Storage and Renewable Energies: Friends or Foes?

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Abstract

Decarbonizing the power sector requires major investments in renewables and storage. Though often seen as complementary, these technologies can act as substitutes from an economic perspective. When renewable output correlates positively with demand and capacity is low, storage may lower renewable profits, and *vice versa*, especially with strategic thermal producers. In markets with negatively correlated renewable availabilities, like solar and wind, storage can benefit one while disadvantaging the other. These findings inform policies on the timing and effectiveness of mandates or subsidies, suggesting that solar investments may need an initial push before supporting storage. Simulations of the Spanish market show that, at high solar penetration, storage boosts solar but reduces wind profits.

Keywords: energy storage, renewable energy, mandates, market power, transmission constraints, electricity markets.

JEL Classification: L94, Q40, Q42, Q48, Q50.

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1 Introduction

Investments in renewable energy are essential for decarbonizing the economy. However, the intermittent nature of solar and wind production makes it challenging to maintain security of supply at all times. Storage technologies, such as batteries and pumped hydro, address this issue by shifting supply from periods of excess renewable generation to periods of scarcity, thereby reducing production costs and carbon emissions.

Reflecting this technological complementarity, conventional wisdom holds that renewables and storage are also strategic complements from an economic perspective.[1] Storage is expected to increase demand and prices when renewables are abundant, benefiting renewable energy producers, while the seasonality of renewables is assumed to enhance arbitrage opportunities for storage firms.

However, this paper demonstrates that this view is incomplete. The key insight is that storage and renewables can also act as competitors. Market prices, determined endogenously by demand and supply fluctuations, play a crucial role in shaping this interaction by influencing the timing of charge and discharge decisions. Storage can depress the prices captured by renewables if it discharges when renewable availability is high, while renewables can diminish storage owners' arbitrage profits by narrowing price differences over time. The strategic interaction between renewable energies and storage impacts the optimal design and timing of support policies.

This paper identifies the conditions under which renewable energy and storage behave as either strategic substitutes or complements, emphasizing the relevance of the demand profile and the technological mix of the power system under consideration. It further examines how these relationships are influenced by market power in both generation and storage, as well as by the presence of transmission constraints.

In particular, the analysis shows that strategic substitutability between renewables and storage can arise in the early phases of solar deployment or in systems with a diverse mix of renewable technologies. This effect is most salient in markets with mild transmission constraints, where the prices faced by renewable producers are primarily shaped by the interplay between their availability, demand conditions, and storage behavior.

To obtain these results, we develop a model of wholesale market competition in an electricity market where strategic thermal producers coexist with renewable and storage firms. Seasonal fluctuations in demand and renewable availability create price variations

[1] For instance, see The Economist (2019): *"Abundant, reliable, clean electricity is the foundation on which many green investments and policies rest. And to work well, clean electricity, in turn, depends on storage."*

over time, which are further amplified by the exercise of market power by thermal producers. Storage owners capitalize on these price differences by charging energy when prices are low and discharging when prices are high, thereby influencing market price dynamics. The interaction between renewables and storage is shaped by the endogenous timing of storage decisions, which can either enhance or reduce storage profitability depending on renewable generation patterns. Similarly, energy storage impacts the profitability of renewables by altering price fluctuations through its charging and discharging cycles.

Our model predicts that the correlation between renewable production and market prices plays a key role in shaping storage behavior and the profitability of both renewables and storage. A positive correlation means that renewables tend to be available when prices are high, coinciding with storage discharge periods. In this case, expanding storage capacity lowers prices precisely when renewables sell a significant share of their output, reducing their profitability. Likewise, increasing renewable capacity depresses prices during storage discharge periods, decreasing the profits of storage. Conversely, when the correlation between renewable availability and market prices is negative, storage and renewables reinforce each other, increasing their profitability.

When should we expect this correlation between prices and renewables availability to be positive or negative? Electricity prices depend on consumption patterns and renewables availability, which vary across markets and technologies. Generally, wind production is higher at night, when demand is lower, leading to a negative correlation between wind availability, demand and prices. For this reason, we refer to wind as a *countercyclical* technology. Conversely, solar production peaks during the day, when demand is high, i.e., a *procyclical* technology, resulting in a positive correlation between prices and solar production when solar capacity is small. However, as solar capacity increases, prices are depressed during peak solar hours, turning the correlation between prices and solar production negative. Consequently, wind and storage are strategic complements, while solar and storage become strategic complements only if solar capacity is sufficiently large. Otherwise, when solar capacity is small, solar and storage investments are strategic substitutes.

The above conclusions should be qualified in markets where both wind and solar coexist, or where existing renewable technologies have negatively correlated availabilities (e.g., sunlight during the day and stronger winds at night). In such cases, storage investments necessarily crowd out one of the renewable technologies, and *vice versa*. Specifically, there is substitutability between storage and the relatively scarce renewable technology, which is not abundant enough to reverse the correlation between market prices and its own output. This condition is more stringent for solar power than for wind power, as solar power must counteract the natural procyclicality of its output.

Market power in the storage segment or binding transmission constraints enrich the model without altering its core predictions. When storage firms exert market power, the fundamental condition for complementarity between renewable energy and storage remains unchanged. However, underinvestment in storage emerges as firms strategically withhold capacity to maximize arbitrage profits, thereby increasing the subsidies required to reach a large renewable deployment target.

In contrast, transmission congestion can influence the nature of the interaction between storage and renewables. Specifically, when storage assets are co-located with renewable plants in the same node of the network, congestion strengthens complementarity by ensuring that market prices respond solely to fluctuations in renewable generation. In this setting, storage owners consistently charge when renewables are abundant and discharge when they are scarce, independently of broader system-wide demand dynamics.

These insights have important policy implications. When renewables are countercyclical (e.g., wind), subsidizing or mandating one technology – whether renewables or storage – creates a positive feedback loop that enhances investments in both. In contrast, when renewables are procyclical (e.g., solar), if the renewable installed capacity is below a critical mass, mandating and subsidizing investments in renewables or storage can act as a barrier to the other technology. This can result in a market equilibrium with low investments in both renewables and storage, leading to high carbon emissions. Therefore, in these markets, an initial push to renewables is necessary to surpass the critical mass and reverse the correlation between renewables and prices, prompting storage operators to charge and discharge in ways that benefit renewables. Once the strategic complementarity between storage and renewables is triggered, policies aimed at promoting one technology will also promote the other, thus reducing the subsidies needed to meet the mandates.

We illustrate these theoretical findings with detailed simulations of the Spanish wholesale electricity market, focusing on the comparison between scenarios of high and low renewable penetration. Specifically, we consider two cases: the Spanish electricity market as of 2019, when renewable penetration was relatively low (with the share of solar and wind capacity at 43%), and projections for 2030, when these capacities are expected to reach 82%. For each scenario, we consider various levels of storage capacity.

In the low renewables scenario, the correlation between prices and renewable production is low, resulting in negligible impacts on the profits of other technologies from the entry of either type. When solar production becomes abundant, the correlation between prices and solar (wind) production becomes negative (positive), as solar generation substantially depresses market prices during midday peaks. Consequently, solar and storage investments complement each other, while storage negatively impacts wind producers.

In line with this, our simulations show that increasing storage capacity from 4 GWh to 40 GWh in the high renewables scenario raises solar captured prices by 16%, while wind captured prices decrease by 14%. Increasing storage capacity reduces wind curtailment (i.e., the loss of excess production when it cannot be stored), but this effect is not strong enough to overturn the price reduction. Thus, increasing storage capacity benefits solar while harming wind. Furthermore, storage benefits from renewables expansion, with arbitrage profits and capacity utilization increasing tenfold from the low to high renewables scenario. However, as more storage capacity is introduced into the market, the cannibalization effect of storage technologies intensifies in the renewables-dominated scenario.

The simulations also show that expanding storage capacity creates additional social benefits, the more so when the market is competitive. In particular, storage reduces generation costs (by substituting expensive peak thermal plants), lowers carbon emissions (by reducing renewable curtailment), and decreases market prices, especially in the high renewable scenario. These effects add to the social benefits of storage technologies, providing a rationale for policy support. However, our theoretical and quantitative results also suggest that policymakers should prioritize expanding renewable power (especially solar) until a critical renewable mass is reached before introducing policies aimed at promoting storage.

Related Literature. This paper contributes to the literature on short-run competition and long-run capacity investment in wholesale electricity markets (e.g., Borenstein and Holland, 2005; Bushnell et al., 2008). A recent branch of this literature addresses how to facilitate investments in intermittent renewable energy sources, examining different instruments such as capacity mechanisms (e.g., Fabra, 2018; Llobet and Padilla, 2018; Elliott, 2022) and transmission expansion (e.g., Davis et al., 2023; Gonzales et al., 2023). This paper relates to this literature by exploring the role of storage technologies in wholesale electricity markets as they interact with renewable energies.

Economists have recently studied the economics of energy storage from various perspectives. Liski and Vehviläinen (2025) examine the impact of storage on consumer prices, while Andrés-Cerezo and Fabra (2023) explore its competitive implications, considering market power in generation and storage and allowing for vertical integration between the two but without incorporating renewable energies. Roger and Balakin (2025) analyze the case of a storage monopolist operating over two periods, where demand is deterministic but subject to random shocks. Additionally, Carson and Novan (2013) and Ambec and Crampes (2021) analyze the impact of storage on emissions, which is reminiscent of the effects of dynamic pricing on emissions (Holland and Mansur, 2008). Junge et al. (2022) explore the efficiency properties of operation and investment decisions in perfectly competitive electricity markets with storage. Reynolds (2024) complements these analyses by highlighting the role of energy storage in providing ancillary services that are essential for keeping the electricity system in balance.

However, few studies explicitly address the interaction between storage and renewables. Three empirical studies support our theoretical findings. In California, Butters et al. (2025) find that for the first storage unit to break even, the renewable share must reach 50%. They also note that storage mandates reduce solar and wind revenues by 14 million USD annually due to battery discharges during solar generation peaks. Karaduman (2021) reports that in South Australia, storage lowers solar revenue by shading high prices but boosts wind returns by reducing curtailment. Holland et al. (2024) show that in the US, cheaper storage diminishes renewable investments, potentially driving renewables out if storage costs drop to zero.[2] Our model provides a theoretical framework to rationalize these results and quantifies the relationship between storage and renewables in the context of the Spanish wholesale electricity market. Moreover, we focus on the implications of this relationship for policy design.

More closely related to our work, Linn and Shih (2019) examine how storage investment costs influence emissions by analyzing the price responsiveness of fossil-fuel and renewable generators. Their study offers valuable insights into the environmental effects of storage, demonstrating that these technologies can function as either complements or substitutes depending on market conditions. However, their analysis does not explicitly address how the interaction between storage and renewables evolves with different levels of renewable penetration, a key focus of our work. In addition, we extend the analysis by incorporating the strategic behavior of storage and generation firms, as well as the impact of transmission constraints.

From an engineering perspective, Peng et al. (2024) use stochastic control theory

[2]Bollinger et al. (2024) focus on the demand-side, studying the potential complementarity between energy storage and rooftop solar. In contrast, we focus on utility-scale battery storage.

to analyze the interaction between storage and renewables, concluding that these technologies may substitute for one another. However, their approach does not identify the correlation between prices and renewable production as the primary determinant of substitutability. Moreover, their model assumes centralized optimization, thereby overlooking the role of market power and transmission constraints. Zhao et al. (2022) highlight strategic competition in storage investments but focus exclusively on arbitrage revenues, without considering renewable-storage complementarity or the effects of spatial constraints.

Relatedly, Gowrisankaran et al. (2025) examine the interaction between wind intermittency and hydroelectric power (an imperfect form of storage), showing their complementarity at low levels of wind penetration. By incorporating market power for both generation and storage while explicitly modeling transmission constraints, our paper bridges these gaps and provides novel insights into the relationship between storage and renewable energies.

Finally, our paper relates to a literature that explores the effectiveness of environmental policies in electricity markets (e.g., Langer and Lemoine, 2022; Stock and Stuart, 2021). In particular, it speaks to debates about the desirability of adapting support schemes and regulatory frameworks to take into account complementarities or substitutabilities between different technologies, particularly when firms' strategic decisions are taken into account (i.e., Fabra and Montero (2023); Fioretti et al. (2024); Fabra and Llobet (2025)).

The remainder of the paper proceeds as follows. In Section 2, we describe the theoretical model. In Section 3, we identify conditions for renewables and storage to be strategic complements or substitutes, and analyze the policy implications in Section 4. The baseline model is extended in Section 5 by introducing market power in storage and binding transmission constraints. Simulations of the Spanish electricity market in Section 6 illustrate our baseline findings. Section 7 concludes. The appendix contains the proofs of the model.[3]

2 Theoretical Framework

We model a wholesale electricity market with perfectly inelastic demand. Demand moves over time around its mean, θ, according to deterministic cycles of amplitude b (with

[3]The online appendix contains extensions and details about the simulations.

$0 \leq b \leq \theta$).[4] At time t, demand is given by

$$D(t) = \theta - b \sin t. \tag{1}$$

Figure 1 illustrates demand fluctuations over time. Demand first takes the value θ at $t = 0$. It then decreases in t up to $t = \pi/2$ when it takes the value $\theta - b$, and it subsequently increases in t up to $t = 3\pi/2$ when it takes the value $\theta + b$. Last, demand reverts to θ at $t = 2\pi$, after which the cycle repeats itself. This pattern mimics a representative electricity demand pattern over a day.

Electricity demand can be served by intermittent renewable energies (wind or solar), thermal generation (gas or coal plants), and storage. These assets are owned by independent firms.[5] We assume price-taking behavior of storage and renewable operators, but we allow for market power in thermal generation.[6] This configuration is common in electricity markets, where thermal assets are typically owned by the incumbent firms, while renewable and storage assets tend to be in the hands of entrants.

The marginal costs of renewable energies are normalized to zero up to their available capacity $\omega(t)K_R$, where K_R denotes the installed renewable capacity and $\omega(t) \in [0, 1]$ is the capacity factor, which moves in deterministic cycles around its mean (normalized to 1/2), with amplitude 1/2. In particular,

$$\omega(t) = \frac{1}{2}\left(1 - \alpha \sin t\right), \tag{2}$$

where the parameter α takes one of two values, $\{-1, 1\}$. Initially, at $t = 0$, the capacity factor is 1/2. Whether it subsequently increases or decreases depends on α, as illustrated in Figure 1. Consider first the case with $\alpha = 1$. The capacity factor decreases to zero as t approaches $\pi/2$, then increases with t until reaching a maximum value of 1 at $t = 3\pi/2$. Finally, it returns to 1/2 at $t = 2\pi$, after which the cycle repeats. Since this pattern mirrors the demand cycle, we say that renewables are *procyclical* with respect

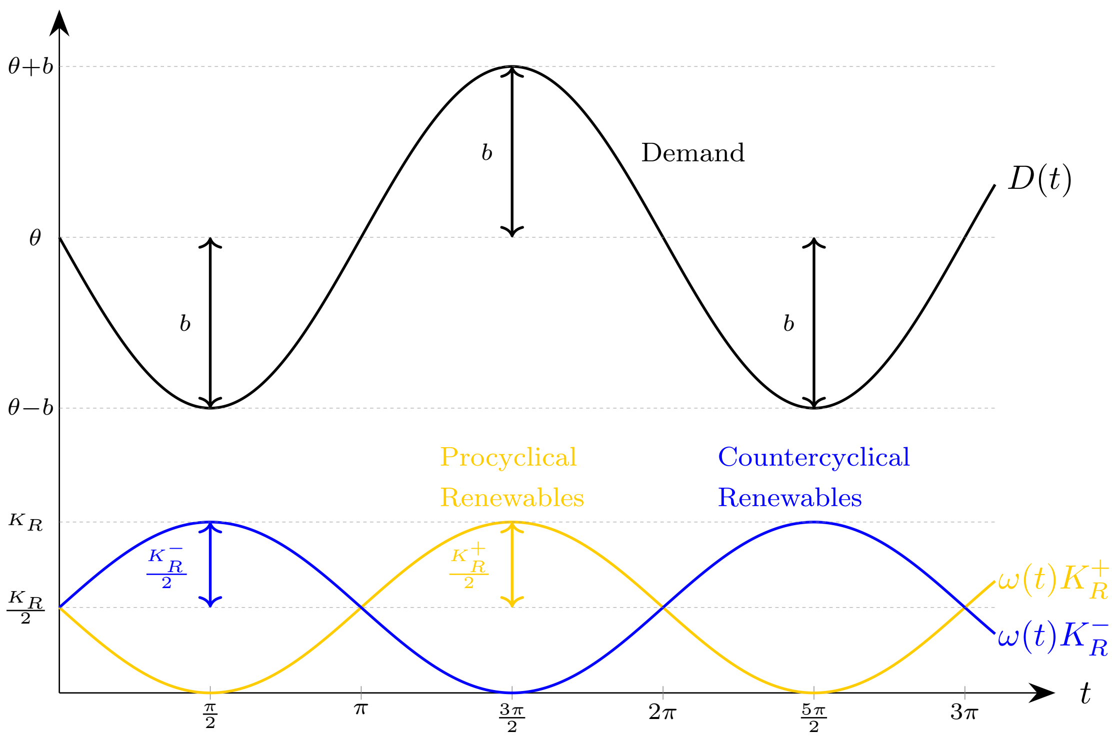
[4] In practice, predictable changes in demand and renewable energy availability are quantitatively more significant than unpredictable ones. To demonstrate this, using data from the Spanish electricity market, we regress realized demand, solar generation, wind generation, and net demand, on their respective day-ahead forecasts. The variation in these outcome variables is almost entirely explained by the day-ahead, as indicated by the high R^2 values obtained in all four regressions: 0.998, 0.993, 0.987, and 0.990, respectively. Moreover, in each case, the estimated coefficient on the forecast variable is not different from one. See Table D.1 in the Online Appendix D.1 for details.

[5] See Andrés-Cerezo and Fabra (2023) for a model with vertical integration between thermal generators and storage firms, and Acemoglu et al. (2017) and Fabra and Llobet (2025) for the analysis of the behavior of firms with diversified portfolios, including renewable and thermal generation assets.

[6] In Subsection 5.1, we allow for strategic behavior by storage firms.

to demand when $\alpha = 1$. Alternatively, if $\alpha = -1$, renewable availability decreases as demand increases. In this case, we describe renewables as *countercyclical.* [7]

Figure 1: Diurnal patterns of demand and renewable energies



Notes: This figure illustrates the time evolution of electricity demand, $D(t)$ (black curve), and renewable energy supply, $\omega(t)K_R$, under two scenarios: procyclical (yellow curve, K_R^+) and countercyclical (blue curve, K_R^-). Demand follows a sinusoidal pattern around the average level θ, with amplitude b. In the procyclical scenario, renewable supply is positively correlated with demand – peaking when demand peaks. In contrast, the countercyclical scenario features renewables peaking when demand is at its lowest. In both cases, total renewable capacity is K_R.

Thermal generation has quadratic costs, which we assume result in the following linear marginal costs at the industry level: $c'(q(t)) = q(t)$.[8] Following Andrés-Cerezo and Fabra (2023), we assume that there are two types of thermal generators: a dominant firm (D) and a set of fringe firms (F). For each cost level, the dominant firm owns a fraction $\beta \in (0, 1)$ of the thermal assets, whereas the fringe owns the remaining fraction $(1 - \beta)$. Note that β is a measure of the dominant firm's size, i.e., at any given price,

[7] An alternative specification that captures a smoother correlation between demand and renewable energies would be $\omega(t) = \frac{1}{2}(1 - \sin(t + a))$, with $a \in (0, \pi)$. In the Online Appendix A we allow for this possibility, and we show that the qualitative results remain unchanged.

[8] In practice, costs jump from one technology to the other, which could have implications for the price elasticity of supply at off-peak and peak levels. The model could be extended to accommodate these.

the higher β the more it can produce without incurring losses. As it will become clear, the dominant firm's size is a proxy for market power.

Operating storage facilities entails no costs other than buying the electricity that will be sold, up to the storage capacity K_S.[9] We use $q_B(t)$ and $q_S(t)$ to denote the quantities that are bought and sold by storage facilities at time t.

Throughout the baseline analysis we treat K_S and K_R as given parameters and fully characterize the operation stage (production and storage decisions). We later map operating profits into investment break-even subsidies when studying investment mandates. In particular, we assume that regulators set technology mandates $\bar{K}_S$ and $\bar{K}_R$ and introduce investment subsidies $\eta_S, \eta_R > 0$ that allow firms to break even (under free entry into the market). We also assume that investment costs are given by the functions $C_i\left(K_i\right)$ for $i = \{S, R\}$, with $C_i'\left(K_i\right) > 0$ and $C_i''\left(K_i\right) \geq 0$.

3 Market Equilibrium

For given capacities, generation firms decide how much to produce, and storage firms decide when and how much energy to charge and discharge, under the assumption of perfect foresight over prices.[10]

Since renewable energies have zero marginal costs and operate competitively, they always produce at their full capacity. This implies that net demand (ND), i.e., market demand minus renewables, can be written as:

$$ND(t, K_R) \equiv D(t) - \omega(t)K_R = \left(\theta - \frac{K_R}{2}\right) + \left(\alpha\frac{K_R}{2} - b\right)\sin t. \tag{3}$$

For simplicity, we assume that renewable capacity is sufficiently small so that net demand is always positive and renewable production is never in excess.[11] The thermal dominant

[9] Energy storage typically entails a round-trip efficiency loss. The model is robust to adding it (Andrés-Cerezo and Fabra, 2023). We also omit constraints on how fast storage plants can charge/discharge. Such constraints, if binding, would lead to smoother charge/discharge decisions. However, the main insights of the model would remain qualitatively unchanged given that charge/discharge decisions would in any event take place in low/high-priced periods, as shown later.

[10] Butters et al. (2025) show that assuming perfect foresight biases results in overestimating the profitability of arbitrage by storage owners. Hence, relaxing this assumption would likely result in lower investments in storage. However, in the Spanish market, predictable changes in demand are quantitatively more important than the unpredictable ones, allowing for good price forecasts (See the Online Appendix D.1).

[11] This assumption simplifies the analysis at the cost of ruling out curtailments of renewable energy, i.e., when consumers' demand is below renewable production. The main results of the model do not rely on this assumption. However, as will be discussed below, when renewable capacity is sufficiently

producer chooses its output $q_D(t)$ in every period in order to maximize its profits over its residual demand:

$$\max_{q_D(t)} \pi_D = \int_0^{2\pi} \left[p\left(t; q_D\right) q_D(t) - c_D\left(q_D(t)\right)\right] dt, \tag{4}$$

where the market price is equal to the fringe's marginal cost,

$$p\left(t; q_D\right) = \frac{ND(t, K_R) - q_D(t)}{1-\beta}.$$

The following lemma characterizes the behavior of the dominant and fringe thermal firms and the resulting market price in the absence of storage.

Lemma 1 *The quantities produced by the dominant and fringe producers are given by*

$$q_D^{NS}(t) = \frac{\beta}{1+\beta} ND(t, K_R) < \frac{1}{1+\beta} ND(t, K_R) = q_F^{NS}(t).$$

Therefore, equilibrium prices in the absence of storage (p^{NS}) are:

$$p^{NS}(t) = \frac{1}{1-\beta^2}\left[\left(\theta - \frac{K_R}{2}\right) + \left(\alpha \frac{K_R}{2} - b\right) \sin t\right]. \tag{5}$$

Renewable energies influence equilibrium prices through two channels, as captured by the two terms in parentheses in equation (5). First, through the first term, renewable capacity K_R reduces the price level. Second, renewable capacity affects the price dynamics through the interaction of K_R and $\sin t$ in the second term. In particular, renewable capacity affects the correlation between equilibrium prices and demand, which is positive (negative) if this term is positive (negative), i.e., if $\alpha = 1$ and $K_R < 2b$, or if $\alpha = -1$ (otherwise). Furthermore, an increase in renewable capacity flattens (amplifies) the price cycle when prices and renewable production are positively (negatively) correlated. These effects are more pronounced the larger the size asymmetries across firms (equivalently, the higher the degree of market power), as the scaling factor in the price equation (5) increases in β.

These dynamics are summarized in the following lemma.

Lemma 2 *Suppose there is a single renewable technology with capacity K_R and $\alpha \in \{-1, 1\}$. For all $\beta \in (0, 1)$, (i) equilibrium prices and demand correlate positively if*

large to generate excess supply, the strategic complementarity between renewable energy and storage weakens.

and only if $\alpha = 1$ and $K_R < 2b$, or if $\alpha = -1$ for all K_R. (ii) Equilibrium prices and renewables correlate positively, and renewables flatten the price cycle if and only if $\alpha = 1$ and $K_R < 2b$.

On the one hand, if renewable energies are procyclical ($\alpha = 1$), the correlation between prices and renewable energies depends on the level of renewable capacity. If $K_R < 2b$, prices positively correlate with renewable energies. Moreover, an increase in renewable capacity flattens price differences across time. Indeed, when $K_R = 2b$, prices become time-invariant. Further increases in renewable capacity, so that $K_R > 2b$, flip the correlation between prices and renewable energies from positive to negative while amplifying the price differences across time.

On the other hand, when renewable energies are countercyclical relative to demand ($\alpha = -1$), prices correlate negatively with renewable energies for all K_R. Moreover, an increase in renewable capacities enlarges the price differences across time.

Through the scaling factor $1/(1-\beta^2)$, market power in thermal generation (proxied by β) increases average prices and affects the amplitude of the price cycle. However, market power does not change the sign of the correlation between prices and renewables.

These properties are important for characterizing storage decisions, given that storage firms charge (discharge) when prices are low (high) and earn profits by arbitraging price differences. Formally, the problem of storage firms is to maximize arbitrage profits by choosing when and how much to buy, $q_B(t)$, and sell, $q_S(t)$, taking market prices as given:

$$\max_{q_B(t), q_S(t)} \Pi_S = \int_0^{2\pi} p\left(t\right)\left[q_S(t) - q_B(t)\right] dt, \tag{6}$$

subject to two intertemporal constraints: they cannot store energy above capacity and cannot sell more energy than previously bought. Since prices in (5) reach a single minimum and maximum within each cycle, storage firms always find it optimal to fully charge (discharge) their batteries when prices are low (high). This allows writing the intertemporal constraints as:

$$\int_0^{2\pi} q_B(t)dt \leq K_S. \tag{7}$$

$$\int_0^{2\pi} q_B(t)dt \geq \int_0^{2\pi} q_S(t)dt. \tag{8}$$

The following Lemma characterizes the equilibrium storage decisions and their price impacts.[12]

[12] A formal statement can be found in the Appendix.

Lemma 3 *The equilibrium strategy of competitive storage owners is characterized as follows:*

(i) They charge a quantity $q_B^*(t)$ during all periods $t \in [\underline{t}_B, \overline{t}_B]$, corresponding to the lowest prices in the absence of storage. The quantities $q_B^*(t)$ are such that equilibrium prices are fully flattened across these periods at $p^*(t) = p^{NS}(\underline{t}_B) = p^{NS}(\overline{t}_B)$, and storage is fully charged by period $\overline{t}_B$.

(ii) They discharge a quantity $q_S^*(t)$ during all periods $t \in [\underline{t}_S, \overline{t}_S]$, corresponding to the highest prices in the absence of storage. The quantities $q_S^*(t)$ are such that equilibrium prices are fully flattened across these periods at $p^*(t) = p^{NS}(\underline{t}_S) = p^{NS}(\overline{t}_S)$, and storage is fully depleted by period $\overline{t}_S$.

(iii) They remain inactive in all other periods, implying $p^*(t) = p^{NS}(t)$.

The behavior of competitive storage operators is illustrated in Figure 2. Storage owners purchase electricity during the lowest-priced periods, i.e., $t \in (\underline{t}_B, \overline{t}_B)$, and sell during the highest-priced periods, i.e., $t \in (\underline{t}_S, \overline{t}_S)$, until prices are fully flattened within these intervals.

When storage capacity is small, it constrains firms' ability to arbitrage across all profitable periods, resulting in some periods of inactivity. As storage capacity increases, the number of active periods grows, eventually reaching a point where capacity is no longer a binding constraint. At that stage, storage operators are active in all periods, and prices become completely flattened across time. This exhausts all further arbitrage opportunities.

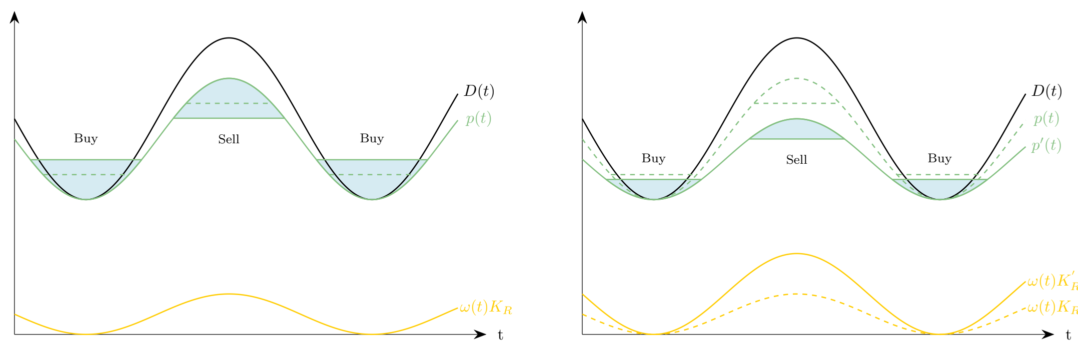
Importantly, when prices and renewable energies are positively correlated (Lemma 2 (*ii*)), discharging occurs when renewable availability is high. Thus, as shown in the upper left panel of Figure 2, an increase in storage capacity pushes prices down precisely when renewable energies are relatively more abundant.[13] While an increase in storage capacity also pushes prices up when charging, this occurs when renewable production is lower. Consequently, expanding storage capacity reduces the profits of renewable energy producers.

[13]Note that our differentiability assumption on the cost function of thermal generators implies that changes in both renewable and storage capacity always affect the market price. In real-world electricity markets, the industry cost function presents jumps, and the marginal cost of the price-setting technology may be the same for different demand levels. In these cases, marginal increases in capacity may not have price impacts if the peaking technology remains unchanged across periods. The same would occur in the presence of excess renewables, as off-peak prices would remain flat at zero.

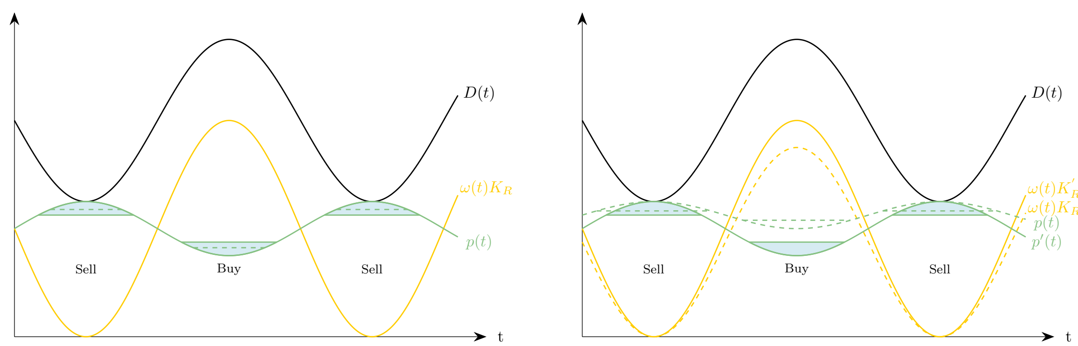
In all periods, market prices go down when renewable capacity goes up. As shown in the upper right panel of Figure 2, when prices and renewable generation are positively correlated, this price-depressing effect is more pronounced during periods when storage firms discharge rather than when they charge. Moreover, by shrinking the price spreads, higher K_R reduces the arbitrage profits of storage owners. Storage firms optimally respond by smoothing charging and discharging, but this only partially mitigates the negative impact of renewable energies on storage profits. The opposite holds when prices negatively correlate with renewable energies (lower panels in Figure 2).

Figure 2: Profit impacts of increasing storage and renewable capacity

(a) Storage and Renewable Energies are Substitutes



(b) Storage and Renewable Energies are Strategic Complements



Notes: These figures depict demand (black), production of renewable energies (yellow), and prices (green) over time, for the case of procyclical renewables ($\alpha = 1$) and no market power in thermal generation ($\beta = 0$). The upper panels illustrate the case of a small renewable capacity ($K_R < 2b$), implying a positive correlation between prices and renewables. The lower panels illustrate the case of a large renewable capacity ($K_R > 2b$), implying a negative correlation between prices and renewables. The left panels consider the effects of increasing storage capacity (from the green dashed to the solid line). The right panels consider the impact of increasing renewable capacity, which increases renewable production (from the yellow dashed to the solid line) and reduces prices (from the green dashed to the solid line).

These conclusions lead to our main Proposition, which characterizes the necessary and sufficient condition for renewables and storage to be strategic substitutes: renewable energies must correlate positively with prices, for which renewables must be procyclical relative to demand and their capacity K_R must not exceed a critical mass equal to $2b$.[14] Alternatively, renewables and storage are strategic complements.

Note that our definition for strategic complements (substitutes) is equivalent to the standard one, $\partial^2\Pi_i/\partial K_i \partial K_j > 0$ (< 0), with a key difference. The standard definition implicitly assumes that firms strategically choose capacities in a first stage. In contrast, our model assumes that capacities are determined through the zero-profit condition, making it relevant to assess the impact of capacity on profit levels, not marginal profits.

Proposition 1 *Suppose there is a single renewable technology with capacity K_R and $\alpha \in \{-1, 1\}$. Let Π_S and Π_R denote the profits of storage and renewables. Renewables and storage are strategic substitutes if and only if prices and renewables correlate positively, i.e.,*[15]

$$\frac{\partial \Pi_R}{\partial K_S} < 0 \textit{ and } \frac{\partial \Pi_S}{\partial K_R} < 0 \Leftrightarrow \alpha = 1 \textit{ and } K_R < 2b.$$

Interestingly, since prices are increasing in β, more market power implies a greater degree of complementarity or substitutability between renewables and storage, i.e., it enlarges the magnitude of the derivatives $\partial\Pi_S/\partial K_R$ and $\partial\Pi_R/\partial K_S$, but does not change the sign of the correlation between prices and renewable energy availability.

Up to this point, we have abstracted from renewable energy curtailments. However, our framework can be used to explore the implications of relaxing this assumption (Andrés-Cerezo and Fabra, 2023). Consider a scenario in which renewable generation is sufficiently large to meet total demand, driving electricity prices to zero in some periods. If storage operators are able to fully charge their capacity during these episodes at no cost, then further increases in renewable capacity do not benefit them: charging prices cannot fall below zero, while discharging into a market with more renewables becomes less profitable for storage operators.

Similarly, expanding storage capacity to absorb otherwise-curtailed renewable energy does not benefit renewable producers. Charging prices remain at zero during curtailment events, and the additional storage capacity may exert downward pressure on prices when renewable producers obtain positive prices. Thus, under curtailment conditions, the strategic complementarity between renewables and storage weakens.

[14] This result is consistent with Butters et al. (2025)'s prediction that, for storage to break even in the Californian market, renewable penetration must reach 50%.

[15] This result arises because all price-shaping effects in the model collapse into a single scalar channel, i.e., the sign of $b - \frac{\alpha K_R}{2}$. In more general setups (e.g., with non-sinusoidal demand/availability or nonlinear supply responses), the two cross-derivatives need not move in tandem.

Our baseline results extend naturally to the case of multiple renewable technologies, with capacities denoted by K^+ and K^-. Technology $+$ is procyclical ($\alpha^+ = 1$) and technology $-$ is countercyclical ($\alpha^- = -1$). Letting $K_R = K_R^+ + K_R^-$, the price equation (5) now becomes

$$p^{NS}(t) \;\;=\;\; \frac{1}{1-\beta^2}\left[\left(\theta - \frac{K_R^+ + K_R^-}{2}\right) + \left(\frac{K_R^+ - K_R^-}{2} - b\right)\sin t\right].$$

In this case, the availability of one technology correlates positively with market prices, while that of the other correlates negatively. If the technologies have the same capacity, the correlation is positive for the procyclical technology and negative for the countercyclical one. The signs are reversed only if the capacity of the procyclical technology becomes much larger (by at least $2b$).

Lemma 4 *Equilibrium prices correlate positively with renewable technology $+$ and negatively with renewable technology $-$ if and only if $K_R^+ < K_R^- + 2b$.*

The above result has important implications for the strategic complementarity or substitutability between renewables and storage. Importantly, unlike the single-technology case, storage necessarily complements one renewable technology but substitutes for the other.

Proposition 2 *Suppose there are two renewable technologies, one with capacity K_R^+ and $\alpha^+ = 1$ and the other one with capacity K_R^- and $\alpha^- = -1$. Let $i, j \in \{+, -\}$ and $i \neq j$. Renewable technology i and storage are strategic substitutes if and only if prices correlate positively with their availability. Furthermore, if renewable technology i and storage are strategic substitutes, renewable technology j and storage are strategic complements:*

$$\frac{\partial \Pi_R^+}{\partial K_S} < 0 \text{ and } \frac{\partial \Pi_R^-}{\partial K_S} > 0, \frac{\partial \Pi_S}{\partial K_R^+} < 0 \text{ and } \frac{\partial \Pi_S}{\partial K_R^-} > 0 \Leftrightarrow \alpha = 1 \text{ and } K_R^+ < K_R^- + 2b.$$

4 The Impact of Mandates

We now analyze the impact of support schemes on long-run investment decisions. Recall that we assume that regulators set technology mandates and introduce investment subsidies that allow firms to break even. This can be achieved by the regulator procuring the mandate through capacity auctions, as long as they are competitive.

The expected profits of storage and renewable firms are:

$$\Pi_S(K_S, K_R, \eta_S) = \int_0^{2\pi} p^*(t)\Big[q_S^*(t) - q_B^*(t)\Big]dt - C_S(K_S) + \eta_S K_S$$
$$\Pi_R(K_S, K_R, \eta_R) = \int_0^{2\pi} p^*(t)\omega(t)K_R dt - C_R(K_R) + \eta_R K_R,$$

where $\eta_S, \eta_R > 0$ denote the investment subsidies for storage and renewables, respectively.[16] Throughout this section, we denote prices and dispatched production as $p^*(t)$, $q^*(t)$ from Lemma 3.

The following proposition characterizes the effect of mandates on the break-even subsidies:[17]

Proposition 3 *Let $\bar{K}_S$ and $\bar{K}_R$ denote the technology mandates for storage and renewables and let $\eta_S^* > 0$ and $\eta_R^* > 0$ be implicitly defined by $\Pi_S(\bar{K}_S, \bar{K}_R, \eta_S^*) = 0$ and $\Pi_R(\bar{K}_S, \bar{K}_R, \eta_R^*) = 0$. Then, for $i, j \in \{S, R\}$ and $i \neq j$, if the mandates are binding (i.e., $\eta_i^* > 0$):*
(i) A higher mandate $\bar{K}_i$ for technology i requires a higher equilibrium subsidy for technology i, η_i^*, i.e.,

$$\frac{\partial \eta_i^*}{\partial \bar{K}_i} > 0.$$

(ii) A higher mandate $\bar{K}_i$ for technology i requires a higher equilibrium subsidy for technology j, η_j^*, if and only if prices and renewable energies correlate positively, i.e.,

$$\frac{\partial \eta_j^*}{\partial \bar{K}_i} > 0 \Leftrightarrow \alpha = 1 \text{ and } \bar{K}_R < 2b.$$

Increasing a technology mandate increases its own investment break-even subsidy because of a cannibalization effect. Whether this raises or reduces the subsidy required to meet the other technology's mandate depends on whether renewables and storage are strategic complements or substitutes (Proposition 1). If they are strategic complements, mandating more capacity for one technology comes with the additional benefit of reduc-

[16] We restrict η_S, η_R to be non-negative in order to focus on cases where policy instruments are designed to promote new deployment of storage and renewable capacity. Allowing for negative values (i.e., taxes) would correspond to setting a storage mandate below the capacity that would arise in the absence of any support, with the implied payment from storage firms to the regulator reducing investment to the target level. This extension would not alter the comparative-statics logic in Propositions 3 and 4: the sign of the cross-effects, and the threshold $K_R = 2b$, would still determine whether support for one technology raises or lowers the break-even support for the other.

[17] The Online Appendix *B* provides an alternative formulation of Proposition 3, expressed in terms of subsidies instead of mandates.

ing the break-even subsidy for the other. In contrast, if they are substitutes, increasing the storage mandate acts as a barrier to deploying renewable energies, and *vice versa*. In this case, a higher storage (renewables) mandate reduces the profitability of renewable energies (storage), which in turn raises the break-even subsidy to meet the renewables (storage) mandate. This result has important implications for the optimal timing of technology mandates in markets where the correlation between renewables availability and consumers' demand is procyclical (i.e., $\alpha = 1$), as we analyze next.

Accordingly, consider a regulator who chooses renewable and storage mandates to minimize carbon emissions. Price-taking behavior minimizes generation costs and, with constant per-unit capacity costs, the market solution also achieves the socially optimal investment. Hence, the only market failure is the unpriced emissions externality.

The regulator can allocate investment subsidies to allow firms to break even up to a limited budget B. Since emissions depend on the amount of thermal production, we denote emissions as $e\Big(q(t)\Big)$ and assume $e'\Big(q(t)\Big) > 0$, $e''\Big(q(t)\Big) > 0$, reflecting the fact that higher marginal cost plants typically have higher emissions (Borenstein and Kellogg, 2023). To simplify the analysis, but w.l.o.g., we also assume $e'''\Big(q(t)\Big) \leq 0$.

Denoting overall emissions as a function of mandates as $\Phi\Big(\bar{K}_S, \bar{K}_R\Big)$, the regulator's problem can be written as:

$$\begin{aligned} \min_{\bar{K}_S, \bar{K}_R} \Phi\Big(\bar{K}_S, \bar{K}_R\Big) &\equiv \int_0^{2\pi} e\Big(q^*(t)\Big)dt \\ \text{s.t. } \eta_S^*(\bar{K}_S, \bar{K}_R)\bar{K}_S &+ \eta_R^*(\bar{K}_S, \bar{K}_R)\bar{K}_R \leq B, \end{aligned}$$

where $q^*(t)$ is defined in Lemma 3 and $\eta_S^* > 0$ and $\eta_R^* > 0$ are implicitly defined by the break-even constraints, $\Pi_S(\bar{K}_S, \bar{K}_R, \eta_S^*) = 0$ and $\Pi_R(\bar{K}_S, \bar{K}_R, \eta_R^*) = 0$.

Increasing renewable capacity reduces emissions by replacing thermal production, especially when renewable availability is high. However, due to the convexity of emissions, the marginal reduction in emissions decreases as renewable capacity increases. Investing in storage capacity also reduces emissions, as the increase in emissions during charging is more than offset by the decrease during discharging. The marginal reduction in emissions decreases with additional storage capacity until storage capacity becomes large enough to flatten thermal production entirely. Beyond that point, additional storage capacity becomes idle and no longer reduces emissions.

The following proposition characterizes the regulator's choice of optimal mandates $\bar{K}_S^*$ and $\bar{K}_R^*$ when the budget is large enough.

Proposition 4 *Let $\alpha = 1$ and denote by $\bar{B}$ the minimum budget level that allows the regulator to mandate $\bar{K}_R \geq 2b$. Then, if $B \geq \bar{B}$, renewable energies and storage are strategic complements at the optimal mandates, i.e., $\bar{K}_R^* \geq 2b$. Moreover, if the mandates are binding (i.e., $\eta_i^* > 0$),*

$$\frac{\partial^2 \Phi}{\partial \bar{K}_S \partial \bar{K}_R} < 0 \Leftrightarrow \bar{K}_R > 2b.$$

This proposition implies that it can never be optimal to set a mandate $\bar{K}_R < 2b$ if the regulator has the financial means to reach that threshold. When $K_R \leq 2b$, both technologies contribute to reducing overall emissions by flattening thermal production across periods. Emissions are fully flattened with any combination of $\bar{K}_R \in [0, 2b]$ and $\bar{K}_S = 2|b - \bar{K}_R/2|$. Flattening thermal production through renewables has the additional benefit of reducing emissions in every period, not just when storage discharges. Therefore, mandating $\bar{K}_R < 2b$ is dominated by $\bar{K}_R \geq 2b$ when the regulator's budget is enough to compensate renewable producers to break even at that target.

Once the critical threshold $K_R = 2b$ is surpassed, the strategic complementarity between storage and renewable investments encourages storage to enter the market (Proposition 1). Moreover, the regulator may find it optimal to set a mandate $\bar{K}_S$ above the investment level K_S that would enter without investment subsidies. This results from a double complementarity: one through an *emissions effect* (Proposition 4) and the other through a *subsidy effect* (Proposition 3). Increasing renewable capacity above the critical mass $2b$ reduces emissions in every period while amplifying emissions differences across periods. This boosts the social value of storage capacity, as it flattens emissions across time, reducing total emissions due to the convexity of the emissions function (*emissions effect*). Additionally, new renewable capacity amplifies price differences across periods, increasing arbitrage profits and thus reducing the storage break-even subsidy. Storage entry raises prices when renewable availability is high, reducing the break-even renewable subsidy (*subsidy effect*). Overall, these complementarities make it optimal to combine both technology mandates.

In contrast, when the critical threshold $K_R = 2b$ cannot be reached, the *emissions* and *subsidy effects* are reversed. On the one hand, increasing the capacity of one of the two technologies reduces the social value of the other, as both contribute to flattening emissions differences across periods (Proposition 4). On the other hand, increasing the amount of one technology raises the per-unit investment subsidy that allows the other technology to break even (Proposition 3). Together, this double substitutability implies that mandating both technologies is often undesirable when the regulator does not have the means to reach the renewable threshold $K_R = 2b$.[18]

5 Extensions

In this section, we extend the model in two key directions: incorporating market power in storage and introducing transmission constraints. Regarding market power in storage, we show that while the fundamental condition for complementarity between renewable energy and storage remains unchanged, the presence of market power leads to underinvestment. This underinvestment, in turn, influences the level of subsidies required to achieve a given renewable deployment target.

Transmission congestion, on the other hand, alters the interaction between storage and renewables in different ways depending on storage location. If storage assets are situated close to demand centers, congestion can weaken or even eliminate the link between storage and renewable generation, as storage decisions are driven primarily by local price dynamics rather than system-wide renewable availability. Conversely, if storage is co-located with renewable plants, congestion can enhance complementarity by ensuring that market prices respond primarily to fluctuations in renewable output. In this case, storage owners consistently charge when renewables are abundant and discharge when they are scarce, reinforcing the economic alignment between the two technologies.

5.1 Market Power in Storage

Consider the case where the storage assets are owned by a storage monopolist. To isolate the effect of market power in storage from the effect of market power in generation, we assume that all thermal generators behave competitively (i.e., $\beta = 0$). The key difference with the case of competitive storage is that the storage monopolist internalizes the price impacts of its charging and discharging decisions. Therefore, the problem of the storage

[18] Our baseline convexity assumption, i.e., that $e''(q) > 0$, implies that higher-marginal-cost plants (e.g., coal) emit more per MWh than lower-cost plants (e.g., gas), a ranking broadly observed in electricity markets in Europe and the US. Instead, if emissions are concave ($e''(q) < 0$), then once solar capacity is large enough, adding storage undoes the emissions reduction delivered by abundant renewables and increases total CO_2. In that case, an emissions-focused planner would allocate its entire budget to renewables (at least until the dirtiest units are displaced) before subsidizing any storage. Importantly, the key result that only renewables should be subsidized at early stages remains unaffected.

firm for given storage capacity is:

$$\max_{q_B(t),q_S(t)} \int_0^{2\pi} \Big[D(t) - \omega(t)K_R - q_S(t) + q_B(t)\Big]\Big[q_S(t) - q_B(t)\Big]dt$$

subject to storage constraints (7) and (8). The following lemma characterizes storage decisions of the storage monopolist and equilibrium market prices:

Lemma 5 *The equilibrium strategy of the storage monopolist is characterized as follows:*

(i) It charges a quantity $q_B^M(t)$ during all periods $t \in [\underline{t}_B^M, \bar{t}_B^M]$, corresponding to the lowest prices in the absence of storage. The quantities $q_B^M(t)$ are such that its marginal expenditure is fully flattened across these periods, and storage is fully charged by period $\bar{t}_B^M$.

(ii) It discharges a quantity $q_S^M(t)$ during all periods $t \in [\underline{t}_S^M, \bar{t}_S^M]$, corresponding to the highest prices in the absence of storage. The quantities $q_S^M(t)$ are such that its marginal revenue is fully flattened across these periods, and storage is fully depleted by period $\bar{t}_S^M$.

(iii) It remains inactive in all other periods, implying $p^*(t) = p^{NS}(t)$.

This result is the analogue of Lemma 3. As in the case of competitive storage, the storage monopolist also purchases electricity when prices are low to resell it when prices are high. However, unlike competitive operators, the storage monopolist does not equalize prices across the periods in which it is active. Rather, it equalizes marginal revenue when it sells (or marginal expenditure when it buys). The reason is that the monopolist internalizes the price impact of its marginal decisions on the prices it pays or receives for its inframarginal charging or discharging. Consequently, it behaves like a *monopsonist* when charging – buying less than a competitive operator would in order to limit upward pressure on prices. Similarly, it behaves like a *monopolist* when discharging – selling less than a competitive operator would to avoid depressing prices.

Since it is optimal for the monopolist to fully utilize its storage capacity, for a given capacity level K_S, the storage monopolist must be active over a greater number of periods than a competitive storage firm in order to fill or empty its storage.[19]

[19] This also implies that the level of storage capacity at which the capacity constraint becomes non-binding is lower under monopoly. See Andrés-Cerezo and Fabra (2023) for further discussion on the behavior of storage monopolists and the resulting inefficiencies.

Although the resulting time path of market prices differs from that under competitive storage, the correlation between prices and renewable production is unaffected by whether storage is operated competitively or strategically. As a result, the condition determining whether storage and renewables are complements remains unchanged, as formalized in the following proposition:

Proposition 5 *Let Π_S^M and Π_R^M denote the profits of storage and renewables when storage assets are owned by a storage monopolist. Renewables and storage are substitutes if and only if prices and renewables correlate positively, i.e.,*

$$\frac{\partial \Pi_R^M}{\partial K_S} < 0 \text{ and } \frac{\partial \Pi_S^M}{\partial K_R} < 0 \Leftrightarrow \alpha = 1 \text{ and } K_R < 2b.$$

As in the baseline model, the central force driving the complementarity between storage and renewables is the correlation between equilibrium electricity prices and renewable generation. Crucially, this correlation is not influenced by the behavior of the storage operators; rather, it depends solely on the time pattern of renewable production and the scale of renewable capacity.

Consistent with the baseline model, when $\alpha = -1$, the correlation is negative. In contrast, when $\alpha = 1$, the correlation is positive at low levels of renewable capacity, indicating that storage firms tend to charge when renewable availability is low. In both the competitive and strategic storage settings, this correlation reverses to negative only once renewable capacity surpasses the same threshold, specifically when $K_R \geq 2b$.

Although strategic storage behavior does not alter the conditions under which storage and renewable technologies complement each other, it does affect long-run capacity investments. The following lemma shows that, for any given renewable capacity mandate $\bar{K}_R$, the storage monopolist under-invests with respect to the competitive case. To isolate the effect of market power on investment, we assume linear investment costs in storage i.e., $C_S(K_S) = c_S K_S$, with $c_S > 0$.[20]

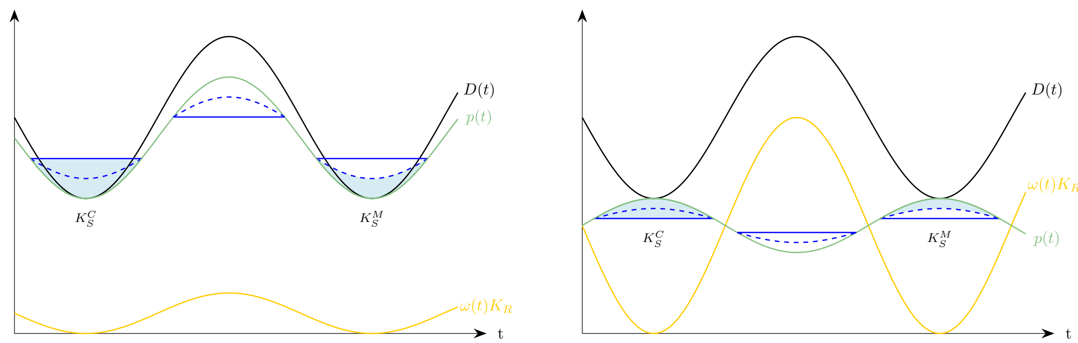
Lemma 6 *Let K_S^C and K_S^M denote equilibrium storage capacity investment for a given renewable mandate $\bar{K}_R$ when storage firms are competitive and strategic, respectively. Then:*

$$K_S^M(\bar{K}_R) < K_S^C(\bar{K}_R), \forall \bar{K}_R.$$

[20] Free-entry implies that competitive firms invest in storage capacity up to the level at which the marginal value of storage equals average investment cost, whereas the storage monopolist invests until the marginal value of storage equals the marginal investment cost. If investments costs are strictly convex, average costs are below marginal costs, giving rise to larger investment differences between the competitive and monopoly cases.

The tendency of the storage monopolist to smooth storage operations in order to limit price impacts diminishes the marginal gains from intertemporal arbitrage. As a result, investment in storage is inefficiently low relative to the competitive benchmark, irrespective of the level of the renewable mandate $\bar{K}_R$.

Figure 3: Price impact of competitive and monopoly storage



Notes: These figures depict demand (black) and production of renewable energies (yellow) over time. The green line captures prices when storage facilities are not active in the market. The solid (dashed) blue line depicts prices in periods when competitive (monopoly) storage firms are active. The left panel illustrates the case of procyclical renewables ($\alpha = 1$) and small renewable capacity ($K_R < 2b$), implying a positive correlation between prices and renewables. The right panel illustrates the case of procyclical renewables ($\alpha = 1$) and large renewable capacity ($K_R > 2b$), implying a negative correlation between prices and renewables. Both figures consider equilibrium capacity investment by competitive and storage firms, so that $K_S^M < K_S^C$ (as shown by the different sizes of the shaded areas).

The resulting under-investment arising from market power in storage weakens the positive feedback loop between storage and renewables when the two technologies are strategic complements, whereas it reinforces the negative feedback loop when the two technologies are substitutes. An important implication of this is that the break-even subsidy required to achieve a renewable mandate differs across different market structures, as shown by the following proposition:

Lemma 7 *Let $\bar{K}_R$ denote a renewable mandate and η_R^C and η_R^M the per-unit investment subsidies that allow renewable firms to break even when storage is competitive and strategic, respectively. Then:*

$$\eta_R^C(K_S^C, \bar{K}_R) > \eta_R^M(K_S^M, \bar{K}_R) \Leftrightarrow \alpha = 1 \ \textit{and} \ \bar{K}_R < 2b.$$

When prices and renewable production are positively correlated, the per-unit investment subsidy required to achieve a renewable technology mandate is lower when storage assets are owned by a monopolist. In contrast, in markets where renewables and prices are negatively correlated, having market power in the storage segment increases the cost of achieving the renewable mandate.

Overall, the effects of market power in storage vary depending on whether renewable generation is countercyclical or procyclical with respect to demand. In markets where renewables are countercyclical, regulators should consistently seek to promote competition in the storage segment, as greater competition leads to higher levels of storage investment, which in turn stimulates investment in renewable capacity.

In contrast, when renewables are procyclical, market power in storage introduces productive inefficiencies but may inadvertently facilitate the achievement of the critical capacity threshold $K_R = 2b$, precisely because it suppresses storage investment. Once this threshold is surpassed, however, regulatory efforts should focus on curbing storage market power in order to enhance both storage deployment and renewable energy investment.

5.2 Transmission Constraints

In this section, we show that, in the presence of transmission constraints, storage and renewable energy can function as strategic complements – even when renewable generation is procyclical and its available capacity is limited. However, this complementarity hinges critically on the geographic location of storage and renewable assets. This is because local transmission congestion can amplify the price effects of renewable generation, thereby altering the incentives of storage operators.

To simplify the exposition and isolate the mechanisms at play, we assume a setting with no market power in either generation (i.e., $\beta = 0$) or storage. Let us assume that final consumers and renewable generation assets are located in two different areas (nodes) that are linked by a lossless transmission line with capacity T. This reflects the fact that, in many real-world examples, renewable energy resources tend to be located far away from large demand centers.[21] More concretely, we assume that all demand $D(t)$ is located in region E. In contrast, all renewable capacity is located in region W. Demand and renewable availability expressions are as in the baseline model.

[21] For example, Australia has vast wind and solar resources in remote regions, such as the deserts of Western Australia and South Australia. Brazil's Northeast is rich in wind and solar potential, whereas major demand centers are in the southeastern cities of São Paulo and Rio de Janeiro. The Atacama Desert in northern Chile has some of the best solar resources in the world, while most of Chile's population and industry is located in the central and southern regions.

For comparability purposes, we assume $K_R < T$, which rules out renewable energy curtailment for sufficiently large consumers' demand. In both regions, E and W, there are competitive thermal generators with quadratic production costs.[22]

We first examine price determination in the absence of storage. When there are no transmission constraints (i.e., for a sufficiently large transmission capacity, T), the equilibrium price at time t is equal for both regions and identical to the one in the baseline model. In particular, renewables always produce at full capacity (due to zero marginal costs), so thermal generators serve the residual demand, $D(t) - \omega(t)K_R$. Since these generators behave competitively and their marginal costs are linear, the supply curve of each is given by $q_i\Big(p(t)\Big) = p(t)/2$. Therefore, using the market clearing condition, the unique market equilibrium price in the absence of storage is as in the baseline model (with competitive generation):

$$p^{NS}(t) = D(t) - \omega(t)K_R. \tag{9}$$

With no transmission constraints, renewable energy flows from region W to region E in every period t. The remaining demand from consumers in region E is equally met by thermal production in both regions, which minimizes generation costs. Hence, introducing storage in this market would have the same effect as in the baseline model. Moreover, the outcome is independent of the location of storage assets since the transmission line is uncongested.

We now examine the scenario where a smaller T leads to transmission congestion in period t. In this scenario, generation costs cannot be minimized. Specifically, there must be more thermal generation in region E than in W, even though producers in region W could produce at lower costs. In particular, thermal generators in region W produce until the line is congested, i.e., $q_W(t) = T - \omega(t)K_R$, and generators in region E produce the remaining energy required to satisfy demand, i.e., $q_E(t) = D(t) - T$.

Market clearing in each node implies that the price is given by the marginal cost of thermal generators, which, given our assumptions, is equal to $2q_i(t)$, for $i = \{E, W\}$. Therefore, the two markets clear at different (nodal) prices, $p_E(t)$ and $p_W(t)$:

$$p_E(t) = 2\Big[D(t) - T\Big]. \tag{10}$$

$$p_W(t) = 2\Big[T - \omega(t)K_R\Big]. \tag{11}$$

[22] This implies that the industry supply curve in the absence of transmission constraints is the same as in the baseline model (when there is no market power in generation).

In what follows, we consider two cases where storage capacity K_S is located in either region E or W. We focus on situations where the transmission line is congested in every period.[23]

Storage close to renewable plants We start by considering the case of storage assets that are co-located with renewable production in region W, so that only prices in region W are affected by storage decisions. Adding storage to equation (11):

$$p_W(t) = 2\Big[T - \omega(t)K_R + q_B(t) - q_S(t)\Big]. \tag{12}$$

From equation (12), it follows that when the transmission line is congested, the correlation between renewable generation, $\omega(t)K_R$, and the price it receives, $p_W(t)$, is always negative – even when renewables are procyclical and their capacity is small. This arises because congestion mutes the demand movements, effectively capping demand at T. As a result, price fluctuations across periods are entirely driven by variations in renewable output rather than changes in market demand.

Storage firms buy (sell) when prices in region W are low (high).[24] Hence, storage pushes prices up (down) when renewables are abundant (scarce), thus implying that renewables and storage located in the same node are always strategic complements in the presence of binding transmission constraints.

This outcome contrasts with the case of an unconstrained transmission network, as in equation (5), where prices depend not only on renewable production but also on demand dynamics. Without congestion, the price effects of renewable fluctuations may not be strong enough to fully offset demand-driven price movements, potentially leading to a positive correlation between renewables and the prices they capture.

Proposition 6 *For sufficiently small T so that the transmission constraint is always binding, renewables and storage are always strategic complements.*

[23]For this, we require $T < [D(t) + \omega(t)K_R]/2$ for all t. We make this assumption for expositional purposes, but it is not crucial for the results as long as transmission capacity is sufficiently small. The key driver behind the results is the fact that, in the presence of congestion, nodal prices in region W are heavily driven by renewable output. Allowing for congestion in some periods and not in others would capture intermediate cases between the one presented here and the baseline model with no transmission constraints.

[24]Lemma 8 in the Appendix characterizes equilibrium storage decisions in the presence of transmission constraints. The key difference with Lemma 3 is that, in this case, storage always charges (discharges) at times when renewables are abundant (scarce) even when their availability is procyclical.

Storage close to demand We now consider the case where storage is located in region E, close to consumers but far from renewable energies. Adding storage to equation (10):

$$p_E(t) = 2\Big[D(t) - T + q_B(t) - q_S(t)\Big]. \tag{13}$$

It follows that storage no longer affects the profits of renewable energies, as the additional demand or supply created by charging or discharging decisions does not affect prices in region W. Hence, the profits of storage and renewable energies are independent of each other.

Overall, the core logic of the baseline model continues to apply. However, it must be interpreted with greater nuance in the presence of transmission constraints. Importantly, even in markets with low aggregate solar penetration, storage and renewables can act as strategic complements – provided that both are located within a congested region. This underscores the importance of accounting for spatial heterogeneity when designing policies to coordinate investment in renewables and storage.

6 Simulations of the Spanish Electricity Market

We illustrate our main theoretical findings on the strategic complementarity and substitutability of renewable energies and storage through simulations of the Spanish electricity market.[25] We conduct a series of simulations to determine equilibrium outcomes on an hourly basis over a year (8,760 hours) under two scenarios: low renewable penetration (2019) and high renewable penetration (2030). The simulations are richer than the theoretical model, in the sense that demand and marginal costs are based on actual hourly and plant-level values, respectively, rather than being constrained to functional forms.[26]

We utilize highly detailed data on key parameters, including technology characteristics (capacity, efficiency rate, emission rate), hourly electricity demand (which is assumed to be price inelastic), hourly availability of renewable resources, and daily fossil fuel prices, among other factors.[27] This information allows us to calculate the marginal

[25]The simulations report equilibrium prices for given generation and storage capacities. Yet, they shed light on the profitability of the investments.

[26]To simplify the analysis, in the simulations we assume away trade with neighboring countries as this would require the endogenous modeling of prices across the two borders.

[27]Hourly demand data, renewable availability, and installed capacity for each technology are publicly available on the Spanish System Operator's website, (Redeia, 2025). Plant characteristics are obtained from (Global Energy Monitor, 2025). Fossil-fuel prices and CO2 EU allowance prices are available at (Bloomberg, 2025).

cost for each plant.[28] For renewable generation, marginal costs are assumed to be equal to operation and maintenance (O&M) costs. Instead, for a thermal plant i, marginal costs also depend on fossil fuel prices as follows:

$$c_i = \frac{p^f}{e_i} + \tau\epsilon_i + om_i$$

where p^f denotes the fossil-fuel price (either gas, coal, nuclear), e_i is the plant's efficiency in converting fuel into electricity, τ is the CO_2 price, ϵ_i is the plant's carbon emission rate (which in turn depends on the fuel it uses and its efficiency), and om_i stands for its O&M cost. This enables us to construct the industry's competitive supply curve on an hourly basis, given the variable availability of renewable energies.[29]

To compute equilibrium market outcomes under strategic bidding, our simulation framework closely replicates the theoretical model presented in Section 2. Specifically, we assume that a single firm controls 25% of all production plants across all technologies, including renewable energies. The remaining 75%, along with the entire storage capacity, is operated by competitive firms.[30] These competitive firms supply output at marginal cost, while the dominant firm meets the residual demand at its profit-maximizing price.[31] Since demand is assumed price inelastic, we need to choose a value for the implicit market price cap, which might be binding at times when the dominant firm is pivotal, i.e., typically, at times of peak demand and low renewable availability. We set the price cap equal to 500 €/MWh.[32]

To assess the model's performance, we have run simulations using 2019 actual market data. Figure 4 shows the simulated electricity prices in the Spanish electricity market and compares them with the observed prices. The average hourly simulated prices are 49.2 €/MWh and 50.5 €/MWh under competitive and strategic bidding,[33] respectively.

[28]The calculation follows established methods in the literature; see, for instance, Fabra and Imelda (2023).

[29]This curve minimizes total production costs, so that if generation from a given plant is positive, then any plant with a lower variable cost must be producing at available capacity.

[30]Varying the parameter β alters the extent of market power the dominant firm can exert, but does not affect the qualitative nature of the results.

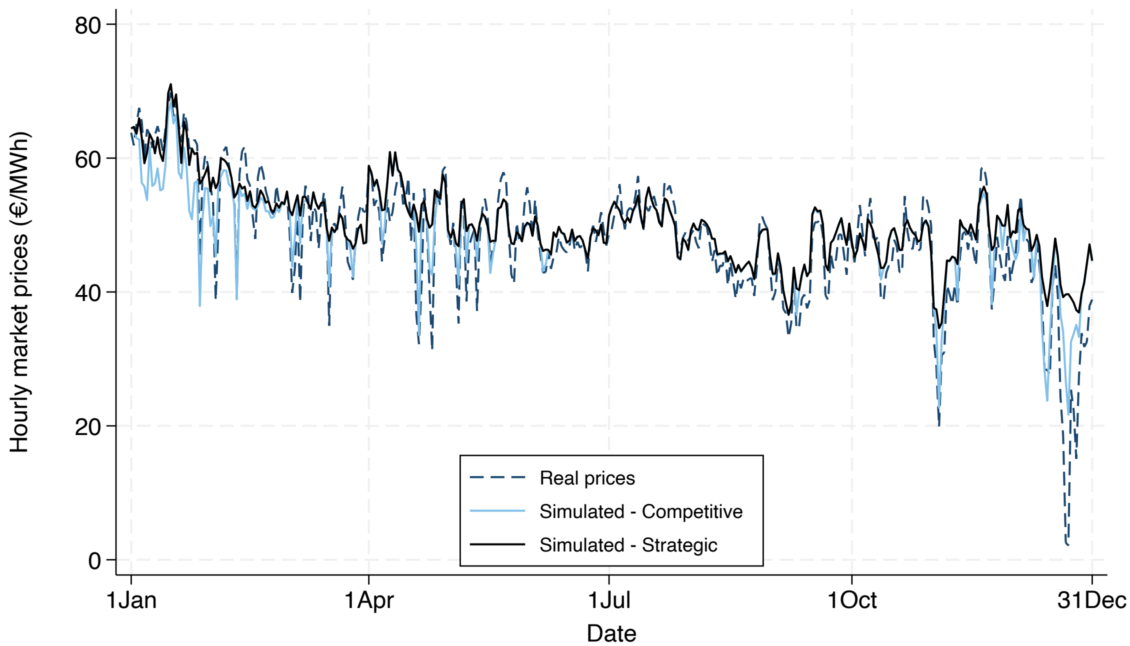
[31]Further details on the simulations can be found in the Online Appendix C. This appendix also reports the main results under the assumption of competitive behavior by all firms.

[32]As with the β parameter, changing the value of the price cap influences price levels by altering the degree of market power, but does not affect the qualitative nature of the results. This is illustrated in the Online Appendix, which presents the outcomes for a scenario with a 1,000 €/MWh price cap.

[33]The simulation under strategic bidding, like the rest of the simulations, assumes that a dominant firm controls 25% of total generation capacity. The discrepancy between observed and simulated prices under this assumption may be explained by the fact that this market structure does not fully reflect the actual one in the Spanish market.

By comparison, the actual average price was slightly lower, at 48.6 €/MWh. The correlation between actual and simulated daily average prices is 0.914 under competitive bidding and 0.859 under strategic bidding. This strong alignment between simulated and observed outcomes supports the model's suitability for conducting counterfactual analyses.[34]

Figure 4: Real versus simulated electricity prices, 2019



Notes: This figure shows the simulated (solid) and real (dash) daily averages of hourly prices in the Spanish electricity market as of 2019. The solid light blue line assumes competitive bidding, while the solid dark blue line assumes strategic bidding with a dominant firm owning 25% of generation capacity.

Scenarios. We consider scenarios with low and high renewable capacity penetration and different levels of storage capacity. These scenarios are meant to replicate the Spanish market as of 2019 and 2030, as contemplated by the Spanish Government in its National Energy and Climate Plan. Table 1 details the technological structure used under the scenarios with low and high renewables. Between 2019 and 2030, solar capacity is projected to grow nearly tenfold – from 8.3 GW to 76.3 GW – while wind capacity is expected to more than double, rising from 25.6 GW to 62.0 GW. As a result, the combined share of solar and wind in total generation capacity increases substantially, from 43.4% to 82.3%. The additional renewable plants are assumed to operate under

[34] The model fails at fully capturing the within-day price variation, an issue that is well documented in perfect competition models unless ramping costs are incorporated (Reynolds, 2024).

the same availability factors as in 2019.

Over the same period 2019-2030, the energy transition is also expected to involve a partial phase-out of nuclear power, with capacity declining from 7.4 GW to 3.2 GW, a complete phase-out of coal-fired power plants, and a 37% increase in electricity demand.

For each of these two scenarios, we consider different amounts of batteries with a 4-hour duration and 90% round-trip efficiency, corresponding to the most common type (NREL, 2022). This means that it takes four hours to fully charge/discharge a battery with a capacity equal to 4 GWh and power equal to 1 GW. Battery operators are assumed to have perfect foresight and to perform price arbitrage within a given natural day, subject to charge/discharge constraints and to available capacity. For each renewable scenario, we consider different levels of storage capacity, ranging from 4 GWh to 40 GWh.

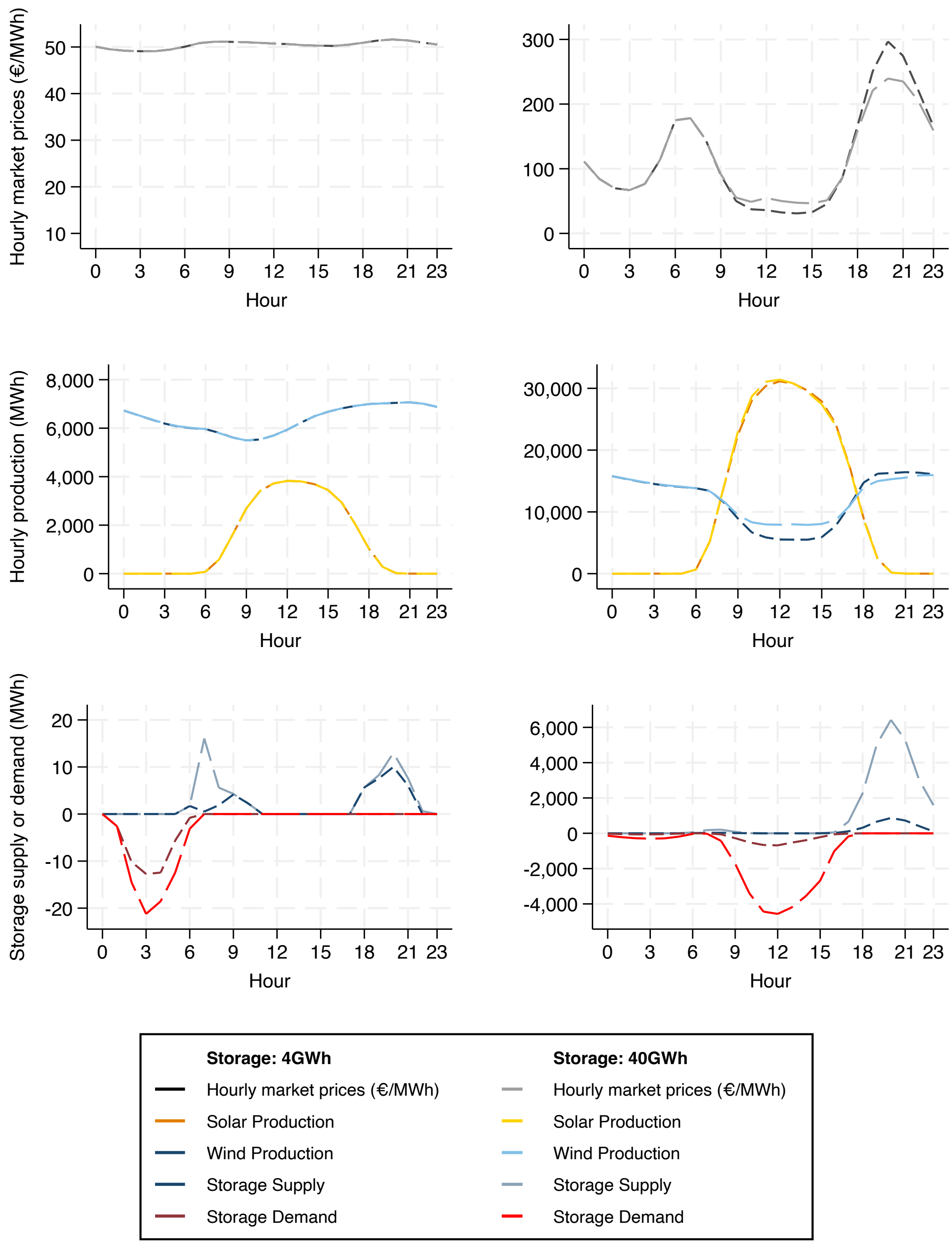
Table 1: Installed capacity by technology and peak demand

	Low RES		**High RES**	
	Capacity (GW)	% of total capacity	Capacity (GW)	% of total capacity
Solar capacity	8.306	10.6	76.278	45.4
Wind capacity	25.584	32.8	62.054	36.9
Nuclear capacity	7.400	9.5	3.182	1.9
Coal capacity	10.160	13.0	0	0
CCGT capacity	26.612	34.1	26.612	15.8
Total capacity	78.062	100	168.126	100
Peak demand	40.150	–	55.268	–

Notes: This table reports the capacity (in GW and shares) of the different generation technologies in the Spanish electricity market. The 2019 values correspond to actual data, while the 2030 projections are based on the targets outlined in Spain's National Energy and Climate Plan (PNIEC).

Results. Figures 4 to 7 and Table 2 present the main results of our simulations. The upper panels in Figure 4 display the average market prices over the day in 2019 (left panel) and 2030 (right panel). Prices in 2019 are nearly flat and unaffected by the presence of storage facilities. Hence, when renewable capacity is low, adding storage

Figure 5: Equilibrium prices, renewables, and storage (with market power)



Notes: The upper panels display the average hourly market prices. The middle panels illustrate the hourly generation from wind (blue) and solar (yellow) sources. The lower panels present the hourly storage activity, with negative (red) values indicating charging and positive (gray) values indicating discharging. All values are annual averages, shown for two levels of storage capacity: 4 GWh (represented by short dashes) and 40 GWh (represented by long dashes). The left column corresponds to the low renewables scenario, while the right column shows results under the high renewables scenario. The simulation model assumes that a dominant firm owns 25% of all generation capacity, and the market price cap is 500 €/MWh.

barely impacts the profitability of renewables or storage.[35] By contrast, in 2030, prices fluctuate significantly throughout the day, reaching lower levels during midday hours. Increasing storage capacity from 4 GWh to 40 GWh raises midday prices and lowers peak prices.

The middle panels of Figure 4 show wind and solar production for 2019 and 2030. Solar generation peaks around midday, when prices in 2030 are lowest, while wind production is relatively higher at night, when 2030 prices tend to be higher.

Finally, the lower panels of Figure 4 depict the charging and discharging behavior of storage facilities. In 2019, charging typically occurs at night, displaying a negative correlation with solar output and a positive one with wind. However, the utilization of storage is limited due to the small intra-day price differentials. In 2030, charging shifts to midday – reversing the correlation pattern with solar and wind – and the storage utilization rate increases markedly, as facilities can now profit from greater price variability. Similar evidence is reported in Figure 6, showing an increase in storage utilization (left panel) and arbitrage profits (right panel).

In 2030, the increase in storage utilization leads to a rise in solar profits. This is mainly driven by storage facilities charging relatively more during periods of high solar output, effectively supporting higher average prices during those hours. Conversely, the expansion of storage capacity reduces wind profits, as batteries typically discharge at night, exerting downward pressure on prices when wind generation is relatively abundant. While storage helps to reduce wind curtailment (Table 2), the effect is comparatively modest relative to the price effect.

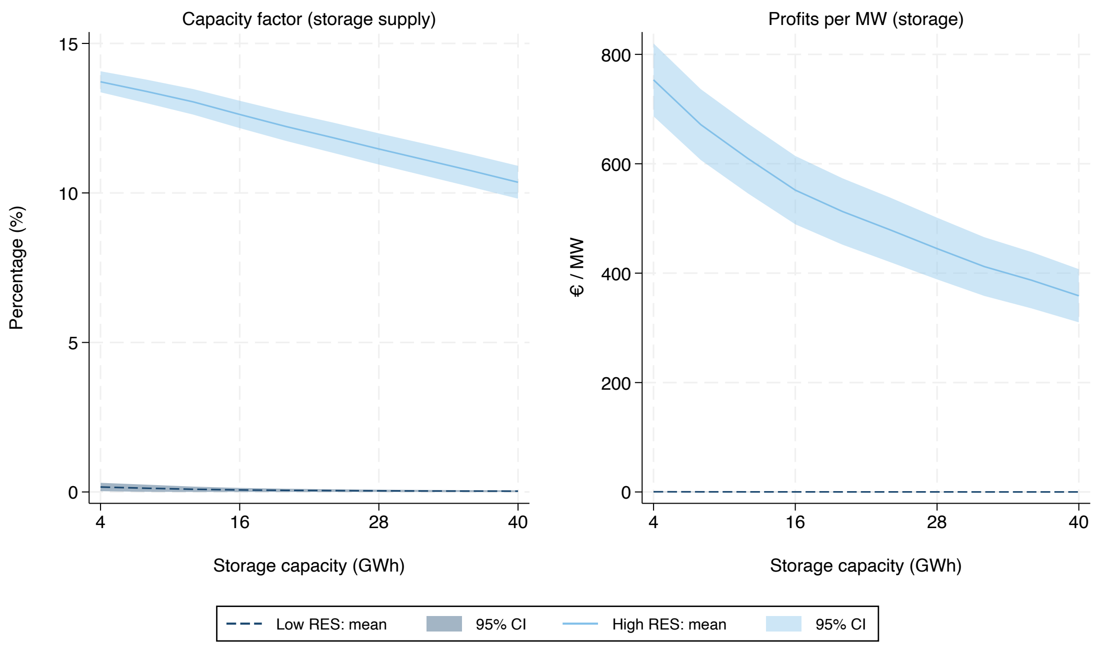
Figure 7 provides further details on the effects of increasing renewable and storage capacities on the prices captured by both assets. In the low renewables scenario (left panels), increasing storage capacity has little effect on the prices captured by solar and wind, which remain close to 50 €/MWh. In contrast, under the high renewables scenario (right panels), captured prices for solar decline markedly due to the cannibalization effect. Meanwhile, captured prices for wind increase, as the phase-out of coal and nuclear power, combined with rising electricity demand, enhances market power during hours when wind generation is relatively abundant.

Expanding storage capacity from 4 GWh to 40 GWh raises the captured price for solar by 16% (from 35.4 to 41.2 €/MWh), while it lowers the captured price for wind by 14% (from 96.5 to 83.0 €/MWh). Thus, greater storage capacity benefits the technology

[35] Carson and Novan (2013) obtain a similar finding for the Texas market at a time when only 8% of total output came from renewables.

whose production is positively correlated with prices (i.e., solar), and adversely affects the one with a negative correlation (i.e., wind).

Figure 6: Capacity factors and profits of energy storage (with market power)



Notes: This figure shows the capacity factor (left panel) and profits (right panel) of energy storage as a function of the installed storage capacity. The capacity factor is computed as the ratio between the supply of energy storage over the maximum supply it could have if it charged and discharged its full capacity (corrected by the round-trip efficiency) every four hours. Profits are computed as the difference between the revenues from discharging minus the costs of charging over storage capacity in MW. The dark blue dashed lines correspond to the 2019 scenario (low renewables), and the light blue dashed lines correspond to the 2030 scenario (high renewables). The cost and performance of battery systems are typically based on an assumption of approximately one cycle per day. Therefore, a 4-hour battery is expected to have a capacity factor of 16.7% ($4/24 = 0.167$). Higher (lower) values imply that there is more (less) than one cycle per day (NREL, 2022).

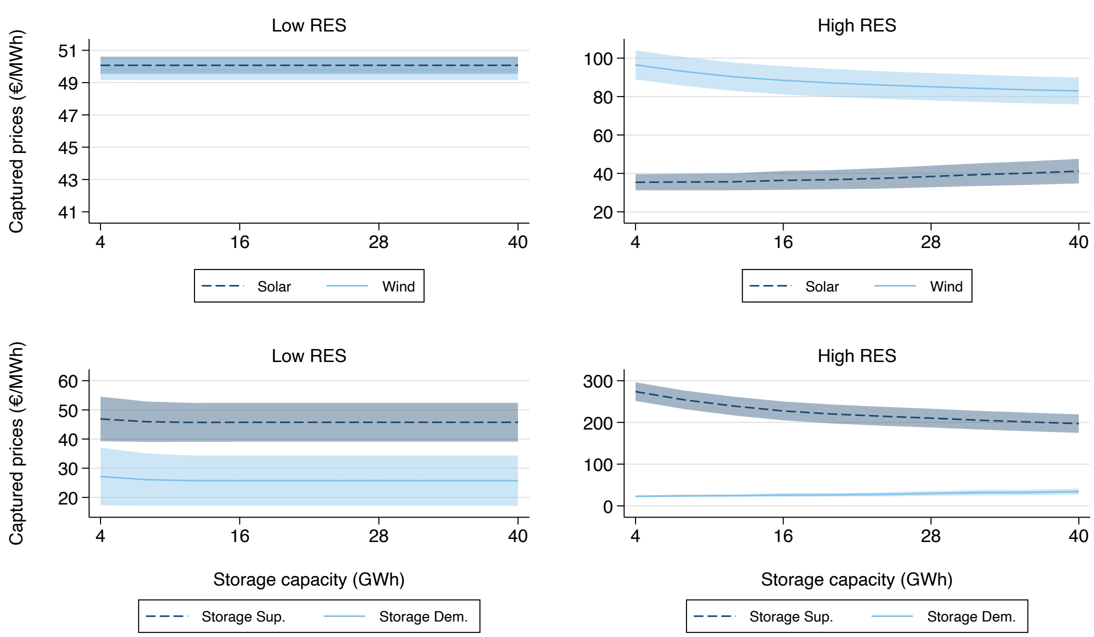
The lower panels of Figure 7 also reveal that, as expected, storage discharges at higher prices than when it charges. It also shows that the arbitrage profit is significantly larger in the high renewables scenario. Moreover, as more storage capacity is added, the cannibalization effect becomes stronger in the high renewables scenario.

Table 2 provides results on the main market outcomes in the scenarios with and without market power. When the market is perfectly competitive, the simulations uncover that (absent investment costs) storage unambiguously improves welfare. Increasing storage capacity reduces generation costs and carbon emissions while avoiding renewables curtailment, especially in the high renewables scenario. Increasing storage also benefits consumers by lowering market prices, especially in the high renewables scenario.

While most of these benefits persist even in the presence of market power, some may be reversed. For instance, firms with market power might strategically withhold solar and wind output (Fabra and Llobet, 2025), and these incentives can intensify as storage capacity increases. This behavior becomes evident as storage expands to 20 GWh in the low renewables scenario, or from 20 to 40 GWh in the high renewables scenario.

Moreover, consistent with the findings of Liski and Vehviläinen (2025), storage expansion does not always lead to lower consumer prices. In the high renewable energy scenario, increasing storage capacity from 20 to 40 GWh results in higher prices. This is again attributed to the exercise of market power, which makes the price-reducing effect of discharging be dominated by the price-increasing effect of charging. While these negative effects are economically modest, they underscore a critical insight: storage enhances market efficiency primarily when the market is competitive.

Figure 7: Captured prices by renewables and storage



Notes: This figure shows the demand-weighted average captured price by each technology per day averaged across all the days of the year for the 2019 scenario (low renewables, left panels) and the 2030 scenario (high renewables, right panels). Increases in storage capacity are shown on the x-axis. Our main result is shown in the right-upper figure, showing that the captured solar prices increase as storage capacity increases while wind prices decrease.

Table 2: Market outcomes under No Market Power and Market Power scenarios

	No Market Power			**Market Power**		
	No Storage	20 GWh	40 GWh	No Storage	20 GWh	40 GWh
Low Renewables (2019)						
Average price (€/MWh)	49.182	49.218	49.217	50.535	50.535	50.535
Generation cost (€/MWh)	18.145	18.105	18.103	18.176	18.175	18.175
CO2 emissions (Ton/MWh)	0.09979	0.09923	0.09921	0.09951	0.09950	0.09950
Excess solar (MWh/MW)	0.000	0.000	0.000	0.0111	0.0112	0.0112
Excess wind (MWh/MW)	2.0227	0.4116	0.000	11.458	10.694	10.674
High Renewables (2030)						
Average price (€/MWh)	32.539	32.346	31.925	122.245	113.971	116.161
Generation cost (€/MWh)	16.256	15.357	14.654	17.862	17.353	17.260
CO2 emissions (Ton/MWh)	0.06897	0.06223	0.05694	0.07759	0.07353	0.07265
Excess solar (MWh/MW)	88.029	55.006	34.411	154.078	136.907	144.594
Excess wind (MWh/MW)	528.320	482.883	436.871	519.973	480.566	449.284

Notes: This table compares the main simulation results with and without market power. The former assumes that there is one dominant firm owning 25% of the generation capacity. Each scenario is simulated under three storage levels (no storage, 20 GWh, and 40 GWh) and the two renewable penetration scenarios (Low: 2019; High: 2030).

7 Conclusion

This paper identifies the conditions under which renewables and storage are either strategic complements or substitutes. Specifically, we find that storage investments tend to crowd out renewable investments, and *vice versa*, when the availability of renewables is positively correlated with market prices. Conversely, when the correlation is negative, renewables and storage complement each other.

Our analysis offers novel insights into the strategic interactions between storage and renewable energy investments. It challenges conventional wisdom by demonstrating that these technologies can be strategic substitutes, particularly in the early stages of renewable deployment or in markets with multiple renewable technologies. Understanding the strategic complementarity or substitutability between renewables and storage is crucial for determining the optimal support policies, ensuring an efficient promotion of both technologies without unintended negative interactions.

Our model assumes deterministic demand and renewable generation. This simplification allows for a clear characterization of the behavior of storage while isolating the main deterministic drivers of price dynamics. An open question, however, is whether introducing stochastic elements would alter the degree of complementarity or substitutability between renewables and storage.

Intuitively, price uncertainty may lead storage operators to reserve part of their capacity to exploit unforeseen price movements, i.e., charging at unexpectedly low prices or discharging at high ones. This behavior reduces the effective capacity used to arbitrage predictable price cycles. Nonetheless, it should not fundamentally change the nature of the relationship between renewables and storage, which hinges on the sign of the correlation between prices and renewable output. That correlation is driven by the level of renewable capacity, not by the amount of storage. Verifying this intuition would require a model with stochastic components linked to renewable variability – an avenue we leave for future research.

In sum, whether renewables and storage strategically complement or substitute each other may vary from one market to another, across technologies, and over time. Policies to promote investments in renewables and storage should evolve accordingly. Our findings suggest that a significant initial push for investments in solar energy is necessary to trigger the strategic complementarity with energy storage, after which further deployment of both technologies can reinforce each other in a virtuous manner.

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Appendix

A Proofs

Proof of Lemma 1

The problem of the competitive fringe is:

$$\max_{q_F(t)} \pi_F = \int_0^{2\pi} \left(p\Big(t; q_D(t)\Big) q_F(t) - \frac{q_F^2(t)}{2(1-\beta)} \right) dt.$$

The first-order condition, which is both necessary and sufficient, is:

$$p\Big(t; q_D(t)\Big) - \frac{q_F(t)}{1-\beta} = 0 \Leftrightarrow q_F(t) = (1-\beta) p\Big(t; q_D(t)\Big), \forall t.$$

The dominant producer chooses its output in order to maximize its profits over the inverse residual demand. That is:

$$\begin{aligned} \max_{q_D(t)} \pi_D &= \int_0^{2\pi} \left(p\Big(t; q_D(t)\Big) q_D(t) - \frac{q_D^2(t)}{2\beta} \right) dt \\ &= \int_0^{2\pi} \left(\frac{ND(t, K_R) - q_D(t)}{1-\beta} q_D(t) - \frac{q_D^2(t)}{2\beta} \right) dt. \end{aligned}$$

Hence, the first-order condition of the problem is:

$$\frac{\partial \pi_D}{\partial q_D(t)} = 0 \Leftrightarrow \frac{ND(t,K_R) - 2q_D(t)}{1-\beta} - \frac{q_D(t)}{\beta} = 0$$
$$\Leftrightarrow q_D(t) = \frac{\beta}{1+\beta} ND(t,K_R), \forall t,$$

with the second-order condition satisfied. Note that the above implies:

$$q_F(t) = \frac{ND(t,K_R)}{1+\beta}, \forall t.$$

Therefore, equilibrium market prices in the absence of storage are:

$$p^{NS}(t) = \frac{ND(t,K_R)}{1-\beta^2} = \frac{1}{1-\beta^2}\left[\left(\theta - \frac{K_R}{2}\right) - \left(b - \alpha\frac{K_R}{2}\right)\sin t\right], \forall t.$$

These definitions will be used throughout the Appendix.

Proof of Lemma 3

Let us re-state Lemma 3 formally as follows, where to ease notation, we have defined

$$A(K_R) \equiv \theta - \frac{K_R}{2},$$
$$\rho(K_R) \equiv b - \alpha\frac{K_R}{2}.$$

Lemma 3 (bis) *Let charging* $\left(t \in [\underline{t}_B, \overline{t}_B]\right)$ *and discharging* $\left(t \in [\underline{t}_S, \overline{t}_S]\right)$ *periods be defined by*

$$\{\underline{t}_B, \overline{t}_B, \underline{t}_S, \overline{t}_S\} = \begin{cases} \{\tau; \pi - \tau; \pi + \tau; 2\pi - \tau\} & \text{if} \quad \rho(K_R) \geq 0 \\ \{\pi + \tau; 2\pi - \tau; \tau; \pi - \tau\} & \text{if} \quad \rho(K_R) < 0 \end{cases}$$

where $\tau \in [0, \pi/2)$ *is implicitly defined by*

$$\cos\tau - (\pi/2 - \tau)\sin\tau = K_S/|2\rho(K_R)|, \tag{A.1}$$

for $K_S \in [0, |2\rho(K_R)|]$*, and* $\tau = 0$ *otherwise.*

(i) Equilibrium storage decisions can be characterized as:

For charging periods $t \in [\underline{t}_B, \bar{t}_B]$,

$$q_B^*(t) = \begin{cases} \rho(K_R)\Big[\sin t - \sin\tau\Big] & \textit{if} \quad \rho(K_R) \geq 0 \\ \rho(K_R)\Big[\sin t + \sin\tau\Big] & \textit{if} \quad \rho(K_R) < 0 \end{cases},$$

and $q_B^*(t) = 0$ *for all other* t.
For discharging periods $t \in [\underline{t}_S, \bar{t}_S]$,

$$q_S^*(t) = \begin{cases} \rho(K_R)\Big[-\sin t - \sin\tau\Big] & \textit{if} \quad \rho(K_R) \geq 0 \\ \rho(K_R)\Big[-\sin t + \sin\tau\Big] & \textit{if} \quad \rho(K_R) < 0 \end{cases},$$

and $q_S^*(t) = 0$ *for all other* t.

(*ii*) *Equilibrium market prices are given by:*

$$p^*(t) = \begin{cases} \Big(A(K_R) - \rho(K_R)\sin\tau\Big)\Big/(1-\beta^2) & \textit{if } \tau \leq t \leq \pi - \tau \\ \Big(A(K_R) + \rho(K_R)\sin\tau\Big)\Big/(1-\beta^2) & \textit{if } \pi + \tau \leq t \leq 2\pi - \tau \\ \Big(A(K_R) - \rho(K_R)\sin t\Big)\Big/(1-\beta^2) & \textit{otherwise} \end{cases}. \qquad \text{(A.2)}$$

To prove the lemma, suppose that storage firms choose $\{q_S(t), q_B(t)\}_{t\in[0,2\pi]}$ to maximize profits:

$$\begin{aligned} \max_{q_S(t),q_B(t)} \Pi_S\Big(q_S(t), q_B(t)\Big) &= \int_0^{2\pi} p(t)\Big[q_S(t) - q_B(t)\Big]dt \\ \text{s.t.} \quad h_1\Big(q_S(t), q_B(t)\Big) &= \int_0^{2\pi} q_B(t)dt - \int_0^{2\pi} q_S(t)dt \geq 0 \\ h_2\Big(q_B(t)\Big) &= K_S - \int_0^{2\pi} q_B(t)dt \geq 0 \\ h_3\Big(q_S(t)\Big) &= q_S(t) \geq 0 \\ h_4\Big(q_B(t)\Big) &= q_B(t) \geq 0, \end{aligned}$$

The constraint set is convex, and the Slater condition is satisfied, so the Karush-Kuhn-Tucker (KKT) optimality conditions we list below apply. The Lagrangian of the problem is:

$$\begin{aligned} \mathbb{L} = &\int_0^{2\pi} p(t)\Big[q_S(t) - q_B(t)\Big]dt + \int_0^{2\pi} \eta_S(t)q_S(t)dt + \int_0^{2\pi} \eta_B(t)q_B(t)dt \\ &+ \lambda\Bigg(\int_0^{2\pi} q_B(t)dt - \int_0^{2\pi} q_S(t)dt]\Bigg) + \mu\Bigg(K_S - \int_0^{2\pi} q_B(t)dt\Bigg), \end{aligned}$$

where $\lambda, \mu, \eta_S(t)$ and $\eta_B(t)$ are the multipliers associated with their respective constraints $h_1(\cdot), h_2(\cdot), h_3(\cdot), h_4(\cdot) \geq 0$. To simplify notation, we have replaced $\mathbb{E}[q_i(t)] \equiv \int_0^{2\pi} q_i(t)dt$

for $i = \{B, S\}$. The KKT conditions are:

$$p(t) - \lambda + \eta_S(t) = 0, \forall t \tag{A.3a}$$

$$p(t) - \lambda + \mu - \eta_B(t) = 0, \forall t \tag{A.3b}$$

$$\int_0^{2\pi} q_B(t)dt - \int_0^{2\pi} q_S(t)dt \geq 0 \tag{A.3c}$$

$$K_S - \int_0^{2\pi} q_B(t)dt \geq 0 \tag{A.3d}$$

and the associated slackness conditions. These conditions are necessary and sufficient, as the constraints are linear and the objective functional Π_S is concave in $q_S(t)$ and $q_B(t)$. W.l.o.g., we can focus attention on cases where, for any $t \in [0, 2\pi]$, $q_B(t) > 0 \to q_S(t) = 0$ and $q_S(t) > 0 \to q_B(t) = 0$. We conjecture that there exist $\{\underline{t}_B, \overline{t}_B, \underline{t}_S, \overline{t}_S\} \in [0, 2\pi]$, with $\underline{t}_B < \overline{t}_B$ and $\underline{t}_S < \overline{t}_S$, such that:

$$\begin{cases} q_B(t) > 0 & \text{if} \quad \underline{t}_B < t < \overline{t}_B \\ q_B(t) = 0 & \text{o.w.} \end{cases} \quad \text{and} \quad \begin{cases} q_S(t) > 0 & \text{if} \quad \underline{t}_S < t < \overline{t}_S \\ q_S(t) = 0 & \text{o.w.} \end{cases}$$

We proceed by finding the expressions for $q_B(t)$ and $q_S(t)$. From condition (A.3a):

$$p(t) = \lambda \text{ , if } \underline{t}_S < t < \overline{t}_S, \tag{A.4}$$

and from (A.3b):

$$p(t) = \lambda - \mu \text{ , if } \underline{t}_B < t < \overline{t}_B. \tag{A.5}$$

The market price is given by the marginal cost of the thermal fringe generators,

$$p(t) = \frac{A(K_R) - \rho(K_R)\sin t - q_S(t) + q_B(t)}{1 - \beta^2}. \tag{A.6}$$

Combining equations (A.4) and (A.5) with (A.6),

$$\lambda = p(t) = \frac{A(K_R) - \rho(K_R)\sin t - q_S(t)}{1 - \beta^2} \text{ , if } \underline{t}_S < t < \overline{t}_S$$

$$\lambda - \mu = p(t) = \frac{A(K_R) - \rho(K_R)\sin t + q_B(t)}{1 - \beta^2} \text{ , if } \underline{t}_B < t < \overline{t}_B.$$

By continuity:

$$q_S(\underline{t}_S) = q_S(\bar{t}_S) = 0 \Rightarrow q_S^*(t) = \rho(K_R)\left(\sin\bar{t}_S - \sin(t)\right) \text{ , if } \underline{t}_S < t < \bar{t}_S$$
$$q_B(\underline{t}_B) = q_B(\bar{t}_B) = 0 \Rightarrow q_B^*(t) = \rho(K_R)\left(\sin t - \sin\underline{t}_B\right) \text{ , if } \underline{t}_B < t < \bar{t}_B.$$

From (A.3c) and (A.3d),

$$\int_{\underline{t}_B}^{\bar{t}_B} \rho(K_R)\left(\sin\underline{t}_B - \sin t\right) dt = \int_{\underline{t}_S}^{\bar{t}_S} \rho(K_R)\left(\sin t - \sin\bar{t}_S\right) dt = K_S. \tag{A.7}$$

By the symmetry of the sine function, $q_S(\underline{t}_S) = q_S(\bar{t}_S) = 0$ and $q_B(\underline{t}_B) = q_B(\bar{t}_B) = 0$, implying $\bar{t}_B + \underline{t}_B = \pi$ and $\bar{t}_S + \underline{t}_S = \pi$. Let

$$\{\underline{t}_B, \bar{t}_B, \underline{t}_S, \bar{t}_S\} = \begin{cases} \{\tau; \pi-\tau; \pi+\tau; 2\pi-\tau\} & \text{for} \quad \rho(K_R) \geq 0 \\ \{\pi+\tau; 2\pi-\tau; \tau; \pi-\tau\} & \text{for} \quad \rho(K_R) < 0. \end{cases}$$

Therefore, from condition (A.7) we obtain that $\tau \in [0, \pi/2)$ is implicitly given by:

$$\cos\tau - \left(\frac{\pi}{2} - \tau\right)\sin\tau = \frac{K_S}{2|\rho(K_R)|}.$$

The value of τ that solves the equation above is decreasing in $K_S/2\rho(K_R)$, it takes value $\tau = 0$ when $K_S = 2|\rho(K_R)|$, and $\tau = \frac{\pi}{2}$ when $K_S = 0$. Equilibrium market prices are:

$$p^*(t) = \begin{cases} \Big(A(K_R) - \rho(K_R)\sin\tau\Big)\Big/(1-\beta^2) & \text{if } \tau \leq t \leq \pi - \tau \\ \Big(A(K_R) + \rho(K_R)\sin\tau\Big)\Big/(1-\beta^2) & \text{if } \pi + \tau \leq t \leq 2\pi - \tau \\ \Big(A(K_R) - \rho(K_R)\sin t\Big)\Big/(1-\beta^2) & \text{otherwise} \end{cases}.$$

Proof of Proposition 1

Storage profits are:

$$\begin{aligned}
\Pi_S(K_S, K_R) &= \int_0^{2\pi} p^*(t)\Big[q_S^*(t) - q_B^*(t)\Big] dt - C_S(K_S) \\
&= \int_{\underline{t}_s}^{\bar{t}_S} p^*(\bar{t}_S) q_S^*(t) dt - \int_{\underline{t}_B}^{\bar{t}_B} p^*(\underline{t}_B) q_B^*(t) dt - C_S(K_S) \\
&= \Big[p^*(\bar{t}_S) - p^*(\underline{t}_B)\Big] K_S - C_S(K_S) \\
&= \frac{2|b - \alpha K_R/2|\sin\tau}{1-\beta^2} K_S - C_S(K_S),
\end{aligned} \tag{A.8}$$

with $\underline{t}_B, \bar{t}_B, \underline{t}_S$ and $\bar{t}_S$ defined in Lemma 3. Partially differentiating equation (A.8):

$$\begin{aligned}\frac{d\Pi_S(K_S,K_R)}{\partial K_R} &= \frac{K_S}{1-\beta^2}\Big[-\alpha\,\mathrm{sign}(2b-\alpha K_R)\sin\tau + 2|b-\alpha K_R/2|\frac{\partial\tau}{\partial K_R}\cos\tau\Big]\\ &= -\alpha\,\mathrm{sign}(2b-\alpha K_R)\frac{K_S}{1-\beta^2}\Big[\sin\tau + \frac{K_S}{2|b-\alpha K_R/2|\big(\pi/2-\tau\big)}\Big]\\ &= -\alpha\,\mathrm{sign}(2b-\alpha K_R)\frac{\cos\tau}{\pi/2-\tau}\frac{K_S}{1-\beta^2}, \qquad \text{(A.9)}\end{aligned}$$

where in the second step we have used the fact that implicitly differentiating equation ($A.1$) yields:

$$\frac{\partial\tau(K_S,K_R)}{\partial K_R} = \frac{-\alpha K_S\,\mathrm{sign}(2b-\alpha K_R)}{4(b-\alpha K_R/2)^2\big(\pi/2-\tau\big)\cos\tau},$$

and in the last step we have substituted for the value of K_S defined by equation (8). Given that $[\cos\tau/(\pi/2-\tau)]$ is positive for all $\tau\in[0.\pi/2)$, we have:

$$\frac{\partial\Pi_S}{\partial K_R} < 0 \Leftrightarrow \alpha = 1 \;\&\; K_R < 2b.$$

The profits of renewable firms are:

$$\begin{aligned}\Pi_R(K_S,K_R) =& \int_0^{2\pi} p^*(t)\frac{1}{2}\big(1-\alpha\sin t\big)K_R dt - C_R(K_R)\\ =&\frac{1}{2}\frac{K_R}{1-\beta^2}\Bigg(\int_0^{\tau}\Big[\theta-K_R/2-\big(b-\alpha K_R/2\big)\sin t\Big]\big(1-\alpha\sin t\big)dt\\ &+\int_{\tau}^{\pi-\tau}\Big[\theta-K_R/2-\big(b-\alpha K_R/2\big)\sin\tau\Big]\big(1-\alpha\sin t\big)dt\\ &+\int_{\pi-\tau}^{\pi+\tau}\Big[\theta-K_R/2-\big(b-\alpha K_R/2\big)\sin t\Big]\big(1-\alpha\sin t\big)dt\\ &+\int_{\pi+\tau}^{2\pi-\tau}\Big[\theta-K_R/2+\big(b-\alpha K_R/2\big)\sin\tau\Big]\big(1-\alpha\sin t\big)dt\\ &+\int_{2\pi-\tau}^{2\pi}\Big[\theta-K_R/2-\big(b-\alpha K_R/2\big)\sin t\Big]\big(1-\alpha\sin t\big)dt\Bigg) - C_R(K_R)\\ =&\Big[\big(\theta-K_R/2)\pi+\alpha\big(b-\alpha K_R/2\big)\big(\tau+\sin\tau\cos\tau\big)\Big]\frac{K_R}{1-\beta^2} - C_R(K_R).\end{aligned} \qquad \text{(A.10)}$$

Partially differentiating equation (A.10):

$$\begin{aligned}\frac{\partial \Pi_R(K_S, K_R)}{\partial K_S} &= \alpha\Big(b - K_R/2\Big)\frac{\partial \tau}{\partial K_S}\Big[1 + (\cos\tau)^2 - (\sin\tau)^2\Big]\frac{K_R}{1-\beta^2} \\ &= \alpha\Big(b - \alpha K_R/2\Big)\frac{(-1)}{2|b - \alpha K_R/2|(\pi/2 - \tau)\cos\tau}\Big[1 + (\cos\tau)^2 - (\sin\tau)^2\Big]\frac{K_R}{1-\beta^2} \\ &= -\alpha\,\text{sign}(2b - \alpha K_R)\frac{\cos\tau}{(\pi/2-\tau)}\frac{K_R}{1-\beta^2}, \qquad \text{(A.11)}\end{aligned}$$

wherein the second step, we have used the fact that implicitly differentiating equation (A.1) yields:

$$\frac{\partial \tau(K_S, K_R)}{\partial K_S} = \frac{(-1)}{2|b - \alpha K_R/2|(\pi/2 - \tau)\cos\tau}.$$

Given that $[\cos\tau/(\pi/2-\tau)]$ is positive for all $\tau \in [0.\pi/2)$, we have:

$$\frac{\partial \Pi_R}{\partial K_S} < 0 \Leftrightarrow \alpha = 1 \;\&\; K_R < 2b.$$

Proof of Proposition 2

It follows the same steps as the proof of Proposition 1. The main difference is that the sign of the analogs of expressions (A.9 and A.11) depends on $\text{sign}(2b - K_R^+ + K_R^-)$.

Proof of Proposition 3

From equations (A.8) and (A.10), the profits of renewable and storage firms meeting the mandates $(\bar{K}_S, \bar{K}_R)$ are given by:

$$\Pi_S(\bar{K}_S, \bar{K}_R, \eta_S) = \frac{2|b - \alpha\bar{K}_R/2|\sin\tau}{1-\beta^2}\bar{K}_S - C_S(\bar{K}_S) + \eta_S\bar{K}_S$$

$$\Pi_R(\bar{K}_S, \bar{K}_R, \eta_R) = \frac{\Big(\theta - \bar{K}_R/2)\pi + \alpha\Big(b - \alpha\bar{K}_R/2\Big)\Big(\tau + \sin\tau\cos\tau\Big)}{1-\beta^2}\bar{K}_R - C_R(\bar{K}_R) + \eta_R\bar{K}_R$$

where $\eta_i \geq 0$ for $i = \{S, R\}$ represents the per-unit of capacity subsidy to technology i. In turn, τ is a function of $\bar{K}_S$ and $\bar{K}_R$, implicitly given by equation (8). The free entry condition implies zero profits, so equilibrium investment subsidies (η_S^*, η_R^*) are given by:

$$\eta_S^*(\bar{K}_S, \bar{K}_R) = \max\left\{\frac{C_S(\bar{K}_S)}{\bar{K}_S} - \frac{2|b-\alpha\bar{K}_R/2|\sin\tau}{1-\beta^2}, 0\right\} \tag{A.12}$$

$$\eta_R^*(\bar{K}_S, \bar{K}_R) = \max\left\{\frac{C_R(\bar{K}_R)}{\bar{K}_R} - \frac{\Big(\theta-\bar{K}_R/2)\pi + \alpha\Big(b-\alpha\bar{K}_R/2\Big)\Big(\tau+\sin\tau\cos\tau\Big)}{1-\beta^2}, 0\right\} \tag{A.13}$$

In the rest of this proof, we assume that mandates $(\bar{K}_S, \bar{K}_R)$ are high enough to guarantee that investment subsidies η_S^* and η_R^* are strictly positive. Differentiation gives:

$$\begin{aligned}
\frac{\partial\eta_S^*(\bar{K}_S, \bar{K}_R)}{\partial\bar{K}_S} =& \frac{C_S'(\bar{K}_S)\bar{K}_S - C(\bar{K}_S)}{\bar{K}_S^2} - \frac{2|b-\alpha\bar{K}_R/2|\cos\tau}{1-\beta^2}\frac{\partial\tau(\bar{K}_S, \bar{K}_R)}{\partial\bar{K}_S} \\
=& \frac{C_S'(\bar{K}_S)\bar{K}_S - C(\bar{K}_S)}{\bar{K}_S^2} - \frac{2|b-\alpha\bar{K}_R/2|\cos\tau}{1-\beta^2}\frac{(-1)}{2|b-\alpha\bar{K}_R/2|(\pi/2-\tau)\cos\tau} \\
=& \frac{C_S'(\bar{K}_S)\bar{K}_S - C(\bar{K}_S)}{\bar{K}_S^2} + \frac{1}{\pi/2-\tau}\frac{1}{1-\beta^2} > 0. \\
\frac{\partial\eta_R^*(\bar{K}_S, \bar{K}_R)}{\partial\bar{K}_R} =& \frac{C_R'(\bar{K}_R)\bar{K}_R - C(\bar{K}_R)}{\bar{K}_R^2} + \frac{\pi+\tau+\sin\tau\cos\tau}{2}\frac{1}{1-\beta^2} \\
& - \alpha\Big(b-\alpha\bar{K}_R/2\Big)\Big(1-(\cos\tau)^2+(\sin\tau)^2\Big)\frac{1}{1-\beta^2}\frac{\partial\tau(\bar{K}_S, \bar{K}_R)}{\partial\bar{K}_R} \\
=& \frac{C_R'(\bar{K}_R)\bar{K}_R - C(\bar{K}_R)}{\bar{K}_R^2} + \frac{1}{1-\beta^2}\Bigg(\frac{\pi+\tau+\sin\tau\cos\tau}{2} \\
& + \Big(b-\alpha\bar{K}_R/2\Big)\Big(1-(\cos\tau)^2+(\sin\tau)^2\Big)\frac{\bar{K}_S\,\mathrm{sign}(2b-\alpha\bar{K}_R)}{4(b-\alpha\bar{K}_R/2)^2\Big(\pi/2-\tau\Big)\cos\tau}\Bigg) \\
=& \frac{C_R'(\bar{K}_R)\bar{K}_R - C(\bar{K}_R)}{\bar{K}_R^2} \\
& + \frac{1}{1-\beta^2}\Bigg(\frac{\pi+\tau+\sin\tau\cos\tau}{2} + \frac{\cos\tau\Big[\cos\tau - \sin\tau(\pi/2-\tau)\Big]}{\pi/2-\tau}\Bigg) > 0.
\end{aligned}$$

with τ implicitly given by equation (8). In the last step of the second expression, we have substituted $\bar{K}_S$ with equation (8). To determine the sign these expressions, we have relied on $\tau \in [0, \pi/2)$ and on the convexity of the cost function, which implies $C'(\bar{K}_i) > C(\bar{K}_i)/\bar{K}_i$ for $i = \{S, R\}$.

We also have:

$$
\begin{aligned}
\frac{\partial \eta_S^*(\bar{K}_S,\bar{K}_R)}{\partial \bar{K}_R} =& \Big(2|b-\alpha\bar{K}_R/2|\cos\tau\frac{\partial\tau(\bar{K}_S,\bar{K}_R)}{\partial\bar{K}_R}+\frac{\alpha}{2}\operatorname{sign}(2b-\alpha\bar{K}_R)\sin\tau\Big)\frac{(-1)}{1-\beta^2}\\
=& \Big(2|b-\alpha\bar{K}_R/2|\cos\tau\frac{-\alpha\bar{K}_S\operatorname{sign}(2b-\alpha\bar{K}_R)}{4(b-\alpha\bar{K}_R/2)^2\big(\pi/2-\tau\big)\cos\tau}+\frac{\alpha}{2}\operatorname{sign}(2b-\alpha\bar{K}_R)\sin\tau\Big)\frac{(-1)}{1-\beta^2}\\
=& \alpha\operatorname{sign}(2b-\alpha\bar{K}_R)\frac{\cos\tau}{(\pi/2-\tau)}\frac{1}{1-\beta^2}.\\
\frac{\partial \eta_R^*(\bar{K}_S,\bar{K}_R)}{\partial \bar{K}_S} =& \Big(-\alpha(b-\alpha\bar{K}_R/2)\Big(1-(\cos\tau)^2+(\sin\tau)^2\Big)\frac{\partial\tau(\bar{K}_S,\bar{K}_R)}{\partial\bar{K}_S}\Big)\frac{(-1)}{1-\beta^2}\\
=& \Big(-\alpha(b-\alpha\bar{K}_R/2)\Big(1-(\cos\tau)^2+(\sin\tau)^2\Big)\frac{(-1)}{2|b-\alpha\bar{K}_R/2|(\pi/2-\tau)\cos\tau}\Big)\frac{(-1)}{1-\beta^2}\\
=& \alpha\operatorname{sign}(2b-\alpha\bar{K}_R)\frac{\cos\tau}{(\pi/2-\tau)}\frac{1}{1-\beta^2}.
\end{aligned}
$$

Therefore, it follows that

$$
\begin{aligned}
\frac{\partial \eta_i^*(\bar{K}_S,\bar{K}_R)}{\partial \bar{K}_i}\Big|_{(\eta_S^*,\eta_R^*)} &> 0,\\
\frac{\partial \eta_i^*(\bar{K}_S,\bar{K}_R)}{\partial \bar{K}_j}\Big|_{(\eta_S^*,\eta_R^*)} &> 0 \Leftrightarrow \alpha=1 \text{ and } \bar{K}_R<2b.
\end{aligned}
$$

Proof of Proposition 4

The regulator's problem can be written as:

$$
\begin{aligned}
\min_{\bar{K}_S,\bar{K}_R} \Phi(\bar{K}_S,\bar{K}_R) \equiv & \int_0^{2\pi} e\Big(q^*(t)\Big)dt\\
\text{s.t. } & \eta_S^*(\bar{K}_S,\bar{K}_R)\bar{K}_S+\eta_R^*(\bar{K}_S,\bar{K}_R)\bar{K}_R \le B,
\end{aligned}
$$

where $q^*(t)$ is defined in Lemma 2 and $\eta_S^*>0$ and $\eta_R^*>0$ are implicitly defined by $\Pi_S(\bar{K}_S,\bar{K}_R,\eta_S^*)=0$ and $\Pi_R(\bar{K}_S,\bar{K}_R,\eta_R^*)=0$. We first show that the solution to this problem always involves setting $\bar{K}_R^*\ge 2b$ when $\alpha=1$ and $B\ge\bar{B}$, where $\bar{B}$ is the minimum budget that allows to mandate $\bar{K}_R=2b$, i.e., $\bar{B}=C_R(2b)-(\theta-b)\pi 2b$. Suppose the regulator chooses $\bar{K}_R<2b$ with the remaining budget allocated to mandate $\bar{K}_S$. Since $\partial\Phi/\partial\bar{K}_S<0$, the largest reduction in emissions occurs when K_S fully flattens emissions, i.e., when the budget is large enough to mandate $\bar{K}_S=\tilde{K}_S(\bar{K}_R)=2|b-\bar{K}_R/2|$.

Total emissions are given by:

$$\Phi(\bar{K}_S, \bar{K}_R) = \int_0^{2\pi} e\Big(\theta - \frac{\bar{K}_R}{2}\Big) dt = 2\pi e\Big(\theta - \frac{\bar{K}_R}{2}\Big).$$

Since these emissions are decreasing in $\bar{K}_R$, they are minimized at $\bar{K}_R = 2b$ and $\bar{K}_S = 0$. Therefore, with a sufficiently large budget, any optimal solution must involve $\bar{K}_R^* \geq 2b$. We now turn to the second part of the proposition. First, total emissions as a function of (binding) technology mandates, are given by:

$$\begin{aligned}\Phi(\bar{K}_S, \bar{K}_R) = &\int_0^{\tau} e\Big(A(\bar{K}_R) - \rho(\bar{K}_R)\sin t\Big) dt + \int_{\tau}^{\pi-\tau} e\Big(A(\bar{K}_R) - \rho(\bar{K}_R)\sin \tau\Big) dt \\ &+ \int_{\pi-\tau}^{\pi+\tau} e\Big(A(\bar{K}_R) - \rho(\bar{K}_R)\sin t\Big) dt + \int_{\pi+\tau}^{2\pi-\tau} e\Big(A(\bar{K}_R) + \rho(\bar{K}_R)\sin \tau\Big) dt \\ &+ \int_{2\pi-\tau}^{2\pi} e\Big(A(\bar{K}_R) - \rho(\bar{K}_R)\sin t\Big) dt.\end{aligned}$$

First, we have:

$$\begin{aligned}\frac{\partial \Phi(\bar{K}_S, \bar{K}_R)}{\partial \bar{K}_S} &= \int_{\tau}^{\pi-\tau} -e'\Big(A(\bar{K}_R) - \rho(\bar{K}_R)\sin \tau\Big)\rho(\bar{K}_R)\cos\tau \frac{\partial \tau}{\partial \bar{K}_S} dt \\ &+ \int_{\pi+\tau}^{2\pi-\tau} e'\Big(A(\bar{K}_R) + \rho(\bar{K}_R)\sin \tau\Big)\rho(\bar{K}_R)\cos\tau \frac{\partial \tau}{\partial \bar{K}_S} dt \\ &= \rho(\bar{K}_R)\cos\tau \frac{\partial \tau}{\partial \bar{K}_S}(\pi - 2\tau)\Big[e'\Big(A(\bar{K}_R) + \rho(\bar{K}_R)\sin\tau\Big) - e'\Big(A(\bar{K}_R) - \rho(\bar{K}_R)\sin\tau\Big)\Big] \\ &= \text{sign}(2b - \bar{K}_R)\Big[e'\Big(A(\bar{K}_R) - \rho(\bar{K}_R)\sin\tau\Big) - e'\Big(A(\bar{K}_R) + \rho(\bar{K}_R)\sin\tau\Big)\Big] < 0.\end{aligned}$$

In order to compute the cross-derivative, note that:

$$\begin{aligned}\frac{\partial\Big[e'\Big(A(\bar{K}_R) - \rho(\bar{K}_R)\sin\tau\Big)\Big]}{\partial \bar{K}_R} &= e''\Big(A(\bar{K}_R) - \rho(\bar{K}_R)\sin\tau\Big)\left(\frac{1}{2}(\sin\tau - 1) - \rho(\bar{K}_R)\cos\tau\frac{\partial\tau}{\partial \bar{K}_R}\right) \\ &= \frac{e''\Big(A(\bar{K}_R) - \rho(\bar{K}_R)\sin\tau\Big)}{2}\left(\frac{\cos\tau}{\pi/2 - \tau} - 1\right). \\ \frac{\partial\Big[e'\Big(A(\bar{K}_R) + \rho(\bar{K}_R)\sin\tau\Big)\Big]}{\partial \bar{K}_R} &= e''\Big(A(\bar{K}_R) - \rho(\bar{K}_R)\sin\tau\Big)\left(\frac{1}{2}(-\sin\tau - 1) + \rho(\bar{K}_R)\cos\tau\frac{\partial\tau}{\partial \bar{K}_R}\right) \\ &= \frac{e''\Big(A(\bar{K}_R) - \rho(\bar{K}_R)\sin\tau\Big)}{2}\left(\frac{-\cos\tau}{\pi/2 - \tau} - 1\right).\end{aligned}$$

To ease notation, in what follows we remove the explicit reference to the dependence of $A(\bar{K}_R)$ and $\rho(\bar{K}_R)$ on $\bar{K}_R$. Then, we have:

$$\frac{\partial^2\Phi(\bar{K}_S,\bar{K}_R)}{\partial\bar{K}_S\partial\bar{K}_R} = \text{sign}(2b-\alpha\bar{K}_R)\left[\left(\frac{\cos\tau}{\pi-2\tau}+\frac{1}{2}\right)e''\Big(A+\rho\sin\tau\Big)+\left(\frac{\cos\tau}{\pi-2\tau}-\frac{1}{2}\right)e''\Big(A-\rho\sin\tau\Big)\right].$$

Since $[\cos\tau/(\pi-2\tau)]>0$ for all $\tau\in[0,\pi/2)$, and since $[A+\rho\sin\tau]>[A-\rho\sin\tau]$ is positive when $\bar{K}_R<2b$, we have that $\partial^2\Phi(\bar{K}_S,\bar{K}_R)/\partial\bar{K}_S\partial\bar{K}_R>0$ for all $\bar{K}_S$ and all $\bar{K}_R<2b$. For the case when $\bar{K}_R>2b$, we define:

$$G(\bar{K}_S,\bar{K}_R)\equiv\left(\frac{\cos\tau}{\pi/2-\tau}+1\right)e''\Big(A+\rho\sin\tau\Big)+\left(\frac{\cos\tau}{\pi/2-\tau}-1\right)e''\Big(A-\rho\sin\tau\Big).$$

Then, we have:

$$\begin{aligned}\frac{\partial G(\bar{K}_S,\bar{K}_R)}{\partial\bar{K}_S}=&\frac{\partial\tau(\bar{K}_S,\bar{K}_R)}{\partial\bar{K}_S}\Bigg(\frac{\cos\tau-(\pi/2-\tau)\sin\tau}{(\pi/2-\tau)^2}\left[e''\Big(A+\rho\sin\tau\Big)+e''\Big(A-\rho\sin\tau\Big)\right]\\&+\rho\cos\tau\left[\left(\frac{\cos\tau}{\pi/2-\tau}+1\right)e'''\Big(A+\rho\sin\tau\Big)+\left(\frac{\cos\tau}{\pi/2-\tau}-1\right)e'''\Big(A-\rho\sin\tau\Big)\right]\Bigg)<0,\end{aligned}$$

where the negative sign comes from the fact that $\partial\tau/\partial\bar{K}_S<0$, from $e'''(q)\leq 0$, and from $\rho(\bar{K}_R)<0$ for $\bar{K}_R<2b$. Therefore, the function $G(\bar{K}_S,\bar{K}_R)$ is minimized at $\bar{K}_S=\tilde{K}_S$ for all $\bar{K}_R>2b$. Evaluating $G(\bar{K}_S,\bar{K}_R)$ at $\bar{K}_S=\tilde{K}_S$, we get:

$$G(\tilde{K}_S,\bar{K}_R)=\frac{2}{\pi}e''\Big(A(\bar{K}_R)\Big),$$

which is strictly positive for all $\bar{K}_R\in(2b,\theta-b]$. Combining all previous results, we have that $G(\bar{K}_S,\bar{K}_R)$ is always strictly positive, so

$$\frac{\partial^2\Phi(\bar{K}_S,\bar{K}_R)}{\partial\bar{K}_S\partial\bar{K}_R}>0\Leftrightarrow\bar{K}_R<2b.$$

Proof of Lemma 5

We state the Lemma more formally as follows, where to ease notation, recall that we have defined

$$A(K_R)\equiv\theta-\frac{K_R}{2},$$
$$\rho(K_R)\equiv b-\alpha\frac{K_R}{2}.$$

Lemma 5 (bis) *Let charging* $\left(t \in [\underline{t}_B, \overline{t}_B]\right)$ *and discharging* $\left(t \in [\underline{t}_S, \overline{t}_S]\right)$ *periods be defined by*

$$\{\underline{t}_B, \overline{t}_B, \underline{t}_S, \overline{t}_S\} = \begin{cases} \left\{\tau^M; \pi - \tau^M; \pi + \tau^M; 2\pi - \tau^M\right\} & if \quad \rho(K_R) \geq 0 \\ \left\{\pi + \tau^M; 2\pi - \tau^M; \tau^M; \pi - \tau^M\right\} & if \quad \rho(K_R) < 0 \end{cases}$$

where $\tau^M \in [0, \pi/2)$ *is implicitly defined by*

$$\cos\tau^M - (\pi/2 - \tau^M)\sin\tau^M = \frac{K_S}{|\rho(K_R)|},$$

for $K_S \in [0, |\rho(K_R)|]$, *and* $\tau^M = 0$ *otherwise.*

(i) *Equilibrium storage decisions are:*
For charging periods $t \in [\underline{t}_B, \overline{t}_B]$,

$$q_B^M(t) = \begin{cases} \rho(K_R)\left[\sin t - \sin\tau^M\right]/2 & if \quad \rho(K_R) \geq 0 \\ \rho(K_R)\left[\sin t + \sin\tau^M\right]/2 & if \quad \rho(K_R) < 0 \end{cases},$$

and $q_B^M(t) = 0$ *for all other* t.
For discharging periods $t \in [\underline{t}_S, \overline{t}_S]$,

$$q_S^M(t) = \begin{cases} \rho(K_R)\left[-\sin t - \sin\tau^M\right]/2 & if \quad \rho(K_R) \geq 0 \\ \rho(K_R)\left[-\sin t + \sin\tau^M\right]/2 & if \quad \rho(K_R) < 0 \end{cases},$$

and $q_S^M(t) = 0$ *for all other* t.

(ii) *Equilibrium market prices are given by:*

$$p^M(t) = \begin{cases} A(K_R) - \rho(K_R)\left(\sin t + \sin\tau^M\right)/2 & if\ \tau^M \leq t \leq \pi - \tau^M \\ A(K_R) - \rho(K_R)\left(\sin t - \sin\tau^M\right)/2 & if\ \pi + \tau^M \leq t \leq 2\pi - \tau^M \\ A(K_R) - \rho(K_R)\sin t & otherwise \end{cases}.$$

To prove it, note that the problem of the storage monopolist is:

$$\max_{q_S(t), q_B(t)} \int_0^{2\pi} \left(D(t) - \omega(t)K_R - q_S(t) + q_B(t)\right)\left(q_S(t) - q_B(t)\right)dt$$

subject to constraints (7) and (8). The structure of the functional optimization problem is identical to the problem of a competitive storage firm. In particular, the optimization problem is convex, so the KKT conditions that we list below are necessary and sufficient. The Lagrangian of the problem, omitting the non-negativity constraints, is given by:

$$\begin{aligned}\mathbb{L} = &\int_0^{2\pi} \Big(A(K_R) - \rho(K_R)\sin t + q_B(t) - q_S(t)\Big)\Big(q_S(t) - q_B(t)\Big)dt \\ &+ \lambda\bigg(\int_0^{2\pi} q_B(t)dt - \int_0^{2\pi} q_S(t)dt]\bigg) + \mu\bigg(K_S - \int_0^{2\pi} q_B(t)dt\bigg),\end{aligned}$$

where λ and μ are the multipliers. W.l.o.g., we can focus attention on cases where, for any $t \in [0, 2\pi]$, $q_B(t) > 0 \to q_S(t) = 0$ and $q_S(t) > 0 \to q_B(t) = 0$. The KKT conditions are:

$$A(K_R) - \rho(K_R)\sin t - 2q_S(t) - \lambda = 0, \forall t \tag{A.14a}$$

$$A(K_R) - \rho(K_R)\sin t + 2q_B(t) - \lambda + \mu = 0, \forall t \tag{A.14b}$$

$$\int_0^{2\pi} q_B(t)dt - \int_0^{2\pi} q_S(t)dt \geq 0 \tag{A.14c}$$

$$K_S - \int_0^{2\pi} q_B(t)dt \geq 0 \tag{A.14d}$$

and the associated slackness conditions. These conditions are necessary and sufficient, as the constraints are linear and the objective functional is concave in $q_S(t)$ and $q_B(t)$. We proceed by finding the expressions for the reaction functions $q_B(t)$ and $q_S(t)$. From condition (A.14a):

$$q_S(t) = \frac{A(K_R) - \rho(K_R)\sin t - \lambda}{2}, \text{ if } \underline{t}_S < t < \bar{t}_S,$$

and from (A.14b):

$$q_B(t) = \frac{-A(K_R) + \rho(K_R)\sin t + (\lambda - \mu)}{2}, \text{ if } \underline{t}_B < t < \bar{t}_B.$$

By continuity:

$$\begin{aligned} q_S(\underline{t}_S) = q_S(\bar{t}_S) = 0 \Rightarrow q_S^M(t) = \rho(K_R)\frac{\sin \bar{t}_S - \sin(t)}{2}, \text{ if } \underline{t}_S < t < \bar{t}_S \\ q_B(\underline{t}_B) = q_B(\bar{t}_B) = 0 \Rightarrow q_B^M(t) = \rho(K_R)\frac{\sin t - \sin \underline{t}_B}{2}, \text{ if } \underline{t}_B < t < \bar{t}_B. \end{aligned}$$

From (A.14c) and (A.14d),

$$\int_{\underline{t}_B}^{\bar{t}_B} \rho(K_R)\frac{\sin t - \sin \underline{t}_B}{2}dt = \int_{\underline{t}_S}^{\bar{t}_S} \rho(K_R)\frac{\sin \bar{t}_S - \sin(t)}{2}dt = K_S. \tag{A.15}$$

By the symmetry of the sine function, $q_S(\underline{t}_S) = q_S(\bar{t}_S) = 0$ and $q_B(\underline{t}_B) = q_B(\bar{t}_B) = 0$, implying $\bar{t}_B + \underline{t}_B = \pi$ and $\bar{t}_S + \underline{t}_S = \pi$. Let

$$\{\underline{t}_B, \bar{t}_B, \underline{t}_S, \bar{t}_S\} = \begin{cases} \left\{\tau^M; \pi - \tau^M; \pi + \tau^M; 2\pi - \tau^M\right\} & \text{for} \quad \rho(K_R) \geq 0 \\ \left\{\pi + \tau^M; 2\pi - \tau^M; \tau^M; \pi - \tau^M\right\} & \text{for} \quad \rho(K_R) < 0. \end{cases}$$

Therefore, from condition (A.15) we obtain that $\tau^M \in [0, \pi/2)$ is implicitly given by:

$$\cos\tau^M - \left(\frac{\pi}{2} - \tau^M\right)\sin\tau^M = \frac{K_S}{|\rho(K_R)|}. \tag{A.16}$$

Equilibrium market prices are given by:

$$p^M(t) = \begin{cases} A(K_R) - \rho(K_R)\frac{\sin t + \sin\tau^M}{2} & \text{if } \tau^M \leq t \leq \pi - \tau^M \\ A(K_R) - \rho(K_R)\frac{\sin t - \sin\tau^M}{2} & \text{if } \pi + \tau^M \leq t \leq 2\pi - \tau^M \\ A(K_R) - \rho(K_R)\sin t & \text{otherwise} \end{cases}.$$

Proof of Proposition 5

The profits of the storage profits monopolist are:

$$\begin{aligned}
\Pi_S^M =& \int_0^{2\pi} p^M(t)\left[q_S^M(t) - q_B^M(t)\right]dt - C_S(K_S) \\
=& \int_{\underline{t}_s}^{\bar{t}_S} p^M(\bar{t}_S)q_S^M(t)dt - \int_{\underline{t}_B}^{\bar{t}_B} p^M(\underline{t}_B)q_B^M(t)dt - C_S(K_S) \\
=& \int_{\pi+\tau^M}^{2\pi-\tau^M} \left(A(K_R) - \rho(K_R)\frac{\sin t - \sin\tau^M}{2}\right)\rho(K_R)\frac{-\sin t - \sin\tau^M}{2}dt \\
&- \int_{\tau^M}^{\pi-\tau^M} \left(A(K_R) - \rho(K_R)\frac{\sin t + \sin\tau^M}{2}\right)\rho(K_R)\frac{\sin t - \sin\tau^M}{2}dt - C_S(K_S) \\
=& \frac{1}{2}\rho(K_R)^2\left[(\pi/2 - \tau^M)\cos 2\tau^M + \sin\tau^M\cos\tau^M\right] - C_S(K_S).
\end{aligned} \tag{A.17}$$

Partially differentiating equation (A.17):

$$\frac{\partial\Pi_S(K_S, K_R)}{\partial K_R} = -\alpha\rho(K_R)\left(\pi/2 - \tau^M - \sin\tau^M\cos\tau^M\right), \tag{A.18}$$

where we have used the fact that implicitly differentiating equation ($A.16$) yields:

$$\frac{\partial \tau^M(K_S,K_R)}{\partial K_R} = \frac{-\alpha K_S \operatorname{sign}(2b-\alpha K_R)}{(b-\alpha K_R/2)^2\Big(\pi/2-\tau^M\Big)\cos\tau^M}.$$

Given that $\left(\pi/2-\tau^M-\sin\tau^M\cos\tau^M\right)$ is positive for all $\tau^M \in [0.\pi/2)$, we have:

$$\frac{\partial \Pi_S^M}{\partial K_R} < 0 \Leftrightarrow \alpha = 1 \;\&\; K_R < 2b.$$

The profits of renewable firms when storage is in the hands of a monopolist are:

$$\begin{aligned}
\Pi_R^M =& \int_0^{2\pi} p^M(t)\frac{1}{2}\Big(1-\alpha\sin t\Big)K_R dt - C_R(K_R)\\
=& \frac{1}{2}K_R\Bigg(\int_0^{\tau^M}\Big(A(K_R)-\rho(K_R)\sin t\Big)\Big(1-\alpha\sin t\Big)dt\\
&+\int_{\tau^M}^{\pi-\tau^M}\Bigg(A(K_R)-\rho(K_R)\frac{\sin t+\sin\tau^M}{2}\Bigg)\Big(1-\alpha\sin t\Big)dt\\
&+\int_{\pi-\tau^M}^{\pi+\tau^M}\Big(A(K_R)-\rho(K_R)\sin t\Big)\Big(1-\alpha\sin t\Big)dt\\
&+\int_{\pi+\tau^M}^{2\pi-\tau^M}\Bigg(A(K_R)-\rho(K_R)\frac{\sin t-\sin\tau^M}{2}\Bigg)\Big(1-\alpha\sin t\Big)dt\\
&+\int_{2\pi-\tau^M}^{2\pi}\Big(A(K_R)-\rho(K_R)\sin t\Big)\Big(1-\alpha\sin t\Big)dt\Bigg) - C_R(K_R). \qquad (A.19)
\end{aligned}$$

Partially differentiating equation (A.19) (applying Leibniz's integral rule and dropping terms that cancel out):

$$\frac{\partial \Pi_R^M(K_S,K_R)}{\partial K_S} = -\alpha \operatorname{sign}(2b-\alpha K_R)K_R\frac{\cos\tau^M}{\pi/2-\tau^M},$$

where in the second step, we have used the fact that implicitly differentiating equation ($A.16$) yields:

$$\frac{\partial \tau^M(K_S,K_R)}{\partial K_S} = \frac{-1}{|b-\alpha K_R/2|(\pi/2-\tau^M)\cos\tau^M}.$$

Therefore, we have:

$$\frac{\partial \Pi_R^M}{\partial K_S} < 0 \Leftrightarrow \alpha = 1 \;\&\; K_R < 2b.$$

Proof of Lemma 6

The problem of the storage monopolist is to choose K_S to maximize profits, conditional on operating storage optimally at the production stage. Note that any optimal K_S must fall on the interval $\left[0, \tilde{K}_S\right]$, where $\tilde{K}_S = |\rho(\bar{K}_R)|$. Thus, the problem is:

$$\begin{aligned}
\max_{K_S \in [0, \tilde{K}_S]} \Pi_S^M &= \int_{\underline{0}}^{2\pi} p^M(t; K_S, \bar{K}_R)\Big(q_S^M(t; K_S, \bar{K}_R) - q_B^M(t; K_S, \bar{K}_R)\Big) dt - c_S K_S \\
&= \int_{\pi+\tau^M}^{2\pi-\tau^M} \left(A(\bar{K}_R) - \rho(\bar{K}_R)\frac{\sin t - \sin \tau^M}{2}\right)\rho(\bar{K}_R)\frac{-\sin t - \sin \tau^M}{2} dt \\
&\quad - \int_{\tau^M}^{\pi-\tau^M} \left(A(\bar{K}_R) - \rho(\bar{K}_R)\frac{\sin t + \sin \tau^M}{2}\right)\rho(\bar{K}_R)\frac{\sin t - \sin \tau^M}{2} dt - c_S K_S
\end{aligned}$$

where τ^M is a function of $\bar{K}_R$ and K_S implicitly given by:

$$\cos \tau^M - \left(\frac{\pi}{2} - \tau^M\right) \sin \tau^M = \frac{K_S}{|\rho(\bar{K}_R)|}. \tag{A.20}$$

Note that the objective function is a continuously differentiable function. Moreover, $[0, \tilde{K}_S]$ is closed, bounded and compact, so the solution set to the problem is non-empty. Therefore, the unique interior solution K_S^M is given by:

$$\frac{\partial \Pi_S^M(K_S, K_R)}{\partial K_S} = 0 \Leftrightarrow 2|\rho(\bar{K}_R)| \sin \tau^M(K_S^M, \bar{K}_R) - c_s = 0. \tag{A.21}$$

with $\tau^M(K_S^M, \bar{K}_R)$ implicitly given by equation (A.20). Moreover, the second order condition is satisfied:

$$\begin{aligned}
\frac{\partial^2 \Pi_S^M(K_S, \bar{K}_R)}{\partial K_S^2} &= 2|\rho(\bar{K}_R)| \cos \tau^M(K_S^M, \bar{K}_R) \frac{\partial \tau^M(K_S, \bar{K}_R)}{\partial K_S} \\
&= \frac{-2}{(\pi/2 - \tau^M\big(K_S, \bar{K}_R\big)} < 0,
\end{aligned}$$

for all $K_S \in [0, \tilde{K}_S]$. Thus, K_S^M is the unique global maximum, which is interior for c_S sufficiently small.

We now turn to compare the investment condition of the storage monopolist with the one for the competitive storage firm. From the proof of Proposition 1, the profits of competitive storage firms at the investment stage when there is no market power in generation (i.e., $\beta = 0$) and investment costs are linear are given by:

$$\Pi_S^C(K_S, \bar{K}_R) = 2|\rho(\bar{K})| \sin \tau^C(K_S, \bar{K}_R) K_S - c_s K_S.$$

with $\tau^C(K_S, \bar{K}_R)$ implicitly given by equation:

$$\cos \tau^C - \left(\frac{\pi}{2} - \tau^C\right) \sin \tau^C = \frac{K_S}{2|\rho(\bar{K}_R)|}. \tag{A.22}$$

Storage firms enter the market until their profits become zero. Therefore, equilibrium competitive storage investment K_S^C given by:

$$\Pi_S^C(K_S^C, \bar{K}_R) = 0 \Leftrightarrow 2|\rho(\bar{K}_R)| \sin \tau^C(K_S^C, \bar{K}_R) - c_s = 0. \tag{A.23}$$

with $\tau^C(K_S^C, \bar{K}_R)$ implicitly given by equation ($A.22$).
Comparing equations ($A.21$) and ($A.23$), since the left hand-side of these equations is monotonically decreasing in τ, it is straightforward to determine that:

$$\tau^M(K_S, \bar{K}_R) < \tau^C(K_S, \bar{K}_R) \Rightarrow \sin \tau^M(K_S, \bar{K}_R) < \sin \tau^C(K_S, \bar{K}_R) \Rightarrow K_S^M(\bar{K}_R) < K_S^C(\bar{K}_R).$$

Proof of Lemma 7

Assuming the renewable mandate $\bar{K}_R$ is above the level of renewable capacity that would enter the market in the absence of renewable subsidies, from equations ($A.10$) (for the case where $\beta = 0$) and equation ($A.19$), we have that the per-unit investment subsides needed to reach $\bar{K}_R$ under competitive and monopoly storage are:

$$\begin{aligned}
\eta_R^C(K_S^C,\bar{K}_R) = \frac{c_R(\bar{K}_R)}{\bar{K}_R} - \frac{1}{2}\bigg(& \int_0^{\tau^C} \Big[A(\bar{K}_R) - \rho(\bar{K}_R)\sin t\Big]\Big(1-\alpha\sin t\Big)dt \\
& + \int_{\tau^C}^{\pi-\tau^C} \Big[A(\bar{K}_R) - \rho(\bar{K}_R)\sin\tau^C\Big]\Big(1-\alpha\sin t\Big)dt \\
& + \int_{\pi-\tau^C}^{\pi+\tau^C} \Big[A(\bar{K}_R) - \rho(\bar{K}_R)\sin t\Big]\Big(1-\alpha\sin t\Big)dt \\
& + \int_{\pi+\tau^C}^{2\pi-\tau^C} \Big[A(\bar{K}_R) + \rho(\bar{K}_R)\sin\tau^C\Big]\Big(1-\alpha\sin t\Big)dt \\
& + \int_{2\pi-\tau^C}^{2\pi} \Big[A(\bar{K}_R) - \rho(\bar{K}_R)\sin t\Big]\Big(1-\alpha\sin t\Big)dt\bigg) \\
\eta_R^M(K_S^M,\bar{K}_R) = \frac{c_R(\bar{K}_R)}{\bar{K}_R} - \frac{1}{2}\bigg(& \int_0^{\tau^M} \Big(A(\bar{K}_R) - \rho(\bar{K}_R)\sin t\Big)\Big(1-\alpha\sin t\Big)dt \\
& + \int_{\tau^M}^{\pi-\tau^M} \left(A(\bar{K}_R) - \rho(\bar{K}_R)\frac{\sin t+\sin\tau^M}{2}\right)\Big(1-\alpha\sin t\Big)dt \\
& + \int_{\pi-\tau^M}^{\pi+\tau^M} \Big(A(\bar{K}_R) - \rho(\bar{K}_R)\sin t\Big)\Big(1-\alpha\sin t\Big)dt \\
& + \int_{\pi+\tau^M}^{2\pi-\tau^M} \left(A(\bar{K}_R) - \rho(\bar{K}_R)\frac{\sin t-\sin\tau^M}{2}\right)\Big(1-\alpha\sin t\Big)dt \\
& + \int_{2\pi-\tau^M}^{2\pi} \Big(A(\bar{K}_R) - \rho(\bar{K}_R)\sin t\Big)\Big(1-\alpha\sin t\Big)dt\bigg).
\end{aligned}$$

From equations ($A.21$) and ($A.23$), we have that, for a given a renewable mandate $\bar{K}_R$, equilibrium investments in storage capacity under competitive and monopoly storage are (assuming they are strictly positive):

$$\begin{aligned}
c_S &= 2|\rho(\bar{K}_R)|\sin\tau^C(K_S^C,\bar{K}_R) \\
c_S &= 2|\rho(\bar{K}_R)|\sin\tau^M(K_S^M,\bar{K}_R).
\end{aligned}$$

Combining these two expressions, we have:

$$\tau^C(K_S^C,\bar{K}_R) = \tau^M(K_S^M,\bar{K}_R) \equiv \tau^*(\bar{K}_R), \forall\bar{K}_R.$$

Therefore,

$$\begin{aligned}\eta_R^C(K_S^C,\bar{K}_R)-\eta_R^M(K_S^M,\bar{K}_R)=&-\frac{1}{2}\Big(\int_{\tau^*}^{\pi-\tau^*}\rho(\bar{K}_R)\frac{\sin t-\sin\tau^*}{2}\Big(1-\alpha\sin t\Big)dt\\&+\int_{\pi+\tau^*}^{2\pi-\tau^*}\rho(\bar{K}_R)\frac{\sin t+\sin\tau^*}{2}\Big(1-\alpha\sin t\Big)dt\Big)\\=&-\frac{\alpha}{2}\rho(\bar{K}_R)\Big(\sin\tau^*\cos\tau^*+\tau^*-\pi/2\Big).\end{aligned}$$

Since $\Big(\sin\tau^*\cos\tau^*+\tau^*-\pi/2\Big)$ is negative for all $\tau^*\in[0,\pi/2)$, we have:

$$\eta_R^C(K_S^C,\bar{K}_R)>\eta_R^M(K_S^M,\bar{K}_R)\Leftrightarrow\alpha=1\ \&\ \bar{K}_R<2b.$$

Proof of Lemma 8

Lemma 8 *Let charging* $\Big(t\in[\underline{t}_B,\bar{t}_B]\Big)$ *and discharging* $\Big(t\in[\underline{t}_S,\bar{t}_S]\Big)$ *periods be defined by*

$$\{\underline{t}_B,\bar{t}_B,\underline{t}_S,\bar{t}_S\}=\begin{cases}\{\hat{\tau};\pi-\hat{\tau};\pi+\hat{\tau};2\pi-\hat{\tau}\} & \textit{if}\quad\alpha=-1\\\{\pi+\hat{\tau};2\pi-\hat{\tau};\hat{\tau};\pi-\hat{\tau}\} & \textit{if}\quad\alpha=1\end{cases}$$

where $\hat{\tau}\in[0,\pi/2)$ *is implicitly defined by*

$$\cos\hat{\tau}-(\pi/2-\hat{\tau})\sin\hat{\tau}=K_S/K_R,$$

for $K_S\in[0,K_R]$, *and* $\hat{\tau}=0$ *otherwise.*

Equilibrium storage decisions are:
For charging periods $t\in[\underline{t}_B,\bar{t}_B]$,

$$\hat{q}_B(t)=\begin{cases}\alpha K_R\Big[\sin\hat{\tau}-\sin t\Big]/2 & \textit{if}\quad\alpha=-1\\\alpha K_R\Big[-\sin\hat{\tau}-\sin t\Big]/2 & \textit{if}\quad\alpha=1\end{cases},$$

and $\hat{q}_B(t)=0$ *for all other* t.
For discharging periods $t\in[\underline{t}_S,\bar{t}_S]$,

$$\hat{q}_S(t)=\begin{cases}\alpha K_R\Big[\sin t+\sin\hat{\tau}\Big]/2 & \textit{if}\quad\alpha=-1\\\alpha K_R\Big[\sin t-\sin\hat{\tau}\Big]/2 & \textit{if}\quad\alpha=1\end{cases},$$

and $\hat{q}_S(t)=0$ *for all other* t.

To prove it, for given K_S, the problem of storage firms located in region W is:

$$\max_{q_S(t),q_B(t)} \int_0^{2\pi} p_W(t)\Big[q_S(t) - q_B(t)\Big]dt$$

subject to constraints (7) and (8). The optimization problem is convex, so the KKT conditions that we list below are necessary and sufficient. The Lagrangian of the problem, omitting the non-negativity constraints, is given by:

$$\mathbb{L} = \int_0^{2\pi} p_W(t)\Big[q_S(t) - q_B(t)\Big]dt + \lambda\bigg(\int_0^{2\pi} q_B(t)dt - \int_0^{2\pi} q_S(t)dt\bigg) + \mu\bigg(K_S - \int_0^{2\pi} q_B(t)dt\bigg)$$

where λ and μ are the multipliers. W.l.o.g., we can focus attention on cases where, for any $t \in [0, 2\pi]$, $q_B(t) > 0 \to q_S(t) = 0$ and $q_S(t) > 0 \to q_B(t) = 0$. The KKT conditions are:

$$p_W(t) - \lambda = 0, \forall t \tag{A.24a}$$

$$p_W(t) - \lambda + \mu = 0, \forall t \tag{A.24b}$$

$$\int_0^{2\pi} q_B(t)dt - \int_0^{2\pi} q_S(t)dt \geq 0 \tag{A.24c}$$

$$K_S - \int_0^{2\pi} q_B(t)dt \geq 0 \tag{A.24d}$$

and the associated slackness conditions. These conditions are necessary and sufficient, as the constraints are linear and the objective functional is concave in $q_S(t)$ and $q_B(t)$. Substituting expression (12), we have:

$$q_S(t) = T - (1 - \alpha \sin t)K_R/2 - \lambda/2 \text{ , if } \underline{t}_S < t < \bar{t}_S$$
$$q_B(t) = (\lambda - \mu)/2 - T + (1 - \alpha \sin t)K_R/2 \text{ , if } \underline{t}_B < t < \bar{t}_B.$$

By continuity:

$$q_S(\underline{t}_S) = q_S(\bar{t}_S) = 0 \Rightarrow \hat{q}_S(t) = \frac{\alpha K_R}{2}\Big(\sin \bar{t}_S - \sin t\Big) \text{ , if } \underline{t}_S < t < \bar{t}_S$$
$$q_B(\underline{t}_B) = q_B(\bar{t}_B) = 0 \Rightarrow \hat{q}_B(t) = \frac{\alpha K_R}{2}\Big(\sin t - \sin \underline{t}_B\Big) \text{ , if } \underline{t}_B < t < \bar{t}_B.$$

From (A.24c) and (A.24d),

$$\int_{\underline{t}_B}^{\bar{t}_B} \frac{\alpha K_R}{2}\Big(\sin t - \sin \underline{t}_B\Big)dt = \int_{\underline{t}_S}^{\bar{t}_S} \frac{\alpha K_R}{2}\Big(\sin \bar{t}_S - \sin t\Big)dt = K_S. \tag{A.25}$$

By the symmetry of the sine function, $q_S(\underline{t}_S) = q_S(\bar{t}_S) = 0$ and $q_B(\underline{t}_B) = q_B(\bar{t}_B) = 0$, implying $\bar{t}_B + \underline{t}_B = \pi$ and $\bar{t}_S + \underline{t}_S = \pi$. Let

$$\{\underline{t}_B, \bar{t}_B, \underline{t}_S, \bar{t}_S\} = \begin{cases} \{\hat{\tau}; \pi - \hat{\tau}; \pi + \hat{\tau}; 2\pi - \hat{\tau}\} & \text{for} \quad \alpha = -1 \\ \{\pi + \hat{\tau}; 2\pi - \hat{\tau}; \hat{\tau}; \pi - \hat{\tau}\} & \text{for} \quad \alpha = 1. \end{cases}$$

Therefore, from condition (A.25) we obtain that $\hat{\tau} \in [0, \pi/2)$ is implicitly given by:

$$\cos\hat{\tau} - \left(\frac{\pi}{2} - \hat{\tau}\right)\sin\hat{\tau} = \frac{K_S}{K_R}. \tag{A.26}$$

Equilibrium market prices are given by:

$$\hat{p}_W(t) = \begin{cases} 2T - (1 - \alpha\sin\hat{\tau})K_R & \text{if } \hat{\tau} \le t \le \pi - \hat{\tau} \\ 2T - (1 + \alpha\sin\hat{\tau})K_R & \text{if } \pi + \hat{\tau} \le t \le 2\pi - \hat{\tau} \\ 2T - (1 - \alpha\sin t)K_R & \text{otherwise} \end{cases}.$$

Proof of Proposition 6

Storage profits are:

$$\begin{aligned} \Pi_S(K_S, K_R) &= \int_0^{2\pi} \hat{p}_W(t)\Big[\hat{q}_S(t) - \hat{q}_B(t)\Big]dt - C_S(K_S) \\ &= \int_{\underline{t}_s}^{\bar{t}_S} \hat{p}_W(\bar{t}_S)\hat{q}_S(t)dt - \int_{\underline{t}_B}^{\bar{t}_B} \hat{p}_W(\underline{t}_B)\hat{q}_B(t)dt - C_S(K_S) \\ &= \Big[\hat{p}_W(\bar{t}_S) - \hat{p}_W(\underline{t}_B)\Big]K_S - C_S(K_S) \\ &= 2K_R\sin\hat{\tau}(K_S, K_R)K_S - C_S(K_S), \end{aligned} \tag{A.27}$$

with $\underline{t}_B, \bar{t}_B, \underline{t}_S$ and $\bar{t}_S$ defined in Lemma 8, and with $\hat{\tau}(K_S, K_R)$ implicitly defined by (A.26). Partially differentiating equation (A.27):

$$\frac{\partial\Pi_S(K_S, K_R)}{\partial K_R} = 2\left(\sin\hat{\tau} + K_R\cos\hat{\tau}\frac{\partial\hat{\tau}}{\partial K_R}\right)K_S = 2\left(\sin\hat{\tau} + \frac{K_S}{\big(\pi/2 - \hat{\tau}\big)K_R}\right)K_S > 0,$$

where in the second step we have used the fact that implicitly differentiating equation (A.26) yields:

$$\frac{\partial\hat{\tau}(K_S, K_R)}{\partial K_R} = \frac{K_S}{\big(\pi/2 - \hat{\tau}\big)K_R^2\cos\hat{\tau}}.$$

The profits of renewable firms are:

$$
\begin{aligned}
\Pi_R(K_S, K_R) =& \int_0^{2\pi} \hat{p}_W(t)\frac{1}{2}\Big(1-\alpha\sin t\Big)K_R dt - C_R(K_R)\\
=& \frac{1}{2}K_R\Bigg(\int_0^{\hat{\tau}}\Big(2T-(1-\alpha\sin t)K_R\Big)\Big(1-\alpha\sin t\Big)dt\\
&+\int_{\hat{\tau}}^{\pi-\hat{\tau}}\Big(2T-(1-\alpha\sin\hat{\tau})K_R\Big)\Big(1-\alpha\sin t\Big)dt\\
&+\int_{\pi-\hat{\tau}}^{\pi+\hat{\tau}}\Big(2T-(1-\alpha\sin t)K_R\Big)\Big(1-\alpha\sin t\Big)dt\\
&+\int_{\pi+\hat{\tau}}^{2\pi-\hat{\tau}}\Big(2T-(1+\alpha\sin\hat{\tau})K_R\Big)\Big(1-\alpha\sin t\Big)dt\\
&+\int_{2\pi-\hat{\tau}}^{2\pi}\Big(2T-(1-\alpha\sin t)K_R\Big)\Big(1-\alpha\sin t\Big)dt\Bigg) - C_R(K_R),
\end{aligned}
$$

with $\hat{\tau}(K_S, K_R)$ implicitly defined by ($A.26$). Partially differentiating the expression above (applying integral rule and omitting terms that cancel out):

$$
\begin{aligned}
\frac{\partial\Pi_R(K_S,K_R)}{\partial K_S} &= \frac{K_R}{2}\left[\int_{\hat{\tau}}^{\pi-\hat{\tau}}\alpha\cos\hat{\tau}\frac{\partial\hat{\tau}}{\partial K_S}(1-\alpha\sin t)dt - \int_{\pi+\hat{\tau}}^{2\pi-\hat{\tau}}\alpha\cos\hat{\tau}\frac{\partial\hat{\tau}}{\partial K_S}(1-\alpha\sin t)dt\right]\\
&= \frac{K_R}{2}\alpha\cos\hat{\tau}\frac{\partial\hat{\tau}}{\partial K_S}\Big(-4\alpha\cos\hat{\tau}\Big) = \frac{2K_R\cos\hat{\tau}}{\pi/2-\hat{\tau}} > 0,
\end{aligned}
$$

where we have used the fact that implicitly differentiating equation ($A.26$) yields:

$$
\frac{\partial\hat{\tau}(K_S,K_R)}{\partial K_S} = \frac{-1}{(\pi/2-\hat{\tau})K_R\cos\hat{\tau}}.
$$

Appendix – For Online Publication

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A Smoother Correlations

In this section, we show that our main results remain robust when renewable production is only partially synchronized with demand, rather than being perfectly procyclical or countercyclical – as assumed in our baseline model. Empirically, most renewable technologies (and, even more so, diversified portfolios that combine wind and solar) have degrees of alignment with demand that are in between the two extreme cases examined in the baseline model.

To capture this richer set of possibilities, we introduce one parameter, $a \in [0, \pi]$, that continuously shifts the availability profile of renewables relative to demand. This single parameter delivers two sufficient statistics: $\rho(D, \omega)$, for the "functional" correlation between demand and renewable availability, and $\rho(p^{NS}, \omega K_R)$, for the "functional" correlation between prices and renewable production. These metrics allow us to trace out how storage behavior, price formation, and the strategic interaction between technologies change as we move away from the extreme benchmark cases.

In what follows, we (i) formalize the notion of time-domain functional correlation, (ii) derive closed-form expressions for prices and correlations as functions of a, and (iii) show that the threshold capacity $K_R^*(a) = 2b \cos a$ endogenously adjusts with the degree of cyclicality, which in turn determines whether storage and renewables act as strategic substitutes or complements. Accordingly, because the phase-shift parameter simply rescales the critical capacity to $K_R^*(a) = 2b \cos a$, every qualitative finding is the same as in the baseline model presented in the body of the paper. Crucially, whether storage and renewables are complements or substitutes depends only on the sign of the correlation between prices and renewable production: a positive correlation makes them substitutes, while a negative one turns them into complements.

Extending the argument to multiple renewable technologies, we still find that storage crowds out one technology and crowds in the other whenever their availability profiles are sufficiently negatively correlated (i.e., when one is sufficiently procyclical and the other is sufficiently countercyclical).

In the new modified version of the model, demand and renewable availability are:

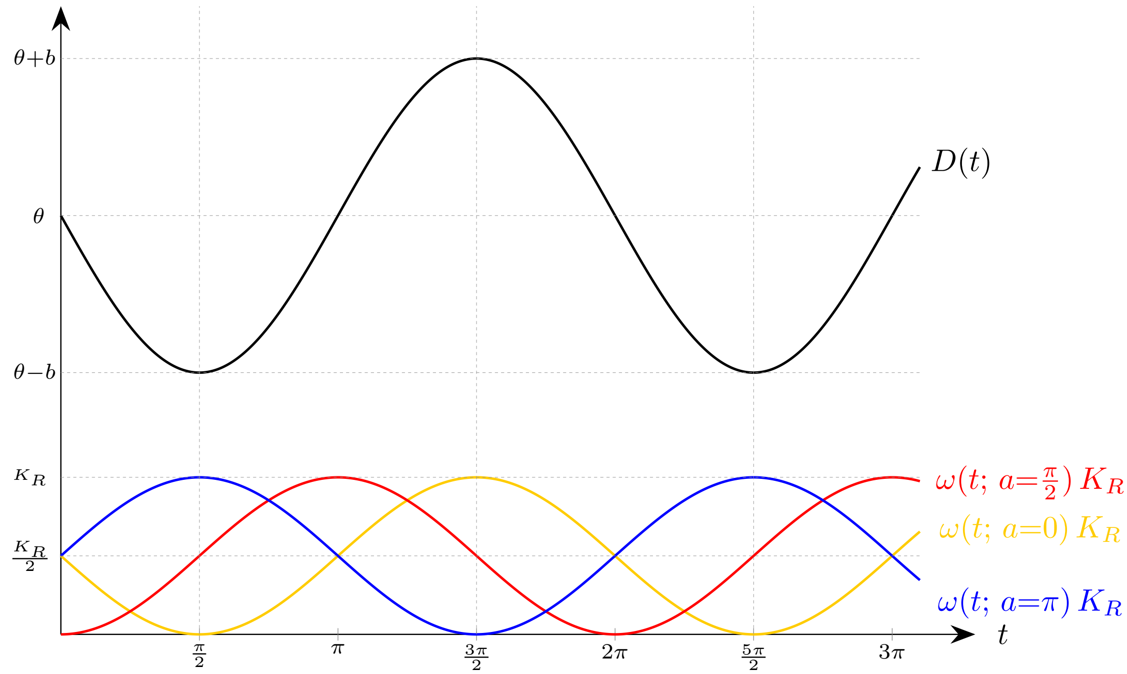
$$D(t) = \theta - b \sin t,$$
$$\omega(t) = \frac{1}{2}\Big[1 - \sin(t + a)\Big].$$

The parameter $a \in [0, \pi]$ shifts horizontally the renewable availability curve. In one extreme, when $a = 0$, the peaks of demand and renewables coincide. In the other extreme, when $a = \pi$, the peak (valley) of demand exactly coincides with the valley (peak) of renewable availability. For intermediate values of a, we have intermediate degrees of cyclicality between demand and renewable availability. We define $\rho(D, \omega)$ as the "*time functional correlation*" between $D(t)$ and $\omega(t)$, which is given by the time covariance between the deviations from their mean of demand and renewable availability (over one day), divided by the time variances of demand and renewables (see the subsection below for the computations):[36]

$$\rho(D, \omega) = \frac{\text{Cov}(D, \omega)}{\sqrt{\text{Var}(D)\ \text{Var}(\omega)}} = \cos a.$$

[36]The intuition behind this concept can be found by asking: at any given moment during the day, when one curve is above its own daily average, is the other typically above or below its own average? To formalize this idea, we use a statistical correlation formula but integrate over time rather than averaging across multiple realizations. This is why we refer to it as a *time-functional correlation*. A positive correlation, for instance, indicates that the two curves tend to lie on the same side of their respective means at the same hours – that is, they tend to peak together.

Figure A.1: Demand and renewable availability under varying functional correlations



Notes: This figure illustrates the time dynamics of electricity demand (black curve) and renewable production (colored curves), for three values of the phase-shift parameter a. When $a = 0$ (yellow curve), renewables and demand are perfectly aligned: both peak at the same time, representing a procyclical scenario. When $a = \pi$ (blue curve), their peaks are misaligned: renewable availability is highest when demand is lowest, and *vice versa*. The intermediate case $a = \frac{\pi}{2}$ (red curve) reflects no clear alignment. The parameter $a \in [0, \pi]$ thus controls the "functional correlation" between demand and renewable supply over time.

This correlation takes value 1 when $a = 0$ (renewable availability peaks exactly with demand), and monotonically decreases in a until it reaches the value -1 when $a = \pi$ (production peaks when demand troughs). When $a = \pi/2$, the correlation is 0 (production is a quarter-cycle out of phase).

We begin by computing net demand and deriving the wholesale price in the absence of storage. We have that:

$$\omega(t)\, K_R = \frac{1}{2}\Big[1 - \sin(t + a)\Big]K_R = \frac{K_R}{2} - \frac{K_R}{2}\left[\sin t \cos a + \cos t \sin a\right].$$

Subtracting from $D(t)$:

$$\begin{aligned} D(t) - \omega K_R &= \theta - b\sin t - \left[\frac{K_R}{2} - \frac{K_R}{2}(\sin t\cos a + \cos t \sin a)\right] \\ &= \left(\theta - \frac{K_R}{2}\right) - \left[b - \frac{K_R}{2}\cos a\right]\sin t + \left[\frac{K_R}{2}\sin a\right]\cos t. \end{aligned}$$

We define:

$$A(K_R) = \theta - \frac{K_R}{2}, \quad \vartheta_{\text{sin}}(K_R, a) = b - \frac{K_R}{2}\cos a, \quad \vartheta_{\text{cos}}(K_R, a) = \frac{K_R}{2}\sin a.$$

Then, in the absence of market power in generation,[37] prices are given by net demand (recall that marginal costs are linear):

$$p^{NS}(t) = D(t) - \omega K_R = A - \vartheta_{\text{sin}}\sin t + \vartheta_{\text{cos}}\cos t.$$

To simplify, we define:

$$R(K_R, a) = \sqrt{\vartheta_{\text{sin}}^2 + \vartheta_{\text{cos}}^2}, \qquad \varphi = \arctan\left(\frac{\vartheta_{\text{cos}}}{\vartheta_{\text{sin}}}\right).$$

Then, using the identity $-\vartheta_{\text{sin}}\sin t + \vartheta_{\text{cos}}\cos t = -\,R\sin(t - \varphi)$, we obtain:

$$p^{NS}(t) = A - R\,\sin\Big(t - \varphi\Big).$$

The minimum price occurs at $t = \varphi + \pi/2$, and the maximum price at $t = \varphi + 3\pi/2$. The parameter R represents the amplitude of the price curve, i.e., the magnitude of price fluctuations over time. The parameter φ captures the influence of renewables on the timing of the price minimum. In the absence of renewables, the minimum price would occur at $t = \pi/2$; thus, φ indicates the extent to which renewable generation "delays" the price valley. As before, we can compute the functional correlation between the price $p^{NS}(t)$ with the renewable production $\omega(t)\,K_R$, which is given by:

$$\rho\Big(p^{NS},\,\omega K_R\Big) \;=\; \frac{\text{Cov}(p^{NS}, \omega K_R)}{\sqrt{\text{Var}(p^{NS})\;\text{Var}(\omega K_R)}} \;=\; \cos(\varphi + a) \;=\; \frac{b\cos a - \frac{K_R}{2}}{R}.$$

When $a \geq \pi/2$, the correlation is always negative. When $a < \pi/2$, we have that the

[37] For clarity of exposition, in this section we assume $\beta = 0$ i.e., there is no market power in generation, but the results remain unchanged if we allow for β taking positive values.

correlation satisfies:

$$\rho\Big(p^{NS},\, \omega K_R\Big) = \begin{cases} > 0, & K_R < 2b\cos a, \\ = 0, & K_R = 2b\cos a, \\ < 0, & K_R > 2b\cos a. \end{cases}$$

The functional correlation captures whether renewable production tends to occur in hours when prices are high (positive), remain constant (zero), or when prices are low (negative), flipping sign exactly when capacity crosses the threshold $K_R^* = 2b\cos a$. Note that the threshold is decreasing in a, which means that the smaller the positive functional correlation between prices and renewables, the lower the renewable capacity size required to flip the correlation from positive to negative.

We now turn to characterize storage decisions. Let the no-storage price in the "rotated time" $u \equiv t - \varphi$ be:

$$p^{NS}(u) = A - R\,\sin u, \qquad u \in [0, 2\pi], \quad R > 0.$$

Note that the price curve still preserves the symmetry properties, which allows us to characterize the behavior of storage operators in the same way as in the benchmark model. The valley occurs when $u = \pi/2$ and the peak when $u = 3\pi/2$. A perfectly competitive storage firm with capacity K_S chooses to charge $q_B(u) \geq 0$ and discharge $q_S(u) \geq 0$ to solve:

$$\max_{q_{B(u)},\, q_S(u)} \int_0^{2\pi} p^{NS}(u)\,\Big[q_S(u) - q_B(u)\Big]\,du$$

subject to

$$\int_0^{2\pi} q_B(u)\,du = K_S, \qquad \int_0^{2\pi}\Big[q_S(u) - q_B(u)\Big]\,du = 0.$$

Lemma 9 *There is a unique* $\tau \in (0, \pi/2)$ *such that*

$$K_S = 2R\Big[\cos\tau - (\tfrac{\pi}{2} - \tau)\sin\tau\Big] \tag{A1}$$

and the optimal rule is:

$$q_B(u) = R[\sin u - \sin\tau] \quad : \quad u \in [\tau,\ \pi - \tau],$$
$$q_S(u) = R[\sin u + \sin\tau] \quad : \quad u \in [\pi + \tau,\ 2\pi - \tau],$$

The market price in those regions is piece-wise constant:

$$p_{buy} = A - R\sin\tau \ < \ p_{sell} = A + R\sin\tau \tag{A2}$$

while outside the trading windows it coincides with the no storage price $p^{NS} = A - R\sin u$. *If* $K_S = 0$, *the solution is* $\tau = \pi/2$ *and no trading occurs. If* $K_S \geq 2R$, *then* $\tau = 0$ *and the whole day is flattened to the single price* A.

Note that the price curve is always a smooth and symmetric price wave. A competitive storage operator flattens this curve in periods of low and high prices, and remains idle when prices take intermediate values. Returning to real time simply shifts those windows forward by φ: charging happens for $t \in [\varphi + \tau,\ \varphi + \pi - \tau]$, discharging for $t \in [\varphi + \pi + \tau,\ \varphi + 2\pi - \tau]$. Whether this behavior helps or *hurts* a renewable producer depends solely on the sign of the correlation between prices and renewable production i.e., $\rho\Big(p^{NS},\, \omega K_R\Big)$. If production peaks in the naturally expensive hours (positive correlation), storage competes against renewables at the very moment it sells, so more storage cuts renewable profits. If production peaks in *cheap* hours (negative correlation), the storage owner buys in those same hours and props the price up, boosting renewable profits. This is formalized in the following proposition:

Proposition 7 *Renewables and storage are strategic substitutes if and only if prices and renewables correlate positively, i.e.,*

$$\frac{\partial \Pi_R}{\partial K_S} < 0 \text{ and } \frac{\partial \Pi_S}{\partial K_R} < 0 \Leftrightarrow \rho\Big(p^{NS},\, \omega K_R\Big) > 0.$$

A positive functional correlation means that renewables generate most of their output in the high-price half of the day. Thus, additional storage flattens those peaks and erodes renewable profits, while extra renewable capacity shrinks price differences and harms storage profits. In contrast, a negative correlation reverses the timing: renewables tend to produce in cheap hours, so storage's charging pushes up prices and both assets benefit from each other. Overall, this new framework keeps the same economic insight as the baseline model: renewables and storage are strategic substitutes when renewable output correlates positively with demand and capacity is low. However, in the new framework, the critical capacity threshold depends on how well the renewable profile lines up with demand: if renewables are not sufficiently procyclical (i.e., if a is not sufficiently small), storage and renewables complement each other.

Our results regarding the effect of storage in markets with multiple renewable technologies also apply in the current framework, albeit with some qualifications. Let technology $+$ be procyclical (i.e., $a^+ \in [0, \pi/2)$) and technology $-$ be countercyclical (i.e., $a^- \in (\pi/2, \pi]$), with capacities K_R^+ and K_R^-, respectively.

Lemma 10 *Equilibrium prices correlate positively with renewable technology $+$ and negatively with renewable technology $-$ if and only if $2b \cos a^+ > K_R^+ + \cos(a^- - a^+)K_R^-$.*

The condition above generalizes the original condition of the benchmark model ($K_R^+ < K_R^- + 2b$)[38]. The left-hand side, $2b \cos a^+$, captures how strongly demand-driven prices rise when the "+" technology (the procyclical one) is abundant.[39] The right-hand side, $K_R^+ + K_R^- \cos(a^- - a^+)$, is the combined dampening effect of the two renewable technologies during those same hours: the $+$ technology's own capacity plus the share of the $-$ technology's capacity that produces simultaneously with the $+$ technology (that share is scaled by $\cos(a^- - a^+)$). Whenever the demand swing on the left is bigger than this total dampening term,

$$2b \cos a^+ \; > \; K_R^+ + K_R^- \cos(a^- - a^+),$$

the $+$ technology still sells mostly in high-price hours, so prices move with the $+$ technology and against the $-$ technology.

If the inequality reverses (because capacities become larger or because the two technologies peak at nearly the same time), the $+$ technology flattens prices enough that it also ends up producing when prices are low, and both renewables become negatively correlated with price. Symmetrically, if the inequality flips enough in the other direction, the $+$ technology becomes negatively correlated with prices, while the $-$ technology becomes positively correlated. Hence, a sufficiently large capacity of the procyclical renewable technology can make storage complement this technology and substitute the countercyclical one.

Note that if the two technologies have the same size (i.e., $K_R^+ = K_R^- = K_R$), the condition simplifies to:

$$K_R < \frac{2b \cos a^+}{1 + \cos(a^- - a^+)}.$$

[38] In fact, we obtain this condition for the case where $a^+ = 0$ and $a^- = \pi$.

[39] The term $2b \cos a^+$ is exactly the price swing driven by demand alone evaluated at the hour when the $+$ technology peaks (it equals 0 if the peak occurs when demand is average, and it equals $2b$ if the peak coincides with the demand peak).

As long as capacity is below that threshold, the + technology is positively correlated with price while the − technology is negatively correlated. Once capacity exceeds it, both technologies end up negatively correlated with prices, and storage complements them both instead of substituting for one of them.

Proposition 8 *Let $i, j \in \{+, -\}$ with $i \neq j$ and define $S_i = \vartheta_{\sin} \cos a_i - \vartheta_{\cos} \sin a_i$, with*

$$\vartheta_{\sin} = b - \tfrac{1}{2}\Big(K_+ \cos a_+ + K_- \cos a_-\Big), \qquad \vartheta_{\cos} = \tfrac{1}{2}\Big(K_+ \sin a_+ + K_- \sin a_-\Big).$$

Then

$$\operatorname{sign}\!\left(\tfrac{\partial \Pi_R^i}{\partial K_S}\right) \;=\; -\operatorname{sign}(S_i), \qquad \operatorname{sign}\!\left(\tfrac{\partial \Pi_S}{\partial K_R^i}\right) \;=\; \operatorname{sign}(S_i).$$

Therefore:

1. *If $S_i > 0$ then storage is a* strategic substitute *to technology i and a* strategic complement *to technology j:*

$$\frac{\partial \Pi_R^i}{\partial K_S} < 0, \qquad \frac{\partial \Pi_R^j}{\partial K_S} > 0, \qquad \frac{\partial \Pi_S}{\partial K_R^i} < 0, \qquad \frac{\partial \Pi_S}{\partial K_R^j} > 0.$$

2. *If $S_i < 0$ the roles reverse: storage complements technology i and substitutes technology j.*

Whether storage helps or hurts a given renewable technology now boils down to a single number, $S_i = \vartheta_{\sin} \cos a_i - \vartheta_{\cos} \sin a_i$, which is the time–covariance between that technology's output and the market price in the absence of storage. If $S_i > 0$, the technology tends to generate in high-price hours, so extra storage depresses its revenues, making storage and renewables strategic substitutes. If $S_i < 0$, they are complements. Under the inequality $2b \cos a^+ > K_R^+ + K_R^- \cos(a^- - a^+)$, we have $S_+ > 0 > S_-$: storage crowds out the pro-cyclical technology and crowds in the counter-cyclical one, exactly as in Proposition 2 of the benchmark model. Reversing the inequality flips the roles.

Computations and Proofs for Appendix A

Functional Correlations. We first compute the functional time correlation between demand and renewable availability. The deviations from their mean, for demand and renewable availability, are:

$$\widetilde{D}(t) = D(t) - \overline{D} = \theta - b\sin t - \theta = -\,b\sin t$$

$$\widetilde{\omega}(t) = \omega(t) - \overline{\omega} = \frac{1}{2}\Big[1 - \sin(t+a)\Big] - \frac{1}{2} = -\,\frac{1}{2}\sin(t+a)$$

So the functional time covariance is:

$$\mathrm{Cov}\Big(D, \omega\Big) = \frac{1}{2\pi}\int_0^{2\pi} \widetilde{D}(t)\,\widetilde{\omega}(t)\,dt = \frac{b}{4\pi}\int_0^{2\pi} \sin t\,\sin(t+a)\,dt.$$

Using the identity $\int_0^{2\pi} \sin t\,\sin(t+a)\,dt = \pi\cos a$, we obtain

$$\mathrm{Cov}\Big(D, \omega\Big) = \frac{b}{4\pi}\cdot \pi\cos a = \frac{b}{4}\cos a.$$

The functional time variances are given by:

$$\begin{aligned}
\mathrm{Var}\Big(D\Big) &= \frac{1}{2\pi}\int_0^{2\pi}\Big[\widetilde{D}(t)\Big]^2 dt = \frac{1}{2\pi}\int_0^{2\pi} b^2\sin^2 t\,dt = \frac{b^2}{2\pi}\Big(\pi\Big) = \frac{b^2}{2}.\\
\mathrm{Var}\Big(\omega\Big) &= \frac{1}{2\pi}\int_0^{2\pi}\Big[\widetilde{\omega}(t)\Big]^2 dt = \frac{1}{2\pi}\int_0^{2\pi}\Big(-\tfrac{1}{2}\sin(t+a)\Big)^2 dt = \frac{1}{4}\,\frac{1}{2\pi}\int_0^{2\pi}\sin^2 t\,dt = \frac{1}{8}.
\end{aligned}$$

Therefore, the functional time correlation between demand and renewable availability is given by:

$$\rho(D,\omega) = \frac{\mathrm{Cov}(D,\omega)}{\sqrt{\mathrm{Var}(D)\ \mathrm{Var}(\omega)}} = \frac{\frac{b}{4}\cos a}{\sqrt{\frac{b^2}{2}\cdot\frac{1}{8}}} = \frac{\frac{b}{4}\cos a}{\frac{b}{4}} = \cos a.$$

We can proceed in a similar way to compute the correlation between prices and renewable production. From

$$p^{NS}(t) = A - R\sin\Big(t-\varphi\Big), \quad \overline{p^{NS}} = A,$$

we set

$$\widetilde{p}(t) = p^{NS}(t) - \overline{p^{NS}} = -\,R\,\sin\Big(t-\varphi\Big).$$

For renewable production,

$$\omega(t)\,K_R = \frac{K_R}{2}\Big[1-\sin(t+a)\Big], \quad \overline{\omega\,K_R} = \frac{K_R}{2},$$

so

$$\widetilde{y}(t) := \omega(t)\, K_R - \overline{\omega\, K_R} = -\frac{K_R}{2}\, \sin(t+a).$$

The functional time covariance is given by:

$$\mathrm{Cov}\Big(p^{NS}, \omega K_R\Big) = \frac{1}{2\pi}\int_0^{2\pi} \widetilde{p}(t)\, \widetilde{y}(t)\, dt = \frac{RK_R}{4}\, \cos(\varphi + a).$$

The functional time variances are given by:

$$\begin{aligned}
\mathrm{Var}\Big(p^{NS}\Big) &= \frac{1}{2\pi}\int_0^{2\pi} \Big[-R\sin\Big(t-\varphi\Big)\Big]^2 dt = \frac{R^2}{2} \\
\mathrm{Var}\Big(\omega K_R\Big) &= \frac{1}{2\pi}\int_0^{2\pi} \Big[-\tfrac{K_R}{2}\sin(t+a)\Big]^2 dt = \frac{K_R^2}{8}.
\end{aligned}$$

Therefore, the functional time correlation is given by:

$$\rho\Big(p^{NS},\, \omega K_R\Big) \;=\; \frac{\mathrm{Cov}(p^{NS}, \omega K_R)}{\sqrt{\mathrm{Var}(p^{NS})\ \mathrm{Var}(\omega K_R)}} \;=\; \frac{\dfrac{RK_R}{4}\ \cos(\varphi+a)}{\sqrt{\dfrac{R^2}{2}\ \dfrac{K_R^2}{8}}} \;=\; \cos(\varphi + a).$$

Since

$$\cos(\varphi + a) = \frac{\vartheta_{\sin}\cos a - \vartheta_{\cos}\sin a}{R} = \frac{b\cos a - \frac{K_R}{2}}{R},$$

we have:

$$\mathrm{sign}\Big[\rho\Big(p^{NS},\, \omega K_R\Big)\Big] = \mathrm{sign}\Big(b\cos a - \frac{K_R}{2}\Big).$$

■

Proof of Lemma 9.

Note that, once we reframe the problem of storage operators in "rotated time" $u = t - \varphi$, we can follow exactly the same steps as the proof of Lemma 3. The main difference is that the amplitude of the price cycle (that appears in the main expressions) is now given by $R(K_R, a)$.

In particular, since $p^{NS}(u)$ is monotone between valley and peak, the buy set and sell set are single symmetric intervals around the valley $u = \pi/2$ and peak $u = 3\pi/2$. Let τ be the left boundary. By symmetry, the four endpoints are $\tau,\ \pi - \tau,\ \pi + \tau,\ 2\pi - \tau$. At $u = \tau$, $p_{\text{buy}} = A - R\sin\tau$, and at $u = \pi + \tau$, $p_{\text{sell}} = A + R\sin\tau$, giving the spread $\gamma = 2R\sin\tau$. Energy charged equals the area between the sine curve and the line p_{buy}

over $[\tau, \pi - \tau]$. Therefore, we have:

$$K_S = 2R\Big[\cos\tau - (\tfrac{\pi}{2} - \tau)\sin\tau\Big].$$

Since the function in brackets decreases strictly from 1 to 0 as τ goes $0 \to \pi/2$, τ is unique. ■

Proof of Proposition 7.

Following the same steps as in the proof of Proposition 1, storage revenue can be written as:

$$\Pi_S \;=\; 2K_S\, R(K_R, a)\, \sin\tau(K_R, K_S, a)$$

where $\tau = \tau(K_S, K_R, a) \in (0, \pi/2)$ is pinned down by the capacity constraint

$$K_S \;=\; 2R\left[\cos\tau - \left(\tfrac{\pi}{2} - \tau\right)\sin\tau\right] \tag{A.1}$$

The derivative with respect to K_R is:

$$\frac{\partial \Pi_S}{\partial K_R} \;=\; 2K_S\left[\frac{dR}{dK_R}\,\sin\tau \;+\; R\,\cos\tau\,\frac{d\tau}{dK_R}\right]. \tag{A.2}$$

Implicitly differentiating equation (A.1) yields:

$$\frac{\partial \tau(K_S, K_R, a)}{\partial K_R} = \frac{\partial R(K_S, K_R, a)}{\partial K_R}\,\frac{\cos\tau - (\pi/2 - \tau)\sin\tau}{R\,(\pi/2 - \tau)\cos\tau},$$

Substituting in equation (A.2) we get:

$$\frac{\partial \Pi_S}{\partial K_R} \;=\; 2K_S\,\frac{dR}{dK_R}\left[\frac{\cos\tau}{\pi/2 - \tau}\right].$$

Because $0 < \tau < \pi/2$, the square bracket in the last equation is positive. Hence the sign of the derivative is the sign of dR/dK_R, which is given by:

$$\frac{dR}{dK_R} = \frac{1}{2R}\left[-\,b\cos a + \frac{K_R}{2}\cos^2 a + \frac{K_R}{2}\sin^2 a\right] = \frac{K_R - 2b\cos a}{4R}.$$

Therefore:

$$K_R < 2b\cos a \implies \frac{\partial \Pi_S}{\partial K_R} < 0$$
$$K_R > 2b\cos a \implies \frac{\partial \Pi_S}{\partial K_R} > 0.$$

The profits of renewables are:

$$\Pi_R(K_R, K_S) = K_R \int_0^{2\pi} p^S(t)\,\omega(t)\,dt.$$

A marginal capacity increase dK_S widens the charge and discharge areas by $d\tau$. Moreover, prices move by $+\,dp$ on the charge area and by $-\,dp$ on the symmetric discharge area (with the same $dp > 0$ and the same width $d\tau$). Hence:

$$d\Pi_R = K_R \int \omega(t)\,dp^S(t)dt = \; 2K_R\,dp \int_0^{2\pi} \Big[\omega(t) - \bar{\omega}\Big] \; \mathrm{sign}\Big[p^{NS}(t) - \bar{p}^{NS}\Big]dt.$$

The last integral has the opposite sign of the covariance $\mathrm{Cov}(\omega, p^{NS})$. Direct integration gives $\mathrm{Cov}(\omega, p^{NS}) = \frac{1}{4}\Big(b\cos a - \frac{K_R}{2}\Big)$. ■

Renewable profits are given by:

$$\Pi_R = K_R \int_0^{2\pi} p^S(u)\,\omega(u)\,du.$$

with $\omega(u) = \frac{1}{2}\Big[1 - \sin(u + a)\Big]$ and where $p^S(u)$ is the price curve with storage. That is:

$$p^S(u) = \begin{cases} A - R\sin\tau, & u \in [\tau, \pi - \tau] \\ A + R\sin\tau, & u \in [\pi + \tau, 2\pi - \tau] \\ A - R\sin u, & \text{otherwise.} \end{cases}$$

Sign of $\partial\Pi_R/\partial K_S$. A marginal increase $dK_S > 0$ widens the buy/sell windows symmetrically and lowers the peak–valley spread $\gamma = 2R\sin\tau$. Equivalently, the flat price in the buy window moves up by $dp > 0$ while the flat price in the sell window moves down by the same amount $dp > 0$. Writing everything in rotated time $u = t - \varphi$, we have

$$p^{NS}(u) = A - R\sin u, \qquad p^S(u) = \begin{cases} A - R\sin\tau, & u \in [\tau, \pi - \tau], \\ A + R\sin\tau, & u \in [\pi + \tau, 2\pi - \tau], \\ A - R\sin u, & \text{otherwise.} \end{cases}$$

Hence the price change induced by dK_S can be written as

$$dp^S(u) = +\,dp \cdot \mathbf{1}_{[\tau,\pi-\tau]}(u) \; - \; dp \cdot \mathbf{1}_{[\pi+\tau,2\pi-\tau]}(u) = dp \cdot \operatorname{sign}\Big(\widetilde{p}^{NS}(u)\Big),$$

where $\widetilde{p}^{NS}(u) = p^{NS}(u) - A = -R \sin u$ and $dp > 0$ is proportional to the change in γ. Renewable revenue changes by

$$d\Pi_R = K_R \int_0^{2\pi} \omega(u)\, dp^S(u)\, du = K_R\, dp \int_0^{2\pi} \Big[\omega(u) - \overline{\omega}\Big] \operatorname{sign}\Big(\widetilde{p}^{NS}(u)\Big)\, du,$$

with $\overline{\omega} = \frac{1}{2}$. Since $\widetilde{p}^{NS}(u)$ is a pure sine and $\widetilde{\omega}(u) = -\frac{1}{2}\sin(u+a)$ is also a pure sine, the integral above has the *same sign* as the covariance integral $\int \widetilde{\omega}(u)\, \widetilde{p}^{NS}(u)\, du$. Therefore

$$\operatorname{sign}\Big(\tfrac{\partial \Pi_R}{\partial K_S}\Big) = -\operatorname{sign}\Big(\operatorname{Cov}(\omega, p^{NS})\Big).$$

Direct computation gives

$$\operatorname{Cov}(\omega, p^{NS}) = \frac{1}{2\pi}\int_0^{2\pi} \Big[-\tfrac{1}{2}\sin(u+a)\Big]\Big[-R\sin u\Big]\, du = \frac{R}{4}\cos(\varphi + a) = \frac{1}{4}\Big(b\cos a - \frac{K_R}{2}\Big).$$

Hence,

$$\operatorname{sign}\Big(\tfrac{\partial \Pi_R}{\partial K_S}\Big) = -\operatorname{sign}\Big(b\cos a - \tfrac{K_R}{2}\Big)$$

Proof of Lemma 10. We can write the price curve with no storage as

$$p^{NS}(t) = A - R\sin\Big(t - \varphi\Big), \quad R = \sqrt{\vartheta_{\sin}^2 + \vartheta_{\cos}^2}, \quad \varphi = \arctan\Big(\tfrac{\vartheta_{\cos}}{\vartheta_{\sin}}\Big),$$

with

$$\vartheta_{\sin} = b - \tfrac{1}{2}\Big(K_+ \cos a_+ + K_- \cos a_-\Big), \qquad \vartheta_{\cos} = \tfrac{1}{2}\Big(K_+ \sin a_+ + K_- \sin a_-\Big).$$

Let $\Delta := a_- - a_+$. For $i \in \{+,-\}$ define $S_i := \vartheta_{\sin}\cos a_i - \vartheta_{\cos}\sin a_i$. A short computation gives

$$S_+ = b\cos a_+ - \frac{K_+}{2} - \frac{K_-}{2}\cos\Delta, \qquad S_- = b\cos a_- - \frac{K_-}{2} - \frac{K_+}{2}\cos\Delta.$$

Since $\rho(p^{NS}, \omega_i K_i) = S_i/R$, the sign of the correlation matches the sign of S_i.

Necessity. If $\rho(p^{NS}, \omega_+ K_+) > 0$ and $\rho(p^{NS}, \omega_- K_-) < 0$, then $S_+ > 0 > S_-$. From $S_+ > 0$ we get $2b\cos a_+ > K_+ + K_-\cos\Delta$.

Sufficiency. Assume $2b\cos a_+ > K_+ + K_- \cos\Delta$. Then $S_+ > 0$. Moreover, using $K_+ < 2b\cos a_+ - K_- \cos\Delta$ in S_-,

$$\begin{aligned} S_- &< b\cos a_- - \frac{K_-}{2} - \frac{1}{2}\Big(2b\cos a_+ - K_- \cos\Delta\Big)\cos\Delta \\ &= b\Big(\cos a_- - \cos a_+ \cos\Delta\Big) - \frac{K_-}{2}\Big(1-\cos^2\Delta\Big) \\ &= -\,b\,\sin a_+\,\sin\Delta - \frac{K_-}{2}\sin^2\Delta \;<\; 0, \end{aligned}$$

with strict inequality unless $\sin a_+ = 0 = \sin\Delta$. Hence $\rho(p^{NS}, \omega_+ K_+) > 0$ and $\rho(p^{NS}, \omega_- K_-) < 0$.

Equal capacities. Setting $K_+ = K_- = K_R$ gives $2b\cos a_+ > 2K_R\cos^2(\Delta/2)$, i.e., $K_R < \dfrac{2b\cos a_+}{1+\cos\Delta}$. ■

Proof of Proposition 8. It follows the same steps as the proof of Proposition 7, with the difference that the sign of the derivatives depends on S_i. ■

B Investment Subsidies

In the baseline model, we discuss how the stringency of technology mandates affects the investment subsidies needed for firms to break even when they invest to meet the mandate. In this section, we take the mirror perspective and analyze the overall effect of investment subsidies on long-run capacity investment, as shown next:

Proposition 9 *Let $i, j \in \{S, R\}$ and $i \neq j$, and use η_i to denote a per-unit of capacity subsidy to technology i. (i) A higher subsidy η_i increases the equilibrium capacity of technology i, i.e.,*

$$\frac{dK_i^*}{d\eta_i} > 0.$$

(ii) A higher subsidy η_i reduces the equilibrium capacity of technology j if and only if prices and renewables correlate positively, i.e.,

$$\frac{dK_j^*}{d\eta_i} < 0 \Leftrightarrow \alpha = 1 \text{ and } K_R^* < 2b.$$

Subsiding one technology increases its profitability, which induces higher investments. However, whether this strengthens or weakens the equilibrium investment of the other technology depends on whether renewables and storage are substitutes or complements (Proposition 1).

When they are strategic complements, promoting investments in one technology through investment subsidies always comes with the additional benefit of promoting investments in the other technology. In particular, the entry of storage (renewable) assets opens up profitable opportunities for renewable (storage) due to the negative correlation between renewables and prices.

Otherwise, promoting renewables or storage too early acts as a barrier to the initial deployment of the other technology due to the positive correlation between prices and renewable production. In this case, storage subsidies induce renewables to exit as they reduce their profitability. Conversely, mandating or subsidizing investments in renewables brings the market closer to the situation where both technologies complement each other. In particular, a large enough renewable investment subsidy would make storage firms exit the market (or make existing storage capacity idle) until renewable capacity reaches the critical mass $K_R = 2b$. From that point onward, the new renewable investments would gradually increase arbitrage profits and encourage the entry of storage firms.

Likewise, when renewables and storage are strategic complements, storage and renewable investment subsidies work at cross purposes. It is more effective to subsidize renewables until the critical mass $K_R = 2b$ is reached than to support both. The reason is that the positive direct effect of the renewables subsidy η_R on renewable investments is counteracted by the negative indirect impact that the storage subsidy η_S has on K_R (by incentivising storage investment).

Proof of Proposition 9

The free entry condition implies zero profits so that equilibrium investment (K_S^*, K_R^*) is implicitly given by:

$$F(K_S^*, K_R^*) = 2|b - \alpha K_R^*/2| \sin\tau - \frac{C_S(K_S^*)}{K_S^*} + \eta_S = 0 \tag{B.1}$$

$$H(K_S^*, K_R^*) = \Big(\theta - K_R^*/2)\pi + \alpha\Big(b - \alpha K_R^*/2\Big)\Big(\tau + \sin\tau\cos\tau\Big) - \frac{C_R(K_R^*)}{K_R^*} + \eta_R = 0 \tag{B.2}$$

with τ being a function of K_S^* and K_R^* implicitly given by equation (8).

We are interested in signing the following expressions:

$$\left.\frac{dK_i^*(\eta_S, \eta_R)}{d\eta_i}\right|_{(K_S^*, K_R^*)} \quad \text{and} \quad \left.\frac{dK_j^*(\eta_S, \eta_R)}{d\eta_i}\right|_{(K_S^*, K_R^*)}$$

For this purpose, given that equations ($B.1$) and ($B.2$) are continuously differentiable in a neighborhood of any equilibrium (K_S^*, K_R^*) (except for $K_R^* = 2b$ when $\alpha = 1$), we can rely on the Implicit Function Theorem (IFT). Totally differentiating equations ($B.1$) and ($B.2$), we get:

$$dF = dK_S F_{K_S} + dK_R F_{K_R} + d\eta_S F_{\eta_S} = 0 \tag{B.3}$$

$$dH = dK_S H_{K_S} + dK_R H_{K_R} + d\eta_R H_{\eta_R} = 0 \tag{B.4}$$

where we have taken the partial derivatives with respect to the subscripts of F and H. Setting $d\eta_R = 0$ and dividing equations ($B.3$) and ($B.4$) by $d\eta_S$, we get the following system (in matrix form):

$$\begin{bmatrix} F_{K_S} & F_{K_R} \\ & \\ H_{K_S} & H_{K_R} \end{bmatrix} \begin{bmatrix} \dfrac{dK_S^*(\eta_S, \eta_R)}{d\eta_S} \\ \\ \dfrac{dK_R^*(\eta_S, \eta_R)}{d\eta_S} \end{bmatrix}_{(K_S^*, K_R^*)} = \begin{bmatrix} -F_{\eta_S} \\ \\ 0 \end{bmatrix}$$

Similarly, setting $d\eta_S = 0$ in equations ($B.3$) and ($B.4$), and dividing by $d\eta_R$ we get the following system (in matrix form):

$$\begin{bmatrix} F_{K_S} & F_{K_R} \\ & \\ H_{K_S} & H_{K_R} \end{bmatrix} \begin{bmatrix} \dfrac{dK_S^*(\eta_S, \eta_R)}{d\eta_R} \\ \\ \dfrac{dK_R^*(\eta_S, \eta_R)}{d\eta_R} \end{bmatrix}_{(K_S^*, K_R^*)} = \begin{bmatrix} 0 \\ \\ -H_{\eta_R} \end{bmatrix}$$

As we will later show, the Jacobian is non-singular at equilibrium, so we can apply the

IFT and Cramer's rule to obtain the following expressions of interest:

$$\left.\frac{dK_S^*(\eta_S,\eta_R)}{d\eta_S}\right|_{(K_S^*,K_R^*)} = \frac{-H_{K_R}}{F_{K_S}H_{K_R}-F_{K_R}H_{K_S}} \tag{B.5}$$

$$\left.\frac{dK_R^*(\eta_S,\eta_R)}{d\eta_S}\right|_{(K_S^*,K_R^*)} = \frac{H_{K_S}}{F_{K_S}H_{K_R}-F_{K_R}H_{K_S}} \tag{B.6}$$

$$\left.\frac{dK_S^*(\eta_S,\eta_R)}{d\eta_R}\right|_{(K_S^*,K_R^*)} = \frac{F_{K_R}}{F_{K_S}H_{K_R}-F_{K_R}H_{K_S}} \tag{B.7}$$

$$\left.\frac{dK_R^*(\eta_S,\eta_R)}{d\eta_R}\right|_{(K_S^*,K_R^*)} = \frac{-F_{K_S}}{F_{K_S}H_{K_R}-F_{K_R}H_{K_S}} \tag{B.8}$$

where we have used the fact that $F_{\eta_S} = H_{\eta_R} = 1$.
Recall that, for all K_S and all K_R (except for $K_R = 2b$ if $\alpha = 1$):

$$\frac{d\tau(K_S,K_R)}{dK_S} = \frac{-\partial g/\partial K_S}{\partial g/\partial \tau} = \frac{(-1)}{2|b-\alpha K_R/2|(\pi/2-\tau)\cos\tau} < 0.$$

$$\frac{d\tau(K_S,K_R)}{dK_R} = \frac{-\partial g/\partial K_R}{\partial g/\partial \tau} = \frac{-\operatorname{sign}(2b-\alpha K_R)\alpha K_S}{4(b-\alpha K_R/2)^2(\pi/2-\tau)\cos\tau}.$$

Using these expressions, we can obtain the following partial derivatives, which we assess for $\tau \in [0,\pi/2)$:

$$F_{K_S} = \frac{(-1)}{\pi/2-\tau} - \frac{C_S'(K_S^*)K_S^* - C(K_S^*)}{(K_S^*)^2} < 0.$$

$$F_{K_R} = -\alpha \operatorname{sign}(2b-\alpha K_R^*)\frac{\cos\tau}{\pi/2-\tau}$$

$$H_{K_S} = -\alpha \operatorname{sign}(2b-\alpha K_R^*)\frac{\cos\tau}{\pi/2-\tau}$$

$$H_{K_R} = \frac{-\left[\pi+\tau-\sin\tau\cos\tau\right]}{2} - \frac{(\cos\tau)^2}{\pi/2-\tau} - \frac{C_R'(K_R^*)K_R^* - C(K_R^*)}{(K_R^*)^2} < 0.$$

with τ implicitly given by equation (8). To determine the sign F_{K_S} and H_{K_R}, we have relied on the convexity of the cost function, which implies $C'(K_i) > C(K_i)/K_i$ for $I = \{S,R\}$. In turn, the partial derivatives F_{K_R} and H_{K_S} are negative if and only if $\alpha = 1$ and $K < 2b$. It remains to show that the Jacobian is non-singular. Its determinant is:

$$\begin{vmatrix} F_{K_S} & F_{K_R} \\ H_{K_S} & H_{K_R} \end{vmatrix} = \frac{\pi + \tau - \cos\tau \sin\tau}{2\Big(\pi/2 - \tau\Big)} + \frac{C_R'(K_R^*)K_R^* - C(K_R^*)}{\Big(K_R^*\Big)^2} \frac{1}{2\Big(\pi/2 - \tau\Big)}$$
$$+ \frac{C_S'(K_S^*)K_S^* - C(K_S^*)}{\Big(K_S^*\Big)^2} \left(\frac{-\Big[\pi + \tau - \sin\tau \cos\tau\Big]}{2} - \frac{(\cos\tau)^2}{\pi/2 - \tau} \right)$$
$$+ \frac{C_S'(K_S^*)K_S^* - C(K_S^*)}{\Big(K_S^*\Big)^2} \frac{C_R'(K_R^*)K_R^* - C(K_R^*)}{\Big(K_R^*\Big)^2}$$

with the four terms being positive given the convexity of the cost functions. Using expressions (B.5) to (B.8) and the signs of the partial derivatives characterized above, it follows that

$$\left.\frac{dK_i^*(\eta_S, \eta_R)}{d\eta_i}\right|_{(K_S^*, K_R^*)} > 0,$$
$$\left.\frac{dK_j^*(\eta_S, \eta_R)}{d\eta_i}\right|_{(K_S^*, K_R^*)} < 0 \Leftrightarrow \alpha = 1 \text{ and } K_R^* < 2b.$$

C Simulations

We model equilibrium market outcomes in the Spanish electricity market over $8,760$ periods (hours), both under competitive bidding as well as under strategic bidding.

In each period t, consumer demand is denoted by $D(t)$. It is assumed to be perfectly inelastic up to a price cap (set at 500 €/MWh for the baseline simulations). Electricity is generated at different plants, each with an installed capacity of k_i and a constant operating cost. This cost, denoted by c_{it}, varies across plants and time (indexed by date t) due to differences in technology and input costs.

The marginal cost of electricity generation depends on a plant's heat rate (energy efficiency), emission rate, and variable operation and maintenance costs. For thermal plants, input costs (e.g., gas, coal, CO2 allowances) fluctuate daily. In contrast, hydro and renewable plants have zero fuel costs, with marginal costs driven solely by operation and maintenance costs, as their inputs are freely available and emission-free.

Each plant operates subject to an hourly capacity factor $\omega_i(t) \in [0, 1]$, which determines the maximum possible generation at time t. Thus, generation $q_i(t)$ from plant i must satisfy $q_i(t) \leq \omega_i(t)k_i$. For thermal technologies, $\omega_i(t) = 0.9$ for all t when the plant is not under maintenance, while for intermittent renewable technologies, it takes values between 0 and 1 reflecting the hourly and monthly seasonality of their availability.

Electricity can be shifted across time through batteries. Let $q_B(t)$ and $q_S(t)$ denote energy charged and discharged by battery operators. The stock of energy in the battery $S(t)$ evolves over time based on charging and discharging, following the equation:

$$S(t) = S(t-1) + \eta q_B(t) - q_S(t)$$

where $\eta \in [0,1]$ captures the round-trip efficiency of the battery. The battery's state must remain within its capacity limits, such that $0 \leq S_t \leq K_S$, where K_S is the amount of storage capacity in the market. Batteries have a ζ-hour duration, which implies that it takes ζ hours to discharge the battery fully at its rated power capacity. Therefore, power constraints (i.e., maximum amount that it can be charged and discharged at period t) are $0 \leq q_j(t) \leq K_S/\zeta$.

Battery operators are assumed to have perfect foresight and engage in price arbitrage within each natural day, subject to charge/discharge constraints and capacity availability.[40] Finally, market clearing requires that supply matches demand on an hourly basis.

Given our assumptions about perfect foresight and price-taking behavior of storage facilities, we can compute the competitive equilibrium using the social planner's problem (see the figures representing the competitive equilibrium below). Since demand is perfectly inelastic, the planner minimizes total generation costs subject to the relevant constraints. Therefore, for each 24 hour cycle, the problem is:

$$\begin{aligned}
\min_{q_i(t),\, q_B(t),\, q_S(t)} \quad & \sum_{t=1}^{8{,}760} \sum_i c_{it} q_i(t) \\
\text{s.t.} \quad & D(t) = q_S(t) - q_B(t) + \sum_i q_i(t), \quad \forall t \\
& S(t) = S(t-1) + \eta q_B(t) - q_S(t), \quad \forall t \\
& 0 \leq S(t) \leq K_S, \quad \forall t \\
& 0 \leq q_j(t) \leq K_S/\zeta, \quad \text{for } j = \{B, S\} \text{ and } \forall t \\
& S(24) = S(0) \\
& 0 \leq q_i(t) \leq \omega_i(t) K_i, \quad \forall i,\, t,
\end{aligned}$$

Under strategic bidding, we assume that there is a single dominant firm, owning 25%

[40] To ensure this, we impose that the energy level at the start and end of each daily cycle must be equal. Given the characteristics of most market batteries, allowing for longer optimization horizons would not significantly alter results but would increase computational complexity.

of each generation plant. This firm chooses its production (or, equivalently, its price) so as to maximize profits over its residual demand, taking as given the competitive behavior of all other firms.

We use data from a representative year, 2019, prior to the pandemic and the energy crisis. Hourly demand, hourly renewable availability, and installed capacity for each technology (Table 1) are sourced from the Spanish System Operator (REE). Our model incorporates all technologies present in the Spanish electricity market, including conventional generation (nuclear, hydro, coal, and gas-fired plants) and renewable sources (solar photovoltaic, solar thermal, and wind).

We obtain daily gas prices from the Spanish Gas Exchange (MIBGAS), as well as CO_2 EU allowances and daily coal prices from Bloomberg. Additionally, we have detailed information on the heat rate and emission rates of each plant. These values align with standard benchmarks for each technology while capturing plant-specific variations, such as differences due to vintage or, in the case of coal plants, other operational characteristics.[41]

For batteries, we assume a round-trip efficiency of $\eta = 0.9$ and a duration of $\zeta = 4$ hours. Hydro generation is allocated to shave demand peaks (net of renewable generation), helping to minimize overall production costs.

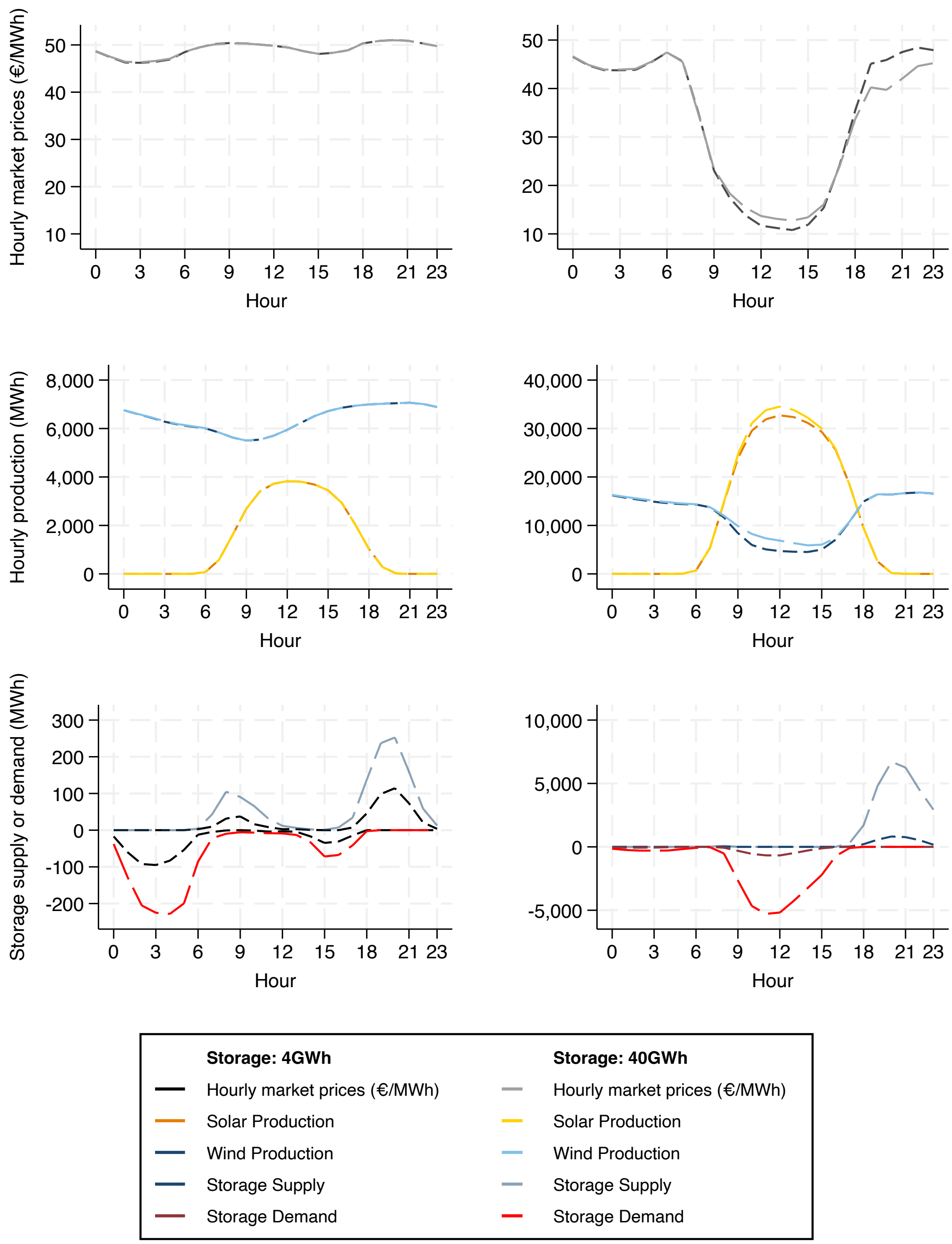
For the counterfactual scenarios, we adopt the assumptions of the Spanish National Energy and Climate Plan for 2030 regarding the energy mix and demand growth forecasts. We leave all other parameters unchanged – including the hourly availability profiles of those technologies.

C.1 Additional Simulations

The baseline simulations assume strategic bidding by a dominant firm that owns 25% of all generation capacity. For completeness, we replicate the main figures below under the alternative assumption of competitive bidding by all firms. As can be seen, equilibrium prices are lower under competitive bidding; however, the overall price patterns and the timing of storage decisions remain qualitatively similar to those in the baseline model with strategic bidding by a dominant firm.

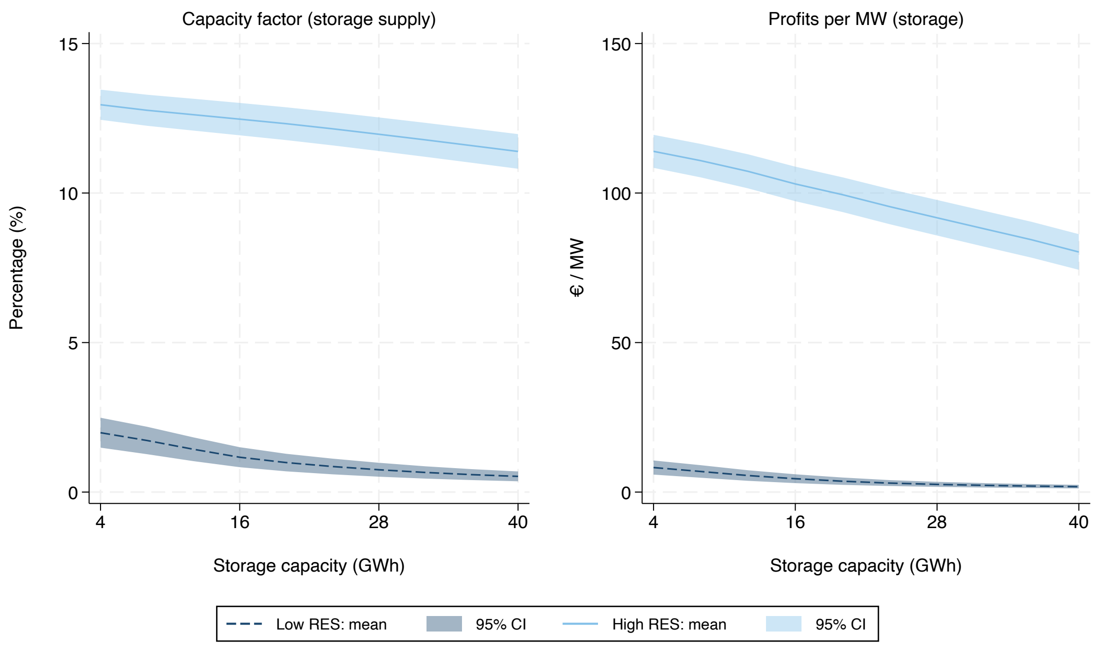
[41]For more details on the computation of marginal costs, see Fabra and Imelda (2023).

Figure C.1: Market prices, renewables generation, and storage decisions (competitive firms)



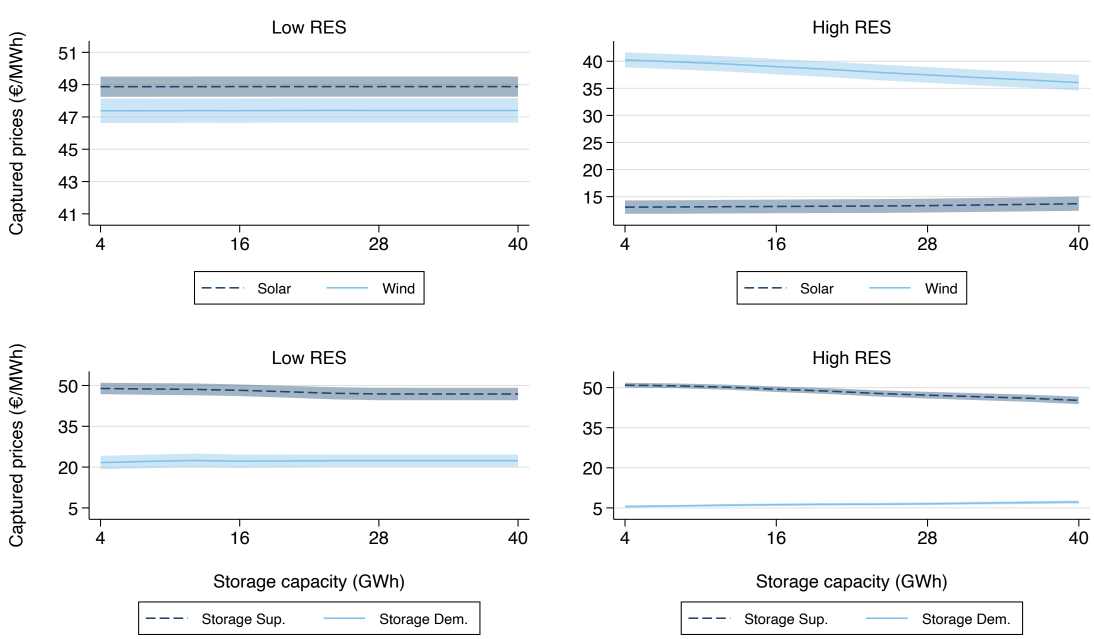
Notes: This figure replicates Figure 4 in the main text assuming perfectly competitive behavior.

Figure C.2: Capacity factors and profits of energy storage (competitive firms)



Notes: This figure replicates Figure 5 in the main text assuming perfectly competitive behavior.

Figure C.3: Captured prices by renewables and storage (competitive firms)



Notes: This figure replicates Figure 6 in the main text assuming perfectly competitive behavior.

Last, as mentioned above, the baseline simulations assume a price cap equal to

500€/MWh. To show that the main results remain qualitatively similar under alternative values of the price cap, Figure C.4 replicates Figure 4 in the main text, under strategic bidding by the dominant firm but now with a 1,000 €/MWh price cap.

D Additional Results

D.1 Predictable changes in demand and renewable energy availability

The following table presents the results of regressions of the realized values of key outcome variables (electricity demand, solar generation, wind generation, and net demand, i.e., demand net of solar and wind generation) on their respective day-ahead forecasts. The analysis is based on hourly data from the Spanish electricity market spanning January 2019 to December 2024, obtained from (https://www.esios.ree.es/es).

Table D.1: Regression Results: Realized vs Forecast Demand and Renewables

	Demand	**Solar**	**Wind**	**Net Demand**
Intercept	15.80***	-43.57***	-36.72***	-77.65***
	(5.6965)	(2.1956)	(3.7848)	(8.1288)
Day-ahead forecast	0.999***	1.013***	1.012***	1.002***
	(0.0002)	(0.0004)	(0.0005)	(0.0004)
R^2	0.998	0.993	0.987	0.990
Observations	52,608	52,587	52,588	52,567

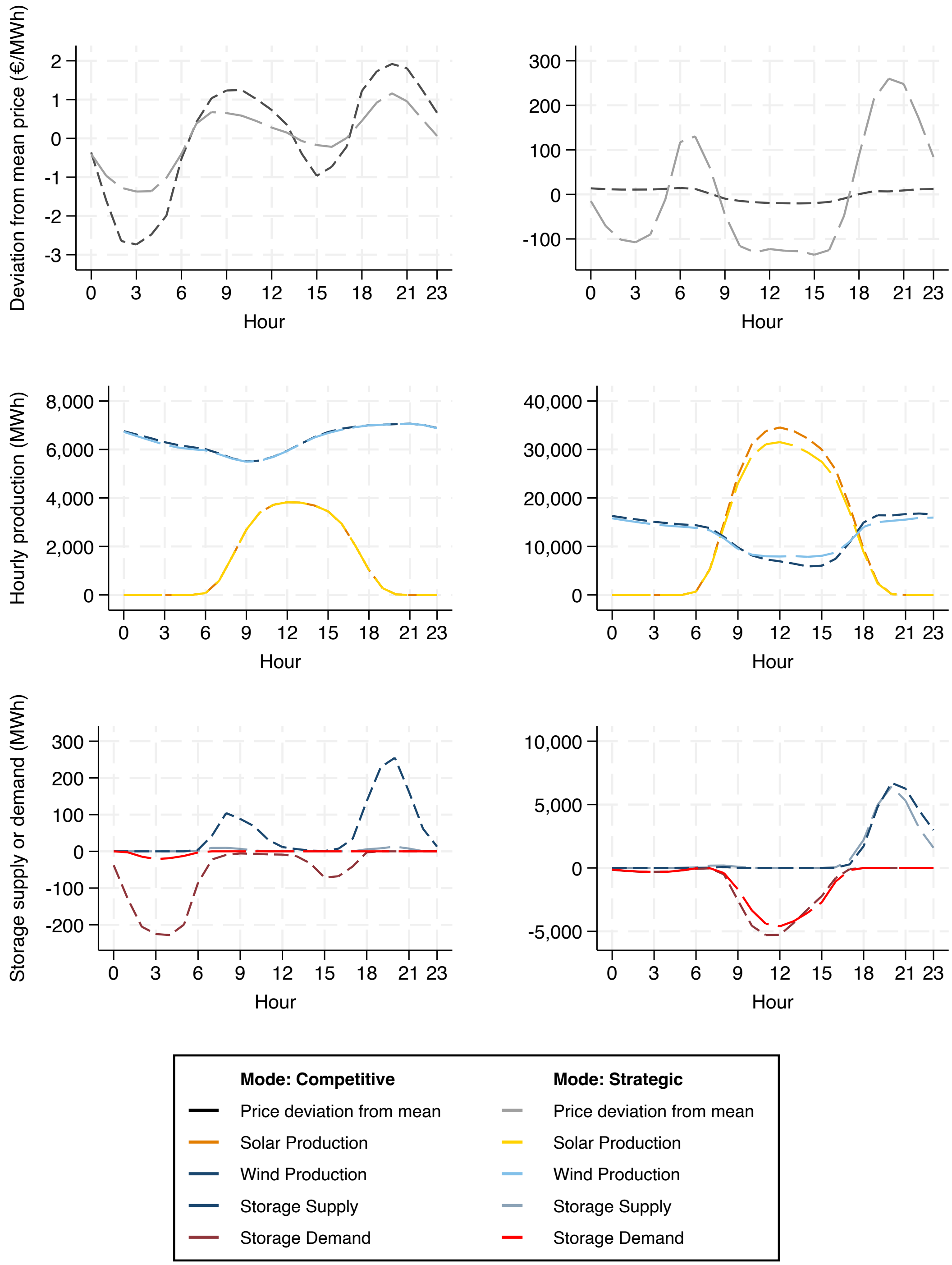
Notes: Standard errors in parentheses. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

The consistently high R^2 values across specifications indicate that a substantial share of the variation in these outcomes is explained by their predictable, deterministic components, highlighting the limited role of stochastic variation at the hourly level.

D.2 Intraday variation dominates demand and renewable supply swings

We estimate a parsimonious calendar fixed–effects specification on six years of hourly Spanish system data. Our goal is to decompose the hourly variation of three key series: realized electricity demand, solar generation, and (onshore) wind generation. The

Figure C.4: Market prices, renewables generation, and storage decisions



Notes: This figure replicates Figure 4 in the main text, with a 1,000 €/MWh price cap.

Table D.2: Adjusted R^2 from calendar fixed–effects regressions

Series	Hour-only R^2	Full R^2 (H+W+M+Y)	Hour/ Full
Demand	0.45	0.77	0.58
Solar	0.65	0.78	0.84
Wind	0.01	0.42	0.01

raw series are drawn from the ENTSO-E transparency platform for January 2019 to December 2024.[42] For each outcome y_t, we run:

$$y_t = \sum_{h=1}^{23} a_h \mathbf{1}\{\text{Hour} = h\} + \sum_{d=1}^{6} \beta_d \mathbf{1}\{\text{Day} = d\} + \sum_{m=1}^{11} \gamma_m \mathbf{1}\{\text{Month} = m\} + \sum_{y=1}^{5} \delta_y \mathbf{1}\{\text{Year=y}\} + \varepsilon_t,$$

where the hour dummies isolate the *diurnal cycle*, weekday dummies capture short-term work-holiday cycles, month dummies capture more seasonal swings, and year dummies capture structural shifts (e.g., solar build-out). We estimate the model by OLS with Newey–West standard errors to control for serial correlation, and we compare specifications via the adjusted R^2.

The resulting variance decomposition in Table D.2 shows that hour-of-day effects alone account for 58% of calendar-explainable variation in demand and for 84% in solar output, suggesting that the fluctuations storage operators face are mostly driven by predictable intraday patterns rather than by higher-frequency noise or inter-day shocks. Note that solar is almost entirely diurnal, leaving little room for seasonal variation and for stochastic shocks beyond cloud cover. In contrast, wind power is weakly linked to the clock but strongly seasonal. These results underscore how Spanish hourly system dynamics are substantially driven by diurnal patterns.

For additional evidence, empirical studies and reports consistently show that a large share of the variability in electricity demand and renewable energy production occurs within the day, rather than across days or weeks, especially for solar production. The US Energy Information Administration highlights that demand follows a strong diurnal pattern, with demand typically peaking during daytime and falling at night (U.S. Energy Information Administration, 2020). Grid operators worldwide plan around a recurring daily load curve.

[42]ENTSO-E sources the data from Red Eléctrica de España's ESIOS database.

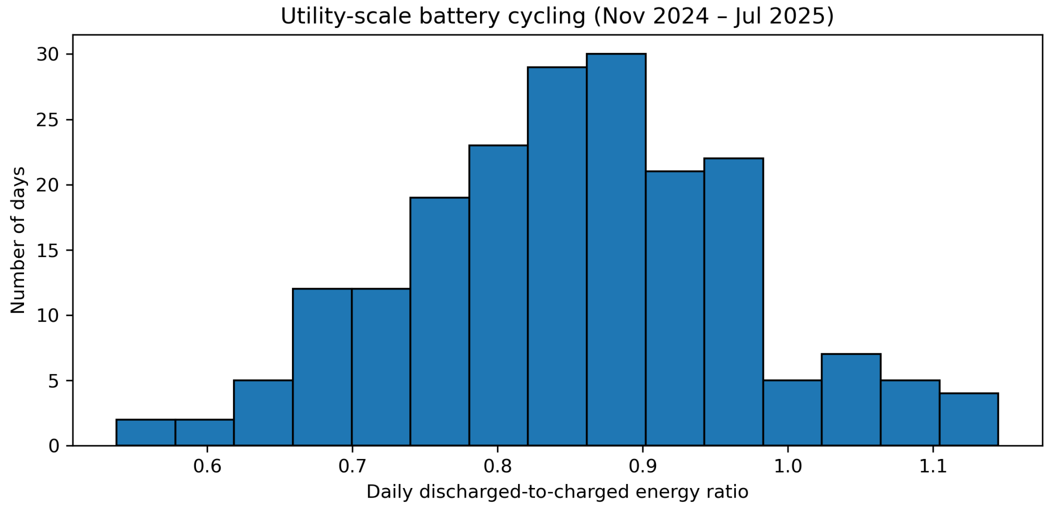


Figure D.1: Distribution of daily discharged-to-charged energy ratios for Spanish utility-scale batteries, 18 Nov 2024–22 Jul 2025. The median is 0.86 and the inter-quartile range is 0.78–0.92.

D.3 Batteries' daily cycle

We have downloaded hourly charge and discharge flows for every utility-scale battery connected to the Spanish transmission grid from *Red Eléctrica de España* on its public data portal ESIOS. We have extracted the files from November 2024 to July 2025 – prior data is not available.

For every calendar day in the sample, we sum all the megawatt-hours that Spain's utility-scale batteries charged and all the megawatt-hours they released. To assess whether the storage cycle occurs within the same 24-hour window, we compared the two by dividing energy discharged by energy charged within the day, producing a single ratio for each day. Values between 0.7 and 0.9 indicate that nearly everything charged was discharged before midnight,[43] while lower ratios indicate that some of the stored energy waited until the following day (or later) to be released. Finally, we plotted all of those daily ratios in a histogram to reveal the fleet's typical operating pattern at a glance.[44]

We find that the median battery releases 86% of the energy it absorbs on the same day. The 25th–75th percentile band is 0.78–0.92, and fewer than 3% of days fall below 0.65. Hence, Spanish grid-scale batteries operate on (almost) one full cycle per 24 hours,

[43] This is because there are some energy losses along the way (round-trip efficiency), which are usually in the range of $10-30\%$.

[44] The ratio of energy discharged over energy charged over the whole sample period is equal to 0.85, a number in line with the standard round-trip efficiency for batteries.

aligning with their 4–6 h energy capacity and the well-known mid-day solar surplus vs. evening peak demand pattern. [45]

Because storage arbitrage and balancing activity overwhelmingly close within the day, a diurnal net-load model captures the dominant economics of battery dispatch. Multi-day optimisation would add complexity without materially changing our main results.

[45]Comparable daily cycling behaviour is documented for California's fleet (CAISO, 2024; Lamp and Samano, 2022) and for the batteries in the Australian NEM (Rangarajan et al., 2023).