Fossil Fuels and Renewable Energy: Mix or Match?*

Natalia Fabra
Universidad Carlos III and CEPR

Gerard Llobet
CEMFI and CEPR

July 6, 2024

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.

*Emails: natalia.fabra@uc3m.es and llobet@cemfi.es. We thank the editor and four referees for their suggestions. This paper has also benefited from comments by Juan José Ganuza, François Salanié, Wouter Vergote, and audiences at the TSE, UIB, Carlos III University (Madrid), Universitat de Barcelona, MIMA-Workshop (CEMFI), DICE (Dusseldorf), EARIE Conference (Rome) and EEA-ESEM Conference (Barcelona). Catarina Pintassilgo provided excellent research assistance. Funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No 772331) and from the Regional Government of Madrid through grant H2019/HUM-5859 is gratefully acknowledged

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,[6] 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.[7] 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.[8]

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 the existence equilibria with high prices and/or low efficiency.

[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] See von der Fehr and Harbord (1993), Fabra et al. (2006), de Frutos and Fabra (2012), Holmberg and Wolak (2018), or Fabra and Llobet (2023), among others.

[7] 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.

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

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 production of the renewable producer 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.[9] 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 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

[9] 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 onwerhsip structure of the new plants is a key determinant of the competitive impacts of such a technological shift.

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 increased 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 studies the effects of 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.[10]

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

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

In our baseline model, we assume that firms' costs and capacities are publicly known.[11]

[10] 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.

[11] Note that a critical difference with Fabra et al. (2006) is that each firm can own both technologies

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, $P > c$.[12]

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.[13]

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.[14]

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.

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^*.

and not just one.

[12]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.

[13]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).

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

(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.*

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

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

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 pure-strategy equilibrium 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, 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 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.,* $k_1 + k_2 > \theta$.

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.*

[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 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 the equilibrium price is* P *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. 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 always (weakly) more efficient when $k < \frac{\theta}{2} < g$.*

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

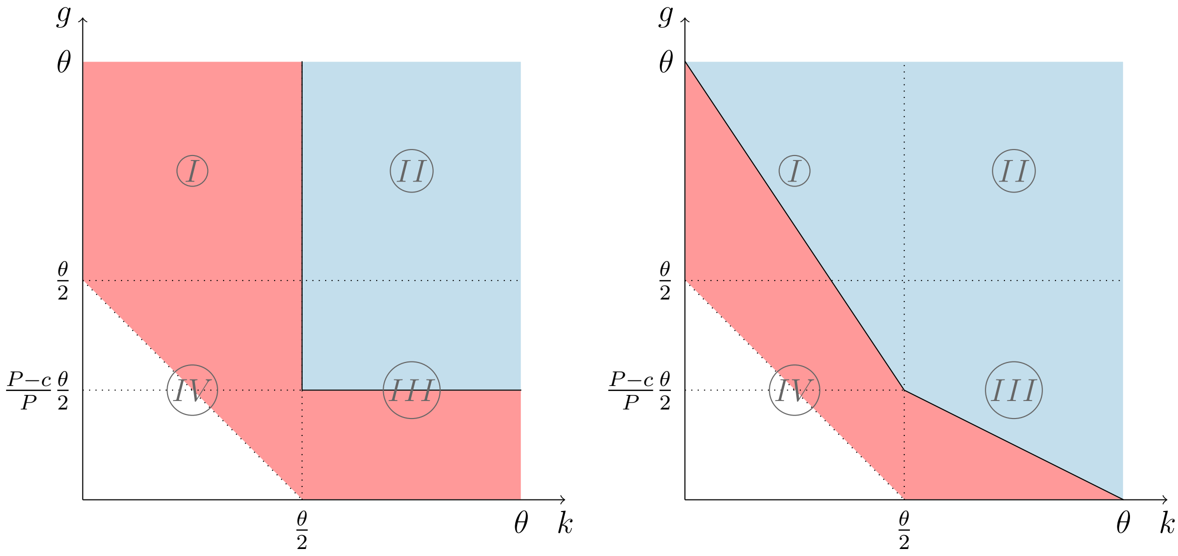

Figure 1: Equilibrium prices under the Specialized and Diversified Ownership Structures

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 $2k + 2g > \theta$.

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.

4 Private Information on Renewable Capacities

In the previous section, the pure-strategy equilibria under diversified ownership involved asymmetric bidding despite firms being symmetric. As previously mentioned, 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

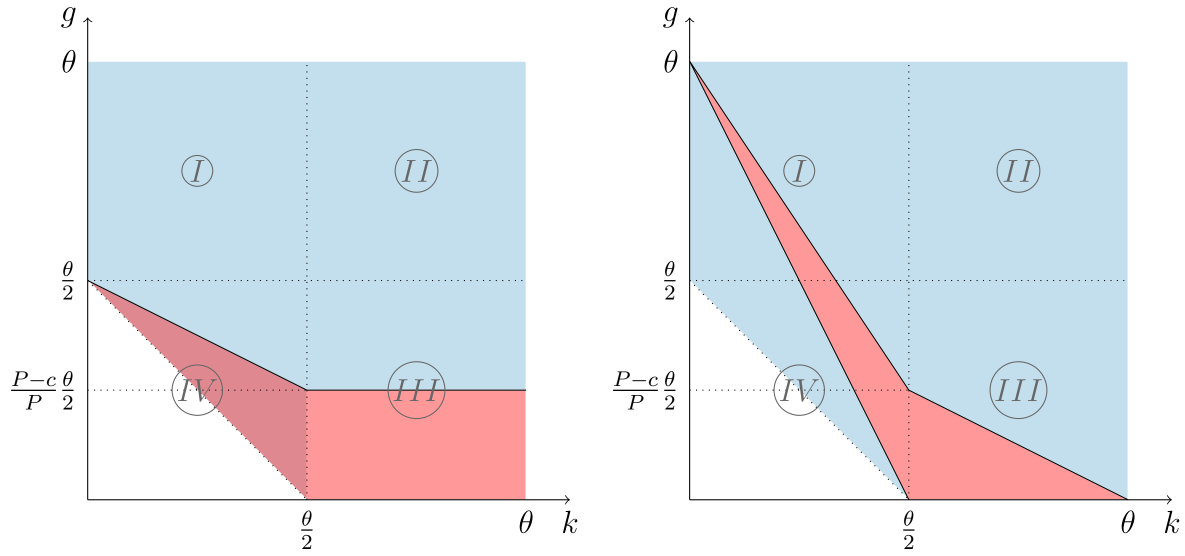

Figure 2: Efficiency under the Specialized and Diversified Ownership Structures

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 $2k + 2g > \theta$.

expect asymmetric firms to bid symmetrically.

In this section, we show that under a diversified ownership structure, private information on renewable capacities — a common feature of electricity markets (Fabra and Llobet, 2023) — gives rise to a symmetric pure-strategy equilibrium.

To characterize the symmetric pure-strategy equilibrium among diversified firms, we now assume that the renewable capacity of each firm is subject to an *i.i.d.* and privately known shock. In particular, 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., $\theta < 2\underline{k} + 2g$.

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. Without loss of generality, we restrict attention to $b_i^R(k_i) \leq b_i^G(k_i)$. Offering renewable production at a price above the thermal bid is never optimal, given that the firm could always increase profits by switching the bids for its two technologies. By doing so, it would dispatch the same quantity at the

[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).

same price but reduce its production costs.

Equilibrium bidding behavior depends on the relationship between demand and the capacity of each technology. For this reason, we focus on three cases. We first look at high-demand cases, i.e., those when the thermal capacity of both firms is required to cover demand. At the other extreme, there are low-demand cases, i.e., those when demand can be covered by renewable energy without relying on thermal plants. Last, in the intermediate-demand case, demand can be met with renewable production and only the thermal production of one plant.[18]

The following analysis assumes that, in expected terms, both technologies are equally sized, i.e., $E(k) = g$. This assumption simplifies the exposition while providing qualitatively similar results as in the case with $E(k) < g$. The case with $E(k) > g$ is analyzed in Appendix A.

4.1 High Demand

We start by establishing some monotonicity conditions that any symmetric equilibrium must satisfy.

Lemma 4. *When firms are diversified and $\theta > 2\overline{k} + g$, in any symmetric Bayesian Nash Equilibrium of the game, the bids of the renewable capacity 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.*

The optimal thermal bid must be decreasing in the firm's renewable capacity. To interpret this result, 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 firm i slightly undercuts its rival with its thermal bid (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

[18] In between these cases, there are others in which either the thermal capacity of two, one, or none of the firms 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.

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, $\theta - g - E(k_j | k_j > k_i)$, diminishes as k_i increases. This implies that the *price effect* decreases in k_i. Combining these two effects, the greater the firm's renewable capacity, the stronger its incentives to submit a low thermal bid, giving rise to an optimal bidding function for the thermal capacity that is decreasing in k_i.

Using the Revelation Principle, we can transform firm i's problem as follows. 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

$$\begin{aligned} \pi_i(k_i, k') = & \int_{\underline{k}}^{k'} \left[b^G(k_j)k_i + (b^G(k_j) - c)g \right] f(k_j)dk_j \\ & + \int_{k'}^{\overline{k}} \left[b^G(k')k_i + (b^G(k') - c)(\theta - k_i - k_j - g) \right] f(k_j)dk_j. \end{aligned} \tag{4}$$

The first term captures cases where firm i's reported capacity exceeds firm j's. Since the bidding function is decreasing in k', $b^G(k') < b^G(k_j)$, 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 its bid is higher. Thus, it fully dispatches its renewable capacity and serves any remaining demand with its thermal production at its thermal bid, $b^G(k')$. As usual, the equilibrium bid function must make it optimal for firm i to report $k' = k_i$.

The following proposition characterizes the unique symmetric equilibrium.

Proposition 5. *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 $b_i^G(\overline{k}) = c$.

In equilibrium, 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

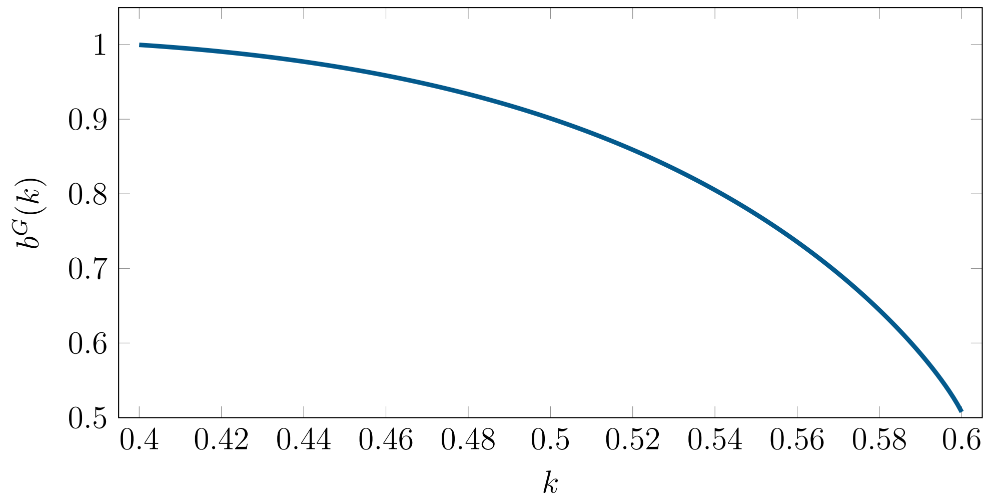

Figure 3: Equilibrium bid for thermal plants at the symmetric equilibrium with diversified firms (high demand)

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 $\theta = 1.7$.

(6), and the price effect, in the denominator. The equilibrium bid, function decreasing in k_i 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 3 illustrates this equilibrium with a numerical example.

4.2 Low Demand

We now consider cases where thermal capacity is never necessary because demand can always be covered with renewable energy, i.e., $\theta \leq 2\underline{k}$. 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.

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

Lemma 5. *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.*

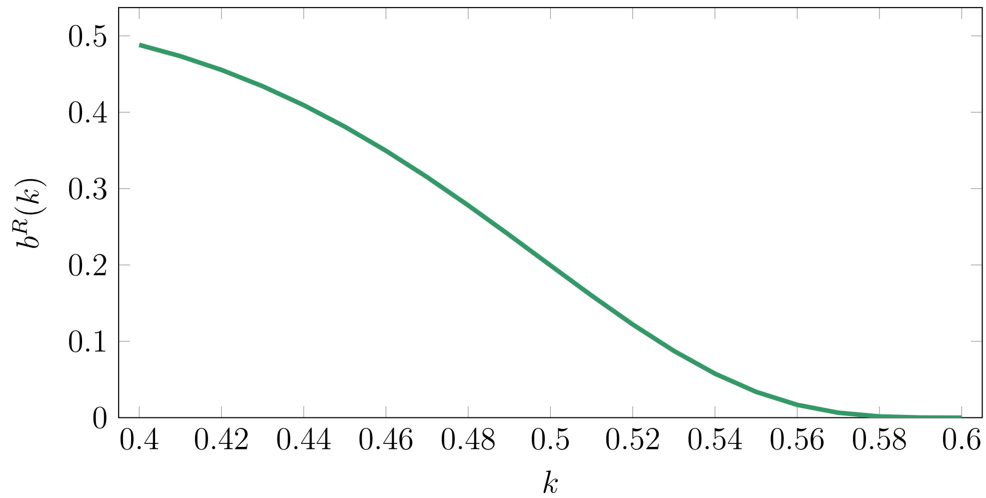

Figure 4: Equilibrium bid for the renewable plant with diversified firms (low demand, low price cap)

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 $\theta = 0.7$.

Again, the equilibrium bid function must strictly decrease in the renewable capacity realization 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 increase and decrease in k_i, respectively, firms choose a lower bid, the larger their realized renewable capacity is.

Proceeding in a similar way as in Section 4.1, Proposition 6 characterizes the symmetric Bayesian Nash equilibrium, which is illustrated in Figure 4.

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

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

where

$$\omega^R(k_i) = \int_{\underline{k}}^{k_i} \frac{(2k - \theta) f(k)}{\int_k^{\overline{k}} (\theta - k_j) f(k_j) dk_j} dk. \tag{7}$$

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

The resulting equilibrium bidding function is as in Fabra and Llobet (2023). That paper considers firms that only own a renewable plant while facing a competitive fringe of thermal producers. Hence, the marginal costs of thermal producers act as a price ceiling for the renewable firms. Proposition 6 above extends these results and shows that the same equilibrium arises when strategic firms own both renewable and thermal capacity, with the latter being sufficiently large.

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.

4.3 Intermediate Demand

In the previous cases, we assumed that either the thermal capacity of both firms was needed to cover demand (high-demand case) or none was (low-demand case). We now consider an intermediate situation where only the thermal capacity of one firm is needed, i.e., $2\overline{k} < \theta < 2\underline{k} + g$. As we will see, the resulting symmetric equilibrium shares some features with both previous cases.

In the baseline model without asymmetric information, an equilibrium with a price equal to c exists if $P < \underline{p}_i$ for both firms, as defined in (3). The analog to this threshold with asymmetric information is

$$\underline{p}(k_i) \equiv c\frac{k_i}{E(\theta - k - g)}. \tag{8}$$

This threshold depends on the realized capacity, k_i, and, therefore, the optimal decision of each firm might differ. This is unlike in previous cases where, contingent on being the marginal bidder, both firms, regardless of their realized capacity, preferred to a bid P when demand was high, or c, when demand was low.

When the price cap P is below the lowest of these thresholds, $\underline{p}(\underline{k})$, 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, the unique equilibrium is symmetric, and both firms bid competitively.

In the remainder of this section, suppose that this is not the case, i.e., $P > \underline{p}(\underline{k})$. To characterize the symmetric equilibrium, it is convenient to introduce the following piece of notation,

$$\rho(k_i|k) \equiv c\frac{(1 - F(k))k_i}{\int_k^{\overline{k}}(\theta - k_j - g)f(k_j)dk_j}. \tag{9}$$

Note that (9) is increasing in k, and it coincides with (8) when $k = \underline{k}$.

Proposition 7. *Assume $P > \underline{p}(\underline{k})$. 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*

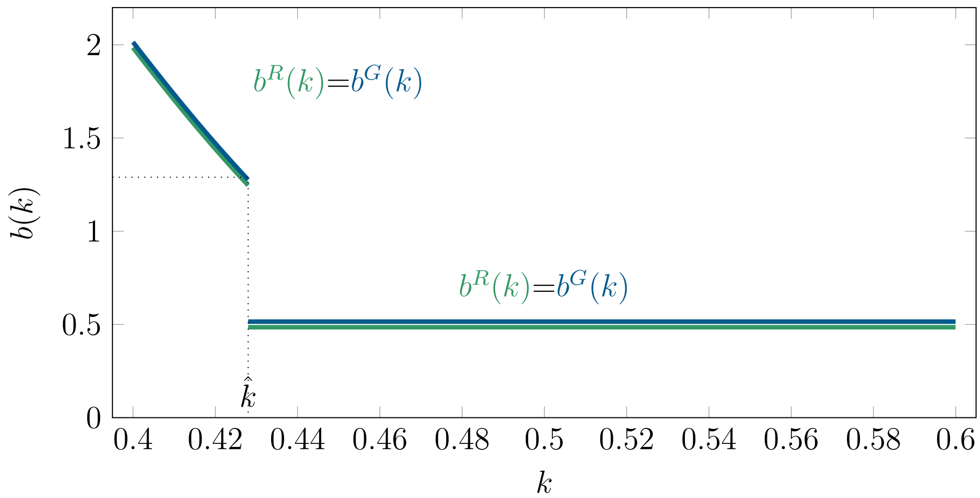

Figure 5: Equilibrium bids for the renewable and thermal plants with diversified firms (intermediate demand, high price cap)

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 $\theta = 1.2$.

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

$$b(k_i) = c + (P - c)exp(-\omega^G(k_i)) - c\left[\gamma(k_i) - \gamma(\underline{k})\right] exp(-\omega^G(k_i)), \tag{10}$$

where $\omega^G(k_i)$ is defined in (6) and $\gamma(k_i)$ is an increasing function of k_i.

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

Figure 5 illustrates this equilibrium. When a firm has a large renewable capacity realization ($k \geq \hat{k}$), it offers its thermal production at a marginal cost of c and the renewable capacity at or below c. This behavior mimics the equilibrium in the low-demand case (Proposition 6), with the difference being that, here, the firm is guaranteed to dispatch its renewable capacity fully, and the bid for this plant is payoff irrelevant as long as it is at or below 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 behavior mimics the equilibrium in the high-demand case (Proposition 5). However, the firm now knows that it does not dispatch any thermal output if it is the high bidder. Hence, its thermal bid is payoff irrelevant as long as it is at or above the renewable plant's bid.

Interestingly, for $k \leq \hat{k}$, the first two terms of the bidding function (10) coincide with the ones in the high-demand case (in Proposition 5, see equation (5)). The relevant marginal cost in that case was c since each firm was competing to serve its thermal capacity. Since the firm is competing to serve its total capacity, the relevant marginal cost is now 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 (10), which lowers the equilibrium bid below the one in (5). 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 ($k \leq \hat{k}$), the strategy prescribed by Proposition 5 is now dominated by submitting a flat bid at P. Indeed, under such a strategy, firm i's profits are ck_i. However, when $P > \underline{p}(\underline{k})$, 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 7 calls for firms to submit equal bids for both plants at higher prices, spanning from P, when renewable capacity is $\underline{k}$, to $\hat{\rho} > c$, when renewable capacity is $\hat{k}$.

The 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. The expression (9) 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.[19]

4.4 Symmetric *versus* Asymmetric Equilibria

The comparison of the asymmetric equilibria versus the symmetric equilibrium when renewable energy capacities are subject to small random shocks, yields two main conclusions.

Regarding prices, the symmetric equilibrium is always more competitive than the asymmetric ones, as prices are between 0 and c instead of c in the low-demand case, and between c and P instead of P in the high-demand case. In the intermediate region, when the symmetric and asymmetric equilibria co-exist, the former yields prices between c and P and the latter always yields a price P.

Regarding efficiency, whenever the asymmetric equilibrium is efficient, the symmetric equilibrium is also efficient. However, in the intermediate case, where the asymmetric equilibrium always implies the inefficient dispatch of all the thermal capacity of one of the firms, the symmetric equilibrium mitigates this distortion. In particular, for large renewable capacity realizations (above $\hat{k}$), firms offer their renewable plants at c, implying

[19]It can be shown that for $P < \underline{p}(\bar{k})$ this equilibrium is unique. For higher values of P, the asymmetric equilibria with one firm setting a price at P also exist.

that they are dispatched before the thermal plants.

In summary, as compared to the asymmetric equilibria, the symmetric equilibrium results in (weakly) lower prices and (weakly) higher 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 (Propositions 6 and 7) 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.[21]

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 4). 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

[20]While these propositions assume $E(k) = g$, Appendix A shows that these results also apply when $E(k) < g$.

[21]Notice that the efficiency losses in the diversified market structure are reduced in the symmetric equilibrium under asymmetric information (see Proposition 7).

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). Therefore, the comparison between equilibrium prices and ownership structures remains ambiguous in this region.

This ambiguity vanishes in the *Late Stages* of the Energy Transition when renewable energy is abundant, $k > \frac{\theta}{2}$ (quadrants II and III). Under specialized ownership, there is a unique equilibrium regardless of whether capacities are publicly or privately known. With complete information, the diversified market structure dominates both in terms of prices and efficiency. Introducing private information on capacities further favors this comparison, as explained in Section 4.4.

6 Simulations

In this section, we illustrate our theoretical findings using data on the Spanish power plants, which we reallocate across 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.[22] This information allows us to compute the marginal cost of each plant,[23] 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

[22]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/.

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

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 different efficiency rates.

Mimicking Proposition 2, characterizing 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.[24]

As shown in Figure 6, 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.

While this comparison between actual and simulated prices gives credibility to our simulation model, in what follows, we will depart from the prevailing market structure in 2019 to consider alternative scenarios and ownership structures that mimick our theoretical framework. In particular, we will consider two scenarios that aim to capture two stages of the Energy Transition. In each, 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.[25]

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

[24] 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.

[25] 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 500€/MWh analysis. Results are available from the authors upon request.

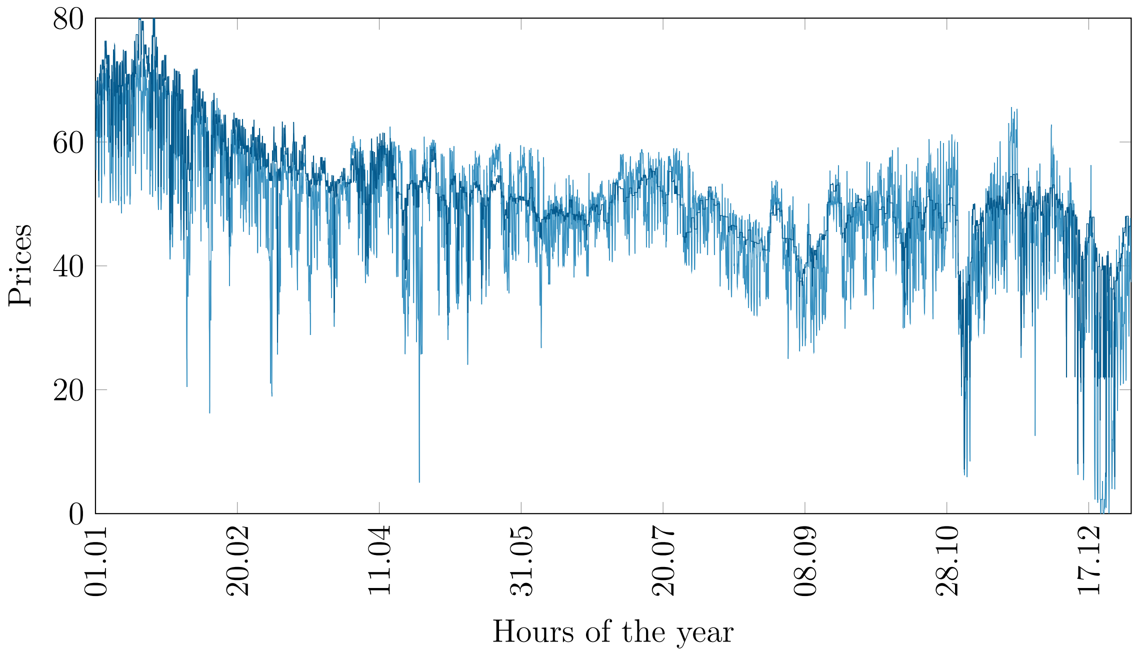

Figure 6: Real and simulated hourly electricity prices

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.

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).[26] 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 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

[26]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.

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	-

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/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 7 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 that 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 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.

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 8. As it turns out, our previous conclusion regarding prices remains unchanged: equilibrium prices are 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).[27]

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

[27] 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 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 ≥ diver	100	-	100	-
Costs				
% hours productive efficiency	99.9	26.4	99.9	25.5
% hours when efficiency spec ≥ diver	73.7	-	74.8	-
Profits				
% hours at competitive profits	0.0	17.5	0.0	17.2
% hours when profits spec ≥ 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 ≥ diver	100	-	100	-
Costs				
% hours productive efficiency	97.0	22.7	88.0	17.5
% hours when efficiency spec ≥ diver	74.6	-	70.8	-
Profits				
% hours at competitive profits	0.0	10.3	0.0	6.8
% hours when profits spec ≥ 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.

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

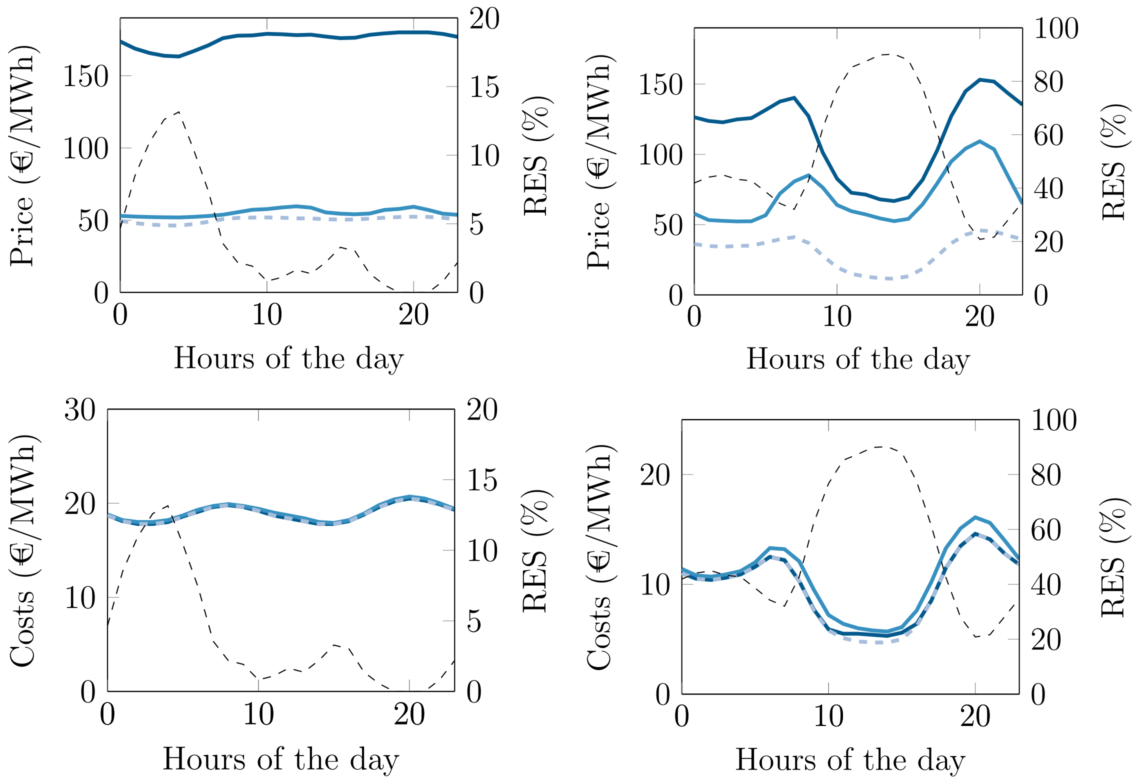

Figure 7: Average prices, ownership structures, and renewable energy penetration with a 180€/MWh price cap

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.

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 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 (keeping the number of existing plants constant). Although more firms make it more likely that the competitive equilibrium emerges under both ownership structures,

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 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.

whenever firms have market power (i.e., if one firm is pivotal), there will always be more competing plants under diversification than under specialization.

References

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

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

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

CNMC, "Informe de Supervisión del Mercado Peninsular Mayorista al Contado de Electricidad. Año 2019," Technical report, CNMC, 2020.

Collard-Wexler, Allan and Jan De Loecker, "Reallocation and Technology: Evidence from the US Steel Industry," *American Economic Review*, 2015, *105*(1), pp. 131–71.

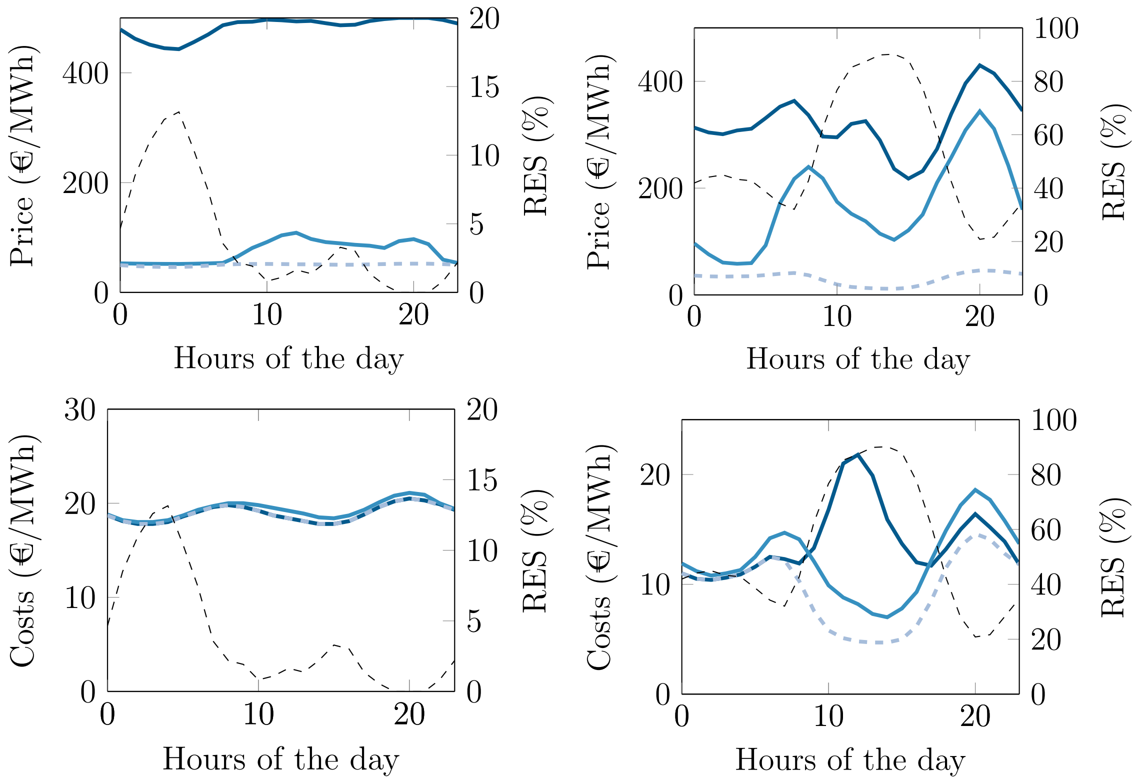

Figure 8: Average prices, ownership structures, and renewable energy penetration with a 500€/MWh price cap

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.

Compte, Olivier, Frédéric Jenny and Patrick Rey, "Capacity constraints, mergers and collusion," *European Economic Review*, 2002, *46* (1), pp. 1–29.

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

De Loecker, Jan, Jan Eeckhout and Gabriel Unger, "The Rise of Market Power and the Macroeconomic Implications*," *The Quarterly Journal of Economics*, 2020, *135* (2), pp. 561–644.

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

Fabra, Natalia and Imelda, "Market Power and Price Exposure: Learning from Changes in Renewables Regulation," *American Economic Journal: Economic Policy*, 2023, *November*.

Fabra, Natalia and Gerard Llobet, "Understanding Competition among Renewables," *The Economic Journal*, 2023, *133*, pp. 1106–1146.

Fioretti, Michele, Junnan He and Jorge A. Tamayo, "Diversified Production and Market Power: Theory and Evidence from Renewable," 2024, mimeo.

Garcia-Diaz, Anton and Pedro L. Marin, "Strategic bidding in electricity pools with short-lived bids: an application to the Spanish market," *International Journal of Industrial Organization*, February 2003, *21* (2), pp. 201–222.

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

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

Jarvis, Stephen, "The Unintended Consequences of Vertical Dis-Integration," Technical report, London School of Economics, 2023.

Joskow, Paul and Jean Tirole, "Reliability and competitive electricity markets," *RAND Journal of Economics*, 2007, *38* (1), pp. 60–84.

Khezr, Peyman and Anne Cumpston, "A review of multiunit auctions with homogeneous goods," *Journal of Economic Surveys*, September 2022, *36* (4), pp. 1225–1247.

Kim, Harim, "Cleaner but Volatile Energy? The Effect of Coal Plant Retirement on Market Competition in the Wholesale Electricity Market," 2023, mimeo.

Klemperer, Paul D. and Margaret A. Meyer, "Supply Function Equilibria in Oligopoly under Uncertainty," *Econometrica*, 1989, *57* (6), pp. 1243–1277.

Ministerio para la Transición Energética y el Reto Demográfico, "Plan Nacional Integrado de Energia y Clima 2021-2030," Ministerio para la Transición Energética y el Reto Demográfico, January 2020.

Nocke, Volker and Andrew Rhodes, "Optimal Merger Remedies," 2024, mimeo.

Perry, Martin K. and Robert H. Porter, "Oligopoly and the Incentive for Horizontal Merger," *American Economic Review*, March 1985, *75*(1), pp. 219–227.

Somogy, Robert, Wouter Vergote and Gabor Virag, "Price Competition with Capacity Uncertainty - Feasting on Leftovers," *Games and Economic Behavior*, 2023, *forthcoming*.

Tenn, Steven and John M. Yun, "The success of divestitures in merger enforcement: Evidence from the Pfizer transaction," *International Journal of Industrial Organization*, 2011, *29*(2), pp. 273–282.

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

von der Fehr, Nils-Henrik and David Harbord, "Spot Market Competition in the UK Electricity Industry," *Economic Journal*, 1993, *103*(418), pp. 531–46.

Appendix

A When Renewable Energy Dominates

In the main sections of the paper, we have focused on situations where $E(k) = g$. 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 weight of the two technologies also give rise to capacity asymmetries across the two firms.

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

It is simple to see that under diversified ownership, when renewable capacity is private information, the main results go through essentially unchanged if $E(k) < g$, i.e., when thermal capacity is relatively large compared to the expected renewable capacity. In contrast, as Proposition 4 illustrates, when g is sufficiently large, i.e., if $2g > \theta$, the equilibrium in which the renewable firm bids P vanishes, giving rise to a unique equilibrium that is efficient. In this case, the specialized ownership structure performs better than the diversified structure in terms of efficiency while giving rise to the same prices.

Results change when $E(k) > g$ and demand is low, $\theta \leq 2\underline{k}$. While in the baseline case, both the renewable 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 significantly impacts equilibrium bidding under both ownership structures.

Under specialized ownership, the results of Proposition 3 still apply, showing that the equilibrium is unique, even when private information exists. In all the equilibria, the thermal firm bids at marginal cost while the renewable firm bids P if and only if

$$P > \underline{p}^s \equiv c \frac{2\theta}{\min\{\theta - 2g\}}. \tag{11}$$

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

$$\underline{p}^d \equiv c \frac{E(\theta - k)}{E(\theta - k - g)}, \tag{12}$$

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. In the case of the asymmetric equilibria, the characterization follows Proposition 4, meaning that the price will be P if greater than $\underline{p}^d$, and c otherwise.

This equilibrium characterization is analogous to that of the specialized case but with a higher threshold, $\underline{p}^d > \underline{p}^s$. 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, $P \leq \underline{p}^d$, 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,

$$\rho_H(k) \equiv c\frac{\int_k^{\overline{k}}(\theta - k_j)f(k_j)dk_j}{\int_k^{\overline{k}}(\theta - k_j - g)f(k_j)dk_j} > c. \tag{13}$$

Note that this expression encompasses $\underline{p}^d$ as $\rho_H(\underline{k}) = \underline{p}^d$. Our next proposition characterizes the symmetric Bayesian Nash equilibrium, in this case, and Figure 9 illustrates it.

Proposition 8. *Assume $P > \rho_H(\underline{k})$. 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*

$$b(k_i) = c + (P - c)exp(-\omega^G(k_i)) - c\left[\gamma(k_i) - \gamma(\underline{k})\right] exp(-\omega^G(k_i)), \tag{14}$$

where $\omega^G(k_i)$ is defined in (6) *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 $b(\hat{k}) = \rho_H(\hat{k}) \equiv \hat{\rho}$.

There is a close analogy between this equilibrium and the one in the intermediate-demand case (Proposition 7). 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 behavior of the renewable plant for large capacity realizations. In

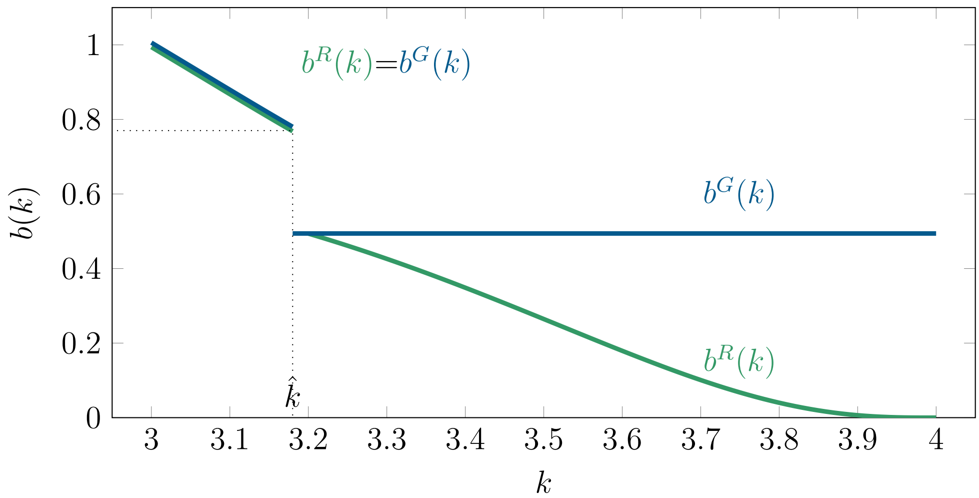

Figure 9: Equilibrium bids for the renewable and thermal plants with diversified firms (low demand, high price cap)

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

the current 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 discussed in Section 4.3, the renewable bids are payoff irrelevant because it is always necessary to dispatch one gas plant to cover total demand. As a result, and as opposed to the current case where market prices fall below c, the fact that prices always stay above or at c, means that any bid for the renewable capacity at or below c is payoff irrelevant and constitutes an equilibrium.

The comparison of the two ownership structures in this case is straightforward. Regardless of the equilibrium selected in the diversified market structure, the equilibrium outcome dominates the specialized one. Prices are always weakly lower and cost efficiency is always greater. Furthermore, when the symmetric equilibrium is selected, the results are strict in both dimensions.

B Proofs

Proof of Lemma 1: First, consider equilibria where firm i is marginal at $p^* \leq c$. Argue by contradiction and assume that firm j is selling $q_j < k_j$. Firm j's profits are $p^* q_j$. However, firm j could deviate by offering,

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

If $k_j \geq \theta$, it would then make profits $(p^* - \varepsilon)\theta > p^* q_j$ for $\varepsilon \to 0$. Otherwise, deviation profits would be $p^* k_j > p^* q_j$, leading to a contradiction.

Second, consider equilibria with $p^* > c$. Argue by contradiction and assume $k_j \leq q_j < k_j + g$. Firm j's profits are $p^* k_j + (p^* - c)(q_j - k_j)$. However, firm j could deviate by offering all its capacity at $b_j'(q) = p^* - \varepsilon$. The deviation would be profitable as, if $k_j + g \geq \theta$, for $\varepsilon \to 0$,

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

whereas if $k_j + g < \theta$,

$$p^* k_j + (p^* - c) g > p^* k_j + (p^* - c)(q_j - k_j),$$

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

It follows that, at the equilibrium price p^*, firm i's residual demand is 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. □

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

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

where

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

Since $\pi_i(P; c_j(\cdot))$ is increasing in P and $\pi_i(c; c_j(\cdot))$ 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 $\pi_i(c; c_j(\cdot)) \leq \pi_i(c_i(\cdot); c)$.

Instead, the firm could consider deviating so as to raise the market price to P. This deviation is not profitable if and only if

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

where

$$\pi_i (c_i(\cdot); c) = ck_i.$$

Since $\pi_i (P; c_j(\cdot))$ is increasing in P and $\pi_i (c_i(\cdot); c)$ 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 $\pi_i (c; c_j(\cdot)) \leq \pi_i (c_i(\cdot); c)$. 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 Lemma 4: 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

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

Notice that these profits are increasing in k_i, since

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

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. □

Proof of Proposition 5: Taking the derivative of $\pi_i(k_i, k')$ in (4) 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

$$b_i^{G\prime}(k_i) + a(k_i)b_i^G(k_i) = ca(k_i), \tag{15}$$

where

$$a(k_i) \equiv \frac{(2g + 2k_i - \theta)f(k)}{\int_{\underline{k}}^{\overline{k}}(\theta - k_j - g)f(k_j)dk_j}. \tag{16}$$

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. □

Proof of Lemma 5: We first show that in equilibrium, thermal bids are payoff relevant. 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 $i = 1, 2$. The rest of the proof follows a structure similar to Lemma 4.

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. $\square$

Proof of Proposition 6: We 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

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

where

$$a(k_i) \equiv \frac{(2k_i - \theta)f(k)}{\int_{\underline{k}}^{\overline{k}} (\theta - k_j)f(k_j)dk_j}. \tag{17}$$

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. $\square$

Proof of Proposition 7: Assume that 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 $\pi_z(k_i, k')$. 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

$$\pi_L(k_i, k') = \int_{\underline{k}}^{k'} \left[b(k_j)k_i + (b(k_j) - c)g\right] f(k_j)dk_j + \int_{k'}^{\overline{k}} b(k')(\theta - k_j - g)f(k_j)dk_j. \quad (18)$$

The first order condition for this problem is

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

Note that $\frac{\partial \pi_L}{\partial k' \partial k_i} = b(k')f(k') > 0$, implying 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

$$\frac{b(k_i)(2k_i + 2g - \theta) - cg}{b'(k_i)} f(k_i) = -\int_{k_i}^{\overline{k}} (\theta - k_j - g)f(k_j)dk_j. \quad (19)$$

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 now 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 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 is 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

$$\hat{\rho} = \rho(\hat{k}|\hat{k}) \equiv c \frac{(1 - F(\hat{k}))\hat{k}}{\int_{\hat{k}}^{\overline{k}} (\theta - k_j - g)f(k_j)dk_j} > c. \tag{20}$$

The characterization of $\hat{\rho}$ and $\hat{k}$ relies on the fact that $b(k_i)$ is decreasing in k_i while $\rho(k_i|k_i)$ 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 $k_i \leq \hat{k}$ with $b_i^G \geq c$. We need to consider 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

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

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,

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

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 as $b_i^G(k_i) = c$. 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 (19) 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 (15) where $a(k_i)$ is defined in (16), and it has an additional term,

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

Since

$$\frac{\partial}{\partial k_i}\left(e^{\int_{\underline{k}}^{k_i} a(k)dk}(b(k_i) - c)\right) = e^{\int_{\underline{k}}^{k_i} a(k)dk}\left(b'(k_i) + a(k_i)(b(k_i) - c)\right), \tag{21}$$

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 (21), 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 (6), 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 P, respectively, which we have shown not to increase profits. Hence, equilibrium profits must be above the minmax. $\square$

Proof of Proposition 8: In many aspects, the proof of this proposition is common to that of Proposition 7.

Suppose that $P > \rho_H(\underline{k})$ and consider the symmetric pure-strategy equilibrium described in the proposition where both firms choose a decreasing and differentiable joint bid for their 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 (18) meaning that $\hat{k} < \overline{k}$ 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

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

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 incentive compatibility. This first-order condition also implies that for $k' = k_i > \hat{k}$ we must have

$$\frac{b^R(k_i)(2k_i - \theta)}{b^{R'}(k_i)} f(k_i) = -\int_{k_i}^{\overline{k}} (\theta - k_j)f(k_j)dk_j. \tag{22}$$

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

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

The characterization of $\hat{\rho}$ and $\hat{k}$ goes as follows. The differential equation (14) 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,

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

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 7, and the proof follows the proof in that case. □