Storage and Renewable Energies: Friends or Foes?

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Abstract

Conventional wisdom claims that renewables and storage are complements. However, we show that this relationship does not always hold. In markets where renewables availability moves procyclically in relation to demand and renewable capacity is small, increasing storage (renewable) capacity negatively impacts renewable (storage) firms. In markets with multiple technologies, at least one of them is negatively impacted by storage. These findings have policy implications for the optimal timing and effectiveness of mandates or subsidies for renewables and storage. Simulations of the Spanish wholesale electricity market illustrate our results.

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1 Introduction

Renewable energies are fundamental to decarbonizing power markets and, through electrification, the whole economy. However, their output fluctuates significantly: solar farms go offline at sunset, and windmills stand still during calm days. To ensure the continuity of electricity supply, the volatility of renewable energies must be addressed. Storage technologies, such as batteries or pumped hydro, provide an effective solution, as they can shift supply from periods with abundant renewable energy to those when it is relatively scarce.

In this article, we seek to understand whether, from the point of view of the investors, renewables and storage are complements or substitutes, i.e., whether promoting renewables encourages or discourages the incentives to invest in storage and vice-versa.[1] This question has important policy implications as governments worldwide seek to boost these investments through mandates and subsidies. For instance, the California Public Utility Commission has mandated utilities to procure energy storage, and new commercial builds are required to install solar power and battery storage. Similarly, several European countries are mandating battery investment as an eligibility requirement for renewable energy subsidies. Both the US as well as Europe have introduced generous subsidies for energy storage.[2]

The conventional wisdom claims that renewable energies and storage complement one another from the point of view of investors.[3] On the one hand, renewable energies enlarge price differences across time due to their volatility, strengthening arbitrage opportunities for firms looking to invest in storage. On the other, energy storage reduces the curtailment of renewable energy by absorbing excess production when it exceeds demand. However, this paper shows that this is only part of the story: price effects imply that storage and renewable investments are not always complementary, particularly in the first stages of the solar roll-out.

We model an electricity wholesale market in which renewables and storage coexist. Storage operators benefit from arbitraging price differences over time: they buy (charge their batteries) when prices are low, and sell (discharge their batteries) when prices are

[1]Our analysis also sheds light on the interaction between dynamic pricing and renewables to the extent that, similarly to storage, dynamic pricing reduces (increases) the required generation when prices are high (low). See Ambec and Crampes (2021) for a related study.

[2]In the US, the Inflation Reduction Act provides federal tax credits. In Europe, storage subsidies are financed through the Recovery and Resilience Facility and the EU's Connecting Europe Facility.

[3]This view is exemplified in this article by 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."*

high. The availability of renewable energy affects the profitability of storage, depending on whether renewable energies are available when storage charges or discharges. Likewise, storage affects the profitability of renewables because charging and discharging push prices up and down, respectively.

Our model predicts that the correlation between renewable availability and market prices is crucial in explaining the profitability of renewables and storage. A negative (positive) correlation means that renewables tend to be available when prices are low (high), which is when storage charges (discharges). This pushes market prices up (down) when renewables sell their output, increasing (decreasing) their profitability. Similarly, expanding renewable capacity depresses prices when storage charges (discharges), thus increasing (decreasing) the profitability of storage.

When should we then expect this correlation to be positive or negative? Electricity prices depend on consumption patterns and renewables availability patterns, which vary across markets and technologies.[4] However, some general conclusions can be drawn. In most markets, the wind blows more at night when electricity demand weakens. Hence, wind production is usually countercyclical, leading to a negative correlation between prices and wind availability. Conversely, solar production tends to be procyclical as solar availability is greater during the mid-day hours when electricity demand peaks. Hence, there is a positive correlation between prices and solar availability unless large solar investments depress prices when solar peaks, in which case the correlation turns negative. Consequently, wind and storage are complements, while in the case of solar, this is true only if there is enough solar capacity. Otherwise, solar and storage investments substitute each other from the investors' point of view.

The above conclusions need to be qualified in markets in which wind and solar coexist. In this case, one of the two technologies necessarily crowds out storage investments and vice-versa. In particular, there is substitutability between storage and the "scarce" renewable technology, meaning that its size is not large enough relative to the other technology. This condition is more stringent for solar than wind, given that solar must counteract the natural procyclicality of its output.

The complementarity or substitutability between renewables and storage has important policy implications. If renewables are countercyclical, promoting renewables (storage) through subsidies or mandates comes with the additional benefit of promoting investments in storage (renewables), creating a positive feedback loop between both assets.

[4] Our baseline model assumes competitive behaviour, but we show that the results are robust to adding market power in the power market.

Similar effects arise if renewables are procyclical, as long as the installed capacity is large enough. However, before reaching that critical mass, mandating or subsidizing investments in renewables (storage) acts as a barrier for the other technology. The market can thus get stuck in an equilibrium with low investments in renewables and storage, jeopardizing the decarbonization of the power sector. In contrast, an initial push to renewables would reverse the sign of the correlation between renewables and prices, inducing storage operators to shift their operations in ways that make renewables better off. Once the complementarity between storage and renewables is triggered, policies aimed at promoting one technology come with the bonus of promoting the other.[5]

We illustrate these theoretical results with detailed simulations of the Spanish electricity market. In this context, we show that the interaction between renewables and storage is relevant in scenarios with high renewable penetration. Considering the Spanish government's planned investments for 2030, we find that solar and storage investments complement each other, while their expansion harms wind producers.

Related Literature. Economists have recently shown great interest in the economics of energy storage from various angles.[6] Liski and Vehviläinen (2023) analyze the impact of energy storage on consumers prices. Andrés-Cerezo and Fabra (2023) assess the competitive implications of energy storage, allowing for market power in the generation and storage segments and vertical integration between storage owners and generators. Other papers have quantified the impact of storage on emissions (Carson and Novan, 2013), which is analogous to the effect of dynamic pricing on emissions (Ambec and Crampes, 2021; Holland and Mansur, 2008).

However, only a few existing papers explicitly analyze the interaction between storage and renewables. Three notable exceptions provide empirical evidence consistent with our main theoretical results. In the Californian market, Butters et al. (2021) show that for the first storage unit to break even by 2024, the renewable energy share must reach 50 %. Furthermore, storage mandates decrease solar and wind revenues by 13 US million annually because batteries discharge when many solar generators are still producing. Using data from the South Australian Electricity Market, Karaduman (2021) also finds that storage decreases solar generators' revenue by shading high prices, while it increases the return to wind generators by reducing curtailment. Last, using 2019 data in thirteen US

[5]The need to reach a critical mass to trigger the complementarity between renewables and storage can give rise to coordination failures, similarly as in other contexts in which environmental end energy policy matter, e.g., EV sales and charging infrastructure (Zhou and Li, 2018).

[6]Using different approaches, and with differing objectives, engineers had paid earlier attention to these issues (Lueken and Apt, 2014; Sioshansi, 2011).

electricity regions, Holland et al. (2022) calibrate a long-run model of free entry and exit of generation and storage capacity. Their simulations show that cheaper storage decreases renewable investments to the extent that, if storage became costless, renewables would be driven out of the market in most parts of the US. Our model provides a theoretical framework that rationalizes these effects beyond the specific market conditions.[7]

The remainder of the paper proceeds as follows. In Section 2 we describe the theoretical model. In Section 3 we identify necessary and sufficient conditions for renewables and storage to be complements or substitutes and discuss their policy implications. In Section 5 we run simulations of the Spanish electricity market. Section 6 concludes.

2 Theoretical framework

We model a wholesale electricity where demand is perfectly inelastic. Demand moves over time around its mean, θ, according to deterministic cycles of amplitude $b \geq 1$. At time t, demand is given by

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

Electricity demand can be served by intermittent renewable energies (wind or solar), dispatchable generation (gas or coal plants), and storage. They are all owned by independent price-taking firms.[8]

The marginal costs of renewables 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, $1/2$,

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

Relative to demand, renewables are countercyclical ($\alpha = -1$), or procyclical ($\alpha = 1$).[9] For simplicity, we assume $K_R < (\theta - b)$, which is sufficient to guarantee that renewable production never exceeds demand.[10]

[7]Transmission capacity links markets across space just as storage links them across time. Gonzales et al. (2023) show that the construction of a new transmission line in the Chilean electricity market fostered investments in solar energy. Market integration increased the profitability of renewable investments because these were located in the constrained region.

[8]In the Online Appendix we allow for market power by allowing the dispatchable generation to behave strategically. The paper's main results are strengthened.

[9]In most markets, wind availability is countercyclical and solar availability is procyclical.

[10]This assumption rules out renewable energy curtailment, but the main results do not rely on this assumption (Andrés-Cerezo and Fabra, 2023).

The costs of dispatchable generation are captured by $c(q)$. For simplicity, we assume linear marginal costs, i.e., $c'(q) = q$.[11] Operating storage facilities entails no costs other than buying the electricity that will be sold, up to the storage capacity K_S.[12]

Investment, production and storage decisions take place in two stages. In the first stage, renewable and storage capacity, K_R and K_S, are determined once and for all by free entry into the market. Investment costs are given by the functions $C_i(K_S)$ for $i = \{S, R\}$, with $C_i'(K_i) > 0$, $C_i''(K_i) > 0$, $C_i(0) = 0$ and $C_i'(0) = 0$. In the second stage, at every period t, production and storage operation decisions are chosen simultaneously.

3 Market Equilibrium

We first consider the second stages, when capacities K_R and K_S are given. Firms make simultaneous quantity choices in order to their maximize profits, taking the rivals' decisions as given (Cournot assumption). Thus, in every period, generation firms decide how much to produce, and storage firms decide when and how much to charge and discharge.

Given that renewables have zero marginal costs, they always offer to produce at capacity. The dispatchable generators serve the residual demand, $D(t) - \omega(t)K_R$. Since they behave competitively and their marginal costs are linear, using (1) and (2) we obtain prices in the absence of storage:

$$p(t) \quad = \quad (\theta - K_R/2) - (b - \alpha K_R/2)\sin t. \tag{3}$$

To ease notation, we define $A(K_R) \equiv \theta - K_R/2$ and $\rho(K_R) \equiv b - \alpha K_R/2$, so that

$$p(t) \quad = \quad A(K_R) - \rho(K_R)\sin t. \tag{4}$$

Renewables affect prices through two channels. First, as captured by $A(K_R)$, renewable capacity shifts prices down by the average renewable production, $K_R/2$. Second, as captured by $\rho(K_R)$, renewables affect the price dynamics, i.e., their correlation with demand and renewables, and the amplitude of the price cycle. In particular, the correlation between prices and demand is positive (negative) if $\rho(K_R) > 0$ (< 0), and the correlation between prices and renewables is positive (negative) if $\rho(K_R)$ and α take the same (opposite) sign. Last, larger renewable capacity amplifies (flattens) the price cycle if prices and renewable production are negatively correlated. This leads to the following Lemma.

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

[12] Energy storage typically entails a round-trip efficiency loss. The model is robust to adding it (Andrés-Cerezo and Fabra, 2023). We also omit constraints on how fast storage plants can charge/discharge.

Lemma 1 *(i) Prices and demand correlate positively if and only if* $\alpha = 1$ *and* $K_R < 2b$ *or if* $\alpha = -1$ *for all* K_R*. (ii) Prices and renewables correlate positively and renewables flatten the price cycle if and only if* $\alpha = 1$ *and* $K_R \leq 2b$*.*

On the one hand, if renewables are procyclical ($\alpha = 1$), the correlation between prices, demand and renewables depends on the level of renewable capacity. If $K_R \leq 2b$, prices are positively correlated with demand and renewables. 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 flip the correlation between prices, demand and renewables from positive to negative, while amplifying the price differences across time.

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

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

$$\max_{q_B(t), q_S(t)} \Pi_S = \int_0^{2\pi} p(t) \left[q_S(t) - q_B(t)\right] dt, \tag{5}$$

subject to two intertemporal constraints: they cannot store energy above capacity, and they cannot sell more energy than previously bought. Since prices in (3) 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:

$$\int_0^{2\pi} q_B(t) dt \leq K_S. \tag{6}$$

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

The following Lemma characterizes the equilibrium storage decisions, which are illustrated in Figure 1.

Lemma 2 *Let*

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

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

$$\cos\tau - (\pi/2 - \tau)\sin\tau = K_S/|2\rho(K_R)|, \tag{8}$$

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

(i) *Equilibrium storage decisions can be characterized as:*
For $t \in [\underline{t}_B, \overline{t}_B]$,

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

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

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

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

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

$$p^*(t) = \begin{cases} A(K_R) - \rho(K_R)\sin \tau & \textit{if}\ \tau \leq t \leq \pi - \tau \\ A(K_R) + \rho(K_R)\sin \tau & \textit{if}\ \pi + \tau \leq t \leq 2\pi - \tau \\ A(K_R) - \rho(K_R)\sin t & \textit{otherwise} \end{cases}. \tag{9}$$

Proof. See the Appendix. ■

Storage owners buy when prices are low, i.e., $t \in (\underline{t}_B, \overline{t}_B)$, and sell when prices are high, i.e., $t \in (\underline{t}_S, \overline{t}_S)$. In all these periods, they buy and sell enough so as to flatten prices. The timing of their decisions depends on the correlation between prices and demand (Lemma 2, (i)): when prices are procyclical, firms charge (discharge) at the beginning (end) of the demand cycle; decisions are reversed when prices are countercyclical.

Increasing storage capacity enlarges the number of periods when storage firms are active (formally, in (8), τ is decreasing in K_S). When storage capacity is large enough, storage owners are always active and prices are entirely flattened across all periods (formally, when $K_S = 2|\rho(K_R)|$, $\tau = 0$ solves (8)).

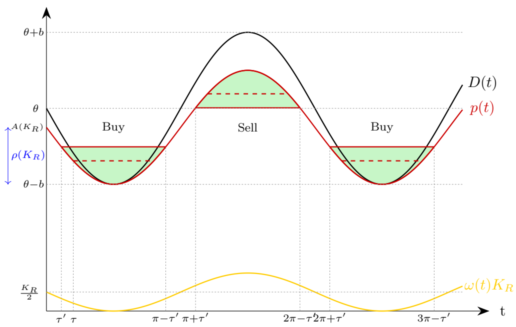
Importantly, when prices and renewables are positively correlated (Lemma 2, (ii)), charging (discharging) occurs at periods of low (high) renewable availability. Thus, as shown in Figure 1 (upper left panel), an increase in storage capacity pushes prices up (down) when renewables are scarce (abundant), also enlarging the number of periods when storage firms are active. As a consequence, an increase in storage capacity reduces renewables' profits.

Additional renewable capacity depresses prices in all periods (see equation (3)). As shown in Figure 1 (upper right panel), when prices and renewables are positively correlated, this price-depressing effect is more pronounced when storage firms sell than when they buy, as in the former case renewables are relatively more abundant. Furthermore, since an increase in renewable capacity flattens price differences (Lemma 3, (*ii*)), arbitrage profits shrink. Storage firms optimally respond by smoothing their charging and discharging decisions, but this only partially mitigates the negative impact of renewables on storage profits.

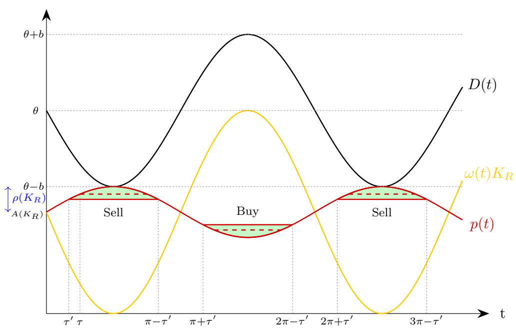
The opposite holds when prices are negatively correlated with renewables. In this case, prices are high (low) in periods of low (high) renewable production, inducing storage to sell (buy) in periods when renewables are scarce (abundant). Hence, storage benefits from increases in renewable capacity because prices go down relatively more when they buy than when they sell (Figure 1, lower left panel). Likewise, renewables benefit from increases in storage capacity because prices go up (down) when renewables produce more (less) electricity (Figure 1, lower right panel).

Figure 1: Profit impacts of increasing storage and renewable capacity

Storage and Renewables are Substitutes



Storage and Renewables are Complements



Notes: These figure depict demand (black), renewables production (yellow) and prices (red) over time. The upper panels illustrate the case of procyclical renewables ($\alpha = 1$) and small renewable capacity ($K_R < 2b$), implying positive correlation between prices and renewables ($\rho(K_R) > 0$). The lower panels illustrate the case of procyclical renewables ($\alpha = 1$) and large renewable capacity ($K_R > 2b$), implying negative correlation between prices and renewables ($\rho(K_R) < 0$). The left panels consider the effects of increasing storage capacity (from the red dashed to the solid line). The rise panels consider the effects of increasing renewable capacity, which increases renewable production (from the yellow dashed to the solid line) ans reduces prices (from the red 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 substitutes: renewables must be pro cyclical and their capacity K_R must not exceed a critical mass $2b$.[13]

Proposition 1 *Let Π_S and Π_R denote the profits of storage and renewables. Renewables and storage are substitutes if and only if prices and renewables correlate positively, i.e.,*

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

Proof. See the Appendix. ■

[13] This result is consistent with Butters et al. (2021)'s prediction that, for storage to break-even in the Californian market, renewable penetration must reach 50%.

The previous 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 ($\alpha^- = -1$). Since $K_R = K_R^+ + K_R^-$, the price equation (3) now becomes

$$p(t) \;=\; \big(\theta - (K_R^+ + K_R^-)/2\big) - \big(b - (K_R^+ - K_R^-)/2\big)\sin t.$$

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. These signs are reversed only if the capacity of the procyclical technology becomes much larger (by at least $2b$).

Lemma 3 *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 complementarity or substitutability between renewables and storage. Importantly, unlike the single-technology case, storage necessarily complements one renewable technology but substitutes the other.

Proposition 2 *Let $i, j \in \{+, -\}$ and $i \neq j$. Renewable technology i substitutes storage if and only if prices correlate positively with its availability. Furthermore, if renewable technology i substitutes storage, renewable technology j complements it:*

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

Proof. See the Appendix. ■

4 The Impact of Investment Subsidies

Our previous results also have important implications for the overall effect of investment subsidies (or equivalently, mandates)[14] on long-run capacity investment, as shown next:

Proposition 3 *Let $i, j \in \{S, R\}$ and $i \neq j$, and use η_i to denote a per-unit of capacity subsidy to technology i.*

[14] With mandates, the analog of Proposition **??** would analyze the following question: how does a more stringent mandate K_i^* affects the subsidy η_i that is needed for firms to break even when they invest to meet the mandate?

(i) A higher subsidy η_i increases the equilibrium capacity of technology i, i.e.,

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

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

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

Proof. See the Appendix. ■

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

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

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

5 Simulations

We illustrate our theoretical results by performing simulations of the Spanish electricity market. We rely on highly detailed data, including plant characteristics, hourly electricity demand and renewables' availability, and daily fossil fuel prices. All simulations are conducted hourly (8,760 simulations the whole year).

We consider scenarios with low and high renewable capacity and different levels of storage capacity. The first scenario, which replicates the Spanish market in 2019, has

34.43 GW of renewable capacity (30.5% belongs to solar and 69.5% to wind), to which the second scenario adds 52.53 GW (44.2% belongs to solar and 55.8% to wind), as planned for 2030 by the Spanish Government.[15] For comparison purposes, we leave all other parameters unchanged across scenarios. Also, we assume away trade with neighboring countries.

For each renewables scenario, we consider different amounts of batteries with a four-hour duration and 90% round-trip efficiency, corresponding to the most common type (NERL, 2022). We assume that the storage cycle is the natural day. To assess the model's performance, we have run simulations using 2019 data. The simulated prices closely mimic the actual ones, with a 0.87 correlation between the two.[16]

Results. Figure 2 shows wind and solar production and electricity market prices over an average day in 2019 and 2030 (left panels), as well as the (average) hourly storage buy and sell decisions (right panels) in these two scenarios. Figure 3 shows the utilization rate and profits of storage.

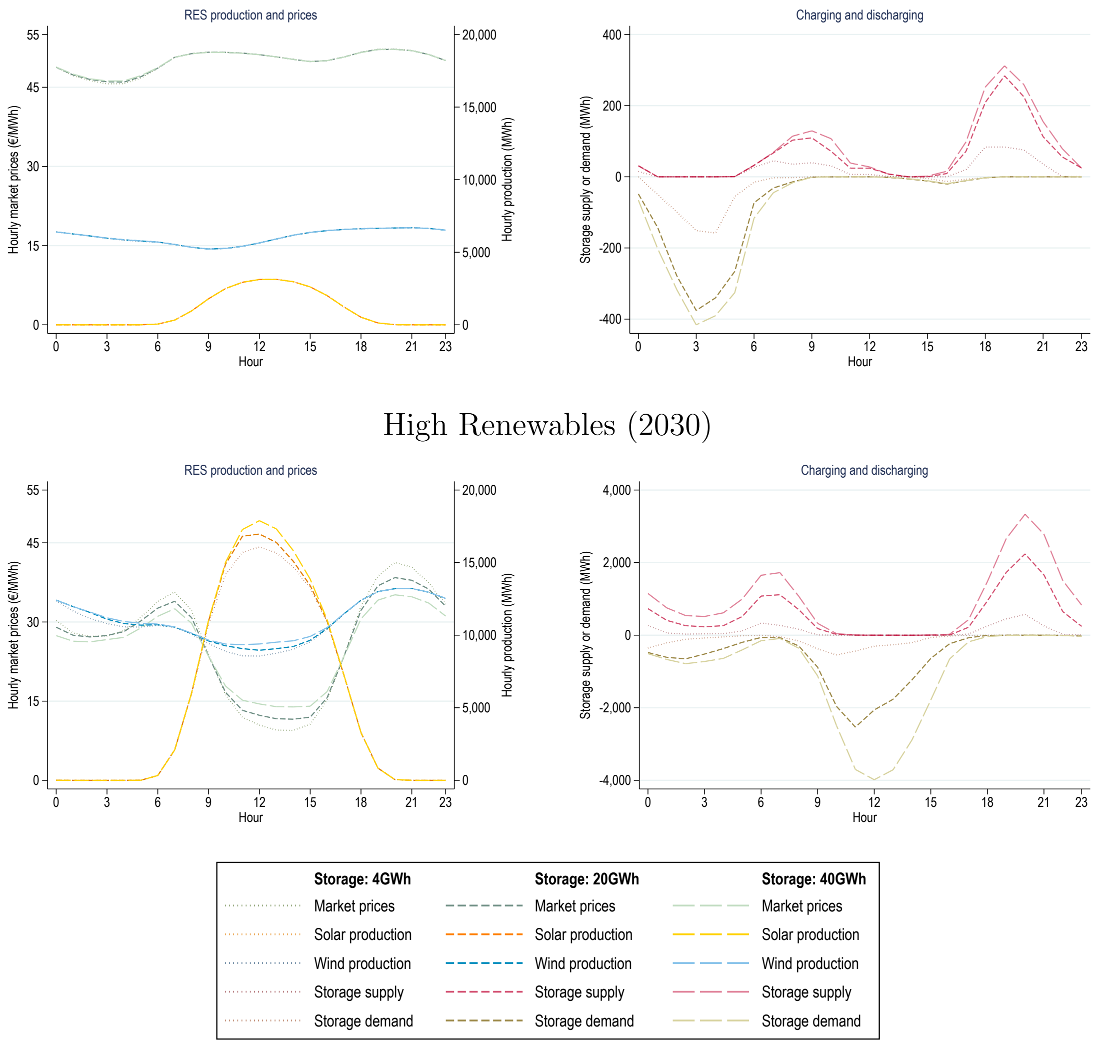
Solar production is concentrated in the mid-day hours when electricity demand peaks, implying a positive correlation between prices and solar production when renewables capacity is small (upper left panel). However, when renewables capacity increases (lower left panel), the correlation between prices and solar becomes strongly negative. As a result, storage firms shift from charging during nighttime when solar generation is low (upper right panel) to charging in the midday hours when solar is abundant (lower right panel).

[15] See Table B.1 in the Online Appendix for details.

[16] See Figure B.1 in the Online Appendix.

Figure 2: Renewables generation, market prices and storage decisions

Low Renewables (2019)

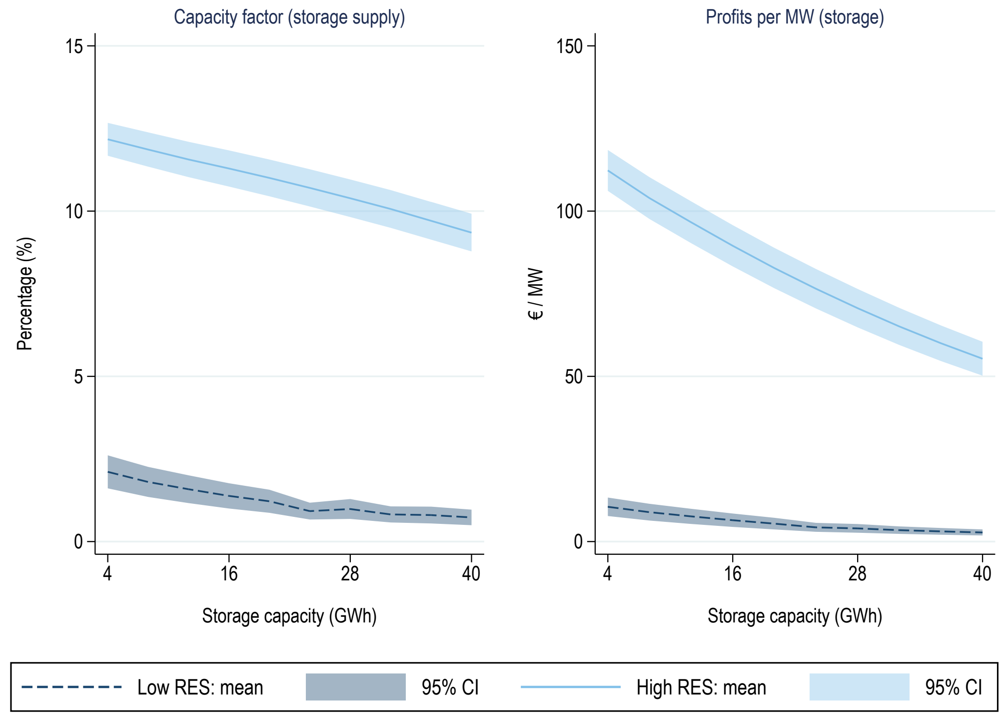


Notes: The left panels show, for each hour of the day, wind (blue) and solar generation (yellow), and market prices (green). The right panels show the hourly amounts charged (negative, green) and discharged (positive, pink) by storage. All results are averaged across the year for the cases of storage capacity 4 GWh (dots), 20 GWh (dash), and 40 GWh (long dash). The upper and lower panels show the results for the scenario with low and high renewables, respectively.

In the low renewables scenario, average wind production is relatively constant across the day, only slightly higher at nighttime, making the correlation between wind production and prices slightly negative. However, when renewable capacity increases, the correlation between prices and wind production turns positive.

What do these patterns imply for the profitability of renewables and storage? When renewables penetration is low (upper panels), adding storage capacity barely has no impact on market prices or renewable production. Hence, the profitability of renewables remains unaffected.[17]

Figure 3: Capacity factors and profits of energy storage



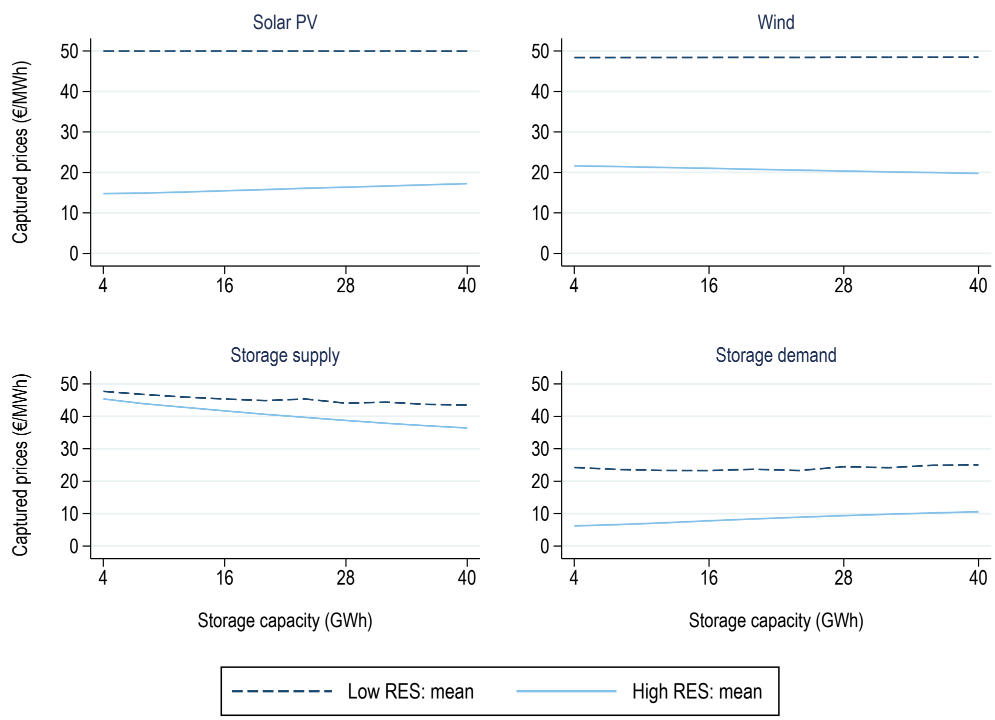
Notes: This figure shows the capacity factor (left panel) and profits (right panel) of energy storage as a function of the installed storage capacity. The capacity factor is computed as the ratio between the supply of energy storage over the maximum supply it could have if it charged and discharged its 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 (NERL, 2022).

However, increasing renewable capacity impacts firms' profitability. First, since price differences across the day widen, storage utilization increases (left panel of Figure 3), and arbitrage profits climb sharply (right panel). Second, increasing storage capacity increases solar profits: since curtailment goes down, solar production goes up; and since storage firms fill their batteries when solar farms produce relatively more, it captures higher prices on average. Conversely, increasing storage capacity reduces wind profits

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

since batteries discharge at night, depressing prices when wind generation is greater. Storage reduces wind curtailment but to a lesser extent.

Figure 4: 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. 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). Increases in storage capacity are shown on the x-axis.

Figure 4 provides further details on the effects of increasing renewable and storage capacities on the prices captured by both assets, as shown in Figure 4. In line with our previous results, in the low renewables scenario (dashed lines), increasing storage capacity does not impact the prices captured by solar and wind, which remain close to the market price, 50€/MWh. In contrast, moving to the high renewables scenario (solid line) has two important implications. First, the two captured prices fall drastically, more so in the case of solar. Second, the impact of increasing storage capacity differs across solar and wind: the prices captured by solar go up by 14.3%, while those by wind go down by 9.5% when storage capacity is increased from 4 GWh to 40 GWh. This result shows that an increase in storage capacity benefits solar producers while it hurts wind producers. All cases depict a clear cannibalization effect, i.e., additional capacity of the same technology lowers the value of the existing one. In particular, the prices captured by solar and wind are much lower in the high-renewables scenario, in which additional storage capacity smooths price differentials across time, thus reducing arbitrage profits.

The lower panels of Figure 4 also reveal interesting facts regarding the market prices faced by storage owners. First, as expected, the prices at which storage discharges (left panel) are higher than those at which it charges (right panel). However, the price difference, i.e., the arbitrage profit, is larger in the high renewables scenario. This price difference gets narrower as more storage capacity is installed, as the prices at which storage discharges go down while the prices at which it charges go up, i.e., the cannibalization effect is stronger in renewables-dominated markets.

Last but not least, our simulations also show that (absent investment costs) storage has positive welfare effects, which explains why investments in storage are promoted in the first place. As shown in Table 1, increasing storage capacity reduces generation costs and carbon emissions, and it allows to use excess renewables that would otherwise be lost, particularly in the high renewables scenario. Increasing storage also benefits consumers as market prices decrease, particularly in the high renewables scenario. However, this price-depressing effect hides across-months heterogeneity, as changes in the hourly consumption patterns and the availability of renewable generation imply that increased storage capacity does not always lower prices, in line with Liski and Vehviläinen (2023). Indeed, in the high renewables scenario, average prices during the summer (winter) go up (down) because the price-increasing effect of storage in summer tends to be stronger. In contrast, the price-depressing impact of storage in winter tends to be weaker.[18]

6 Conclusion

Our paper characterizes a necessary and sufficient condition for renewables and storage to be complements or substitutes from investors' point of view. In particular, investments in storage crowd out investments in renewables, and vice-versa, if renewables availability correlates positively with market prices. This is the case when renewables move procyclically relative to demand and the renewable capacity is not yet large enough. Otherwise, renewables and storage complement one another.

For instance, solar investments and storage are substitutes in the early stages of the solar rollout but become strong complements when solar capacity exceeds a critical mass. Likewise, in the presence of multiple technologies, wind investments and storage are substitutes in markets with a strong solar penetration. Still, they are complements if wind capacity exceeds a critical mass relative to solar capacity.

[18]In the Online Appendix, Table B.2 shows the quarterly market prices, and Figures B.2 and B.3 depict winter and summer's generation and price patterns.

Table 1: Market prices, generation costs, emission and renewable curtailment

	(1) No storage	(2) 20 GWh	(3) 40 GWh
Low Renewables (2019)			
Annual average price (€/MWh)	50.135	50.176	50.203
Per-unit generation cost (€ / MWh)	0.067	0.067	0.067
Carbon emissions (Ton / MWh)	2.973	2.956	2.954
Excess renewables - solar (MWh / MW)	0.000	0.000	0.000
Excess renewables - wind (MWh / MW)	0.016	0.000	0.000
High Renewables (2030)			
Annual average price (€/MWh)	25.925	25.558	25.079
Per-unit generation cost (€ / MWh)	0.033	0.033	0.033
Carbon emissions (Ton / MWh)	0.571	0.433	0.369
Excess renewables - solar (MWh / MW)	0.670	0.522	0.423
Excess renewables - wind (MWh / MW)	0.691	0.588	0.535

Notes: This table reports generation per-unit costs (costs over demand), carbon emissions, and excess renewables (normalized by installed renewable capacity) averaged across all days of year. Results are shown for the cases with no storage (1), storage capacity of 20 GWh (2) and 40 GWh (3). The upper and lower panels show the results for the scenario with low and high renewable energy penetration, respectively.

We also discuss the implications that the complementarity or substitutability between renewables and storage has on the optimal path of investment subsidies or mandates.

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Appendix: Proofs

Proof of Lemma 2

Storage firms choose $\{q_S(t), q_B(t)\}_{t\in[0,2\pi]}$ to maximize profits:

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

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

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

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

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

$$p(t) - \lambda + \eta_S(t) = 0, \forall t \tag{10a}$$

$$p(t) - \lambda + \mu - \eta_B(t) = 0, \forall t \tag{10b}$$

$$\int_0^{2\pi} q_B(t)dt - \int_0^{2\pi} q_S(t)dt \geq 0 \tag{10c}$$

$$K_S - \int_0^{2\pi} q_B(t)dt \geq 0 \tag{10d}$$

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

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

We proceed by finding the expressions for $q_B(t), q_S(t)$,

From condition (10a):

$$p(t) = \lambda \text{ , if } \underline{t}_S < t < \bar{t}_S, \tag{11}$$

and from (10b):

$$p(t) = \lambda - \mu \text{ , if } \underline{t}_B < t < \bar{t}_B. \tag{12}$$

The market price is given by the quantity produced by thermal generators,

$$p(t) = A(K_R) - \rho(K_R)\sin t - q_S(t) + q_B(t) \tag{13}$$

Combining equations (11) and (12) with (13),

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

By continuity:

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

From (10c) and (10d),

$$\int_{\underline{t}_B}^{\bar{t}_B} \rho(K_R)\left(\sin \underline{t}_B - \sin t\right) dt = \int_{\underline{t}_S}^{\bar{t}_S} \rho(K_R)\left(\sin t - \sin \bar{t}_S\right) dt = K_S. \tag{14}$$

By the symmetry of the sin function, $q_S(\underline{t}_S) = q_S(\bar{t}_S) = 0$ and $q_B(\underline{t}_S) = q_B(\bar{t}_S) = 0$, 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 (14) 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 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 $K_S = 0$.

Proof of Proposition 1

Storage profits are:

$$\begin{aligned}
\Pi_S(K_S, K_R) &= \int_0^{2\pi} p^*(t)\big[q_S^*(t) - q_B^*(t)\big]\,dt - C_S(K_S) \\
&= \int_{\underline{t}_s}^{\bar{t}_S} p^*(\bar{t}_S) q_S^*(t) dt - \int_{\underline{t}_B}^{\bar{t}_B} p^*(\underline{t}_B) q_B^*(t) dt - C_S(K_S) \\
&= \big[p^*(\bar{t}_S) - p^*(\underline{t}_B)\big] K_S - C_S(K_S) \\
&= \big(|2b - \alpha K_R| \sin\tau\big) K_S - C_S(K_S), \qquad (15)
\end{aligned}$$

with $\underline{t}_B, \bar{t}_B, \underline{t}_S$ and $\bar{t}_S$ defined in Lemma 2. Partially differentiating with respect to K_R:

$$\begin{aligned}
\frac{\partial \Pi_S(K_S, K_R)}{\partial K_R} &= K_S\left[- \alpha * \text{sign}(2b - \alpha K_R) * \sin\tau + |2b - \alpha K_R| \frac{\partial \tau}{\partial K_R} \cos\tau \right] \\
&= -\alpha\, \text{sign}(2b - \alpha K_R) K_S \left[\sin\tau + \frac{K_S}{|2b - \alpha K_R|\big(\pi/2 - \tau\big)} \right], \qquad (16)
\end{aligned}$$

where in the second step we have used the fact that implicitly differentiating equation (8) yields:

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

The term in brackets in expression (16) is always positive. Therefore:

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

The profits of renewable firms are:

$$
\begin{aligned}
\Pi_R(K_S, K_R) =& \int_0^{2\pi} p^*(t)\frac{1}{2}\big(1-\alpha\sin t\big)K_R dt - C_R(K_R)\\
=&\frac{1}{2}K_R\bigg(\int_0^{\tau}\big[\theta - K_R/2 - \big(b-\alpha K_R/2\big)\sin t\big]\big(1-\alpha\sin t\big)dt\\
&+\int_{\tau}^{\Pi-\tau}\big[\theta - K_R/2 - \big(b-\alpha K_R/2\big)\sin \tau\big]\big(1-\alpha\sin t\big)dt\\
&+\int_{\Pi-\tau}^{\Pi+\tau}\big[\theta - K_R/2 - \big(b-\alpha K_R/2\big)\sin t\big]\big(1-\alpha\sin t\big)dt\\
&+\int_{\Pi+\tau}^{2\Pi-\tau}\big[\theta - K_R/2 + \big(b-\alpha K_R/2\big)\sin \tau\big]\big(1-\alpha\sin t\big)dt\\
&+\int_{2\Pi-\tau}^{2\Pi}\big[\theta - K_R/2 - \big(b-\alpha K_R/2\big)\sin t\big]\big(1-\alpha\sin t\big)dt\bigg) - C_R(K_R)\\
=&\big[\big(\theta - K_R/2\big)\pi + \alpha\big(b-\alpha K_R/2\big)\big(\tau+\sin\tau\cos\tau\big)\big]K_R - C_R(K_R). \qquad (17)
\end{aligned}
$$

The partial derivative with respect to K_S is:

$$
\begin{aligned}
\frac{\partial \Pi_R(K_S,K_R)}{\partial K_S} &= \alpha\bigg(b - \frac{\alpha K_R}{2}\bigg)\frac{\partial\tau}{\partial K_S}\bigg[1+(\cos\tau)^2-(\sin\tau)^2\bigg]K_R\\
&= \alpha\bigg(b - \alpha\frac{K_R}{2}\bigg)\frac{-\operatorname{sign}(2b-\alpha K_R)}{(2b-\alpha K_R)(\pi/2-\tau)\cos\tau}\bigg[1+(\cos\tau)^2-(\sin\tau)^2\bigg]K_R\\
&= -\alpha\operatorname{sign}(2b-\alpha K_R)\frac{2}{(\pi/2-\tau)\cos\tau}\bigg[1+(\cos\tau)^2-(\sin\tau)^2\bigg]K_R. \qquad (18)
\end{aligned}
$$

Given that the term in brackets if always positive,

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

Proof of Proposition 2

It follows the same steps as the proof of Proposition 1. The main difference is that the sign of the analogues of expressions (16 and 18) depends on $\operatorname{sign}(2b - K_R^+ + K_R^-)$.

Proof of Proposition 3

From equations (15) and (17), the profits of renewable and storage firms are given by:

$$
\begin{aligned}
\Pi_S(K_S,K_R) &= \big[|2b-\alpha K_R|\sin\tau\big]K_S - C_S(K_S) + \eta_S K_S\\
\Pi_R(K_S,K_R) &= \big[\big(\theta - K_R/2\big)\pi + \alpha\big(b-\alpha K_R/2\big)\big(\tau+\sin\tau\cos\tau\big)\big]K_R - C_R(K_R) + \eta_R K_R
\end{aligned}
$$

where η_i for $i = \{S, R\}$ represents the per-unit of capacity subsidy to technology i. The free entry condition implies zero profits so that equilibrium investment (K_S^*, K_R^*) is implicitly given by:

$$F(K_S^*, K_R^*) = |2b - \alpha K_R^*| \sin\tau - \frac{C_S(K_S^*)}{K_S^*} + \eta_S = 0 \tag{19}$$

$$H(K_S^*, K_R^*) = \big(\theta - K_R^*/2\big)\pi + \alpha\big(b - \alpha K_R^*/2\big)\big(\tau + \sin\tau\cos\tau\big) - \frac{C_R(K_R^*)}{K_R^*} + \eta_R = 0 \tag{20}$$

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

We are interested in signing the following expressions:

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

For this purpose, given that equations (19) and (20) are continuously differentiable in a neighborhood of any equilibrium (K_S^*, K_R^*) (except for $K_R^* = 2b$ when $\alpha = 1$), we can rely on the Implicit Function Theorem (IFT). Totally differentiating equations (19) and (20), we get:

$$dF = dK_S F_{K_S} + dK_R F_{K_R} + d\eta_S F_{\eta_S} = 0 \tag{21}$$

$$dH = dK_S H_{K_S} + dK_R H_{K_R} + d\eta_R H_{\eta_R} = 0 \tag{22}$$

where we have taken the partial derivatives with respect to the subscripts of F and H. Setting $d\eta_R = 0$ and dividing equations (21) and (22) by $d\eta_S$, we get the following system (in matrix form):

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

Similarly, setting $d\eta_S = 0$ in equations (21) and (22), and dividing by $d\eta_R$ we get the following system (in matrix form):

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

As we will later show, the Jacobian is non-singular at equilibrium, so we can apply the IFT and Cramer's rule to obtain the following expressions of interest:

$$\left.\frac{dK_S^*(\eta_S,\eta_R)}{d\eta_S}\right|_{(K_S^*,K_R^*)} = \frac{-H_{K_R}}{F_{K_S}H_{K_R}-F_{K_R}H_{K_S}} \tag{23}$$

$$\left.\frac{dK_R^*(\eta_S,\eta_R)}{d\eta_S}\right|_{(K_S^*,K_R^*)} = \frac{H_{K_S}}{F_{K_S}H_{K_R}-F_{K_R}H_{K_S}} \tag{24}$$

$$\left.\frac{dK_S^*(\eta_S,\eta_R)}{d\eta_R}\right|_{(K_S^*,K_R^*)} = \frac{F_{K_R}}{F_{K_S}H_{K_R}-F_{K_R}H_{K_S}} \tag{25}$$

$$\left.\frac{dK_R^*(\eta_S,\eta_R)}{d\eta_R}\right|_{(K_S^*,K_R^*)} = \frac{-F_{K_S}}{F_{K_S}H_{K_R}-F_{K_R}H_{K_S}} \tag{26}$$

where we have used the fact that $F_{\eta_S} = H_{\eta_R} = 1$.
In what follows, we compute the partial derivatives F_l and H_l for $l = \{K_S, K_R, \eta_S, \eta_R\}$ to sign the above expressions. For this purpose, we first use equation (8) to define $g(\tau, K_S, K_R)$ as:

$$g(\tau, K_S, K_R) = \cos\tau - (\pi/2-\tau)\sin\tau - K_S/|2b-\alpha K_R| = 0.$$

Using the IFT (note that g is a continuously differentiable function and $\partial g/\partial\tau \neq 0$), we obtain that, for all K_S and all K_R (except for $K_R = 2b$ if $\alpha = 1$):

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

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

$$\begin{aligned}
F_{K_S} =& \frac{-1}{\pi/2-\tau} - \frac{C_S'(K_S^*)K_S^* - C(K_S^*)}{(K_S^*)^2} < 0. \\
F_{K_R} =& -\alpha\operatorname{sign}(2b-\alpha K_R^*)\left(\frac{K_S^*}{|2b-\alpha K_R^*|(\pi/2-\tau)} + \sin\tau\right) \\
H_{K_S} =& -\alpha\operatorname{sign}(2b-\alpha K_R^*)\frac{\cos\tau}{(\pi/2-\tau)} \\
H_{K_R} =& \frac{-\left[\pi + (\tau+\sin\tau\cos\tau)\right]}{2} - \frac{K_S^*\cos\tau}{|2b-\alpha K_R^*|(\pi/2-\tau)} - \frac{C_R'(K_R^*)K_R^* - C(K_R^*)}{(K_R^*)^2} < 0.
\end{aligned}$$

with τ implicitly given by equation (8). Note that to sign F_{K_S} and H_{K_R} we have relied on the convexity of the cost function, which implies $C'(K_i) > C(K_i)/K_i$ for $i = \{S, R\}$. In turn, the partial derivatives F_{K_R} and H_{K_S} are negative if and only if $\alpha = 1$ and $K < 2b$.

It remains to show that the Jacobian is non-singular. Its determinant is:

$$\begin{vmatrix} F_{K_S} & F_{K_R} \\ H_{K_S} & H_{K_R} \end{vmatrix} = \frac{\pi + (\tau + \cos\tau \sin\tau)}{\pi - 2\tau} + \frac{C_R'(K_R^*)K_R^* - C(K_R^*)}{\left(K_R^*\right)^2} \frac{2}{\pi - 2\tau}$$
$$+ \frac{C_S'(K_S^*)K_S^* - C(K_S^*)}{\left(K_S^*\right)^2} \left(\frac{\pi + (\tau + \sin\tau \cos\tau)}{2} + \frac{2K_S^* \cos\tau}{|2b - \alpha K_R^*|(\pi - 2\tau)} \right)$$
$$+ \frac{C_S'(K_S^*)K_S^* - C(K_S^*)}{\left(K_S^*\right)^2} \frac{C_R'(K_R^*)K_R^* - C(K_R^*)}{\left(K_R^*\right)^2}$$

with the four terms being positive given the convexity of the cost functions.

Using expressions (23) to (26), and the signs of the partial derivatives characterized above, it follows that

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

Online Appendix

“Storage and Renewable Energies: Friends or Foes?”

A Adding Market Power

In the baseline model, we assumed that all firms are price-takers so electricity prices reflect the cost of thermal generation. We now allow for market power by allowing dispatchable generation to behave strategically. More specifically, following Andrés-Cerezo and Fabra (2023), we assume that there are two types of dispatchable 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 dispatchable assets, whereas the fringe owns the remaining fraction $(1-\beta)$. This means that their marginal costs are $c_D'(q) = q/\beta$ and $c_F'(q) = q/(1-\beta)$, respectively. Note that β is a measure of the dominant firm's size, i.e., at any given price, the higher β the more it can produce without incurring losses.

Taking $\{q_S(t), q_B(t)\}$ as given (Cournot assumption), the dominant producer chooses its output $q_D(t)$ in every period in order to maximize its profits over its residual demand,

$$\max_{q_D(t)} \pi_D = \int_0^{2\pi} \left[p\left(t; q_S, q_B, q_D\right) q_D(t) - c_D\left(q_D(t)\right)\right] dt. \tag{A.1}$$

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

$$p\left(t; q_S, q_B, q_D\right) = \frac{(\theta - K_R/2) - (b - \alpha K_R/2)\sin t - q_D(t) - q_S(t) + q_B(t)}{1-\beta}.$$

Following Lemma 2 in Andrés-Cerezo and Fabra (2023), it is straightforward to show that, in equilibrium, for given $q_B(t)$ and $q_S(t)$, the quantities produced by the dominant and fringe producers are given by

$$q_D^*(t) = \frac{\beta}{1+\beta}\big(p(t) - q_S(t) + q_B(t)\big) < \frac{1}{1+\beta}\big(p(t) - q_S(t) + q_B(t)\big) = q_F^*(t),$$

where $p(t)$ is given in the main text by (3).

The resulting equilibrium market price is now given by

$$p\left(t; q_S, q_B, q_D^*\right) = \frac{(\theta - K_R/2) - (b - \alpha K_R/2)\sin t - q_S(t) + q_B(t)}{1-\beta^2}. \tag{A.2}$$

Therefore, the equilibrium price is the same as in the baseline model, simply re-scaled by the market power term $1/(1-\beta^2)$, which is increasing in β. Therefore, market power in the power market (proxied by β) increases the price level, captured by $A(K_R;\beta)$, and the amplitude of the price cycle, captured by $\rho(K_R;\beta)$, where $A(K_R;\beta) \equiv A(K_R)/(1-\beta^2)$ and $\rho(K_R;\beta)) \equiv \rho(K_R)/(1-\beta^2)$, with $A(K_R)$ and $\rho(K_R)$ defined as in (3). However, market power does not change the sign of the correlation between prices and renewables. It follows that Proposition 1 remains unchanged. Interestingly, since $\rho(K_R;\beta)$ is increasing in β, an increase in market power strengthens the 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 $\partial\Pi_R/\partial K_S$.

B Details on the Simulations

In this appendix we provide further details on the simulations reported in Section 5 of the paper.

Market structure. Table B.1 provides details on the market structure used under the scenarios with low and high renewables.

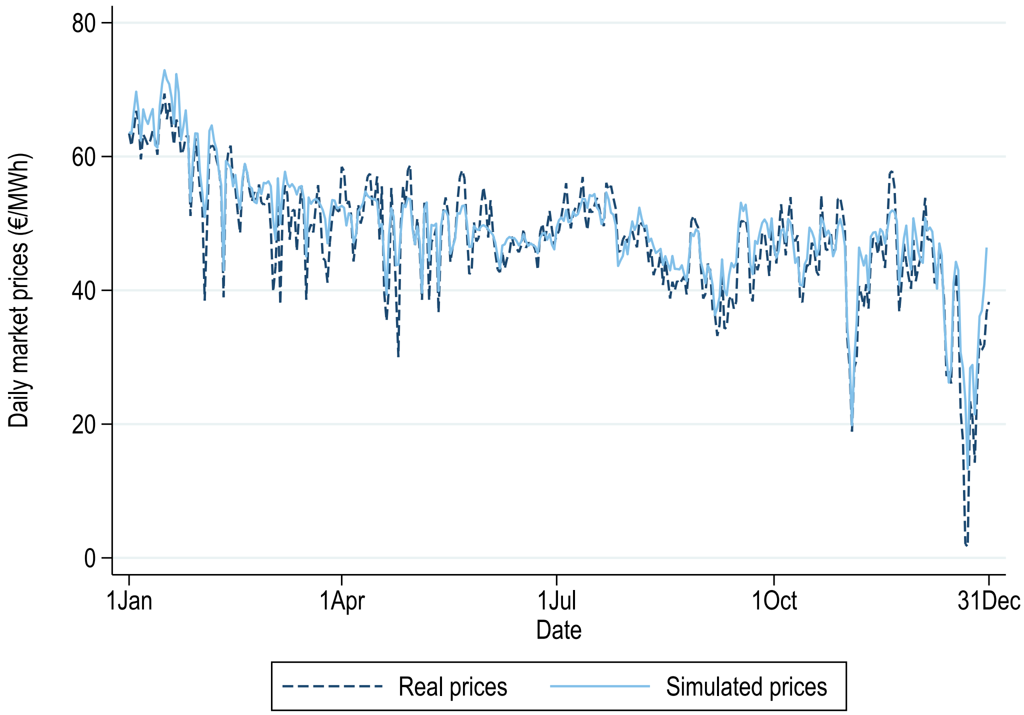
Table B.1: Installed capacity by technology and peak demand

	Low RES		High RES	
	Capacity (GW)	% of total capacity	Capacity (GW)	% of total capacity
Solar capacity	8.749	10.5	38.404	28.3
Wind capacity	25.680	30.8	48.550	35.7
Nuclear capacity	7.397	8.9	7.397	5.4
Coal capacity	14.638	17.6	14.638	10.8
CCGT capacity	26.941	32.3	26.941	19.8
Total capacity	83.405	100	135.930	100
Peak demand	40.150	-	40.150	-

Simulation Model's Accuracy. Figure B.1 shows the simulated electricity prices in the Spanish electricity market, using system conditions as of 2019, and compares them with the observed prices. The average hourly simulated and real prices are 49.4 €/MWh and 47.9 €/MWh, respectively, and the correlation between the two is 0.87. This good performance of the model supports its use to conduct counterfactual analyses.

Price Impacts. In the paper we argued that the price impacts of storage could be positive or negative, depending on the supply and demand elasticities at times of charging

Figure B.1: Real versus simulated electricity prices, 2019



[scale=0.80]

Notes: This figure shows the simulated (solid) and real (dash) electricity prices in the Spanish electricity market as of 2019. To make it clearer, the figure shows the daily averages of the hourly prices.

and discharging. Whereas the average effect of storage over the year is to depress prices (as reported in Table 1 of the paper), this hides heterogeneity across the year. Indeed, as shown in Figures B.2 and B.3, for high renewables scenario, average prices during the summer (winter) go up (down). Compared to the rest of the year, the price-increasing effect of storage in summer tends to be stronger, while the price-depressing impact tends to be weaker. Coupled with the fact that demand tends to be relatively higher during the mid-hours of the day, this evidence implies that the price-increasing effect (price-depressing effect) weighs relatively more in summer (winter) than during other seasons.

Table B.2 reports the quarterly averages. In line with the graphical evidence, prices in $Q2$ under the low renewables scenario and prices in $Q3$ under the high renewables scenario slightly go up when stroage capacity is increased.

Figure B.2: Renewable generation, storage and prices over the day: Winter

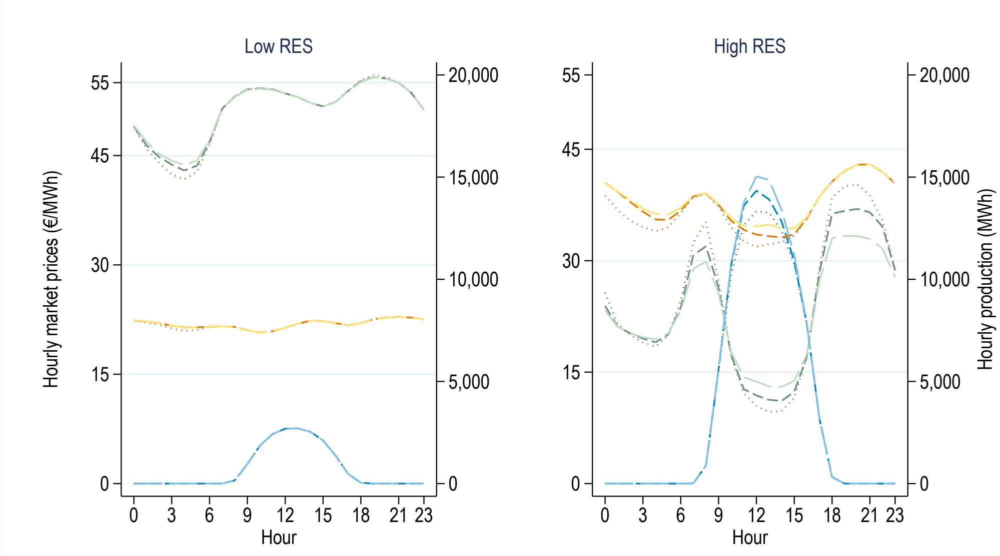
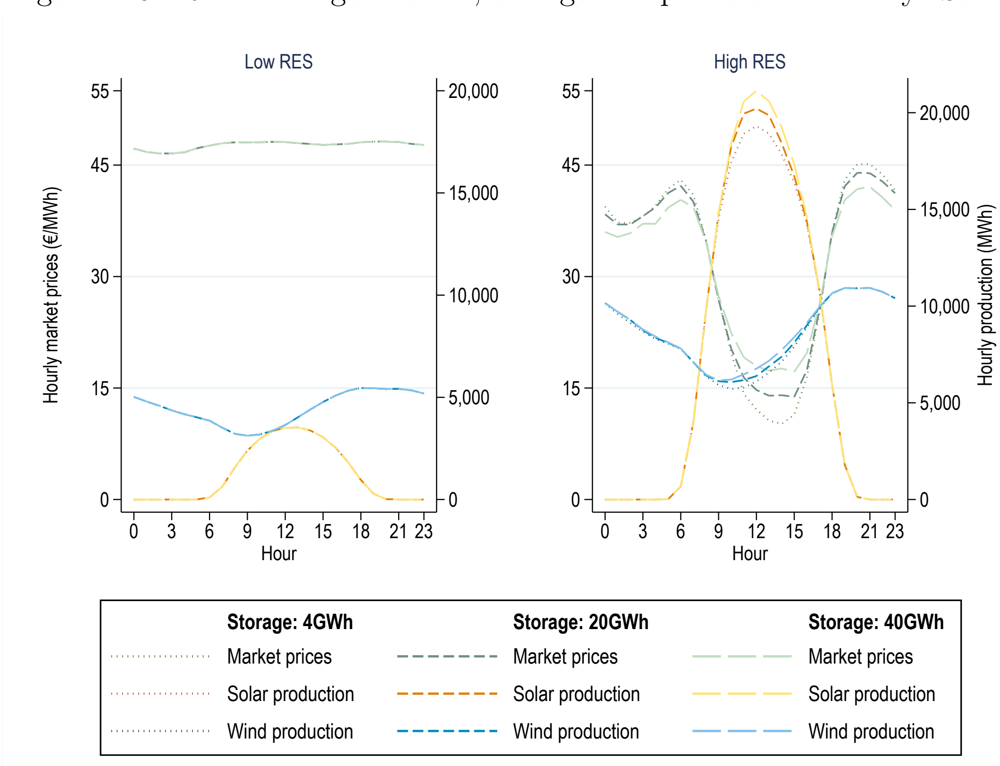


Figure B.3: Renewable generation, storage and prices over the day: Summer



Notes: These figures show, for each hour of the day, wind generation (blue), solar generation (yellow) and market prices (green), averaged across the winter (1st November until 28th February) in Figure B.2 and across the summer (1st June until 30th September) in Figure B.3. Results are shown for the cases with no storage (dots), storage capacity of 20 Gwh (dash) and 40 GWh (long dash). The left and right panels respectively show the results for the scenario with low and high renewable energy penetration.

Table B.2: Average market prices: annual and quarterly averages

	(1) No storage	(2) 20 GWh	(3) 40 GWh
Low Renewables (2019)			
Annual average price (€/MWh)	50.135	50.176	50.203
Quarterly average (€/MWh)			
Q1	59.219	59.223	59.223
Q2	49.148	49.151	49.151
Q3	47.831	47.831	47.831
Q4	43.940	44.103	44.210
High Renewables (2030)			
Annual average price (€/MWh)	25.925	25.558	25.079
Quarterly average (€/MWh)			
Q1	26.995	26.006	24.795
Q2	19.912	18.777	17.612
Q3	31.594	32.361	32.978
Q4	24.704	24.547	24.357

Notes: This table reports market prices, averaged across all hours of year and the quarters. Results are shown for the cases with no storage (1), storage capacity of 20 GWh (2) and 40 GWh (3). The upper and lower panels show the results for the scenario with low and high renewable energy penetration, respectively.