Storage power purchase agreements to enable the deployment of energy storage in Europe

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Publication date:
2022-08-19

Permanent link:
https://doi.org/10.3929/ethz-b-000560746

Originally published in:
iScience 25(8), https://doi.org/10.1016/j.isci.2022.104701

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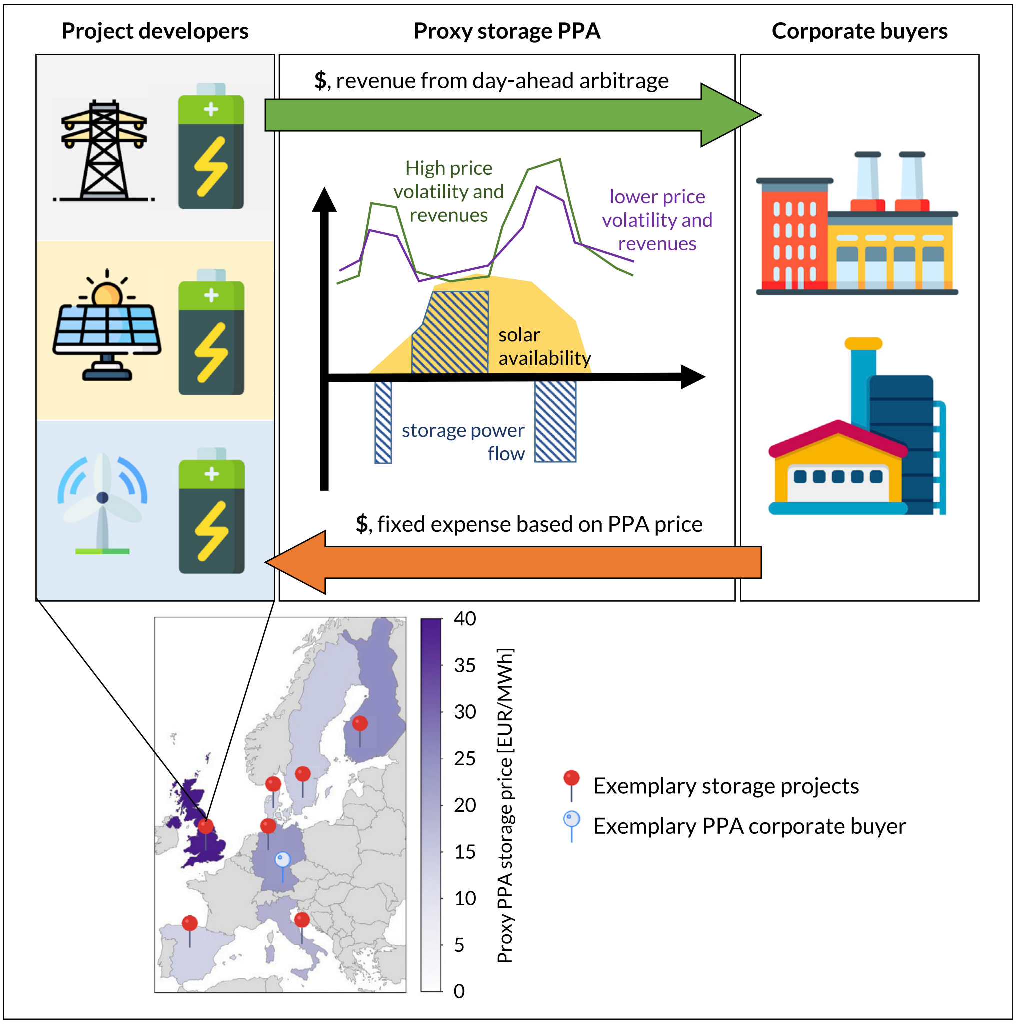

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Highlights

Novel contractual setup for power purchase agreements (PPAs) with energy storage

Calculation of PPA threshold price defining profitable cases for buyers in Europe

The UK and Germany are the most promising European markets for storage PPAs

For high-price scenarios, storage PPAs can generate 180 MEUR/year in 2030 in Europe

Gabrielli et al., iScience *25*, 104701
August 19, 2022
https://doi.org/10.1016/j.isci.2022.104701

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Storage power purchase agreements to enable the deployment of energy storage in Europe

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SUMMARY

We propose a contractual setup, the proxy storage power purchase agreement (PPA), to foster the deployment of energy storage technologies. We define a threshold price below which the PPA becomes financially attractive for PPA buyers. We compute the threshold price for several storage technologies and configurations, in seven European countries. Such threshold prices overlap with the best-case forecast of the battery levelized cost of storage in 2030, indicating that proxy storage PPAs can play a role in enabling battery storage installations within the next ten years in Europe (generating about €180 million per year). Moreover, we identify UK and Germany as the most attractive countries for storage PPAs in Europe due to the high projected threshold prices and planned storage capacities. We show that revenues are maximized when coupling storage with wind energy generation rather than solar. This points to the design of policies that efficiently subsidize storage installations.

INTRODUCTION

Several countries worldwide, including the European Union, have pledged to become carbon neutral by 2050 (Hale et al., 2022; Council of the European Union, 2020) to limit global warming below 1.5C (IPCC et al., 2018, 2021). This requires finding new routes for energy provision, which rely on increasing shares of intermittent renewable energy (RE) generation and might pose challenges to today's electricity system (IEA, 2021a). These challenges include adapting the grid for high shares of RE generation and balancing energy demand and supply in a cost-efficient way, which can be tackled via grid-scale energy storage (Denholm et al., 2021). However, the deployment of grid-scale energy storage is currently hindered by the high investment costs of energy storage technologies and by the lack of guaranteed revenues (Miller and Carriveau, 2018). Whereas similar limitations have been faced in the past by wind and solar energy installations, they have been largely overcome via a reduction in installation cost and perceived financial risk, government incentives, and financing mechanisms such as power purchase agreements (PPAs) (Miller and Carriveau, 2018).

This work investigates the possibility of extending PPAs to grid-scale (also called front-of-the-meter) energy storage technologies, and aims at understanding the potential of storage PPAs in fostering the deployment of such technologies. To this end, we propose a contractual structure that guarantees fixed revenues based on the arbitrage potential of the day-ahead market, thereby improving the ability of project developers to secure funding to install and operate storage projects. Based on this, we estimate the potential revenues of energy storage PPAs from the buyer's perspective in selected European countries; we do so for historical (2015–2019) and future years (2030–2034). We focus on pumped hydro and battery storage, as the former is currently the most spread energy storage technology in Europe (European Commission, Directorate-General for Energy, 2022), and as the latter is leading in terms of capacity additions (George and Shai Hassid, 2021). Furthermore, battery storage cost is expected to decrease due to scaling effects linked to electric vehicle adoption (Schmidt et al., 2017).

We address three aspects that are necessary to evaluate storage PPAs from the buyer's perspective. These are: (1) the assessment of the levelized cost of storage (LCOS); (2) the impact of co-located RE facilities on the revenue of storage PPAs, and the optimal size of the energy storage technology to maximize the revenue; (3) the identification of the most attractive European markets for storage PPAs.

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https://doi.org/10.1016/j.isci.2022.104701

Power purchase agreements (PPAs)

PPAs are bilateral contracts between two parties, namely a project developer (e.g. an RE generator) and an energy buyer, which agree to sell and buy a predetermined volume of electricity, respectively, for a predetermined number of years and price structure. Various PPA contractual structures exist, and one of the most common is the virtual PPA (Miller and Carriveau, 2018; Gabrielli et al., 2022a). In virtual PPAs, there is no direct physical transfer of electricity from the generator to the buyer, and the same financial effect of selling electricity is achieved through a contract-for-difference. More specifically, the generator sells the electricity produced on the local wholesale electricity spot market, and the difference between the electricity spot market price and the price agreed in the PPA is settled between the buyer and the generator separately (Ghiassi-Farrokhfal et al., 2021). If the price agreed in the PPA is lower than the price set in the wholesale market, the buyer receives the difference in price from the generator. Conversely, the generator receives the difference in price. Other PPA contractual structures include physical PPAs where the electricity is directly wired to the buyer's manufacturing facilities or industrial plants.

In 2020 alone, PPAs supported about 25 GW of RE capacity installation worldwide and guaranteed fixed revenues to the RE project developers (IEA, 2021b). Overall, PPAs prove to be an effective instrument to address the major limitations of RE projects, such as high upfront investment costs and lack of guaranteed revenues. With the same limitations being faced today by energy storage technologies, PPAs might represent a valuable tool to foster their deployment. However, while RE plants mainly create revenues from selling electricity on the wholesale market, storage technologies can also exploit price arbitrage and intraday and ancillary services markets (Miller and Carriveau, 2018). This calls for more complex operation strategies and PPA structures.

Existing types of storage PPAs

Energy utilities and traders, and electricity market operators in general, embrace contract structures that are based on multiple revenue streams and that allow the direct control of the generation or storage asset. In contrast, corporate buyers often enter a PPA to hedge against energy market volatility, to reduce their environmental footprint and energy costs, and to demonstrate sustainability commitment. They typically welcome simple contract structures, where they do not have the full control of the generation or storage asset. Three contractual structures for storage PPAs are currently available:

Tolling agreement

This grants the buyer the right to control the storage and to operate it on multiple markets such as ancillary services, intraday arbitrage, and day-ahead market arbitrage. The seller of the contract receives energy payments to cover operational costs and capacity payments to cover fixed costs (Sinaiko, 2018). This setup is most suited for energy traders and utilities, which have extensive expertise in energy markets, and it is applied to wind-charged storage projects in Germany (ee-news, 2021).

Energy contracts

Here, the buyer pays a fixed price for the electricity produced by an RE plant coupled with an energy storage technology (Sinaiko, 2018). These contracts create an incentive mismatch, as the buyer only profits from day-ahead market revenues while the seller can also profit from offering ancillary services and performing intraday arbitrage. Whereas mechanisms exist to reduce this incentive mismatch (e.g. defining different PPA prices for certain hours of the day or defining periods where available energy has to be delivered), they also reduce the capability of the asset to deliver grid services (Sinaiko, 2018). Energy contracts are currently adopted for several solar projects combined with battery storage in the US (Mayr, 2020).

RE-store contract

This is offered by Levelten, a company managing a PPA marketplace, and is based on each day's electricity price difference between the highest and lowest priced hour of the day-ahead auction (LevelTen Energy, 2020). As the cash flows are independent of the operation of the storage asset and based on day-ahead market prices, this setup is well suited to corporate PPA buyers. Due to the focus of the RE-store contract on the price spread, this contract mimics revenues of grid-charged storage, but it cannot be adapted to mimic revenues of wind- or solar-charged storage or to consider different round-trip efficiencies of the storage technology. We propose a similar but more versatile setup in Section 2 that can be adapted to wind- and solar-charged storage and to different values of the round-trip efficiency.

A novel contractual structure: The proxy storage PPA

We propose the proxy storage PPA, a novel contractual structure for virtual storage PPAs that is suitable for various storage configurations. The project developer and the energy buyer agree to sell and buy a predetermined amount of electricity, here the maximum energy discharged by the energy storage in one day, at a fixed price, for a fixed time interval. From the energy buyer perspective, the cash flows of proxy storage PPAs are based on the revenues of the optimal operation of a virtual energy storage technology (with predefined characteristics) on the day-ahead market. We determine the optimal operation, which we refer to as the virtual storage operation, with an optimization algorithm based on day-ahead market auction results. The virtual storage can either be charged from grid electricity (grid-charged), or from electricity generated by co-located wind and solar facilities (wind- and solar-charged). As proxy storage PPAs are based on day-ahead market revenues and do not give the control over the storage asset to the buyer, the contract aims to be attractive for corporate PPA buyers. Being based on potential revenues of an energy facility, the proxy storage PPA is similar to proxy PPAs for wind and solar, and the PPA does not restrict the operation of the storage asset in any market. Thus, it does not limit the potential market revenues for the project developer.

Various approaches determine the optimal operation of storage technologies for arbitrage with perfect foresight, see e.g. (Sioshansi et al., 2009; Barbour et al., 2012; Zhang et al., 2021; Pusceddu et al., 2021; Ikechi Emmanuel and Denholm, 2022). While the revenues based on the optimal storage operation are not necessarily achieved on the day-ahead market during actual operations, this approach simplifies the contract formulation and the calculation of the cash flows. Uncertain forecasts of price and renewable energy generation, as well as potential unavailability of RE assets, imply that actual day-ahead market revenues for project developers are lower than those considered with proxy storage PPAs. Zucker et al. estimate that real operational strategies can yield around 80% of the revenues determined by assuming perfect foresight (Joint Research Centre and Institute for Energy and Transport et al., 2013). However, as other revenues could potentially be achieved through the storage asset, e.g. performing intraday arbitrage and offering ancillary services, the total revenue for storage operators can in principle exceed the one attained via proxy storage PPA.

Different constraints are used to model the specifics of the storage technology and of the PPA contract, such as fixed storage cycles and the possibility to charge only from wind and solar power generation.

Materials and methods

The assessment of proxy storage PPAs is performed via two models, illustrated by the two red boxes in Figure 1. The *dispatch optimization model* determines the dispatch (or operation) of the virtual storage that maximizes the revenue of the energy buyer, based on (i) the hourly resolved electricity price, (ii) the parameters describing the virtual storage, and (iii) the hourly resolved wind or solar generation, if the storage is

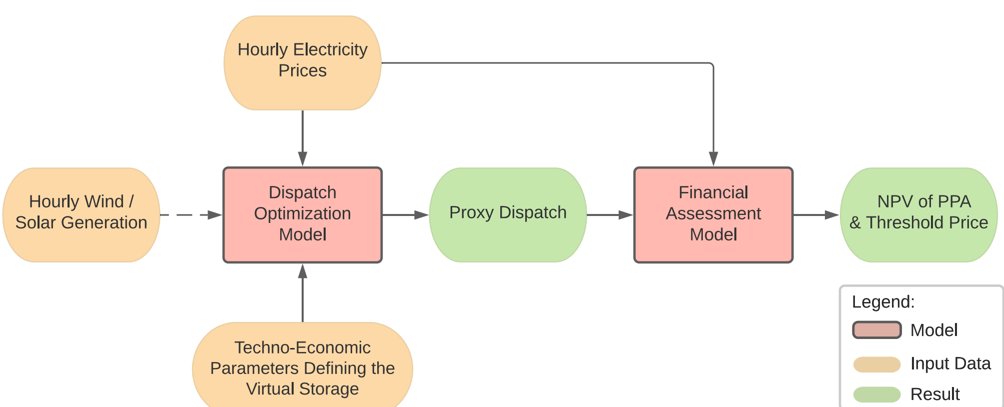

Figure 1. Overview of proxy storage PPA assessment method

The red boxes indicate the assessment models, namely the dispatch optimization model and the financial assessment model. The yellow boxes indicate the input data to the assessment models, namely hourly electricity prices and renewable energy generation, and storage techno-economic parameters. The green boxes indicate the result of the assessment models, namely the optimal dispatch of the storage unit and the corresponding NPV and proxy storage PPA threshold price.

only charged from co-located renewable generation assets. The *financial assessment model* calculates the financial performance of the proxy storage PPA based on (i) the output of the dispatch optimization model, (ii) the contract price, and (iii) the discount rate. The financial performance is evaluated in terms of (i) net present value (NPV) from the perspective of the corporate buyer, and (ii) threshold price, i.e. the contract price below which subscribing the PPA is profitable for the buyer.

Input data and assumptions

Hourly electricity prices. For assessing historical performance of proxy storage PPAs, we use day-ahead auction settlement prices with hourly resolution from the ENTSO-E Transparency Platform (ENTSO-E, 2022). Historical prices cover the 2015–2019 time interval, which does not include effects of the COVID-19 pandemic on electricity prices. For assessing future performance of proxy storage PPAs, we create hourly resolved price forecasts (low, average, and high-price scenarios) by adopting a data-driven price forecasting model presented elsewhere (Gabrielli et al., 2022b). A five-year time interval from 2030 to 2034 is used for the projected PPA prices. Further details on forecasted electricity prices are provided in the STAR Methods section.

Hourly wind and solar generation. Within proxy storage PPAs, the storage unit can be charged by using electricity from the grid or from a co-located RE project. Historical, hourly resolved wind and solar generation profiles are obtained through the work of Pfenninger and Staffel (Pfenninger and Staffell, 2016; Staffell and Pfenninger, 2016), based on the CM-SAF SARAH and the MERRA-2 datasets (Rienecker et al., 2011; Müller et al., 2015). Future renewable generation is computed by sampling the yearly profiles within the 2000–2019 time interval and by scaling the entire yearly profiles according to country-specific climate correction factors provided for solar (Jerez et al., 2015) and wind (Tobin et al., 2016). Further details on renewable energy generation are provided in the STAR Methods section.

Projections are considered for renewable energy generation and for electricity market prices to assess the future revenues of proxy storage PPAs and their uncertainty. This determines the future role of proxy storage PPAs in light of decreasing cost of energy storage.

Techno-economic parameters of energy storage technologies. Multiple energy storage technologies and generation-storage configurations are considered. These are characterized by parameters defining: (i) the maximum stored energy capacity, (ii) the maximum charging and discharging power, (iii) the maximum energy charged and discharged during a given time interval, e.g. one day, and (iv) the charging and discharging efficiencies.

Dispatch optimization model

A linear program is formulated by using CVXPY (Diamond and Boyd, 2016; Agrawal et al., 2018) and solved with an interior point method using the commercial solver ECOS (Domahidi et al., 2013).

Objective function. The optimization algorithm determines the optimal dispatch of the virtual storage that maximizes the revenue of the buyer, J, over the considered time horizon, T, while fulfilling the storage constraints. The revenues stem from day-ahead arbitrage, i.e. the possibility of buying and selling electricity when it is most convenient:

$$J = \sum_{t=1}^{T} p_t (V_t - U_t) \Delta t \quad \text{(Equation 1)}$$

where U_t is the power used to charge the storage and V_t is the power discharged from the storage during the time step t, of duration Δt. The energy for charging and discharging the virtual storage is bought and sold, respectively, at the known day-ahead market price p_t. U_t and V_t are decision variables of the optimization problem for all time steps $t \in \{1, \ldots, T\}$.

Constraints: Behavior of storage technologies. The energy stored within the storage unit in a given time step, E_{t+1}, is expressed as a linear function of the energy stored, E_t, the energy charged into the storage, $U_t \Delta t$, and the energy discharged from the storage, $V_t \Delta t$, during the previous time step, and of the charging and discharging efficiencies, η_C and η_D. Self-discharging losses are neglected, as they are negligible when operating the storage with daily cycles (Petkov and Gabrielli, 2020; Petkov et al., 2021).

Accordingly, the storage behavior is expressed through the following equation, which holds for all time steps $t \in \{1, \ldots, T - 1\}$:

$$E_{t+1} = E_t + \eta_C U_t \Delta t - \frac{V_t \Delta t}{\eta_D} \quad \text{(Equation 2)}$$

The energy stored, and the charging and discharging power are non-negative quantities. Furthermore, the energy stored is constrained by the installed storage energy capacity, E_{max}, and the charging and discharging power is limited by the maximum charging and discharging power of the unit, E_{max}/τ, also referred to as the storage power capacity. Thus, the following constraints apply for all time steps $t \in \{1, \ldots, T\}$:

$$0 \leq E_t \leq E_{max} \quad \text{(Equation 3)}$$

$$0 \leq U_t \leq \frac{E_{max}}{\tau}, \quad 0 \leq V_t \leq \frac{E_{max}}{\tau} \quad \text{(Equation 4)}$$

where τ is the time required to fully charge or discharge the storage.

The maximum amount of energy discharged by the storage technology over a certain time horizon, ε, is defined by the developer to avoid overuse and fast degradation of the storage unit, and identifies here the volume of energy that the buyer agrees to buy within the PPA. ε is specified for each interval, i, of duration equal to σ time steps. Therefore, for all $i \in \{1, \ldots, T/\sigma\}$:

$$\sum_{t=(i-1)\sigma+1}^{i\sigma} V_t \Delta t \leq \varepsilon \quad \text{(Equation 5)}$$

A periodicity constraint is imposed to force the same state of charge (i.e. the same energy stored) at the beginning and at the end of given time intervals (e.g. a day) (Gabrielli et al., 2018, 2019). This allows daily and weekly products. The dispatch of the storage is determined individually for each period, *i*, of duration equal to φ time steps, and the energy stored at the beginning and at the end of each period coincides. For all periods $i \in \{1, \ldots, T/\varphi\}$:

$$E_1 = E_{i\varphi+1} \quad \text{(Equation 6)}$$

The pattern of U_t and V_t does not have to be the same during each period *j*. The energy stored at the beginning of each period is not predefined but is a decision variable.

Coupling with generation asset. Storage units can be charged by using electricity from a co-located RE asset. If this is the case, the charging power of the storage unit is restricted to be lower or equal than the power produced by the co-located asset, P_t, for all $t \in \{1, \ldots, T\}$:

$$U_t \leq P_t \quad \text{(Equation 7)}$$

In this case, the energy is bought from the generation asset at the day-ahead market price, p_t.

Financial assessment model

Net present value (NPV). The NPV of a proxy storage PPA is computed as the sum of the discounted cash flows during the contract duration, from the buyer perspective. For the sake of clarity, here we express the generic time index $t \in \{1, \ldots, T\}$ via a yearly, $y \in \{1, \ldots, Y\}$, and a daily time index, $d \in \{1, \ldots, D\}$.

The seller receives a fixed cash flow from the buyer, based on the PPA price, k, and on the predetermined energy volume (i.e. the maximum amount of energy discharged, ε); the buyer gets the variable cash flows of the virtual storage from the seller, based on the day-ahead electricity market price, which results in the daily revenue J_d as expressed in Equation (1). Therefore, the NPV is obtained by subtracting the cost of the contract from the revenue, and by discounting this via a discount rate, r (typically defined by the buyer on a yearly basis):

$$\text{NPV} = \sum_{y=y_0}^{Y} \sum_{d=1}^{D} \frac{J_d - \varepsilon k}{(1+r)^{(y-y_0)}} \quad \text{(Equation 8)}$$

where Y is the PPA duration in years, y_0 is the starting year of the contract, and D is the number of days in a year. We also refer to the numerator of NPV as net revenue. If the expenditure, εk, is smaller than the revenue, then the buyer sees a positive net revenue hence makes a profit.

Table 1. Summary of input data

Quantity	Symbol	Value
Storage energy capacity	E_{max}	12 MWh
RE generation capacity (if present)	P_{max}	10 MW
Time to fully charge or discharge the storage	τ	4 h
Charging efficiency	η_C	0.95
Discharging efficiency	η_D	0.95
Number of time intervals for periodicity constraint	Φ	24
Number of time intervals for discharge constraint	ε	24
Maximum energy discharged during one day	E	12 MWh
Discount rate (yearly)	r	7.5%
Length of time step	Δt	1 h
Start date of the contract		2015-01-01/2030-01-01
End date of the contract		2019-12-31/2034-12-31
Countries (number of solar, wind projects)		Germany (5,5), Denmark (6,5), Spain (5,5), Finland (5,5), Italy (5,5), Sweden (4,5), United Kingdom (5,5)

Reference storage unit for the assessment of proxy storage PPAs.

Threshold price. The proxy storage PPA threshold price, k^*, is the price of the proxy storage PPA for which the NPV in Equation (8) is equal to zero. The threshold price depends on the day-ahead market price expectations, the techno-economic parameters of the storage unit, and the discount rate. The threshold price is also a measure of financial performance, i.e. the higher the threshold price, the higher the revenues of the virtual storage. For a project, if a PPA is offered below the threshold price, it is financially attractive for the buyer, and vice versa. From a general perspective, k^* quantifies the feasibility of the proxy storage PPA contract, because it provides an estimate of the cost of storage for which a developer would offer the contract.

RESULTS

Table 1 reports the specifications of the projects used for the quantification of the proxy storage PPAs (see STAR Methods section).

Optimal dispatch of virtual energy storage

Figure 2 shows the optimal dispatch of a battery storage co-located with a wind power plant (i.e. the charging of the storage unit is constrained by the available wind energy) during one week in 2019. During the first two days and the second to last day, sufficient wind power is available at all times and does not limit the operation of the battery storage. In contrast, wind power production constrains the storage operation during the remaining four days where, during most hours, the generated wind power is lower than the storage power capacity. Charging is stretched out on the last of the depicted days while it would be ideal to charge it at the maximum rate during the most convenient hours.

While fulfilling all operational constraints, the dispatch of the storage is optimized to charge and discharge during hours of low and high electricity price, respectively. Figure 2 shows that in general discharging occurs during the morning and evening price peaks; charging happens more distributed throughout the day. Further details on the optimal storage operation are provided in the STAR Methods section.

Proxy storage PPA threshold prices

The proxy storage PPA threshold price, k^*, can be used to benchmark PPA offers and to compare how favorable different countries and scenarios are for the deployment of storage PPAs. Figure 3 shows the threshold prices for seven European countries, for historical (2015–2019) and projected (2030–2034) RE generation and day-ahead electricity prices, and for three different contractual setups, namely storage

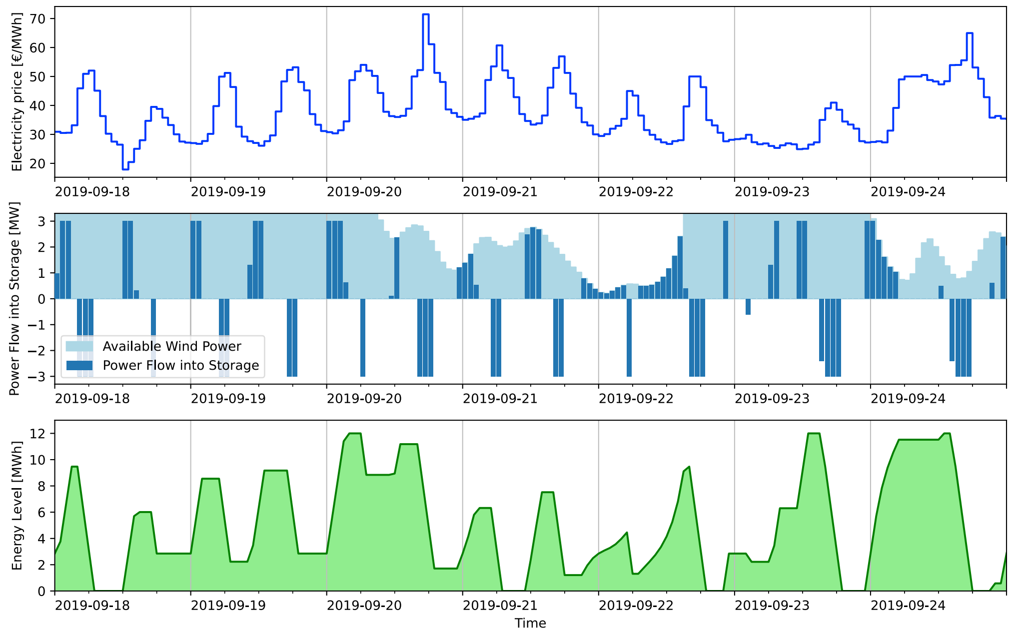

Figure 2. Example of optimal storage operation in perspective with renewable energy generation and electricity price

Optimal dispatch and energy levels of a battery storage in Germany (DE) shown for one week in September 2019 for given hourly electricity price and available wind power. Wind-charged storage, specified as described in Table 1.

charged from the grid (grid-charged), charged from co-located solar energy (solar-charged), and charged from co-located wind energy (wind-charged).

Impact of time-dependent RE generation and electricity price on threshold price

The most relevant parameters to determine the value of the proxy storage PPA threshold price are the available electricity and the electricity market price, which determine the time-dependent availability of electricity to operate the storage unit.

For grid-charged proxy storage PPAs spanning years 2015–2019, the average PPA threshold prices vary between 12.4 and 34 €/MWh across the considered countries (Figure 3, top-left). Coupling storage with co-located RE plant results in lower threshold prices due to the limited operational flexibility of RE generation.

Solar-charged storage is most impacted because the average capacity factor of wind power generation is higher than that of solar power generation (see STAR Methods section). Therefore, more power is available for charging storage from wind than from solar on average, hence increasing the operation flexibility of the storage unit. Overall, the threshold price increases for larger values of the average RE capacity factor and of the average electricity market price, with the latter having the greatest impact (Figure 4).

Furthermore, the time profiles of RE generation and electricity price matter. Solar power is generated during daytime, when electricity prices are usually high, whereas wind power is also generated at night when prices are usually low. This effect is especially pronounced in Spain, where solar energy generation occurs during diurnal hours when prices are very high due to air conditioning. As a result, threshold prices in Spain are significantly lower than in other countries with similar average values of RE generation and electricity price, i.e. Italy.

Impact of storage-to-generation capacity ratio

When energy storage is co-located with an RE power plant, the power capacity of the storage technology relative to the one of the generation technology strongly effects the project revenue and the threshold price. Figure 5 shows the proxy storage PPA threshold prices for solar- and wind-charged storage in

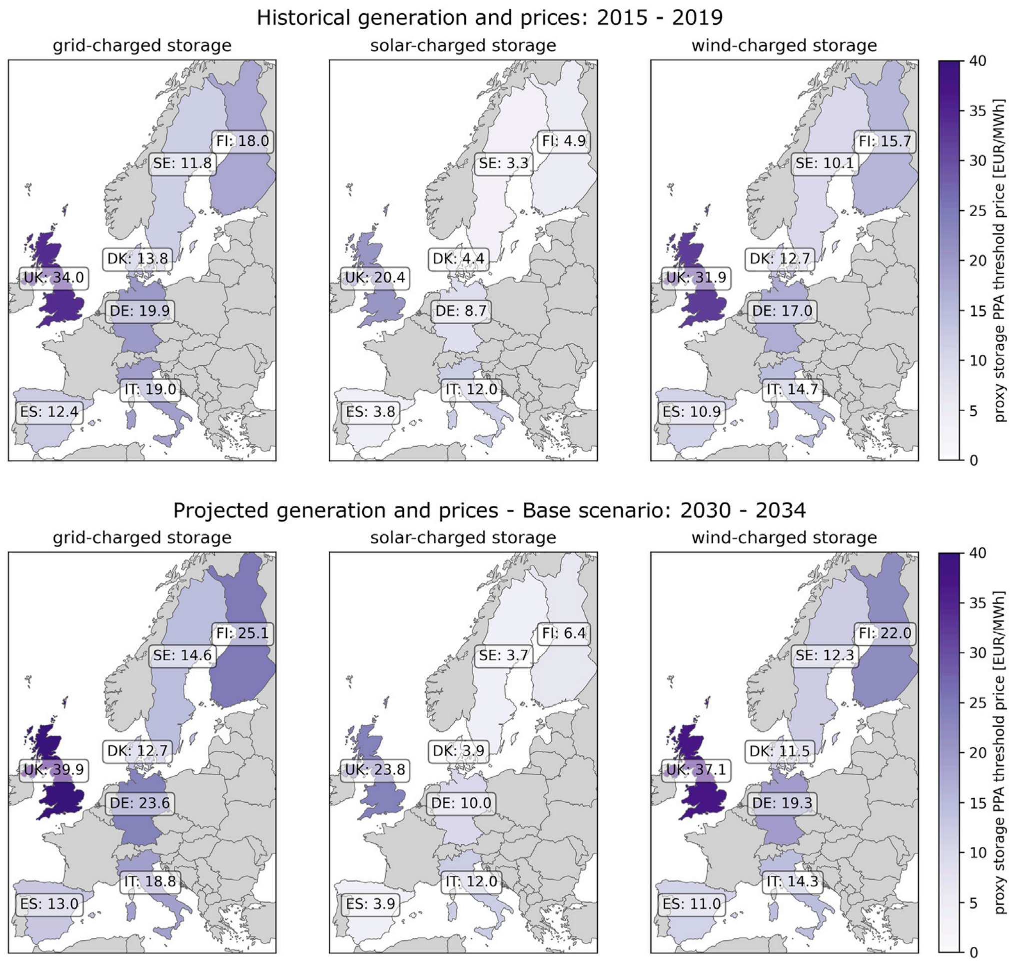

Figure 3. Average proxy storage PPA threshold prices for the considered countries

Seven European countries are considered (Table 1), namely Germany (DE), Denmark (DK), Spain (ES), Italy (IT), Finland (FI), Sweden (SE), and the United Kingdom (UK). Historical (2015–2019, top) and projected (2030–2034, bottom) electricity prices and RE generation are considered for three different contractual setups, namely storage charged by using electricity from the grid (left), solar energy (center), and wind energy (right).

Germany as a function of the ratio of the storage power capacity, $E_{\max}/\tau$, to the generation power capacity, $P_{\max}$, denoted as capacity ratio. For equal storage capacity, the larger the RE generation capacity, the faster and more flexibly the storage can be charged. Therefore, high storage PPA threshold prices are associated with lower storage-to-generation capacity ratios.

The purple lines in Figure 5 show the energy storage usage as a function of the capacity ratio. A value of 100% means that the storage unit undergoes full discharge every day, whereas a value of 50% means that the storage unit provides an average energy per day equal to 50% of the maximum amount allowed (i.e. 0.5ε, or 6 MWh in this case—see Table 1). The energetic usage is lower for solar-charged than for wind-charged storage, due to the lower capacity factor of solar generation, to the lower availability at hours with low electricity prices, and to stronger seasonal patterns. In winter, solar energy generation is low and the storage cannot be fully charged within one day.

Optimal storage capacity

Figure 5 shows that the maximum PPA threshold price is achieved for the smallest capacity ratio, i.e. for the smallest size of the energy storage for a given size of the RE generation, due to the higher charging flexibility of the storage.

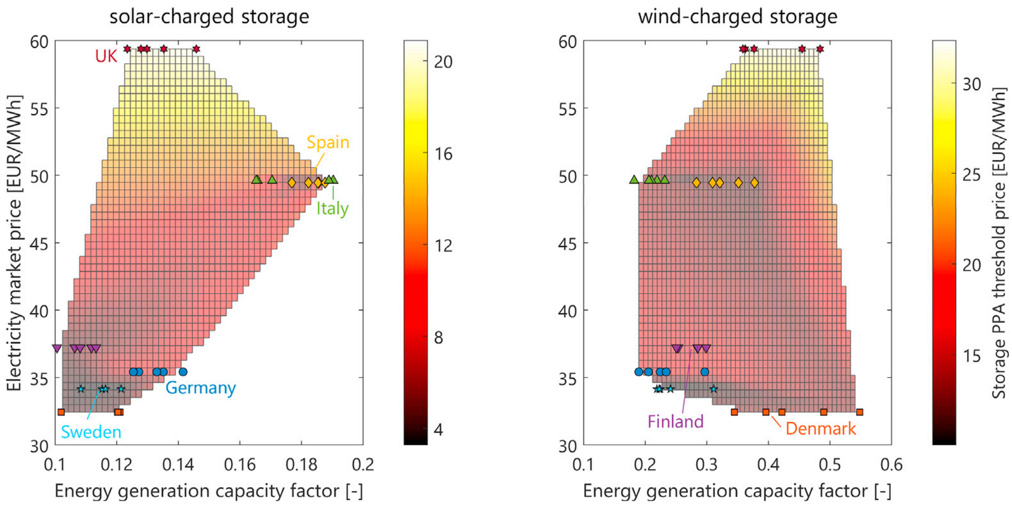

Figure 4. Dependence of proxy storage PPA threshold price on time-dependent electricity price and renewable energy generation

Proxy storage PPA threshold price (colorbar) is reported as a function of the average capacity factor of RE generation and of the average electricity market price for solar-charged (left-hand side) and wind-charged storage (right-hand side). Based on historical electricity prices and RE generation for 2015–2019. Markers are reported to indicate the conditions of all specific projects across the markets of interest; their colors do not follow the colorbar and simply indicate different countries.

However, the amount of energy that can be sold to the market, hence the potential revenue of the PPA, increases with the capacity of the energy storage. Thus, an optimal storage size exists that maximizes the revenue of proxy storage PPAs, and is a trade-off between higher revenues per unit of discharged energy for small storage power capacities, and larger amount of energy sold to the market for large storage power capacities. The revenue of solar- and wind-charged storage PPAs per unit installed RE is reported in Figure 6, which shows the optimal capacity ratios (gray dashed line) for different PPA prices. For a given RE project, such values define the storage power capacity that should be installed to maximize the revenue of the storage PPAs from the buyers perspective.

Generally, low PPA prices increase both the optimal capacity ratio and the total PPA net present value. At equal PPA prices, the optimal size for wind-charged storage and its net revenues are higher than those of solar-charged storage.

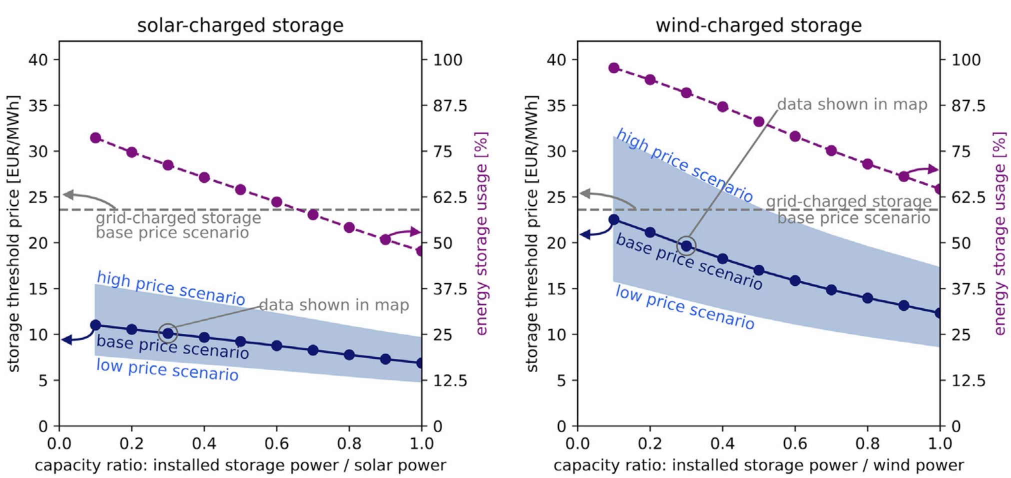

Figure 5. Dependence of proxy storage PPA threshold price on storage-to-generation capacity ratio

Proxy storage PPA threshold price is reported as a function of storage-to-generation capacity ratio for solar-charged (left-hand side) and wind-charged storage (right-hand side) in Germany (DE). The usage of the storage units as a function of the storage-to-generation capacity ratio is also reported (purple lines) for the base price scenario (right-hand side x axis). Based on projected electricity prices and RE generation for 2030–2034.

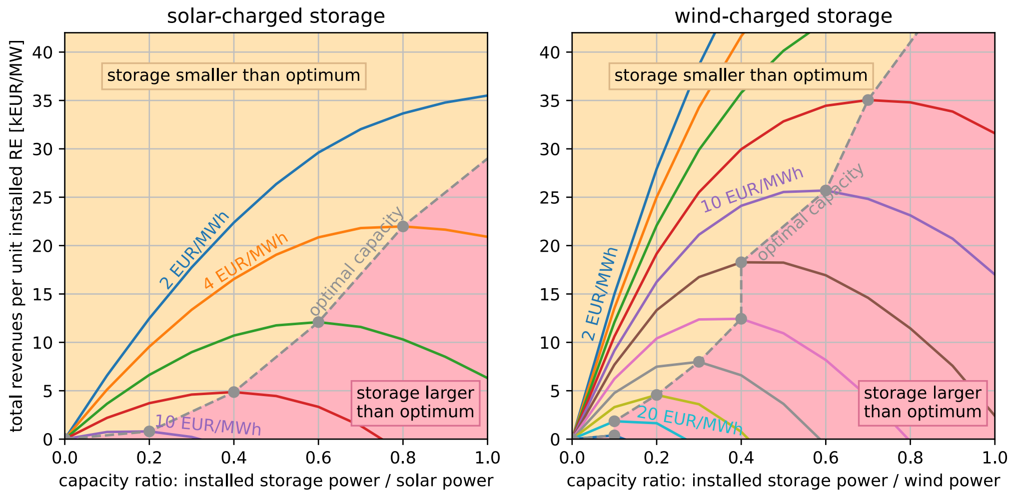

Figure 6. Dependence of total revenue of storage PPAs on storage-to-generation capacity ratio

Total revenue of storage PPAs per installed RE capacity is reported as a function of the storage-to-generation capacity ratio for different proxy storage PPA prices, for solar-charged (left-hand side) and wind-charged storage (right-hand side) in Germany (DE). Based on projected electricity prices (base price scenario) and RE generation for the years 2030–2034.

Finally, we perform a sensitivity analysis to investigate the impact of storage round-trip efficiency, stored energy at the beginning of the day, discharge duration, and maximum number of cycles per day. Results are shown in Figure S1 and discussed in the STAR Methods section.

DISCUSSION

Potential for proxy storage PPAs in Europe

Proxy storage PPAs are adopted, if they are economically convenient for both the PPA buyer and the PPA seller (project developer). From the perspective of the project developer, proxy storage PPAs are attractive when the total revenues of the storage project—typically day-ahead market arbitrage, day-ahead, intraday and ancillary service markets—exceed the total cost of the storage. While we consider the revenues from the perspective of the PPA buyer, the perspective of the storage developer allows us to assess the feasibility of PPA threshold prices, i.e. the possibility for the developer to be able to offer PPAs at a price that the buyer is willing to accept. To this aim, we compare the proxy storage PPA threshold prices and the LCOS. The former provides an estimate of the maximum cost of storage, i.e. of the maximum LCOS, for which developers would be able to offer a PPA.

Two points are worth making for the comparison. On the one hand, developers might be able to offer a PPA even if the LCOS is greater than the threshold price, provided that the difference between the two is covered by services offered outside the contract, e.g. ancillary service markets. On the other hand, the revenues of proxy storage PPAs are based on perfect foresight, hence it may not be achieved due to forecasting uncertainty in the day-ahead market (Zucker et al. estimate that around 80% of the revenues with perfect foresight can be harnessed (Joint Research Centre and Institute for Energy and Transport et al., 2013)). Thus, the LCOS might need to include such uncertainty. Furthermore, the LCOS includes the cost of energy losses and it can thus be compared to the PPA threshold prices for a lossless storage (i.e., 100% round-trip efficiency).

Beuse et al. calculate LCOS values for different technologies and applications in the electricity sector for the years 2017 and 2030 (Beuse et al., 2020). They estimate the LCOS of lithium-ion (LI) batteries to range between 145 and 260 €/MWh (median of 195 €/MWh) in 2017. In 2030, the LCOS of battery storage is predicted to be significantly lower. In the worst case scenario, the LCOS ranges between 75 and 150 €/MWh (median of 100 €/MWh); in the base case, the LCOS ranges between 40 and 85 €/MWh (median of 55 €/MWh); and in the best case, it ranges between 27 and 55 €/MWh (median of 35 €/MWh). The LCOS of PHS is predicted to range between 47 and 115 €/MWh (median: 80 €/MWh) in 2030.

For LI battery storage, the lowest LCOS values reported for 2017 are about four times higher than the storage PPA threshold prices obtained for historical RE generation and electricity prices (see Table S4 of the Supplemental Information, 100% efficiency). This suggests that today proxy storage PPAs would not be an effective instrument to foster battery storage deployment. However, the values of LCOS in 2030 overlap with the values of storage PPA threshold price in all considered electricity price scenarios (see Figure 3 and Tables S4–S6 of the Supplemental Information). This suggests that within the next ten years battery storage might become cheap enough for corporate buyers to engage in storage PPAs, hence supporting the deployment of non-subsidized LI battery storage units in Europe. Under these conditions, storage PPAs represent a simple and effective mechanism that can be used to meet sustainability targets while reducing the energy costs of corporate buyers. Similar considerations apply to PHS, and possibly to other storage technologies such as hydrogen storage (Gabrielli et al., 2020). However, due to the longer lifetimes, payback times, and planning procedures of PHS (Foley et al., 2015), which often result in heavy public involvement, proxy storage PPAs might be less suited in this case.

Subsidies can make proxy storage PPAs attractive even when storage costs surpass market revenues. In contrast, grid fees could prevent the adoption of grid-charged proxy storage PPAs due to their negative effect on arbitrage revenues. The applicability of grid fees differs between countries, technologies, and applications in Europe (European Commission, Directorate-General for Energy et al., 2020; Bundesministerium der Justiz, 2005), but discussions are ongoing to harmonize this from a central European perspective (European Commission, Directorate-General for Energy et al., 2020).

Several factors affect the deployment of proxy storage PPAs. In 2021, as a result of high natural gas and CO_2 emission prices, the electricity price and its fluctuations were significantly higher as compared to 2015–2019. Therefore, the 2021 proxy storage PPA threshold prices are much higher than the 2015–2019 threshold prices and exceed the high-price scenario projections. For grid-charge energy storage, threshold prices above 50 €/MWh are obtained in Spain and Denmark, and threshold prices above 60 €/MWh are obtained in Finland and Sweden. In the event that electricity prices remain as high and volatile as in 2021, proxy storage PPAs may enable a faster deployment of storage technologies.

Most attractive countries for storage PPAs

A national electricity market is attractive for proxy storage PPAs, if threshold prices are high and if the country offers a regulatory situation that fosters energy storage. We use the installed and announced energy storage capacities as a proxy for the markets attractiveness toward energy storage.

When considering the 2015–2019 profiles of RE generation and electricity prices, the highest threshold prices are obtained in the UK, followed by DE, IT, and FI. Projected threshold prices are also the highest in the UK, but the difference with the following countries (DE, DK, and FI) reduces.

Table 2 shows operational and planned capacities for battery storage and PHS installations in the seven analyzed countries. Around 7 GW of PHS storage is installed in DE and IT, while nearly 5 GW are installed in Spain and 3 GW in the UK. Significant expansion of PHS capacity is announced in Germany, Spain, and the UK. Germany and the UK have the highest installed battery storage power capacity at 350 and 570 MW, respectively.

Overall, the UK seems to be the most attractive country for proxy storage PPAs in Europe due to its high proxy storage PPA threshold price and its large operational and planned storage capacities. Additionally, Germany is a potentially attractive country for proxy storage PPAs owing to the planned storage capacity expansion and the relatively high PPA threshold prices.

The ability of proxy storage PPAs to enable the deployment of energy storage in Europe is assessed by computing the total revenue obtained when considering the total and planned storage capacities reported in Table 2. For battery storage, the sum of operational and planned capacity across the considered countries covers about 60% of the capacity projected in 2030 by the National Trends and Global Ambition scenarios published by TYNDP (Ten-Year Network Development Plan) and about 50% of the capacity projected by the Distributed Energy scenario. Proxy storage PPAs in 2030–2034 are considered; PPA prices are taken equal to the projected values of LCOS in 2030 (Beuse et al., 2020), which is a realistic estimate of the price at which project developers could offer the contract. In the base scenario for the LCOS, proxy storage PPAs do not create positive net revenues because the LCOS exceeds the proxy storage PPA threshold

Table 2. Operational and planned storage power capacities in MW for considered European countries

	PHS		Battery		Projected battery in TYNDP scenarios		
Country	Operational	Planned	Operational	Planned	National Trend	Global Ambition	Distributed energy
DE	6703	5730	350	50	3990	3990	5060
DK	0	0	0	0	0	441	442
ES	4704	8147	11	164	2500	1618	2175
FI	0	0	2	9	0	250	250
IT	7331	0	56	0	1535	499	1560
SE	91	0	5	0	0	973	974
UK	3161	3571	570	4220	100	1037	1037

Operational and planned storage capacity are taken from the European database of energy storage technologies and facilities (European Commission, Directorate-General for Energy, 2022); projected battery capacity in 2030 according to three TYNDP (Ten-Year Network Development Plan) scenarios are reported for comparison (European Commission, Directorate-General for Energy, 2021).

prices. In contrast, in the best scenario for the LCOS of batteries, proxy storage PPAs create positive net revenues. In the base electricity price scenario, the UK is the only country where proxy storage PPAs create a positive net revenue (around € 50 million per year for grid-charged storage projects). Conversely, in the high electricity price scenarios, proxy storage PPAs create positive net revenues across all considered countries, for a total of € 180 million per year for grid-charged energy storage. In these conditions, project developers can offer proxy storage PPAs and buyers can make profits.

Comparison to net revenues of other storage PPA structures

Different contractual structures for storage PPAs result in different cash flows and revenues (see Section 1.2). The RE-Store contract is the most similar to the proxy storage PPA, which can be configured to have the same contract revenues. The RE-Store and the proxy storage PPA cash flows are independent of the operation of the asset, and therefore the market revenues of the storage unit are the same.

Energy contracts are similar to proxy storage PPAs because they are only based on day-ahead market revenues and the seller is responsible for the operation of the storage asset. However, the revenues of energy contracts are based on the actual operation of the asset and perfect foresight does not apply. Therefore, energy contracts lead to lower net revenues for the buyer for the same proxy storage PPA price.

With a tolling agreement, the seller gets a fixed revenue, does not bear any market risk, and is not responsible for the operation of the asset. The buyer profits from all revenue streams and is responsible for operation. Depending on the market conditions and the operation strategies, net revenues are potentially much higher than those of proxy storage PPAs, at the cost of a greater involvement, hence required know-how, of the buyer.

Current prominence of solar-charged storage PPAs

Our results indicate that wind-charged storage PPAs have higher performance than solar-charged ones. However, looking at Germany as an example, many storage systems are currently coupled with solar generation, thanks to subsidies, while only one is coupled with wind generation (Bundesnetzagentur, 2021). To be eligible for the subsidies, the storage unit should be charged only by using electricity generated by the co-located RE project and should be able to store at least the equivalent of 2 h of peak production.

With a discharge duration, $\tau = 4$ h, this translates into a storage-to-generation capacity ratio of 0.5 as defined in Figures 5 and 6:

$$\text{capacity ratio} = \frac{E_{max}}{\tau P_{max}} = \frac{2P_{max}}{4P_{max}} = 0.5 \qquad \text{(Equation 9)}$$

Figure 5 shows that solar-charged storage is used less than 70% at this capacity ratio, while wind-charged storage is used more than 90%. Furthermore, the revenues of solar-charged storage PPAs are 56%, or 12€/MWh lower, than those of wind-charged storage PPAs (base price scenario). Therefore, for a given RE generation capacity, wind-charged storage is used to a larger extent and requires less subsidies. Hence, subsidies could be efficiently allocated to wind-charged storage projects for lowering the barrier for private investments that are hampered by the larger size of the storage unit.

Storage units are only subsidized in combination with an RE plant in Germany and subsidies are granted to the combinations of storage and RE generation projects that ask for the lowest subsidy level. Solar-charged and wind-charged storage projects take part in the same auction (Bundesministerium der Justiz, 2020). Despite the fact that the lowest bids get the subsidy, we argue that this process is cost-inefficient as, for equal performance of the RE project, the subsidy required for a solar-charged storage unit is higher than that required for a wind-charged one, because the latter generates higher revenues. The driver for solar-storage combinations being able to place lower bids than wind-storage combinations is the cost of the RE technologies. Therefore, solar-charged storage projects can win the subsidy auctions despite the lowest revenue resulting from the storage asset.

We suggest two alternative policy measures to improve the cost efficiency of the subsidy-allocation process and to achieve a fairer competition between wind- and solar-charged storage. (1) Independent auctions should be set up for solar-charged and wind-charged storage projects. (2) Independent auctions should be set up for RE projects and for energy storage.

Conclusions

This paper introduces a novel PPA contractual structure, the proxy storage PPA, which deals with energy storage and is suitable for corporate PPA buyers as (i) they are not responsible for the operation of the asset, and (ii) the revenue depends on day-ahead market arbitrage only. This PPA structure is independent of any specific storage technology and it is applicable to any storage project where day-ahead market arbitrage is a potential source of revenue, though this does not need to be the only or main source of revenue. The cash flows resulting from proxy storage PPAs are defined based on the optimal operation of the storage assets and are independent of their actual operation. The cash flows are determined based on known closed market prices and by solving a linear optimization problem.

The financial performance of the proposed proxy storage PPAs is assessed to evaluate their role in enabling the deployment of energy storage in Europe, by ensuring a guaranteed revenue stream via day-ahead market arbitrage. While arbitrage revenues could only cover a fraction of the costs of energy storage in past years, we show that proxy storage PPAs have the potential to foster unsubsidized energy storage installations in Europe within the next decade, especially when the storage is charged from the electricity grid or from co-located wind energy generation assets. The UK followed by Germany is identified as the most attractive European countries for proxy storage PPAs due to the highest expected revenues and storage capacity expansion plans. In a scenario of low storage costs and high electricity prices, proxy storage PPAs would enable the deployment of current and projected battery facilities (about 60% of battery capacity projected by TYNDP in 2030) by generating about € 180 million per year in Europe.

Limitations of the study

The analysis presented in this work can be expanded in multiple directions. First, proxy storage PPAs are based on day-ahead market arbitrage only, whereas in principle storage technologies can be operated on multiple markets, such as ancillary services and intraday market arbitrage. Determining the optimal operation of energy storage when participating in several markets would result in higher revenues, hence in higher threshold prices, and possibly in a greater deployment of energy storage technologies. Potential challenges to perform such assessment include collecting forecasts for grid services revenues, which are not readily available.

Moreover, the analysis could be expanded to cover all countries in Europe and diverse geographical scopes, and to focus both on mature and emerging markets for PPAs. This is relevant as different boundary conditions (e.g. different pricing structures, differently regulated energy markets) might result in different dependencies of revenues and threshold prices, and affect the potential of proxy storage PPAs overall. Similarly, the analysis could be expanded to consider different energy price scenarios and time-dependent price and renewable generation profiles, especially in the light of the ongoing European energy crisis.

Finally, while the proposed contractual setup is general, our discussion focuses on electricity storage. However, a multi-energy perspective, e.g. by investigating thermal energy storage, could increase the financial value of storage PPAs.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

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SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.isci.2022.104701.

ACKNOWLEDGMENTS

The research published in this report was carried out with the support of Innosuisse - Swiss Innovation Agency, Energy & Environment (E&E), under the project 41263.1 IP-EE, and of the Swiss Federal Office of Energy SFOE as part of the SWEET EDGE project. The authors bear sole responsibility for the conclusions and the results. The authors thank the entire working team at South Pole, a Swiss carbon finance consultancy, and especially Ayça Taşli, Paul Hill, Antonia Weitzer, and Patrick Horka, for the very helpful and insightful discussions within the domain of power purchase agreements. Furthermore, the authors thank the interviewed industry experts that helped framing the topic and gaining helpful insights, and especially Christian Herbst and Patrick Kronenberger from KfW IPEX, Davide Alfonso from Enel X, as well as Michiel van Asseldonk, Linnea Tjernlund, Nicolas Brouwer, and Carlaxel Wiborg from OX2.

AUTHOR CONTRIBUTIONS

Conceptualization, P.G.; Methodology, all; Software, P.H.; Formal analysis, P.H., P.G.; Data curation, P.H.; Writing – original draft: P.H., P.G.; Writing – review and editing: all; Visualization: all; Supervision: P.G., G.S.; Project administration: P.G.; Funding acquisition: P.G., G.S.

DECLARATION OF INTEREST

The authors declare no competing interests.

Received: April 4, 2022
Revised: May 23, 2022
Accepted: June 27, 2022
Published: August 19, 2022

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited data		
Raw and analyzed data	This paper (supplemental information); Mendeley Data	Tables S1–S3; https://data.mendeley.com/datasets/mcf3vt7k2c/1
Historical, hourly-resolved wholesale electricity market prices	Entso-e Transparency platform	https://transparency.entsoe.eu/
Projected, hourly-resolved wholesale electricity market prices	This paper (supplemental information); Mendeley Data	Table S7; https://data.mendeley.com/datasets/mcf3vt7k2c/1
Software and algorithms		
Python version 3.8	Python Software Foundation	https://www.python.org
ECOS	Domahidi et al. (2013)	https://ieeexplore.ieee.org/document/6669541
CVXPY	Diamond and Boyd (2016); Agrawal et al. (2018)	https://doi.org/10.48550/arXiv.1603.00943; https://doi.org/10.1080/23307706.2017.1397554

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Paolo Gabrielli (gapaolo@ethz.ch).

Materials availability

Not applicable.

Data and code availability

- The data needed to reproduce all figures and results have been deposited at Mendeley Data and are publicly available as of the date of publication. The DOI is listed in the key resources table.
- This paper does not report original code.
- Any additional information required to reproduce the results reported in this paper is available from the lead contact upon reasonable request.

METHOD DETAILS

The assessment of proxy storage PPAs is performed via the methodology described in Section 3 and illustrated in Figure 1. Further details on some aspects of the assessment and optimization models are provided below.

Forecasted electricity prices

For all considered European countries (Germany (DE), Denmark (DK), Spain (ES), Italy (IT), Finland (FI), Sweden (SE), United Kingdom (UK)), values of the price drivers (i.e. energy-related quantities that influence the electricity price) as projected by the EU Reference Scenario are used (European Commission et al., 2021). We characterize the uncertainty associated with future electricity prices based on that of the price drivers (Gabrielli et al., 2022b), and we create low, average and high price scenarios based on the 25th, 50th and 75th percentiles of the resulting price distributions.

The average yearly values of the projected day-ahead market electricity prices are reported in Table S7 in the Supplemental Information.

Wind and solar generation

When charging the storage from a co-located renewable energy project, the charging power of the storage is constrained to be smaller or equal than the renewable power generation (see Section 3.2).

Within each of the considered European countries, four to six geographic locations corresponding to existing projects are used to properly describe the wind and solar energy generation of a country (OpenStreetMap Foundation, 2022). The average generation across these projects is considered for all countries and for both solar and wind technologies. The geographic locations of the considered solar and wind projects are reported in Tables S1 and S2, respectively; the average historical and projected capacity factors are reported in Table S3.

Optimal dispatch of virtual energy storage: Discharge and periodicity constraints

While fulfilling all operational constraints, the dispatch of the storage is optimized to charge and discharge during hours of low and high electricity price, respectively. Figure 2 shows that in general discharging occurs during the morning and evening price peaks; charging happens more distributed throughout the day.

The discharge limit of ε = 12 MWh/day forces the storage unit to undergo one cycle per day. The discharge limit, which is defined when the PPA is signed, avoids overuse and fast degradation of the energy storage technology. The periodicity constraint results in an energy stored of about 2.8 MWh at the beginning of each day. Low values of stored energy at the beginning of the day are favorable in market conditions where low prices are observed in the night or in the morning and high prices are observed in the middle or at the end of the day. In Figure 2, the storage is charged during the low-price morning hours and discharged later in the day.

The periodicity constraint simplifies the calculation of the payments between the PPA buyer and seller, allows us to determine the optimal storage dispatch and the cash flows between the two parties for each time interval individually, and ensures that the results are reproducible for individual days (Gabrielli et al., 2018). However, it reduces the revenues of the virtual storage.

Sensitivity analysis to most relevant parameters

A sensitivity analysis is performed to investigate the impact of storage round-trip efficiency, stored energy at the beginning of the day, discharge duration, and maximum number of cycles per day. Results are shown in Figure S1 in the Supplemental Information.

The charging and discharging efficiencies of the virtual storage are not necessarily the efficiencies of the actual asset; they could, in principle, be set to typical values of the underlying storage technology, or to 100% to simplify the contract and the cash flows calculation. The value of 100% is also of interest to compare storage PPA threshold prices with the LCOS (see Discussion in the article). Understanding the effect of the round-trip efficiency on the threshold price allows comparing different proxy storage PPA offers. Figure S1A shows the proxy storage PPA threshold price as a function of the storage round-trip efficiency and highlights typical values for PHS and battery storage. Energy losses imply that a part of the electricity bought for charging cannot be sold later, with lower round-trip efficiencies leading to lower PPA revenues and threshold prices. Proxy storage PPAs signed without considering losses feature threshold prices two to 6 €/MWh higher than PPAs based on typical efficiencies values for battery storage, and seven to 10 €/MWh higher than PPAs based on typical efficiencies values for PHS.

Figure S1B shows the storage PPA threshold price as a function of the optimal energy stored at the beginning (and at the end) of the day, which is the same for all days. The optimal storage level at the beginning of the day is about 5, 24, and 22% of the storage capacity for grid-, wind-, and solar-charged storage, respectively. For values ranging between 0 and 50%, the threshold price is not significantly affected (less than 1.5 €/MWh difference with respect to optimal values), while greater discrepancies with respect to the optimal values are observed going toward full storage at the beginning of the day (100% initial level). The dashed lines in the plot show the threshold prices for the case when no periodicity constraint is considered, and the energy level may be different on different days. These prices are 0.6 and 1.1 €/MWh higher than the optimal prices obtained when considering the periodicity constraint for grid- and wind-charged storage. This difference becomes about 3 €/MWh for solar-charged storage PPAs.

Figure S1C shows the storage PPA threshold price for different discharge durations. A shorter discharge duration means that a storage can charge and discharge faster, and can thus capture a higher price spread than a longer discharge duration. Threshold prices at 1-h discharge duration are more than twice as high as at 12-h discharge duration for grid- and wind-charged storage, and more than three times as high for solar-charged storage. Thus, the comparison between costs and revenues of storage options with different discharge durations is key and provides a decision element for project developers planning a storage project and for manufacturers producing storage technologies.

Figure S1D shows the storage PPA threshold price as a function of the maximum number of cycles per day. The threshold price (units of €/MWh) is a function of the revenues (€) divided by the maximum allowed discharged energy (MWh). Allowing the virtual storage to perform more cycles increases the denominator and typically leads to lower PPA threshold prices despite the fact that the absolute revenue of the virtual storage increases. When changing the allowed number of cycles of the grid-charged storage from 1 to 0.5, the threshold price increases from 24 to 30 €/MWh, though the absolute revenue decreases by $1 - 0.5\frac{30}{24} = 37\%$. Therefore, limiting the storage to perform a maximum of 0.5 cycles per day significantly constrains storage revenues. In contrast, if the allowed number of cycles decreases from 3.2 to 1.6 cycles per day (grid-charged storage), revenues only decrease by $1 - 0.5\frac{18}{9.3} = 3\%$. Therefore, the virtual storage generates negligible additional revenues by performing more than 1.6 cycles per day.