Storage and Renewable Energies: Friends or Foes?

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Abstract

Decarbonizing the power sector requires substantial investments in renewable energies and storage. Although often viewed as complements, these technologies can also act as strategic substitutes. When renewable output coincides with high demand, storage may reduce renewable profits, and *vice versa*, particularly when coal and gas generators adjust their production strategically. In markets where renewable technologies, such as solar and wind, produce at different times, storage can benefit one technology while disadvantaging the other. These findings inform the design and sequencing of mandates and subsidies: in solar-dominated systems, an initial push for solar may be needed before storage and renewables become mutually reinforcing. Simulations of the Spanish electricity market confirm that, at high solar penetration, storage increases solar profitability but lowers wind revenues.

Keywords: storage, renewables, mandates, market power, transmission constraints.
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1 Introduction

Investments in renewable energy are essential for decarbonizing the economy. Yet, because solar and wind generation fluctuate with weather conditions, ensuring a reliable power supply remains a challenge. Storage technologies —such as batteries and pumped hydro— help address this problem by shifting electricity from periods of excess renewable production to periods of scarcity, thereby lowering system costs and emissions.

Given this technological complementarity, it is often assumed that renewables and storage are also *complements* from an economic viewpoint.[1] Storage is expected to raise prices when renewables are abundant, increasing their revenues, while renewable intermittency is thought to enhance arbitrage opportunities for storage firms.

This paper shows that this view is incomplete. We demonstrate that renewables and storage can also behave as economic *substitutes*. Market prices —shaped by both demand and supply— govern the timing of charging and discharging decisions, and thus determine whether storage supports or competes with renewables. When storage releases energy at times of high renewable availability, it can lower renewable revenues; conversely, when renewables reduce price fluctuations over time, they can limit storage profits. These strategic interactions affect how renewables and storage evolve together and have implications for the design and timing of policy support.

We identify the conditions under which renewables and storage behave as economic substitutes or complements —what we term *strategic* substitutes or complements,— highlighting how demand patterns, the mix of renewable technologies, and support policies shape their interactions. We also examine how these relationships are affected by market power in generation and storage, as well as by binding transmission constraints.

Our analysis highlights that strategic substitutability is more likely in the early stages of solar deployment, when the timing of solar generation still coincides with high demand and high prices. It can also arise in systems that combine technologies with contrasting output profiles —for example, solar and wind, which generate mainly during daytime and nighttime hours, respectively. In contrast, binding transmission constraints between a supply and a demand node eliminate substitutability, as the local prices for electricity generation become independent of demand conditions. In such settings, if storage is co-located with renewable plants, it consistently charges when renewable generation drives prices down and discharges when renewable energy is scarce.

[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."

Many electricity systems pursue renewable energy and storage deployment targets through mandates or investment subsidies, reflecting market failures that may cause decentralized investment decisions to diverge from system-level needs. First, renewable generation and storage investments are inherently lumpy and often require coordination over time: the profitability of storage depends on the price patterns induced by renewable generation, and *vice-versa*. While private investors make decisions independently, a planner or regulator can internalize these complementarities and coordinate investments over time. Second, the presence of market power in thermal generation and/or storage, or the failure to fully internalize carbon emissions, can lead to price spreads that deviate from their efficient levels, thereby distorting the incentives to invest in storage capacity. These failures prompt policymakers to rely on technology-specific support instruments as a second-best solution for aligning private and social objectives.

Examples of support policies for renewable energies and storage can be found in California, where the California Public Utility Commission requires utilities to purchase energy storage, and new commercial buildings must install solar power and battery storage. Similarly, several European countries mandate battery investments as a condition for renewable energy subsidies. Both the US and Europe have introduced substantial subsidies for energy storage.[2] In the US, the Inflation Reduction Act provides federal tax credits for investing in storage and renewable energies. The Recovery and Resilience Facility and the EU's Connecting Europe Facility provide funds to subsidize these investments in Europe.

In this paper, we develop a model of wholesale competition in an electricity market where coal and gas generators interact strategically with renewable and storage firms. Seasonal fluctuations in demand and renewable availability generate price variations over time, which can be amplified when thermal generators exercise market power. Storage operators take advantage of these price differences by charging when prices are low and discharging when prices are high, thereby influencing market price dynamics. The interaction between renewables and storage depends on the timing of these storage operations, which can either enhance or erode the profitability of each technology, depending on renewable generation patterns.

Our model shows that the relationship between renewable output and market prices plays a key role in determining the profitability of both renewables and storage. When renewable generation takes place during high-price hours —precisely when storage finds it optimal to discharge— the two technologies effectively compete. In this case, ex-

[2] For instance, in November 2025, Spain has allocated €840 million funds for storage projects.

panding storage reduces prices at the times when renewables sell a large share of their output, and expanding renewables further compresses price spreads, lowering storage profits. Conversely, when renewable generation occurs primarily during low-price periods, renewables and storage reinforce each other: renewables depress prices when storage charges, and storage boosts prices when renewable generation is more abundant, increasing the profitability of both technologies.

Whether this relationship is positive or negative depends on market characteristics and the technology mix. Indeed, electricity prices are shaped by both demand patterns and renewable output, which differ across technologies and regions. Wind generation typically peaks at night, when demand is low, creating a negative correlation between wind availability and prices —making wind a *countercyclical* technology. In contrast, solar generation peaks during the day, when demand is high —making solar a *procyclical* technology. This gives rise to a positive correlation between solar output and prices, but only when solar capacity is limited. As solar capacity expands, however, prices fall during peak production hours, eventually reversing the correlation. Consequently, wind and storage act as strategic complements, while solar and storage become complementary only once solar capacity is sufficiently large. At lower levels of solar penetration, they behave as strategic substitutes.

These dynamics are most evident in systems dominated by a single renewable technology, where its generation profile largely shapes the temporal pattern of electricity prices. When multiple technologies with opposing production profiles —such as solar during the day and wind at night — coexist, the effects partially offset each other across time. In such contexts, storage tends to complement the technology producing mainly in low-price periods (when it charges), while reducing revenues for the one producing when prices are higher (when it discharges). More generally, storage substitutes for the relatively scarce renewable technology whose output remains positively correlated with prices, a condition that is typically more restrictive for solar than for wind, given solar's natural procyclicality with demand.

Introducing market power in the storage segment or accounting for binding transmission constraints enriches the analysis without altering its main insights. When storage operators possess market power, the fundamental condition for complementarity between renewable generation and storage remains intact. However, strategic capacity withholding by the storage operator leads to underinvestment, as the storage firm seeks to enhance arbitrage profits. This behavior, in turn, increases the level of subsidies required to achieve ambitious renewable deployment targets.

In contrast, transmission congestion can alter the interaction between storage and renewable generation. When storage assets are co-located with renewable plants, congestion strengthens their complementarity by making local prices respond primarily to fluctuations in renewable output. In this case, storage operators consistently charge when renewable generation is abundant and discharge when it is scarce, largely independent of broader system-wide demand conditions.

These insights carry important policy implications. After characterizing the interaction between storage and renewables in the electricity market, we can evaluate whether market revenues are sufficient to meet technology-specific deployment targets or whether subsidies are required. In particular, we can assess whether tightening a storage (or renewable) mandate affects the subsidy needs of the other.

When renewables are countercyclical —such as wind— mandating or subsidizing storage generates a positive feedback loop that stimulates investment in renewables, and *vice-versa*. In contrast, when renewables are procyclical —such as solar— if installed capacity remains below a critical threshold, promoting storage technology can crowd out investment in renewables, and *vice-versa*, leading to low investment levels and high emissions. In such cases, an initial policy push for renewables is required to reach the critical mass that reverses the sign of the correlation between renewable output and prices. Once this threshold is crossed, strategic complementarity between storage and renewables emerges, so that policies supporting one technology reinforce investment in the other, ultimately reducing the subsidies needed to meet the deployment targets.

The relevance of these findings is underscored by ongoing policy debates in jurisdictions that are simultaneously expanding renewable generation and introducing storage targets. In California, for instance, the storage procurement mandates adopted by the California Public Utilities Commission were designed to absorb growing solar surpluses during midday hours, but have also raised concerns among solar producers about price suppression during periods when they earn a large share of their revenues — precisely the substitution mechanism identified in our analysis.

Similarly, Spain's 2030 National Energy and Climate Plan (PNIEC) envisions significant additions of both photovoltaic capacity and battery storage. Our results suggest that the sequencing of these investments can have implications for the budgetary cost of support policies. Related discussions have emerged at the EU level in the context of the 2023–24 electricity market design reform, where regulators debated whether storage should receive additional remuneration or rely solely on market arbitrage, and how support schemes should account for interactions with renewables. The UK's Review of

Electricity Market Arrangements (REMA) process is likewise considering how to remunerate low-carbon flexibility in renewables-based systems.

Collectively, these examples illustrate that policymakers increasingly rely on mandates and investment subsidies to coordinate lumpy, interdependent investments in renewables and storage – often in markets with some degree of market power and incomplete carbon pricing. Our framework provides a rationale for such interventions and highlights that their effectiveness depends on the sign of the price–output correlation induced by the electricity mix in each system.

We illustrate these theoretical results with simulations of the Spanish wholesale electricity market, comparing cases of low and high renewable penetration. Specifically, we analyze two scenarios: the market configuration in 2019, when renewables accounted for roughly 43% of installed capacity (mainly solar and wind), and projections for 2030, when this share is expected to reach about 82%. For each case, we evaluate outcomes under different levels of storage capacity.

In the low-renewables scenario, the relationship between prices and renewable generation is weak, so changes in renewable or storage capacity have limited effects on the profitability of other technologies. As solar production becomes more abundant, however, the correlation between prices and solar (wind) output turns negative (positive): solar generation substantially depresses market prices during midday peaks. In this setting, solar and storage investments reinforce each other, while storage tends to reduce wind producers' revenues.

Consistent with these patterns, our simulations show that increasing storage capacity from 4 GWh to 40 GWh in the high-renewables scenario raises the average price captured by solar producers by 16%, while reducing the average price received by wind producers by 14%. Although additional storage reduces wind curtailment —i.e., the loss of excess generation that cannot be absorbed— this effect is not large enough to offset the decline in prices. Thus, expanding storage capacity benefits solar while adversely affecting wind. Moreover, storage itself gains from renewable expansion: arbitrage profits and utilization rates increase roughly tenfold between the low- and high-renewables scenarios. However, as storage penetration grows, competition among storage units intensifies, leading to a *cannibalization effect* that limits further profitability in a renewables-dominated system.

The simulations also reveal that expanding storage capacity generates social benefits, particularly in competitive markets. In particular, storage reduces generation costs by displacing expensive peak thermal plants, lowers carbon emissions by mitigating renewable curtailment, and decreases wholesale electricity prices —especially under high renewable penetration. These effects highlight the broader social value of storage technologies and provide a rationale for targeted policy support. However, both our theoretical and quantitative analyses suggest that policymakers should first focus on expanding renewable capacity —especially in the case of solar— until a critical mass is achieved. Beyond that point, policies promoting storage become more effective and mutually reinforcing with renewable deployment.

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 balancing the electricity system.

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.[3] 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 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 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 renewable energies and storage.

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

[3] 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.

are considered (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.[4]

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 $0 \leq b \leq \theta$).[5] 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 sinusoidal function approximates typical intra-day electricity demand cycles.

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.[6] We assume price-taking behavior of storage and renewable operators, but we allow for market power in thermal generation.[7] This configuration is common in

[4]The Online Appendix contains extensions and details about the simulations.

[5]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 1 in Online Appendix D.1 for details.

[6]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.

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

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.

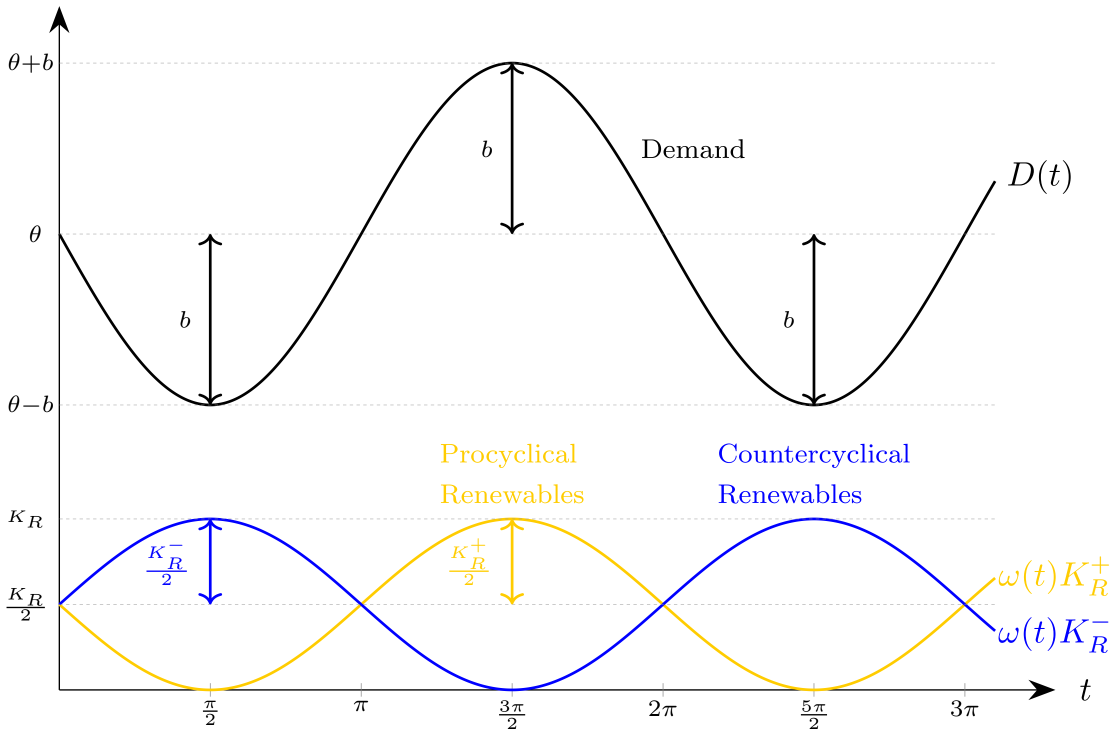
The marginal costs of renewable energies are normalized to zero up to their available capacity $\omega(t)K_R$, where K_R denotes the installed renewable capacity and $\omega(t) \in [0,1]$ is the capacity factor, which moves in deterministic cycles around its mean (normalized to 1/2), with amplitude 1/2. 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 to demand when $\alpha = 1$. Alternatively, if $\alpha = -1$, renewable availability decreases as demand increases. In this case, we describe renewables as *countercyclical.* [8]

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

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, resulting in the following linear marginal costs at the industry level: $c'(q(t)) = q(t)$.[9] Furthermore, it produces carbon emissions, denoted as $e\Big(q(t)\Big)$, which are assumed to be increasing and concave in output given that higher-cost generators tend also to be more carbon-intensive (Borenstein and Kellogg, 2023), i.e., $e'\Big(q(t)\Big) > 0$, $e''\Big(q(t)\Big) > 0$; for tractability, we further assume $e'''\Big(q(t)\Big) \leq 0$. Therefore, without a carbon price, thermal generation implies an unpriced negative externality.

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

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

firm's size, i.e., at any given price, 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.[10] 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 $C_i(K_i)$ for $i = \{S, R\}$, with $C_i'(K_i) > 0$ and $C_i''(K_i) \geq 0$.

3 Market Equilibrium

For given capacities, generation firms decide how much to produce, and storage firms choose when and how much energy to charge and discharge, under the assumption of perfect foresight over prices.[11]

Since renewable energies have zero marginal costs and operate competitively, they always produce at 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.[12] The thermal dominant

[10] 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 the rate at which 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, occur in low/high-priced periods, as shown later.

[11] 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 Online Appendix *D*.1).

[12] 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 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 distinct channels: one affecting the overall price level, and another affecting price fluctuations over time, as shown 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 the 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.[13]

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

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

(i) The competitive storage operators 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) The competitive storage operators 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) The competitive storage operators 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.

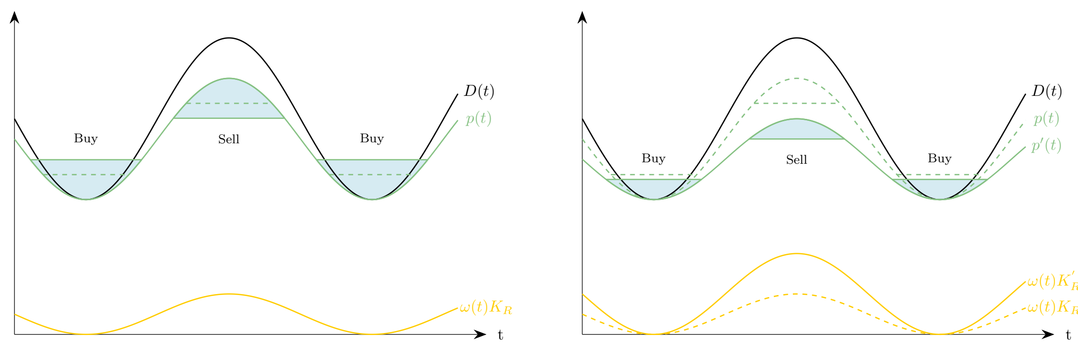
Importantly, when prices and renewable energies are positively correlated (Lemma 2 (*ii*)), discharging occurs when renewable availability is high. Thus, as shown in the upper left panel of Figure 2, an increase in storage capacity pushes prices down precisely when renewable energies are relatively more abundant.[14] 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.

[14] 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 remain constant for different demand levels. In these cases, marginal increases in capacity may not impact prices 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.

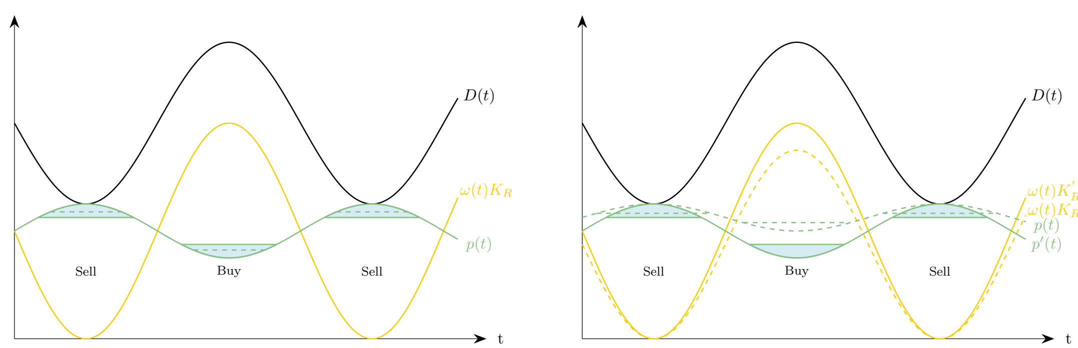
In all periods, market prices decrease when renewable capacity increases. As shown in the upper right panel of Figure 2, when prices and renewable generation are positively correlated, this price-depressing effect is more pronounced during periods when storage firms discharge rather than when they charge. Moreover, by shrinking the price spreads, a 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 $2b$.[15] 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.,*[16]

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

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.

[15]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%.

[16]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

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

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 with 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

In the absence of market failures, investment and operational decisions would be efficient, and no regulatory intervention would be required. In practice, however, market imperfections—such as market power in generation and unpriced thermal emissions—distort these decisions. Market power amplifies price spreads by introducing larger markups during periods of high demand and high prices (Lemma 1), thereby leading to over-investment in storage capacity (Andrés-Cerezo and Fabra, 2023). Conversely, the lack of carbon pricing flattens price patterns relative to true social marginal costs, inducing underinvestment in storage capacity. Together, these distortions provide a rationale for regulatory intervention.

To isolate the effects of these two market failures, in this section, we focus on the case without market power ($\beta = 0$), in which the environmental externality remains unpriced. In this setting, where the market delivers insufficient storage investment, regulatory intervention—through instruments such as mandates or investment subsidies—is needed to ensure cost recovery and to align private incentives with the socially optimal levels of renewable and storage investment.

For these reasons, we now turn to examining how support schemes affect firms' profits and, consequently, their long-run investment decisions. This analysis will help us study the regulator's policy choices aimed at inducing socially optimal investment outcomes.

Letting $\eta_S, \eta_R > 0$ denote the investment subsidies for storage and renewables, respectively,[17] the expected profits of storage and renewable firms can be written as:

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

where prices $p^*(t)$ and dispatched production $q^*(t)$ are those in Lemma 3.

The following proposition characterizes the effect of mandates, denoted as $\bar{K}_S$ and $\bar{K}_R$, on the break-even subsidies:[18]

Proposition 3 *Assume $\beta = 0$ 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 tech-

[17] 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.

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

nology 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.,

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

Increasing a technology mandate increases its own investment break-even subsidy because additional capacity reduces profitability — a 'cannibalization effect'. Whether this raises or decreases 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 can reduce the subsidy required for the other technology to break even. 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.

Now, consider a regulator who chooses renewable and storage mandates to maximize social welfare in a market where carbon emissions are unpriced. Note that, with price-inelastic demand and in the absence of market power, maximizing social welfare is equivalent to minimizing carbon emissions. The regulator has a limited budget, B. 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 $\eta_S^* > 0$ 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 it becomes large enough to flatten thermal production entirely. Beyond that point, any additional storage capacity would become idle, no longer reducing 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 over 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 $K_R = 2b$.[19]

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, market power in the storage sector leads storage firms to under-invest in capacity to preserve arbitrage profits. 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 the location of storage assets. If storage assets are situated close to demand centers, congestion can weaken or even eliminate the link between storage and renewable generation. The reason is that 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

[19] 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 the early stages remains unaffected.

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 that of market power in generation, we assume that all thermal generators behave competitively (i.e., $\beta = 0$). The key difference relative to 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 firm for a 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 the 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 $t \in [\underline{t}_B^M, \overline{t}_B^M]$, corresponding to the lowest prices in the absence of storage. The quantities $q_B^M(t)$ are such that the marginal expenditure is fully flattened across these periods, and storage is fully charged by period $\overline{t}_B^M$.

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

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

This result is analogous to 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.[20]

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 $c_S > 0$.[21]

[20]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.

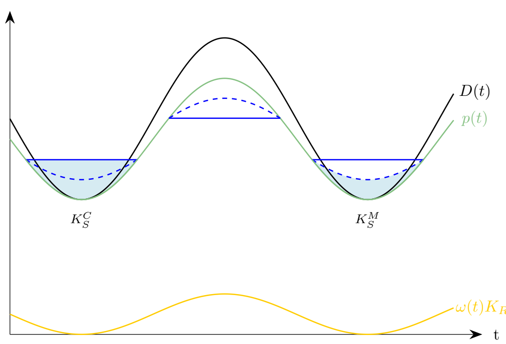
[21]Free entry implies that competitive firms invest in storage capacity up to the level at which the

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

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

The tendency of the storage monopolist to smooth storage operations 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:

marginal value of storage equals the average investment cost, whereas the storage monopolist invests until the marginal value of storage equals the marginal investment cost. If investment costs are strictly convex, average costs are below marginal costs, resulting in larger investment differences between the competitive and monopoly cases.

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:*

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

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.[22] 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.

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.[23]

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

[22]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.

[23]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).

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 $p_W(t)$:

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

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

In what follows, we consider two cases with storage capacity K_S located in either region E or W. We focus on situations where the transmission line is congested in every period.[24]

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 in market demand.

Storage firms buy (sell) when prices in region W are low (high).[25] 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

[24] 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.

[25] 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.

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.*

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 still applies. 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 the investment efforts 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.[26] 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.[27]

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

[27]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.

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.[28] This information allows us to calculate the marginal cost for each plant.[29] 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.[30]

We base the simulation on the theoretical model presented in Section 2, but allow the strategic firm to own a share of capacity across all technologies. This is a modest generalization of the model, in which market power is concentrated in the thermal segment. 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.[31] These competitive firms supply output at marginal cost, while the dominant firm meets the residual demand at its profit-maximizing price.[32] Since demand is assumed to be 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.[33]

[28]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).

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

[30]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.

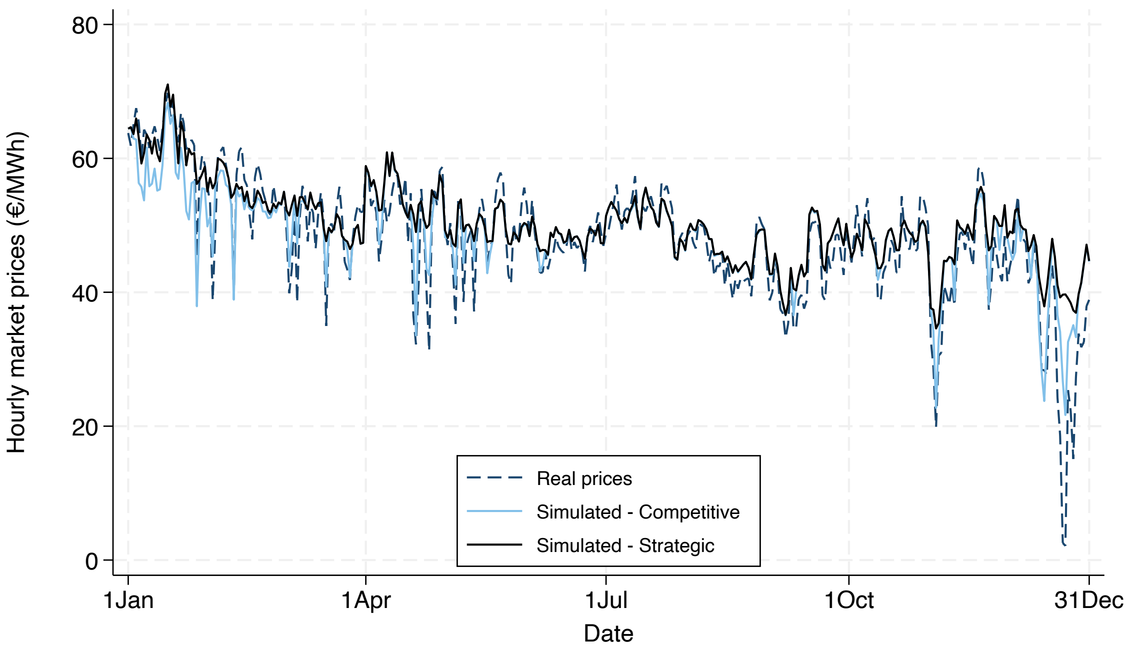
[31]Varying the parameter β alters the extent of market power that the dominant firm can exert, but it does not affect the qualitative nature of the results.

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

[33]As with the β parameter, changing the value of the price cap influences price levels by altering the

To assess the model's performance, we have run simulations using the 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,[34] respectively. 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.[35]

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.

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.

[34]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.

[35]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).

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 renewable energies. 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 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.

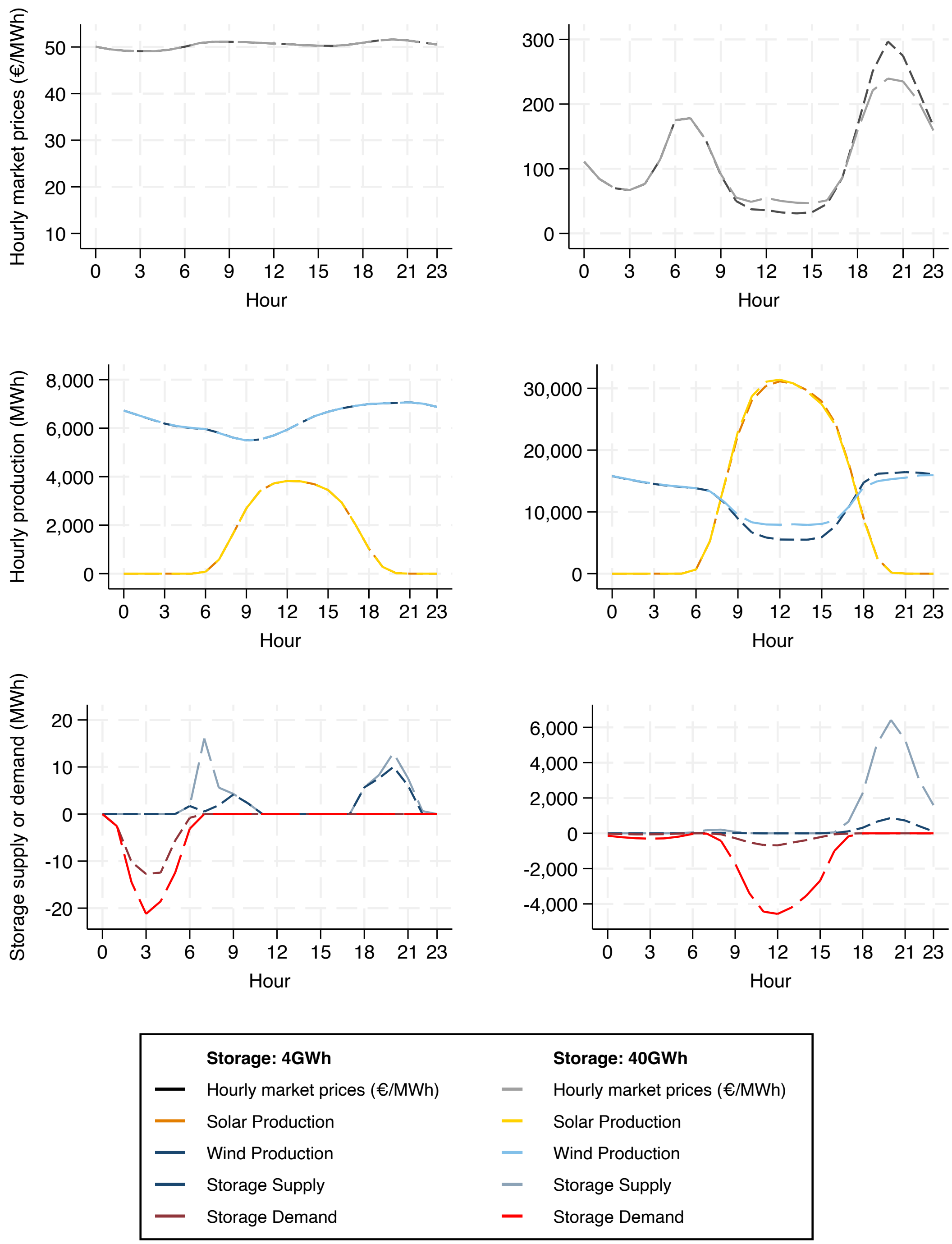
For each of these two scenarios, we consider different amounts of batteries with a 4-hour duration and 90% round-trip efficiency, corresponding to the most common type (NREL, 2022). This means that it takes four hours to fully charge/discharge a battery with a capacity equal to 4 GWh and power equal 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 given their available capacity. For each renewable scenario, we consider different levels of storage capacity, ranging from 4 GWh to 40 GWh.

Results. Figures 5 to 7 and Table 2 present the main results of our simulations. The upper panels in Figure 5 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 barely impacts the profitability of renewables or storage.[36] 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 5 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.

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

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.

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).

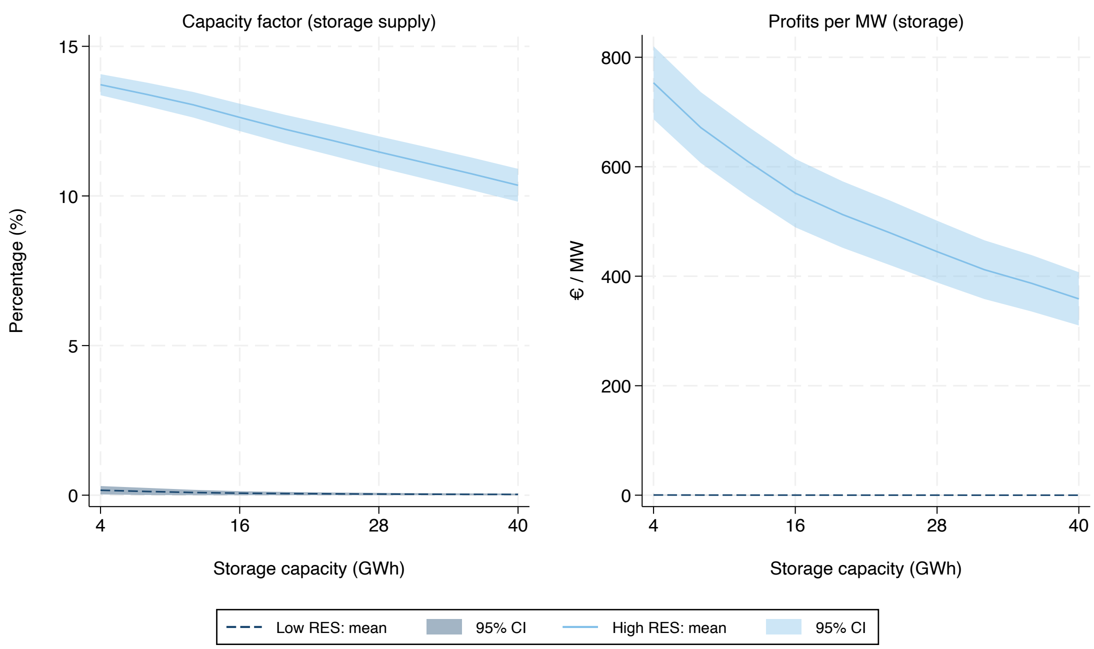
Finally, the lower panels of Figure 5 depict the charging and discharging behavior of storage facilities. In 2019, charging typically occurred at night, displaying a negative correlation with solar output and a positive one with wind. However, the utilization of storage is limited due to the small intra-day 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 reducing 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 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).

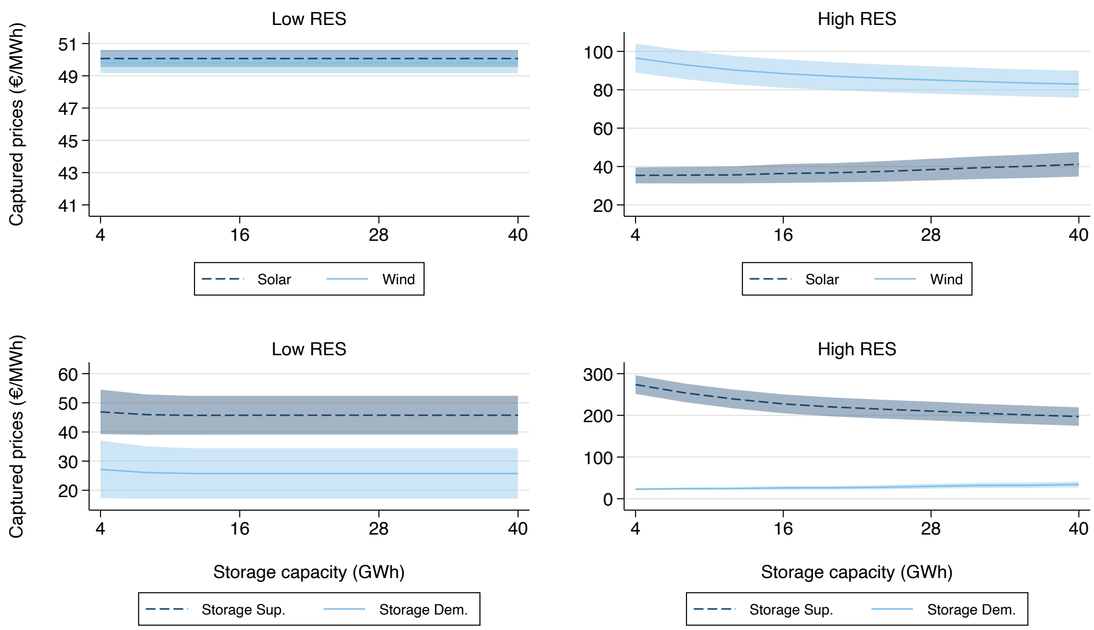
The lower panels of Figure 7 also reveal that, as expected, storage discharges at higher prices than when it charges. It also shows that the arbitrage profit is significantly larger in the high renewables scenario. Moreover, as more storage capacity is added, the cannibalization effect becomes stronger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

Table 2 presents the 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 under 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.

7 Conclusion

This paper identifies the conditions under which renewables and storage act as either strategic complements or substitutes. We find that storage investments tend to crowd out renewable investments, and *vice versa*, when renewable generation tends to coincide with high market prices. Conversely, when renewables produce mainly during low-price periods, the two technologies become complementary.

Our analysis provides new insights into the strategic interaction between renewable and storage investments. It challenges the conventional view that these technologies are always complementary, showing instead that they can behave as strategic substitutes — particularly in the early stages of renewable deployment or in systems combining several renewable technologies. Understanding whether renewables and storage complement or compete with each other is key to designing support policies that promote both efficiently

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).

and avoid unintended interactions.

The model assumes deterministic demand and renewable generation, allowing us to isolate the main drivers of price dynamics and clearly characterize storage behavior. A natural question is whether introducing uncertainty would change the degree of complementarity or substitutability between renewables and storage. Intuitively, price uncertainty could lead storage operators to reserve part of their capacity to respond to unexpected price movements —charging at unexpectedly low prices or discharging at high ones. This behavior would reduce the capacity used for predictable price arbitrage, but it should not alter the fundamental nature of the relationship, which depends on how renewable output affects market prices. Since this correlation is determined primarily by renewable capacity rather than by storage availability, the key mechanisms should remain intact. Assessing this formally would require extending the model to include stochastic components linked to renewable variability —an avenue left for future research.

In sum, whether renewables and storage act as strategic complements or substitutes may vary from one market to another, across technologies, and over time. Policy instruments should therefore evolve as these conditions change. Our results suggest that an initial policy push for solar investment may be needed to trigger complementarity with storage, after which the two technologies can reinforce each other in a virtuous cycle of deployment.

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Appendix

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:

$$\begin{aligned}\frac{\partial \pi_D}{\partial q_D\left(t\right)} = 0 &\Leftrightarrow \frac{ND(t, K_R) - 2q_D(t)}{1-\beta} - \frac{q_D(t)}{\beta} = 0 \\ &\Leftrightarrow q_D(t) = \frac{\beta}{1+\beta} ND(t, K_R), \forall t,\end{aligned}$$

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

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

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

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

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

$$\cos\tau - (\pi/2 - \tau)\sin\tau = K_S/|2\rho(K_R)|, \tag{14}$$

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:*

$$p^*(t) = \begin{cases} \Big(A(K_R) - \rho(K_R)\sin\tau\Big)\Big/(1-\beta^2) & \textit{if } \tau \leq t \leq \pi - \tau \\ \Big(A(K_R) + \rho(K_R)\sin\tau\Big)\Big/(1-\beta^2) & \textit{if } \pi + \tau \leq t \leq 2\pi - \tau \\ \Big(A(K_R) - \rho(K_R)\sin t\Big)\Big/(1-\beta^2) & \textit{otherwise} \end{cases}. \tag{15}$$

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

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

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:

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

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:

$$p(t) - \lambda + \eta_S(t) = 0, \forall t \tag{16a}$$
$$p(t) - \lambda + \mu - \eta_B(t) = 0, \forall t \tag{16b}$$
$$\int_0^{2\pi} q_B(t)dt - \int_0^{2\pi} q_S(t)dt \geq 0 \tag{16c}$$
$$K_S - \int_0^{2\pi} q_B(t)dt \geq 0 \tag{16d}$$

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 $t \in [0, 2\pi]$, $q_B(t) > 0 \rightarrow q_S(t) = 0$ and $q_S(t) > 0 \rightarrow q_B(t) = 0$. 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 (16a):

$$p(t) = \lambda \text{ , if } \underline{t}_S < t < \bar{t}_S, \tag{17}$$

and from (16b):

$$p(t) = \lambda - \mu \text{ , if } \underline{t}_B < t < \bar{t}_B. \tag{18}$$

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

$$p(t) = \frac{A(K_R) - \rho(K_R)\sin t - q_S(t) + q_B(t)}{1-\beta^2}. \tag{19}$$

Combining equations (17) and (18) with (19),

$$\begin{aligned} \lambda = p(t) &= \frac{A(K_R) - \rho(K_R)\sin t - q_S(t)}{1-\beta^2} \text{ , if } \underline{t}_S < t < \bar{t}_S \\ \lambda - \mu = p(t) &= \frac{A(K_R) - \rho(K_R)\sin t + q_B(t)}{1-\beta^2} \text{ , if } \underline{t}_B < t < \bar{t}_B. \end{aligned}$$

By continuity:

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

From (16c) and (16d),

$$\int_{\underline{t}_B}^{\bar{t}_B} \rho(K_R)\left(\sin \underline{t}_B - \sin t\right) dt = \int_{\underline{t}_S}^{\bar{t}_S} \rho(K_R)\left(\sin t - \sin \bar{t}_S\right) dt = K_S. \tag{20}$$

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 (20) 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:

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

Proof of Proposition 1

Storage profits are:

$$\begin{aligned} \Pi_S(K_S, K_R) &= \int_0^{2\pi} p^*(t)\Big[q_S^*(t) - q_B^*(t)\Big]dt - C_S(K_S) \\ &= \int_{\underline{t}_s}^{\bar{t}_S} p^*(\bar{t}_S)q_S^*(t)dt - \int_{\underline{t}_B}^{\bar{t}_B} p^*(\underline{t}_B)q_B^*(t)dt - C_S(K_S) \\ &= \Big[p^*(\bar{t}_S) - p^*(\underline{t}_B)\Big]K_S - C_S(K_S) \\ &= \frac{2|b - \alpha K_R/2|\sin\tau}{1-\beta^2}K_S - C_S(K_S), \end{aligned} \tag{21}$$

with $\underline{t}_B, \bar{t}_B, \underline{t}_S$ and $\bar{t}_S$ defined in Lemma 3. Partially differentiating equation (21):

$$\begin{aligned} \frac{d\Pi_S(K_S, K_R)}{\partial K_R} &= \frac{K_S}{1-\beta^2}\left[-\alpha\,\text{sign}(2b - \alpha K_R)\sin\tau + 2|b - \alpha K_R/2|\frac{\partial\tau}{\partial K_R}\cos\tau\right] \\ &= -\alpha\,\text{sign}(2b - \alpha K_R)\frac{K_S}{1-\beta^2}\left[\sin\tau + \frac{K_S}{2|b - \alpha K_R/2|\Big(\pi/2 - \tau\Big)}\right] \\ &= -\alpha\,\text{sign}(2b - \alpha K_R)\frac{\cos\tau}{\pi/2 - \tau}\frac{K_S}{1-\beta^2}, \end{aligned} \tag{22}$$

where in the second step we have used the fact that implicitly differentiating equation (14) yields:

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

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:

$$
\begin{aligned}
\Pi_R(K_S, K_R) = &\int_0^{2\pi} p^*(t)\frac{1}{2}\Big(1-\alpha\sin t\Big)K_R dt - C_R(K_R)\\
=&\frac{1}{2}\frac{K_R}{1-\beta^2}\Bigg(\int_0^{\tau}\Big[\theta-K_R/2-\Big(b-\alpha K_R/2\Big)\sin t\Big]\Big(1-\alpha\sin t\Big)dt\\
&+\int_{\tau}^{\pi-\tau}\Big[\theta-K_R/2-\Big(b-\alpha K_R/2\Big)\sin\tau\Big]\Big(1-\alpha\sin t\Big)dt\\
&+\int_{\pi-\tau}^{\pi+\tau}\Big[\theta-K_R/2-\Big(b-\alpha K_R/2\Big)\sin t\Big]\Big(1-\alpha\sin t\Big)dt\\
&+\int_{\pi+\tau}^{2\pi-\tau}\Big[\theta-K_R/2+\Big(b-\alpha K_R/2\Big)\sin\tau\Big]\Big(1-\alpha\sin t\Big)dt\\
&+\int_{2\pi-\tau}^{2\pi}\Big[\theta-K_R/2-\Big(b-\alpha K_R/2\Big)\sin t\Big]\Big(1-\alpha\sin t\Big)dt\Bigg) - C_R(K_R)\\
=&\Big[\Big(\theta-K_R/2\Big)\pi+\alpha\Big(b-\alpha K_R/2\Big)\Big(\tau+\sin\tau\cos\tau\Big)\Big]\frac{K_R}{1-\beta^2} - C_R(K_R).
\end{aligned} \tag{23}
$$

Partially differentiating equation (23):

$$
\begin{aligned}
\frac{\partial \Pi_R(K_S, K_R)}{\partial K_S} &= \alpha\Big(b-K_R/2\Big)\frac{\partial\tau}{\partial K_S}\Big[1+(\cos\tau)^2-(\sin\tau)^2\Big]\frac{K_R}{1-\beta^2}\\
&= \alpha\Big(b-\alpha K_R/2\Big)\frac{(-1)}{2|b-\alpha K_R/2|(\pi/2-\tau)\cos\tau}\Big[1+(\cos\tau)^2-(\sin\tau)^2\Big]\frac{K_R}{1-\beta^2}\\
&= -\alpha\,\mathrm{sign}(2b-\alpha K_R)\frac{\cos\tau}{(\pi/2-\tau)}\frac{K_R}{1-\beta^2},
\end{aligned} \tag{24}
$$

wherein the second step, we have used the fact that implicitly differentiating equation (14) 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 (22 and 24) depends on $\mathrm{sign}(2b - K_R^+ + K_R^-)$.

Proof of Proposition 3

From equations (21) and (23), the profits of renewable and storage firms meeting the mandates $(\bar{K}_S, \bar{K}_R)$ are given by:

$$\Pi_S(\bar{K}_S, \bar{K}_R, \eta_S) = 2|b - \alpha\bar{K}_R/2| \sin\tau \bar{K}_S - C_S(\bar{K}_S) + \eta_S\bar{K}_S$$
$$\Pi_R(\bar{K}_S, \bar{K}_R, \eta_R) = \Big[\Big(\theta - \bar{K}_R/2)\pi + \alpha\Big(b - \alpha\bar{K}_R/2\Big)\Big(\tau + \sin\tau\cos\tau\Big)\Big]\bar{K}_R - C_R(\bar{K}_R) + \eta_R\bar{K}_R$$

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:

$$\eta_S^*(\bar{K}_S, \bar{K}_R) = \max\left\{\frac{C_S(\bar{K}_S)}{\bar{K}_S} - 2|b - \alpha\bar{K}_R/2|\sin\tau, 0\right\} \tag{25}$$
$$\eta_R^*(\bar{K}_S, \bar{K}_R) = \max\left\{\frac{C_R(\bar{K}_R)}{\bar{K}_R} - \Big[\Big(\theta - \bar{K}_R/2)\pi + \alpha\Big(b - \alpha\bar{K}_R/2\Big)\Big(\tau + \sin\tau\cos\tau\Big)\Big], 0\right\} \tag{26}$$

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:

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

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:

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

Therefore, it follows that

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

Proof of Proposition 4

The regulator's problem can be written as:

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

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 $\bar{K}_R^* \geq 2b$ when $\alpha = 1$ and $B \geq \bar{B}$, 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:

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

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 $e'''(q)\leq0$, 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. 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* $\Big(t \in [\underline{t}_B, \overline{t}_B]\Big)$ *and discharging* $\Big(t \in [\underline{t}_S, \overline{t}_S]\Big)$ *periods be defined by*

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

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 $t \in [\underline{t}_B, \overline{t}_B]$,

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

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

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

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

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

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

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

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

subject to 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:

$$A(K_R) - \rho(K_R)\sin t - 2q_S(t) - \lambda = 0, \forall t \tag{27a}$$

$$A(K_R) - \rho(K_R)\sin t + 2q_B(t) - \lambda + \mu = 0, \forall t \tag{27b}$$

$$\int_0^{2\pi} q_B(t)dt - \int_0^{2\pi} q_S(t)dt \geq 0 \tag{27c}$$

$$K_S - \int_0^{2\pi} q_B(t)dt \geq 0 \tag{27d}$$

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 (27a):

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

and from (27b):

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

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 (27c) and (27d),

$$\int_{\underline{t}_B}^{\bar{t}_B} \rho(K_R)\frac{\sin t - \sin \underline{t}_B}{2}dt = \int_{\underline{t}_S}^{\bar{t}_S} \rho(K_R)\frac{\sin \bar{t}_S - \sin(t)}{2}dt = K_S. \tag{28}$$

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 (28) we obtain that $\tau^M \in [0, \pi/2)$ is implicitly given by:

$$\cos\tau^M - \left(\frac{\pi}{2} - \tau^M\right)\sin\tau^M = \frac{K_S}{|\rho(K_R)|}. \tag{29}$$

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:

$$\begin{aligned}
\Pi_S^M =& \int_0^{2\pi} p^M(t)\Big[q_S^M(t) - q_B^M(t)\Big]dt - C_S(K_S) \\
=& \int_{\underline{t}_s}^{\bar{t}_S} p^M(\bar{t}_S)q_S^M(t)dt - \int_{\underline{t}_B}^{\bar{t}_B} p^M(\underline{t}_B)q_B^M(t)dt - C_S(K_S) \\
=& \int_{\pi+\tau^M}^{2\pi-\tau^M}\left(A(K_R) - \rho(K_R)\frac{\sin t - \sin\tau^M}{2}\right)\rho(K_R)\frac{-\sin t - \sin\tau^M}{2}dt \\
& - \int_{\tau^M}^{\pi-\tau^M}\left(A(K_R) - \rho(K_R)\frac{\sin t + \sin\tau^M}{2}\right)\rho(K_R)\frac{\sin t - \sin\tau^M}{2}dt - C_S(K_S) \\
=& \frac{1}{2}\rho(K_R)^2\Big[(\pi/2 - \tau^M)\cos 2\tau^M + \sin\tau^M\cos\tau^M\Big] - C_S(K_S).
\end{aligned} \tag{30}$$

Partially differentiating equation (30):

$$\frac{\partial\Pi_S(K_S, K_R)}{\partial K_R} = -\alpha\rho(K_R)\Big(\pi/2 - \tau^M - \sin\tau^M\cos\tau^M\Big), \tag{31}$$

where we have used the fact that implicitly differentiating equation (29) 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:

$$\begin{aligned}
\Pi_R^M =& \int_0^{2\pi} p^M(t) \frac{1}{2} \Big(1 - \alpha \sin t\Big) K_R dt - C_R(K_R) \\
=& \frac{1}{2} K_R \Bigg(\int_0^{\tau^M} \Big(A(K_R) - \rho(K_R) \sin t\Big)\Big(1 - \alpha \sin t\Big) dt \\
&+ \int_{\tau^M}^{\pi - \tau^M} \left(A(K_R) - \rho(K_R) \frac{\sin t + \sin \tau^M}{2}\right)\Big(1 - \alpha \sin t\Big) dt \\
&+ \int_{\pi - \tau^M}^{\pi + \tau^M} \Big(A(K_R) - \rho(K_R) \sin t\Big)\Big(1 - \alpha \sin t\Big) dt \\
&+ \int_{\pi + \tau^M}^{2\pi - \tau^M} \left(A(K_R) - \rho(K_R) \frac{\sin t - \sin \tau^M}{2}\right)\Big(1 - \alpha \sin t\Big) dt \\
&+ \int_{2\pi - \tau^M}^{2\pi} \Big(A(K_R) - \rho(K_R) \sin t\Big)\Big(1 - \alpha \sin t\Big) dt \Bigg) - C_R(K_R). \qquad (32)
\end{aligned}$$

Partially differentiating equation (32) (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 (29) 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:

$$\cos \tau^M - \left(\frac{\pi}{2} - \tau^M\right)\sin \tau^M = \frac{K_S}{|\rho(\bar{K}_R)|}. \tag{33}$$

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:

$$\frac{\partial \Pi_S^M(K_S, K_R)}{\partial K_S} = 0 \Leftrightarrow 2|\rho(\bar{K}_R)| \sin \tau^M(K_S^M, \bar{K}_R) - c_s = 0. \tag{34}$$

with $\tau^M(K_S^M, \bar{K}_R)$ implicitly given by equation (33). 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:

$$\cos \tau^C - \left(\frac{\pi}{2} - \tau^C\right) \sin \tau^C = \frac{K_S}{2|\rho(\bar{K}_R)|}. \tag{35}$$

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

$$\Pi_S^C(K_S^C, \bar{K}_R) = 0 \Leftrightarrow 2|\rho(\bar{K}_R)| \sin \tau^C(K_S^C, \bar{K}_R) - c_s = 0. \tag{36}$$

with $\tau^C(K_S^C, \bar{K}_R)$ implicitly given by equation (35).
Comparing equations (34) and (36), 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 (23) (for the case where $\beta = 0$) and equation (32), we have that the per-unit investment subsidies 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 (34) and (36), we have that, for a given a renewable energy 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,

$$\eta_R^C(K_S^C,\bar{K}_R)-\eta_R^M(K_S^M,\bar{K}_R)=-\frac{1}{2}\Bigg(\int_{\tau^*}^{\pi-\tau^*}\rho(\bar{K}_R)\frac{\sin t-\sin\tau^*}{2}\Big(1-\alpha\sin t\Big)dt$$

$$+\int_{\pi+\tau^*}^{2\pi-\tau^*}\rho(\bar{K}_R)\frac{\sin t+\sin\tau^*}{2}\Big(1-\alpha\sin t\Big)dt\Bigg)$$

$$=-\frac{\alpha}{2}\rho(\bar{K}_R)\Big(\sin\tau^*\cos\tau^*+\tau^*-\pi/2\Big).$$

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*

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

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

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

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

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

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 $t \in [0, 2\pi]$, $q_B(t) > 0 \rightarrow q_S(t) = 0$ and $q_S(t) > 0 \rightarrow q_B(t) = 0$. The KKT conditions are:

$$p_W(t) - \lambda = 0, \forall t \tag{37a}$$

$$p_W(t) - \lambda + \mu = 0, \forall t \tag{37b}$$

$$\int_0^{2\pi} q_B(t)dt - \int_0^{2\pi} q_S(t)dt \geq 0 \tag{37c}$$

$$K_S - \int_0^{2\pi} q_B(t)dt \geq 0 \tag{37d}$$

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 (37c) and (37d),

$$\int_{\underline{t}_B}^{\bar{t}_B} \frac{\alpha K_R}{2}\Big(\sin t - \sin \underline{t}_B\Big)dt = \int_{\underline{t}_S}^{\bar{t}_S} \frac{\alpha K_R}{2}\Big(\sin \bar{t}_S - \sin t\Big)dt = K_S. \tag{38}$$

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 (38) we obtain that $\hat{\tau} \in [0, \pi/2)$ is implicitly given by:

$$\cos\hat{\tau} - \left(\frac{\pi}{2} - \hat{\tau}\right)\sin\hat{\tau} = \frac{K_S}{K_R}. \tag{39}$$

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:

$$\begin{aligned} \Pi_S(K_S, K_R) &= \int_0^{2\pi} \hat{p}_W(t)\Big[\hat{q}_S(t) - \hat{q}_B(t)\Big]dt - C_S(K_S) \\ &= \int_{\underline{t}_s}^{\bar{t}_S} \hat{p}_W(\bar{t}_S)\hat{q}_S(t)dt - \int_{\underline{t}_B}^{\bar{t}_B} \hat{p}_W(\underline{t}_B)\hat{q}_B(t)dt - C_S(K_S) \\ &= \Big[\hat{p}_W(\bar{t}_S) - \hat{p}_W(\underline{t}_B)\Big]K_S - C_S(K_S) \\ &= 2K_R\sin\hat{\tau}(K_S, K_R)K_S - C_S(K_S), \end{aligned} \tag{40}$$

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 (39). Partially differentiating equation (40):

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

where in the second step we have used the fact that implicitly differentiating equation (39) 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 (39). Partially differentiating the expression above (applying the 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 (39) yields:

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