, the diversified market structure outperforms in terms of both prices and efficiency. Introducing private information on capacities further strengthens this comparison, as discussed in Section 4.

6 Simulations

In this section, we illustrate our theoretical findings using data on the Spanish power plants, which we will reallocate among two hypothetical firms to mimic the setup discussed in earlier sections. We perform a series of simulations of the equilibrium outcomes at the hourly level over a year (8,760 hours). This exercise provides a magnitude of the effects uncovered in our previous analysis.

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 daily prices of fossil fuels, among others.[21] This information allows us to compute the marginal cost of each plant,[22] and thus construct the industry competitive supply curve at the hourly level (since the availability of renewables changes hourly). Matching market demand (assumed to be inelastic at the realized hourly level) and competitive supply gives us the competitive hourly price and efficient output allocation.

The strategic equilibria. To characterize the strategic equilibria, we focus on the case with known capacities, as in the baseline model in Section 2.1. This simulation approach extends our previous theoretical analysis to more than two technologies and plants with

[21] The hourly demand data, the hourly availability data of renewable plants 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/.

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

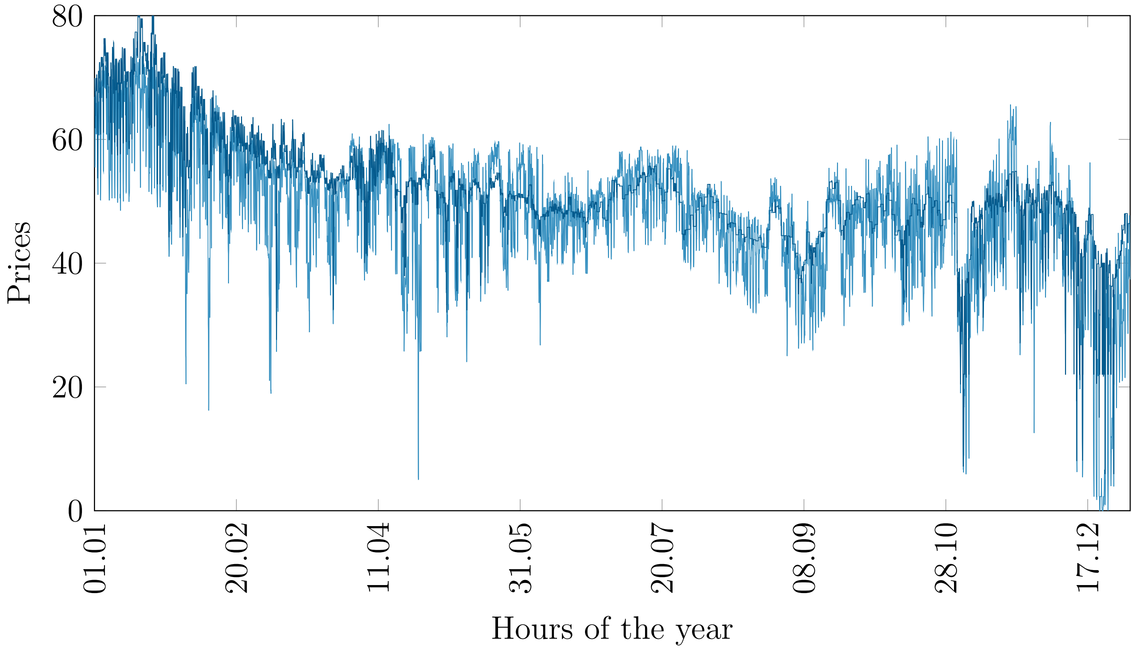

Figure 5: Real and simulated hourly electricity prices

Notes: This figure plots the real (light blue) simulated (dark blue) hourly prices during 2019 in the Spanish electricity market under the prevailing 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.

different efficiency rates.

Mimicking Proposition 2, characterization of the equilibria involves two steps: (i) identify the price that each marginal firm would like to set, i.e., its best response to the rival firm bidding at marginal cost, and (ii) for each of the candidate marginal firms, verify that the rival does 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.[23]

As shown in Figure 5, simulations using the actual market structure reproduce well the observed hourly prices in the Spanish electricity market during 2019. At that time, almost 40% of total electricity was produced using intermittent renewable energy plants, including wind (21%) and solar (5%), while the remaining 60% was conventional generation, including nuclear (22%), hydro (10%), gas (21%) and coal (5%). Three firms dominated the market, Endesa, Iberdrola, and EDP, with market shares 17%, 19%, and 19%, respectively, giving rise to an HHI index of 1,190 (CNMC, 2020). The prevailing price cap was 180 €/MWh. The similarity between actual and simulated prices gives credibility to our simulation framework.

[23]In case of multiplicity, differences across equilibrium prices tend to be small. Hence, reporting one equilibrium or the other does not affect the main conclusions.

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	-

In what follows, we will depart from the prevailing market structure in 2019 and consider alternative scenarios and ownership structures that mimic our theoretical framework. In particular, we will consider two scenarios that aim to capture two stages of the Energy Transition. In each one, we will compare the performance of the diversified and specialized ownership structure. We will also consider different levels of the price cap: 180€/MWh (in place in 2019) and 500 €/MWh.[24]

Stages of the Energy Transition. The two scenarios we consider differ in renewable and thermal capacity. The first one is meant to illustrate what we previously referred to as an *Early Stage* of the Energy Transition. It 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).[25] 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 energy is enough to 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

[24]For robustness, we have also run simulations with price caps of 1,000 €/MWh, 2,00 0€/MWh, and 3,000 €/MWh. We do not report the results as they provide insights similar to the 500 €/MWh analysis. Results are available from the authors upon request.

[25]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 conducting these simulations, the new objectives had not yet been approved by the European Commission.

move from the *Early* to the *Late* stages.

Ownership structures. We transform the market structure into a hypothetical duopoly to which we allocate all thermal and renewable plants. To abstract from other competitive effects, we assign the remaining assets (nuclear and hydropower plants) 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. We do not allow imports from or exports to neighboring countries. These assumptions are equivalent to assuming that the duopoly faces a lower and flatter residual demand than if nuclear and hydropower plants were also under their control, and imports/exports were considered. For the purposes of this study, these assumptions are qualitatively inconsequential.

We compare situations with specialized and diversified ownership structures, mimicking the analysis 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.

6.1 Simulation Results

Low price cap. Consider first the case of a 180 €/MWh price cap, i.e., the one in place in the Spanish electricity market as of 2019. Figure 6 depicts hourly prices (upper panels) and production costs (lower panels) along the day, averaged across the year. The left and right figures show the results for the *Early* and *Late* stages of the Energy Transition. The figures report the results under competitive pricing (dashed), and strategic pricing for the two ownership structures, specialized (dark solid) and diversified (light solid). The figure 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 (right axis).

In both stages, prices are higher under the specialized ownership structure than under diversification. Quantitatively, the difference is substantial and larger during the *Early Stage* (Table 3), where prices under specialization are 3.2 times higher than under diversification, compared to a ratio of 1.6 in the *Late Stage*. As we move through the Energy Transition this wedge across ownership structures shrinks due to both the decrease in prices under specialization and the increase under diversification. With the increase in renewable capacity and the reduction in thermal capacity, it becomes more profitable for diversified firms to raise the renewable price offers even at the expense of losing output. On the contrary, the firm specializing in renewable energy often has enough capacity to

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.

serve the market on its own, facing the competitive constraint of the thermal producer. Hence, market prices are usually set at the marginal cost of the thermal producer and not at the price cap.

These conclusions (i.e., higher average prices under specialization than under diversification and a smaller price wedge during the *Late Stage*) also apply at the hourly level, 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, diversified firms only attain the price cap 1.2% of the time, and equilibrium prices are only 10% above the competitive level (Table 3). During the *Late Stage*, specialized and diversified firms reach the price cap 47.9% and 13.9% of the time, respectively.

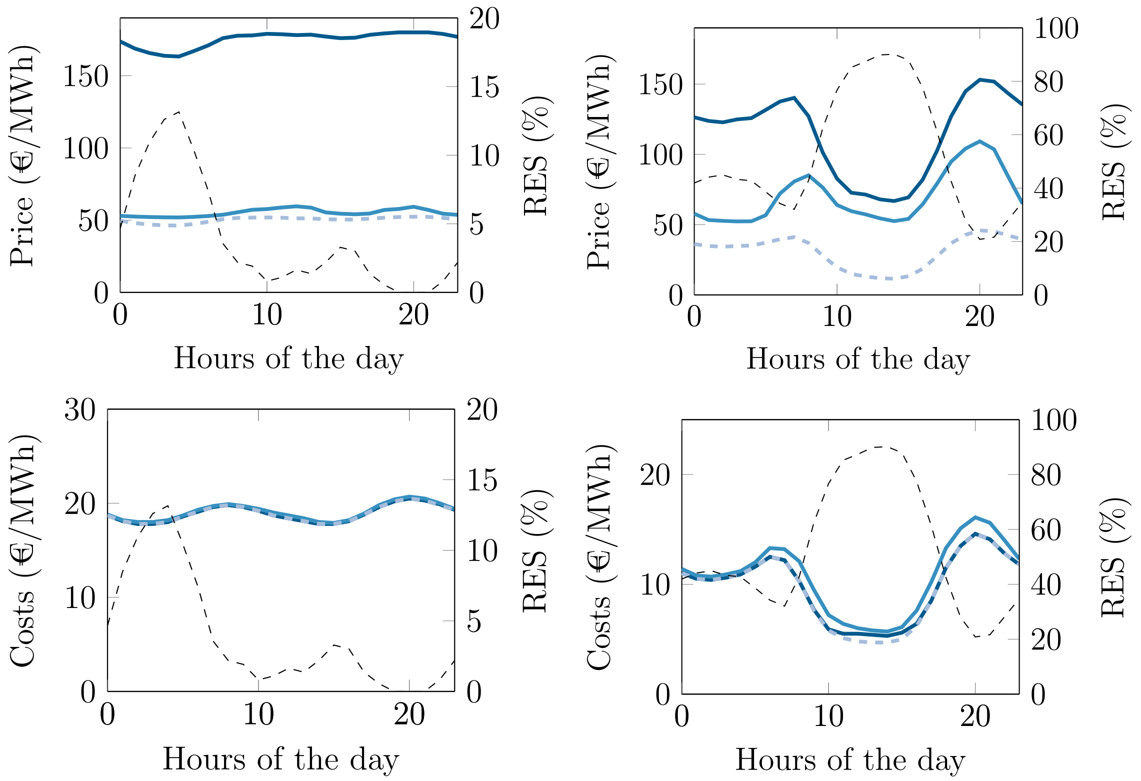

Figure 6: Average prices, ownership structures, and renewable energy penetration with a 180€/MWh price cap

Notes: These figures plot hourly prices (upper figures) and production costs (lower figures) during the day, averaged across the year. The dark and light blue lines represent prices or costs under the specialized and diversified ownership structures, respectively. The dashed blue line represents the price or 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 *Early* and *Late* stages of the Energy Transition, respectively.

During the *Early Stage* of the Energy Transition, production is close to being fully efficient under both structures, particularly under specialization. In the *Late Stage*, specialization remains close to being fully efficient whereas when firms are diversified, costs are 12% above the competitive benchmark.

High price cap. The equilibrium prices and costs when the price cap is raised to 500€/MWh are depicted in Figure 7. Consistent with Corollary 2, equilibrium prices are always higher under specialization. The impact of raising the price cap is more pronounced under specialization, as equilibrium prices are more often set at the price cap (see Table 2).[26]

Relative to the low price-cap case, the efficiency comparison across ownership struc-

[26]Yet, in line with our theoretical predictions, equilibrium prices in the diversified case are also affected, as some equilibrium prices shift from the marginal cost of thermal generation to the price cap, increasing the percentage time when the price cap is reached.

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	1,060	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 behavior 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.

tures becomes richer. In particular, during the *Late Stage*, production costs under the diversified structure become lower than under the specialized structure (Table 3). This result is particularly noticeable in the midday hours when solar production is abundant, as 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 (Table 3).

7 Concluding Remarks

In this paper, we have studied how prices and productive efficiency in oligopolistic markets depend on the composition of firms' technological portfolios. Motivated by the performance of electricity markets, we have uncovered a fundamental trade-off between the diversified and specialized ownership structure during the early stages of the Energy Transition. On the one hand, competition among firms with diversified technological portfolios is more intense than among specialized firms, leading to lower electricity prices. On the other hand, competition among specialized firms enhances productive efficiency, resulting in lower production costs and lower emissions. However, at later stages of

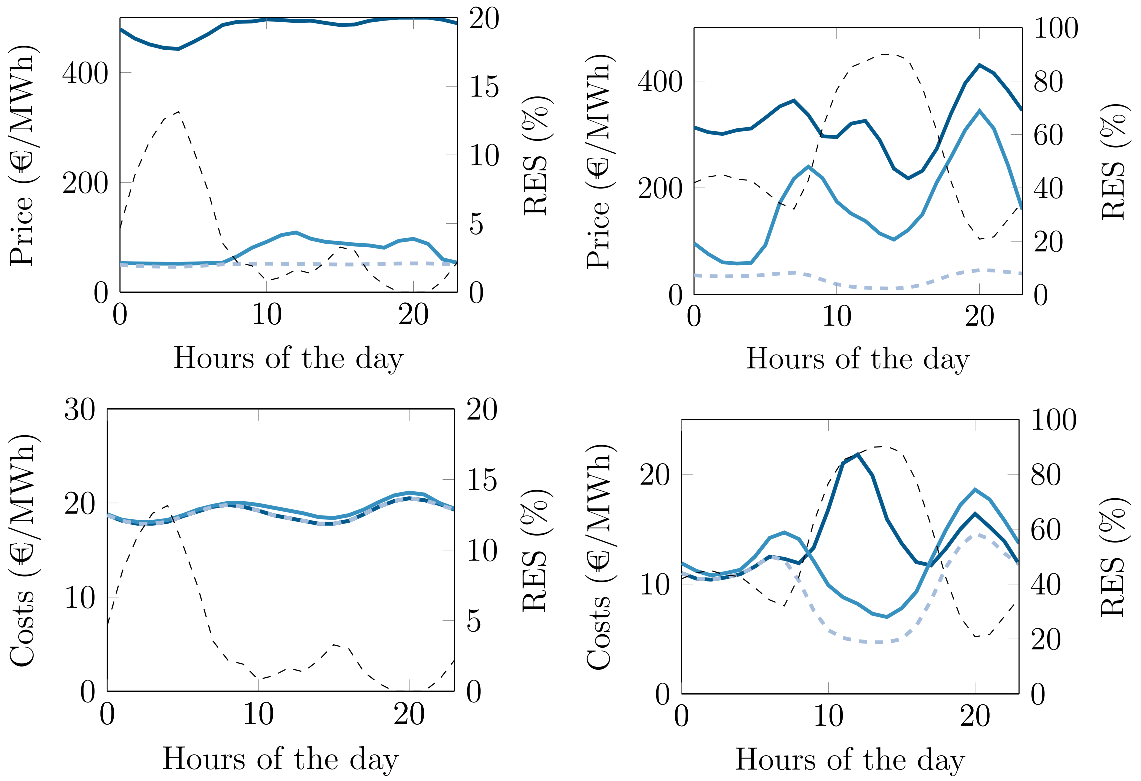

Figure 7: Average prices, ownership structures, and renewable energy penetration with a 500€/MWh price cap

Notes: These figures plot hourly prices (upper figures) and production costs (lower figures) during the day, averaged across the year. The dark and light blue lines represent prices or costs under the specialized and diversified ownership structures, respectively. The dashed blue line represents the price or 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 *Early* and *Late* stages of the Energy Transition, respectively.

the Energy Transition, once renewable energy investments have outgrown existing fossil-fuel capacity, this trade-off disappears. The specialized ownership structure can lead to substantial efficiency losses, making the diversified ownership structure socially preferable in both dimensions.

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 (for a given number of plants). Although more firms make it more likely that the competitive equilibrium emerges under both ownership structures, whenever firms have market power, there will always be more head-to-head competition under diversification than under specialization.

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Appendix

A Proofs

Proof of Lemma 1: Denote as q_j the quantity sold in equilibrium by firm j.

First, consider equilibria where firm i is marginal at $p^* < c$. We rule out bids below marginal cost as they are weakly dominated by marginal cost bidding. Hence, it must be the case that firm i is offering its renewable plant at $p^* < c$ and its thermal plant at c. Argue by contradiction and suppose that $q_j < k_j$. Firm j's profits are $p^* q_j$. However, firm j could deviate by offering:

$$b_j'(q) = \begin{cases} p^* - \varepsilon & \text{for } q \leq k_j, \\ P & \text{for } q > k_j. \end{cases}$$

This leads to profits $(p^* - \varepsilon)k_j > p^* q_j$ for $\varepsilon \to 0$, and it implies a contradiction.

Second, consider equilibria with $p^* = c$. If $\theta \leq k_i + q_j$, the earlier argument applies. Hence, suppose that $\theta > k_i + q_j$ and consider possible deviations for firm j. In equilibrium, firm i is offering its gas plant at c and its renewable plant at any price weakly below. The incentives to deviate are minimized when firm i's renewable plant is offered at marginal cost, 0. In that case, the best deviation takes the same form as before and yields profits $(p^* - \varepsilon)(\theta - k_i) > p^* q_j$ if $k_j \geq \theta - k_i$, or $p^* k_j > p^* q_j$ otherwise. Again, a contradiction. Assuming that firm i's renewable bid is above its marginal costs would (weakly) increase firm j's deviation profits.

Third, consider equilibria with $p^* > c$. If $\theta \leq k_i + q_j$, earlier arguments apply. If $\theta > k_i + q_j$, assume again that firm i offers its gas plant at p^* and its renewable plant at marginal cost to minimize deviation gains. Argue by contradiction and assume $k_j \leq q_j < k_j + g_j$. Firm j's profits are now

$$p^* k_j + (p^* - c)(q_j - k_j).$$

However, firm j could deviate by offering all its capacity at $b_j'(q) = p^* - \varepsilon$. The deviation would be profitable because:

- If $k_j + g_j \geq \theta - k_i$, for $\varepsilon \to 0$,

$$(p^* - \varepsilon)k_j + (p^* - \varepsilon - c)(\theta - k_j - k_i) > p^* k_j + (p^* - c)(q_j - k_j).$$

- If $k_j + g_j < \theta - k_i$,

$$p^* k_j + (p^* - c)g_j > p^* k_j + (p^* - c)(q_j - k_j).$$

This leads to a contradiction. The proof for the case with $p^* > c$ and $q_j < k_j$ is analogous and hence omitted.

It follows that, at the equilibrium price p^*, firm i's residual demand is the total demand minus the capacity of firm j's plants with marginal costs strictly below p^*. Since firm i is a monopolist over that demand, p^* must maximize its profits over it. $\square$

Proof of Proposition 1 and 2: Consider a candidate equilibrium where firm i is marginal at P. Setting the market price at P is optimal for firm i if and only if

$$\pi_i\left(P; c_j(\cdot)\right) \geq \pi_i\left(c; c_j(\cdot)\right),$$

where

$$\begin{aligned}
\pi_i\left(P; c_j(\cdot)\right) &= P \min\left\{\theta - k_j - g_j, k_i\right\} + (P - c) \max\left\{\theta - k_j - g_j - k_i, 0\right\} \\
\pi_i\left(c; c_j(\cdot)\right) &= c \min\left\{\theta - k_j, k_i\right\}
\end{aligned}$$

Since $\pi_i\left(P; c_j(\cdot)\right)$ is increasing in P and $\pi_i\left(c; c_j(\cdot)\right)$ is independent of P, there exists $\underline{p}_i$ such that the optimal price is P if and only if $P \geq \underline{p}_i$. Since the competitive bidder cannot profitably deviate as it is already making maximum profits, there exists an equilibrium in which firm i is marginal at P if and only if $P \geq \underline{p}_i$.

It also follows that for $\underline{p}_i \leq P \leq \underline{p}_j$, there is a unique equilibrium with firm i setting the price at P. For $P > \underline{p}_j$, there are two equilibria with either firm 1 or 2 setting the price at P. While these equilibria are price-equivalent, they might differ in efficiency if the two firms have asymmetric gas capacities.

Likewise, consider a candidate equilibrium in which firm j is marginal at c. Would firm i like to deviate from being the competitive bidder to becoming the marginal bidder? Clearly, deviating to become marginal at c is not profitable, as the market price would not change, but the firm's quantity could go down, implying $\pi_i\left(c; c_j(\cdot)\right) \leq \pi_i\left(c_i(\cdot); c\right)$. Instead, the firm could consider deviating in order to raise the market price to P. This deviation is not profitable if and only if

$$\pi_i\left(P; c_j(\cdot)\right) \leq \pi_i\left(c_i(\cdot); c\right),$$

where

$$\pi_i\left(c_i(\cdot); c\right) = c k_i.$$

Since $\pi_i\left(P; c_j(\cdot)\right)$ is increasing in P and $\pi_i\left(c_i(\cdot); c\right)$ is independent of P, there exists $\overline{p}_i$ such that firm i does not find it optimal to deviate if and only if $P \leq \overline{p}_i$. Note that $\underline{p}_i \leq \overline{p}_i$ since $\pi_i\left(c; c_j(\cdot)\right) \leq \pi_i\left(c_i(\cdot); c\right)$. It follows that there exists an equilibrium in which firm j sets the price at c if and only if $P \leq \underline{p}_j$ (i.e., the marginal bidder optimally sets the price at c) and $P \leq \overline{p}_i$ (i.e., the competitive bidder does not want to become the marginal bidder at P). If $P \leq \underline{p}_j$ and $P \leq \underline{p}_i$, there are two of such equilibria, as either firm 1 or 2 could act as marginal bidders. However, the two equilibria are equivalent in terms of prices and efficiency, even though each firm is better off at the equilibrium where it acts as competitive bidder, as it sells more at the same price. If $P \leq \underline{p}_j$ and $\underline{p}_i \leq P \leq \overline{p}_i$ (i.e., the competitive bidder does not want to become the marginal bidder at P but, conditionally on being the marginal bidder, it would optimally set the price at P), there exist two equilibria, one in which firm j is the marginal bidder at c and another in which firm j is the marginal bidder at P.

It follows that a necessary and sufficient condition for the existence of the equilibrium with price c is $P \leq \widehat{p} = \min \left\{ \overline{p}_1, \underline{p}_2 \right\}$, where we have indexed firms such that $\underline{p}_1 \leq \underline{p}_2$. Likewise, a necessary and sufficient condition for the existence of the equilibrium with price P is $P \geq \underline{p} = \underline{p}_1$. □

Proof of Lemma 2: The renewable firm, firm 1, prefers to choose a price of P, given that the thermal firm, firm 2, chooses a price c if and only if

$$P \max \{\theta - 2g, 0\} > c \min \{\theta, 2k\},$$

which determines the threshold for P, $\underline{p}_1$. This condition also determines the incentives for firm 1 to deviate from a price c, $\overline{p}_1$.

Firm 2 prefers to set a price P when firm 1 bids at c of below if and only if

$$(P - c) \min \{\theta - 2k, 0\} > 0,$$

which occurs if $2k \leq \theta$. This implies $\underline{p}_2 = \overline{p}_2 = c$. Otherwise, a bid c is a weakly dominant strategy and $\underline{p}_2 = \overline{p}_2 = \infty$. □

Proof of Proposition 3: Regarding prices, it is useful to distinguish two cases. When $k < \frac{\theta}{2}$, using Lemma 2, there is always an equilibrium where firm 2 sets the price at P. The other possible equilibrium arises when $g < \frac{\theta}{2}$ and $P > \underline{p}_1 = c\frac{2k}{\theta - 2g}$, so that firm 1 sets the price p and firm 2 bids at or close to c. When $k \geq \frac{\theta}{2}$ firm 2 always bids at c. Hence, the equilibrium price will be P if and only if $p > \overline{p}_1 = c\frac{\theta}{\theta - 2g}$.

Inefficiencies can only occur when the price is P, and firm 1 sets the price. This is the only equilibrium when $k < \frac{\theta}{2}$ and $P > \underline{p}_1$. This equilibrium price also arises when $k \geq \frac{\theta}{2}$ and $P > \overline{p}_1$. This outcome is not unique since, in that region, an efficient equilibrium exists when firm 2 sets the price P. □

Proof of Lemma 3: First notice that if $\theta - k - g < 0$, an equilibrium with price P will never exist, as the marginal firm will obtain no residual demand.

Then, suppose $\theta - k - g < 0$. We need to distinguish three cases depending on the value of k. Suppose $k \leq \theta - k - g$. An equilibrium with a price P will always exist since the profits of the marginal bidder become

$$Pk + (P - c)(\theta - 2k - g) \geq ck,$$

or $P \geq c$. If $\theta - k - g < k \leq \frac{\theta}{2}$, an equilibrium with a price P will exist if and only if

$$P(\theta - k - g) \geq ck.$$

Finally, if $k > \frac{\theta}{2}$, an equilibrium with a price P will exist if and only if

$$P(\theta - k - g) \geq c(\theta - k).$$

The combination of these three conditions yields the expressions for $\underline{p}_i = \overline{p}_i$ for $i = 1, 2$, in the text. □

Proof of Proposition 4: When $g \geq \theta - k$, using Lemma 3, $\underline{p}_i = 0$ for $i = 1, 2$, and the equilibrium price must be c.

For the rest of the proof, consider the case where $g < \theta - k$. If $k > \frac{\theta}{2}$, an equilibrium with price P exists if $P \geq \underline{p}_1 = c\frac{\theta-k}{\theta-k-g}$ or $g \leq \frac{P-c}{P}(\theta - k)$, as stated in the proposition.

If $\theta - k - g \leq k \leq \frac{\theta}{2}$, the equilibrium price is P if it is larger than $\underline{p}_1 = c\frac{k}{\theta-k-g}$ or $g \leq \theta - \frac{P-c}{P}k$. Finally, if $g \leq \theta - 2k$, $\underline{p}_i = c$ and the equilibrium price is always P. This condition is implied by $g \leq \theta - \frac{P-c}{P}k$.

An inefficiency can only arise in situations where the price is P and $\theta - 2k - g > 0$ so that the marginal bidder cannot dispatch all the renewable capacity. □

Proof of Proposition 5: We start by proving the following Lemma:

Lemma 4. *When firms are diversified and $2\underline{k} \geq \theta$, in any symmetric Bayesian Nash Equilibrium of the game thermal bids are payoff irrelevant. Equilibrium bidding for the renewable capacity is in pure strategies, and the function $b_i^R(k_i)$ must be strictly decreasing in k_i. The market price is set by the firm owning the smallest realized renewable capacity.*

Proof of Lemma 4: We first show that in equilibrium, thermal bids are payoff irrelevant. Since $g = E(k) > \underline{k}$, each firm can cover the whole market, $g + \underline{k} > \theta$. A Bertrand-competition argument, together with the fact that $b^R(k_i) \leq b^G(k_i)$ for $i = 1, 2$ implies that in equilibrium it must be that $b^G(k_i) = c$ for all k_i and $i = 1, 2$.

We now focus on the bid by renewable 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 $\Phi_j(b_j^R|k_j)$. 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

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

Notice that these profits are increasing in k_i since

$$\frac{\partial v_i}{\partial k_i}(b_i^G, k_i, \Phi_j) = \int_{\underline{k}}^{\overline{k}} \int_{\underline{b}(k_j)}^{\overline{b}(k_j)} b \Pr(b_i^R \leq b) d\Phi_j(b|k_j) f(k_j) dk_j > 0.$$

Furthermore, this derivative is strictly decreasing in b_i^R and, thus, the function v_i is submodular in b_i^R 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^R and $\hat{b}_i^R$ with $b_i^R < \hat{b}_i^R$. By Bertrand's arguments, it has to be the 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, $\hat{b}_i^R$, 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 $\hat{b}_i^R(k_i)$ decreasing in k_i. Lastly, Bertrand's arguments rule out flat segments in the bidding function. □

We now return to the proof of the Proposition and characterize the symmetric equilibrium $b^R(k)$. Using the Revelation Principle, we characterize the profit function of firm i when it has capacity k_i, and it declares a capacity k', as

$$\pi_i(k_i, k') = \int_{\underline{k}}^{k'} b^R(k_j) k_i f(k_j) dk_j + \int_{k'}^{\overline{k}} b^R(k')(\theta - k_j) f(k_j) dk_j.$$

Taking the derivative with respect to k', we obtain

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

Notice that $\frac{\partial \pi_i}{\partial k' \partial k_i} = b^R(k') f(k') > 0$, meaning that k_i is increasing in k' and the necessary monotonicity condition for incentive compatibility is satisfied.

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

$$b^R(k_i)(2k_i - \theta) f(k_i) + b^{R'}(k_i) \int_{k_i}^{\overline{k}} (\theta - k_j) f(k_j) dk_j = 0.$$

This expression can be rewritten as a differential equation of the form

$$b_i^{R\prime}(k_i) + a(k_i)b_i^R(k_i) = 0,$$

where

$$a(k_i) \equiv \frac{(2k_i - \theta)f(k)}{\int_{\underline{k}}^{\overline{k}}(\theta - k_j)f(k_j)dk_j}. \tag{7}$$

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

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

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

Proof of Proposition 6: Similarly as above, we start by establishing some monotonicity conditions that a symmetric equilibrium must satisfy.

Lemma 5. *When firms are diversified and $\theta > 2\overline{k} + g$, in any symmetric Bayesian Nash Equilibrium of the game, the renewable-capacity bids are payoff irrelevant. Equilibrium bidding for thermal capacity is in pure strategies, and the function $b_i^G(k_i)$ is strictly decreasing in the firm's renewable capacity realization, k_i. The market price is set by the thermal production owned by the firm with the smallest realized renewable capacity.*

Proof of Lemma 5: 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

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

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's arguments, it has to be the 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's arguments rule out flat segments in the bidding function. □

We now return to the proof of the Proposition. Using the Revelation Principle, consider the situation where both firms choose the same thermal bid $b^G(k)$, which from the previous lemma is assumed to be decreasing in k. Firm i with capacity k_i reports a renewable capacity k', which results in a bid $b^G(k')$. In this transformed problem, the expected profits of firm i can be expressed as

$$\begin{aligned}\pi_i(k_i, k') = &\int_{\underline{k}}^{k'} \left[b^G(k_j)k_i + (b^G(k_j) - c)g\right] f(k_j)dk_j \\ &+ \int_{k'}^{\overline{k}} \left[b^G(k')k_i + (b^G(k') - c)(\theta - k_i - k_j - g)\right] f(k_j)dk_j.\end{aligned} \tag{8}$$

Taking the derivative in (8), 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,

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

This expression can be rewritten as a differential equation of the form

$$b_i^{G'}(k_i) + a(k_i)b_i^G(k_i) = ca(k_i), \tag{9}$$

where

$$a(k_i) \equiv \frac{(2g + 2k_i - \theta)f(k)}{\int_k^{\overline{k}} (\theta - k_j - g)f(k_j)dk_j}. \tag{10}$$

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

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

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