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Comparing Storage Technologies for Participation in Day-Ahead and Primary Reserve Markets

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Abstract—Energy Storage Systems (ESS) operators generate revenues by providing electricity products, i.e., energy, capacity, and/or reserve, possibly participating simultaneously in several markets to stack revenues while playing with the discrepancies between prices and provision constraints. This study compares various storage technologies in terms of first-order expected revenues when participating in the Day-Ahead (DA) and Frequency Containment Reserve (FCR) markets, i.e., focusing on their function rather than detailed modeling. Comparisons are thus investigated with a 1 MW-rated asset and data for the French energy markets from 2018 to 2021. The effects of storage parameters, including round-trip efficiency, self-discharge rate, and energy capacity, are considered. Results highlighted that technologies like pumped hydro, compressed air, lead-acid, and Li-ion batteries are the most suitable for participation in DA markets. The FCR market prioritizes higher efficiencies, and technologies like flywheel, super capacitor, and superconducting magnetic energy storage are the most profitable in that market. Ultimately, batteries are the best suited for services stacking, meeting both the DA and FCR market demands.

Keywords—Storage, Technologies, Energy Markets, Day-Ahead, Frequency Containment Reserve, Comparison

I. INTRODUCTION

The role of grid-connected Battery Energy Storage Systems (BESSs) in enhancing grid reliability and efficiency has been extensively studied. However, in practice, the high upfront costs of BESS installations often drive owners to pursue multiple revenue streams from a single asset to justify their investment [1]. By simultaneously engaging in various energy markets, BESSs can boost their economic returns by leveraging the price differentials between markets, such as those for energy and frequency reserves [2, 3]. As an example, the study in [4] assessed the maximum achievable profits in both the Day-Ahead (DA) and Intra-Day (ID) markets. Overall, offering multiple grid services can nearly double the profitability of energy storage systems compared to providing a single one [5]. The present work builds upon earlier research by the same authors, which examined the provision of energy, reserve, and capacity products within the French market context [6]. Notably, the findings reveal that combining participation in the DA and Frequency Containment Reserve (FCR) markets yields profits 57 % higher than the sum of profits obtained from participating in either market individually. This improvement stems from the ability of BESSs to adjust their state of charge in the DA market, thereby extending the duration for which a given power reserve can be reliably offered—and thus monetized.

The different energy and reserve products require diverse dynamics and magnitude in terms of power/energy provision. Thus, from the ESS perspective, the expected economic profits strongly depend on its nature and technical parameters [7], as well as the targeted market(s). This paper then investigates different types of ESS while estimating their revenues from the participation in DA, FCR, or both. The

impact of the energy and reserve prices in these markets is also considered through simulation over successive years from 2018 to 2021. The objective is to identify, through a simplified model and optimization, which technologies are the best suited for the different market participations before diving into a more detailed modelling of the behavior of the then selected storage technology for economic assessment (considering for instance dynamic models of the frequency response, degradation modeling, and uncertainty in markets biddings and frequency events).

II. PROPOSED METHODOLOGY

A. Optimization over Time

The estimation of the revenues taken from DA and/or FCR takes the form of an optimization problem over time ($t \in T$, resolution dt) that accounts for the (more or less precise) storage model and market specificities. As further detailed in this section, note that DA and FCR markets have their dedicated time horizons and resolution (depicted in Fig. 1). In France, DA has an hourly resolution (dt^{da}). The FCR provision consists of reserving a power capacity along 4-hour slots (dt^r) that could be “activated” upward/downward in real-time (dt^a) based on frequency measurements.

B. Generic ESS Model

For the sake of a technology-agnostic comparison, a generic model for the ESS is proposed based on typical constraints. The storage charge/discharge (p_t^+ , p_t^-) cannot exceed the rated power (p_{max}) as in (1) and (2) with the corresponding binary variables for the charge/discharge modes (u_t^+ , u_t^-). An additional logical constraint (3) is introduced in case the ESS does not operate to account for the self-discharge (binary variable u_t^{sd}). The state of charge (soc_t) is updated at any point in time, accounting for the efficiency (η), approximated as the square root of the rated round-trip efficiency. The corresponding ESS model equation (4) accounts for the nominal capacity (e_{max}) and self-discharge rate (δ^{sd}). Finally, constraints ensure that the state of charge remains between specific bounds (soc_{min} , soc_{max}) all along the system's operation (5).

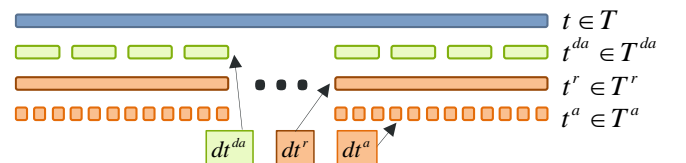


Fig. 1: Timeframe for DA and FCR markets.

$$0 \leq p_t^+ \leq p_{max} \times u_t^+ \quad \forall t \in T \quad (1)$$

$$0 \leq p_t^- \leq p_{\max} \times u_t^- \quad \forall t \in T \quad (2)$$

$$u_t^+ + u_t^- + u_t^{sd} = 1 \quad \forall t \in T \quad (3)$$

$$soc_t = soc_{t-1} + \left(p_t^- \times \eta - p_t^+ / \eta \right) \times \frac{100 \times dt}{e_{\max}} - u_t^{sd} \times \delta^{sd} \times dt \quad (4)$$

$$soc_{\min} \leq soc_t \leq soc_{\max} \quad \forall t \in T \quad (5)$$

C. Participation in the DA Market

For ESS participating in DA markets, revenues are typically generated from the arbitrage on energy prices (in €/MWh), which vary over time, e.g., hourly resolution dt^{da} in France. The underlying idea is to charge when prices are low to sell energy when the rates increase, following the optimization objective in (6). The overall DA optimization problem accounts for constraints (1)-(5).

$$\min obj^{da} = \sum_{t^{da} \in T^{da}} \left(p_{t^{da}}^- - p_{t^{da}}^+ \right) \times \pi_{t^{da}}^{DA} \times dt^{da} \quad (6)$$

D. Participation in the FCR Market

ESS participating in the FCR market first gets remunerated for the capacity they reserve p_r^{res} at a price π_r^{res} (in €/MW), based on bids the day before delivery. In real-time, in case some capacity is reserved, the upward/downward provision ($p_{t^a}^{fcr+}, p_{t^a}^{fcr-}$) leads to revenue in case of discharge or cost in the case of activation, at a price $\pi_{t^a}^{fcr}$ (in €/MWh). The FCR objective is summarized in (7) while the optimization for FCR participation is also subject to the constraints (1)-(5). An additional constraint ensures that the reserve capacity does not exceed the storage capacity (8). More importantly, constraint (9) describes the reserve activation in response to the frequency deviations Δf_{t^a} measured in real-time. Especially, the ESS is expected to be activated proportionally to the observed deviations with the reference frequency and to deliver the entire reserve capacity in case of extreme events ($\Delta f_{\max} = 200$ mHz). There is also a dead-band $\Delta f_{db} = \pm 10$ mHz within which the ESS does not have to react [7]. Lastly, a specific regulation from the French TSO enforces the ESS to be able to provide a reserve capacity of 15 minutes at any point in time. This leads to strengthened state of charge constraints for both upper and lower bounds, as in (10) and (11).

$$\min obj^{fcr} = \sum_{t^r \in T^r} \pi_{t^r}^{res} \times p_{t^r}^{res} + \sum_{t^a \in T^a} \pi_{t^a}^{fcr} \times dt^a \times \left(p_{t^a}^{fcr+} - p_{t^a}^{fcr-} \right) \quad (7)$$

$$p_{t^r}^{res} \leq p_{\max} \quad (8)$$

$$p_{t^a}^{fcr+}, p_{t^a}^{fcr-} = \begin{cases} p_{t^r}^{res}, & \text{if } |\Delta f_{t^a}| \geq |\Delta f_{\max}| \\ \left(|\Delta f_{t^a}| / |\Delta f_{\max}| \right) \times p_{t^r}^{res}, & \text{if } |\Delta f_{db}| \leq |\Delta f_{t^a}| \leq |\Delta f_{\max}| \\ 0, & \text{if } |\Delta f_{t^a}| \leq |\Delta f_{db}| \end{cases} \quad (9)$$

$$soc_{\max} = 1 - 0.25h \times p_{t^r}^{res} \times (1 / E_{cap}) \quad (10)$$

$$soc_{\min} = 0.25h \times p_{t^r}^{res} \times (1 / E_{cap}) \quad (11)$$

E. Joint Participation in the DA and FCR Market

In the case of an ESS jointly participating in DA and FCR, the targeted optimization objective encompasses both markets (12). Previous FCR constraints shall be ensured. Additionally, the charge/discharge power accounts for the actual provisions of the two products with (13) and (14) when constraints (1)-(5) are considered.

$$\min obj^{da} + obj^{fcr} \quad (12)$$

$$p_t^+ = p_{t^{da}}^{da+} + p_{t^a}^{fcr+} \quad (13)$$

$$p_t^- = p_{t^{da}}^{da-} + p_{t^a}^{fcr-} \quad (14)$$

F. Investigated Scenarios and Technologies

An ESS of 1 MW is selected to perform the comparison of ESS technologies while running the yearly optimization problems introduced before. This power is a minimum requirement to participate in energy markets, even though it can be assumed to be an aggregation of storage systems, depending on the considered technology. This value is relevant for setting a lower limit on benefit evaluations. In the results section, energy ranges will vary through the capacity (in hours), but not the power of the ESS. Prices and frequency data from 2018 to 2021 were considered (Fig. 2). The prices became more volatile over the years, either for energy or reserve, which may impact the results. It should be noted that prices were high in 2018, but due to the integration of renewables and BESS into the grid, prices subsequently decreased, and markets like FCR became saturated. However, with COVID-19, prices increased significantly in 2021 and became more volatile, even affecting the FCR reserve.

Compared technologies present different characteristics, listed in Table I, focusing on three main parameters: efficiency, self-discharge, and capacity. In this paper, each parameter is studied separately, i.e., with the others fixed. Three scenarios are repeated for the DA market, the FCR market, and the DA + FCR markets. First, efficiency ranges between 0.6 and 1, with a self-discharge of 0 %, and an energy capacity of 1 h. Second, self-discharge ranges between 0 and 100 %, with an efficiency of 100 %, and an energy capacity of 1 h. Finally, energy capacity ranges between 0.25 h and 10 h, with an efficiency of 100 %, and a self-discharge of 0 %. The TSO regulations for BESS state of charge limits are not considered in this section, as not applicable to generic ESS. To simplify, the same limit is imposed on all ESS: $soc_{\min} = 0$ %, and $soc_{\max} = 90$ %. However, the allowed FCR reserve is still considered as a ratio of the ESS energy capacity to ensure sufficient energy.

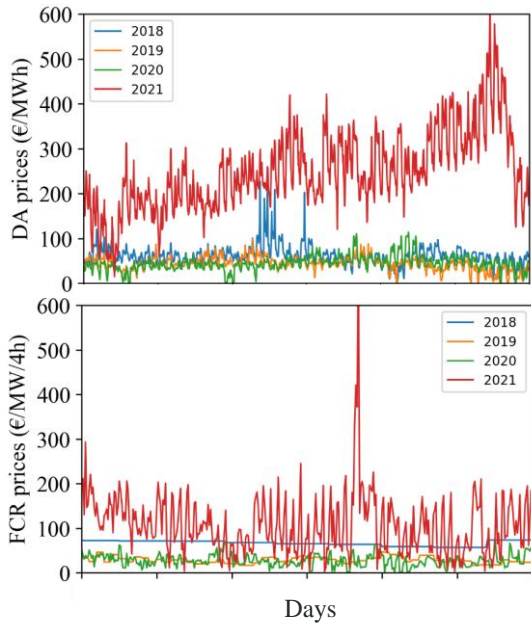


Fig. 2: Historical data for DA and FCR capacity prices.

Some storage types are designed for long-duration, or low-power applications etc., but integrating the diverse operational characteristics and constraints inherent to each ESS type is not the goal of a decision support tool. As ESS characteristics are different, we shall compare the function they provide for an initial assessment. To that end, the assumption of a fixed power and uniform state of charge across all ESS technologies has been made. For the same reason, real-world response delays and power electronics dynamics are not considered, as well as uncertainty in markets bidding and frequency events.

TABLE I. INVESTIGATED ESS TECHNOLOGIES [7].

Technology	Efficiency (%)	Self-discharge (%/day)	Capacity (h)
Pumped Hydro - PHES	70–85	3	2–10
Compressed air - CAES	60–70	5	2–10
Flywheels - FW	85–95	100	< 1
Lead-Acid battery - LA	70–90	0.1–0.3	0.25–10
Lithium-ion battery - LI	85–95	0.15–0.35	0.25–10
Sodium sulfur - NaS	80–90	20–40	0.25–10
Capacitors - CAP	60–70	40	0.25–2
Superconducting - SMES	90–95	15	< 1

III. RESULTS

A. One-Day Sample Illustration

Before comparing ESS technologies based on the three main parameters listed in Table I, let's illustrate typical results on energy markets. For improved readability, a 10 MW / 10 MWh ESS operation is presented along a representative day only in this section. The sizing of the ESS systems comes from a systematic benefits evaluation. In the results, the negative values correspond to charging, and the positive ones to discharging. For participation in the DA market only, price arbitrage leads to charge/discharge at an hourly resolution and high power to maximize the gain in terms of “shifted energy” (Fig. 3a). In the case of FCR provisions, the activated power follows proportionally the frequency deviations that remain small (Fig. 3b). Note that

along a day, those deviations almost display a null value. Thus, the revenue for the FCR activation is almost zero, and most of the profit is generated through the reserve capacity (remuneration in €/MW along 4-hour slots). Participating in both the DA and FCR markets allows operators to make use of the energy markets to adapt the state of charge of their ESS. For the considered day, more capacity is reserved between 8 am and 12 pm compared to a case in which only FCR is provided. This led to a daily profit higher than the sum of the individual DA and FCR revenues. DA only: 1189 €, FCR: 3971 €, and DA+FCR: 5541 €.

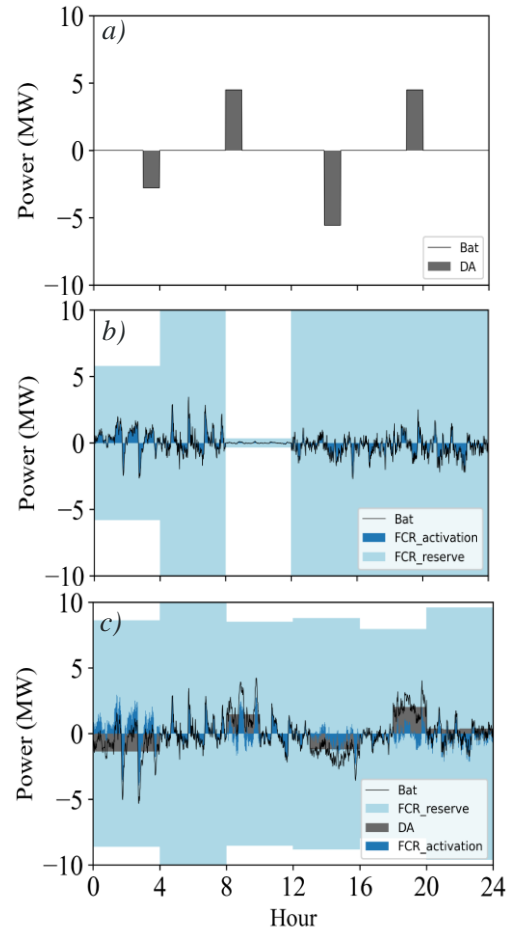


Fig. 3: Sample of daily operations: a) DA market, b) FCR market, c) DA+FCR markets.

B. Annual Profits

Yearly simulations are performed, adjusting the ESS parameters of efficiency, self-discharge, and size (in hours) for a 1 MW ESS, the minimum size to participate in energy markets, following the scenarios presented in Section II-F. Fig. 4 shows that high efficiency is critical for participating in the DA market, where revenues are relatively low at efficiencies below 0.8. In contrast, efficiency has a lower impact on profits in the FCR market, where revenues depend on reserved capacity rather than energy. However, FCR market profits can still be affected by low efficiency during energy activations, as these activations reduce the ESS's capacity to provide reserve, thereby diminishing profits. Combining revenues from both markets (DA and FCR) increases overall profits, potentially doubling those from FCR alone and quadrupling those from DA alone. This strategy also mitigates the impact of efficiency on profits by leveraging the different revenue structures of the two markets. Across all

scenarios (DA, FCR, and DA+FCR), greater price volatility leads to higher profits, as observed in 2018 and 2021 compared to 2019 and 2020.

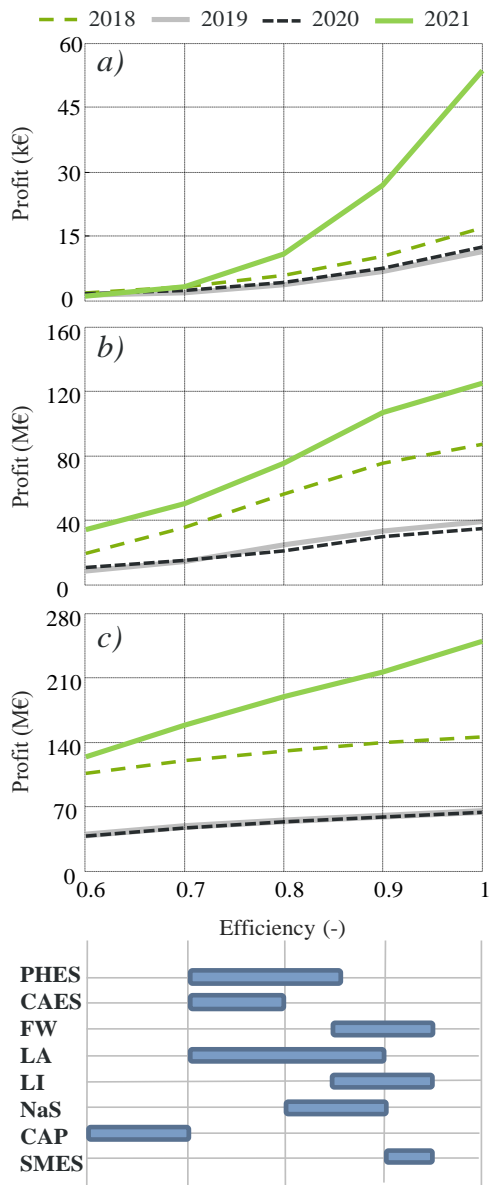


Fig. 4 Annual profit for different efficiencies: a) DA market, b) FCR market, c) DA+FCR markets.

The annual simulations in Fig. 5 demonstrate that the self-discharge rate significantly impacts revenues in the DA market due to the reliance on energy arbitrage for generating income. As for efficiency, there is minimal effect on revenues in the FCR market, where profits depend on the reserve capacity rather than the energy itself. The impact of self-discharge is more pronounced when stacking both services, largely because the majority of profits are derived from the FCR reserve.

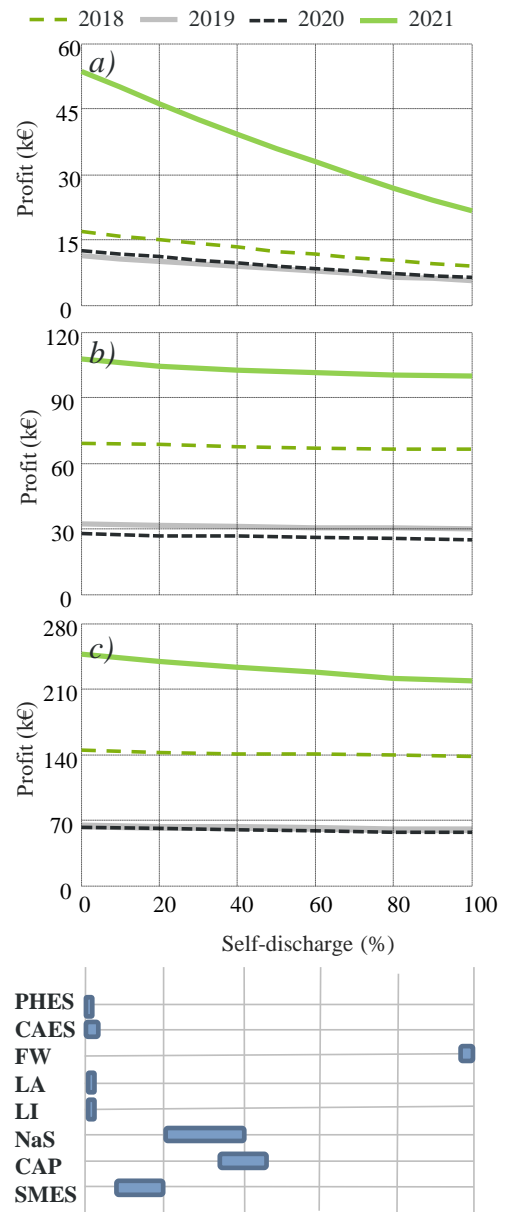


Fig. 5 Annual profit for different self-discharge: a) DA market, b) FCR market, c) DA+FCR markets.

The effect of the ESS commercial energy size is presented in Fig. 6. The results of the DA market illustrate the dependency on the energy capacity, as the relation is nearly linear between the ESS size and the annual profits. In the FCR market, profits increase significantly as battery size expands up to 4 h. Beyond this point, profits continue to rise but at a slower rate. This is because the FCR reserve is a function of the energy capacity to ensure that the ESS has enough energy to be activated when needed in the frequency regulations. Stacking services in both DA and FCR tend to be more prevalent as the FCR market about the battery size. This is because most of the profits are generated from the FCR reserve. However, at low ESS sizes, the stacked services operation also manages to achieve high revenues by performing energy arbitrage in the DA market. Furthermore, the analysis shows that ESS size has a high impact on the stacked revenues at high volatility markets, as in 2021.

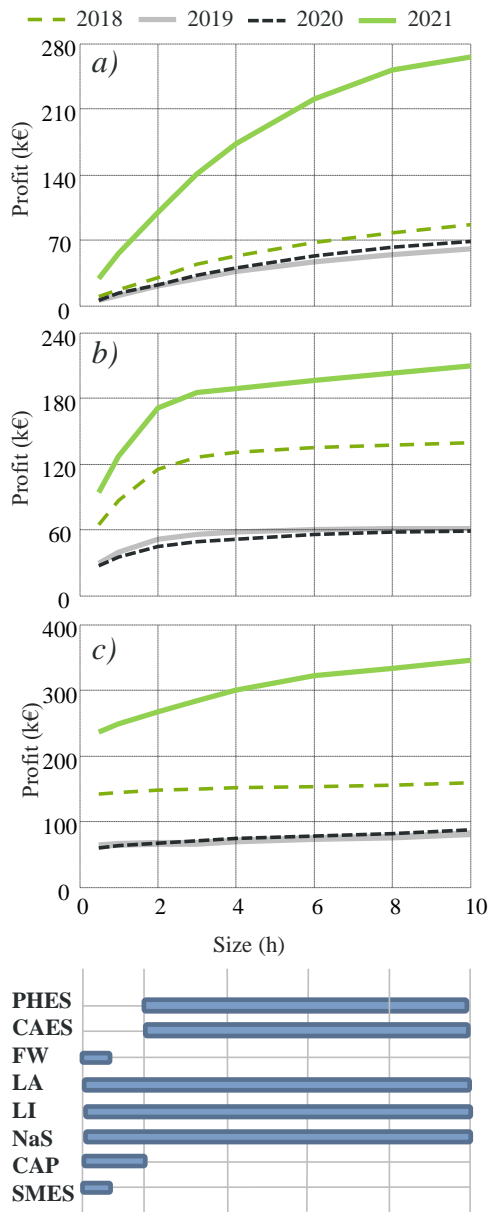


Fig. 6 Annual profit for several sizes: a) DA market, b) FCR market, c) DA+FCR markets.

IV. CONCLUSIONS

The paper compares ESS technologies participating in DA, FCR, or both energy markets, considering three main parameters: efficiency, self-discharge, and capacity. It showed that the DA market requires high efficiency and low self-discharge due to its significant impact on revenues. Additionally, energy arbitrage in the DA market depends heavily on the energy capacity of the ESS. It can be concluded that PHES, CAES, LA, and Li-ion are optimal for maximizing revenues in the DA market. In contrast, while high efficiency is necessary for the FCR market, self-discharge and energy capacity do not significantly affect revenues as they do in the DA market. This makes FW, SC, SMES, NaS, LA, and Li-ion suitable candidates for the FCR market. Combining both services requires meeting the demands of both markets, and

only battery technologies (LA and Li-ion) can provide both services and achieve high revenues. Another possibility is to consider hybrid installations.

One ESS technology is selected with the help of the presented decision support tool, degradation modelling should be considered for actual long-term profitability assessments, including aging, cycling limits, and operational expenses.

V. ACKNOWLEDGMENT

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