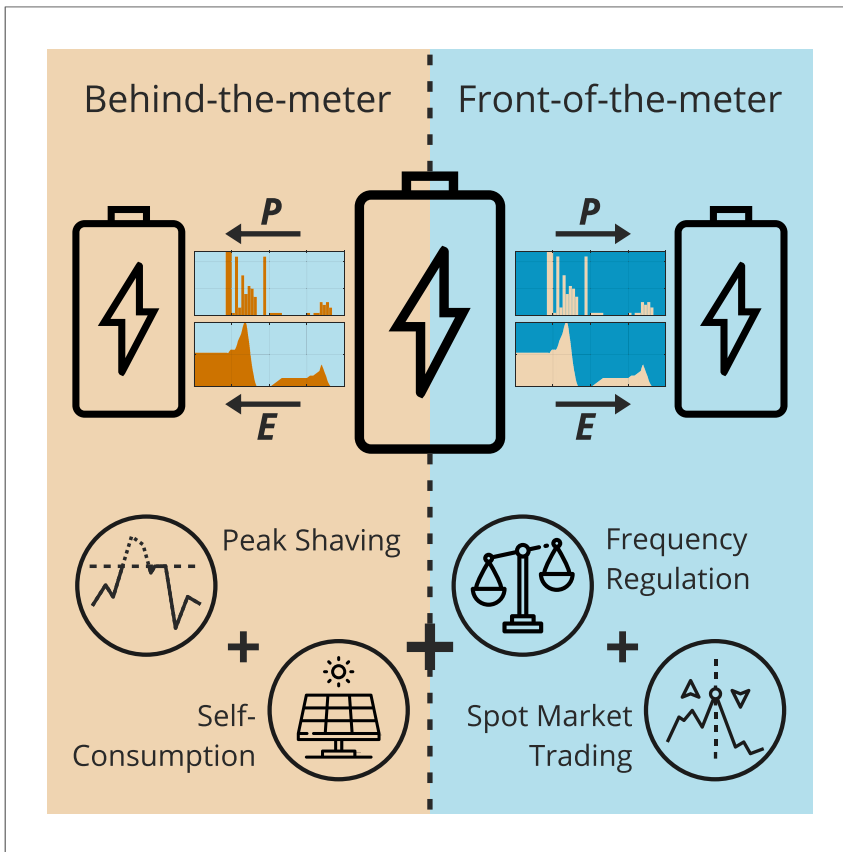


Article

Unlocking the Potential of Battery Storage with the Dynamic Stacking of Multiple Applications



The simultaneous stacking of multiple applications on single storage is the key to profitable battery operation under current technical, regulatory, and economic conditions. Englberger et al. introduce an optimization framework for dynamic multi-use that considers both behind-the-meter and front-of-the-meter applications with distinct power and energy capacity allocations.

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HIGHLIGHTS

Stacking of multiple applications enables profitable battery operation

Dynamic stacking is superior to parallel or sequential multi-use

Optimized battery utilization yields significant techno-economic benefits

For realization of multi-use, both energy and power capacities need to be allocated

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Article

Unlocking the Potential of Battery Storage with the Dynamic Stacking of Multiple Applications

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SUMMARY

The ability of a battery energy storage system (BESS) to serve multiple applications makes it a promising technology to enable the sustainable energy transition. However, high investment costs are a considerable barrier to BESS deployment, and few profitable application scenarios exist at present. Here, we show that by tapping into multiple revenue streams using the dynamic stacking of applications, profitable operation is viable under current regulatory conditions. We develop a multi-use optimization framework which distinguishes between behind-the-meter and in-front-of-the-meter applications and considers how power capacity is allotted in addition to energy capacity allocation. The algorithm uses a rolling horizon optimization with an integrated degradation model and is fed with real-world data from a stationary lithium-ion battery in Germany. When combining peak shaving with frequency containment reserve, a net present value per Euro invested of 1.00 is achieved, and 1.24 with the addition of arbitrage trading on the intraday continuous market.

INTRODUCTION

With the undeniable need for a worldwide sustainable energy transition,^{1,2} battery energy storage systems (BESSs) are a highly promising technology to successfully integrate large shares of renewable generation into existing energy systems.^{3–6} Despite rapidly falling battery system costs,^{7,8} the high investment requirement is primarily cited as the most significant barrier to energy storage deployment.^{9–11} To help realize the high cost-reduction potential,¹² demand-pull policies can increase deployment and drive battery technologies down their respective learning curves.^{8,10,13} As an alternative to the cost-side perspective, the investment attractiveness of energy storage can likewise be boosted by increasing revenue generation.

As a multi-purpose technology,¹⁰ energy storage can serve a wide variety of applications.^{14–16} For instance, a BESS can be an energy buffer for intermittent generation or increase grid power quality by providing frequency regulation services. Therefore, it can generate economic value for its stakeholders at different points in the electricity value chain.^{10,17} However, under a single-use operation—in other words, serving one application only—BESSs struggle to attain profitability¹⁸ and are often idle or underused.^{17,19} Calendar degradation processes are still ongoing during battery idle times, where no application is actively served.^{20,21} These can be reduced by serving multiple applications, as their complementing demands on the system result in better battery utilization. Thus, by stacking compatible applications on one BESS, a multi-use operation strategy can maximize storage value.^{3,22,23}

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Central to the implementation of such a strategy is the question of how the limited energy and power capacities of the BESSs are allocated to the different applications. There are three types of multi-use, sequential, parallel, and dynamic, which differ in the way the applications are stacked.²⁴ The dynamic approach is the most flexible, as multiple applications can be served simultaneously with variable capacity allocations. In addition to the complex technical demands to the BESS's energy management system (EMS), regulatory requirements can pose another barrier to multi-use. For instance, unbundling laws require the separation of value generation in different stages of the electricity supply chain.¹⁸ Behind-the-meter (BTM) applications serve end-consumer purposes, whereas applications improving grid stability are served in-front-of-the-meter (FTM).^{17,24} To simultaneously address applications from different origins in the value chain, it is necessary that the physical storage system is separated into distinct virtual partitions.²⁵ Thus, for its practical implementation, a multi-use strategy requires an EMS and power electronics with the ability to clearly distinguish between BTM and FTM partitions, preventing any inter-energy exchange.

Several studies have investigated the various facets of multi-use, highlighting its high profitability potential.^{18,19,26–30} Two gaps have been identified in the literature, one regulatory and the other technical, which need to be addressed to enable practical implementation. First, the distinct treatment of BTM and FTM, which will allow simultaneous service of both types of applications in compliance with regulatory requirements. Second, from a technical perspective, although both energy and power capacities are delivered by the BESS, these need to be allocated separately in a real-world system. We are not aware of a study that considers the role of power electronics in a multi-use operation; all of the identified quantitative studies address only the capacity allocation of energy, ignoring the equally important consideration of power. We developed a dynamic multi-use optimization framework to close the identified gaps and enable a practical implementation and profitable BESS operation under current regulatory conditions.

In this article, we analyze the techno-economic performance of single-use and multi-use operation strategies on a stationary lithium-ion BESS serving a characteristic commercial consumer in Germany. Our results show that the stationary BESS is highly profitable under a dynamic multi-use operation strategy. Based on our findings, stationary BESS stakeholders have a strong incentive to adopt this approach, and increased investor interest is expected. We focus on the implications to current and potential BESS stakeholders, but also discuss relevance to policy makers and identify areas for future research.

RESULTS

Increasing Performance through Application Stacking

We developed our multi-use optimization framework to evaluate the techno-economic performance of single-use and multi-use operation strategies on the same utility-scale, stationary BESS (see [Experimental Procedures](#) and [Table S1](#) for details). To this end, the four applications—self-consumption increase (SCI; BTM), peak shaving (PS; BTM), frequency containment reserve (FCR; FTM), and spot market trading (SMT; FTM)—are compared and combined. We chose these applications because they enjoy the most widespread usage in stationary storage installations.¹⁴ The BESS's equivalent full cycles (EFCs), state of health (SOH), and operating profit, by application and in total, at the end of the first year of operation, as well as the end-of-life (EOL) in years is determined for the seven scenarios (see [Table 1](#)). This is

Table 1. Overview of the Techno-economic Performance of a Large-Scale BESS under Single-use and Multi-use Operations

Scenario	Annual Operating Profit/EUR kWh ⁻¹					EFC	SOH/%	EOL/a
	PS	SCI	FCR	SMT	Total			
PS	43.3	-0.8	0	0	42.6	46.1	96.5	14.9
FCR	0	0	47.5	-1	46.5	128.6	96.5	14.7
SMT	0	0	0	58.8	58.8	214.7	95.1	9.5
PS + FCR	43.2	-0.7	45.4	-1.1	86.8	159.7	96	13.1
PS + SMT	42.9	-0.7	0	57.3	99.5	261	94.5	8.3
FCR + SMT	0	0	41.3	51.2	92.5	266.2	94.9	9.3
PS + FCR + SMT	42.9	-0.7	38.9	50.6	131.7	300.7	94.5	8.6

Behind-the-meter (BTM) applications peak shaving (PS) and self-consumption increase (SCI) relate to the power and energy costs, respectively, of the commercial consumer. Frequency containment reserve (FCR) and spot market trading (SMT) generate profit in-front-of-the-meter (FTM) on the frequency regulation and intraday continuous markets, respectively. The energy to power (E:P) ratio of the BESS is 1.34 MWh to 1.25 MW. The operating profit per installed energy capacity, number of equivalent full cycles (EFCs), and state of health (SOH) resulting from the first year of operation, as well as the end-of-life (EOL) is presented. BESS, battery energy storage system. /a, per annum.

followed by the illustration of the investment attractiveness by scenario (see [Figure 1](#)). Our results show that total profitability increases with the stacking of more applications, as do EFCs as the battery utilization also increases, but with only limited additional SOH loss.

Of the single-use scenarios, SMT generates the highest annual profit, but with significantly more EFCs and the shortest lifetime. The total profit in the PS scenario is composed of the revenue from the demand charge reduction (PS) and the cost of the energy purchased (SCI) to shave the demand peak. Analogously, in the single-use FCR scenario, total profit is made up of both the revenue generated on the frequency regulation market (FCR) and the net costs of scheduled transactions on the spot market (SMT). The single-use scenario with only SCI is not viable for the commercial player modeled in this work, as the residual load (load generation) is rarely negative and opportunities to generate revenue through energy savings do not arise. Comparing the PS and FCR single-use scenarios, identical SOHs and very similar battery lifetimes are observed despite the significant discrepancy in EFCs. This can be explained by the considerably greater depth-of-discharge required by PS, which makes a strong contribution to cyclic degradation.^{21,31,32} Also, the BESS fluctuates around the medium state of charge (SOC) range during FCR provision; the SOC dependency of lithium-ion batteries is considered in the battery degradation model.^{20,21}

The most profitable multi-use scenario is that with all three applications, PS + FCR + SMT. The authors agree that it is not viable to estimate multi-use earning potential simply by adding the respective earnings of the single-use scenarios,³⁰ due to trade-offs from power and energy capacity sharing between applications. Nevertheless, the extent of the synergistic effects is remarkably high in the multi-use scenarios modeled (for illustration, see [Figure S1](#)). For example, in the PS + FCR + SMT multi-use scenario, 99.2%, 83.6%, and 86.2% of the single-use earning potential is maintained, respectively. This positive effect is also demonstrated when two applications are combined, which indicates that under single-use operation the battery power and energy capacities are severely underused. Hence, the full earning potential of a BESS is realized only in a multi-use operation.

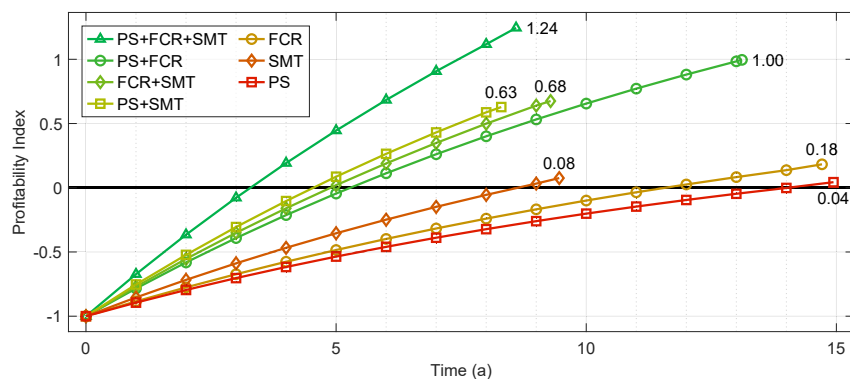


Figure 1. Investment Attractiveness of Single-use and Multi-use Scenarios

The profitability index equals the net present value normalized to the initial capital expenditures of 509 kEUR. Various combinations of the three applications, peak-shaving (PS), frequency containment reserve (FCR), and spot-market trading (SMT), are evaluated, considering the different battery energy storage system lifetimes applicable to the chosen operation strategy.

Each scenario is executed in the optimization model until the EOL is reached and the annual profits are discounted, to calculate the profitability index (PI) over battery lifetime, which equals the net present value (NPV) divided by the initial investment (for further details, see [Experimental Procedures](#) and [Figure S2](#)). The EOL criterion is set to 80% of remaining initial energy capacity, as the literature reveals that nonlinear degradation mechanisms and battery safety aspects are more prominent at lower SOH levels.^{32,33} Investment costs of 380 EUR/kWh^{34–36} for the given energy:power (E:P) ratio and a discount rate of 6%, as appropriate for utility-scale applications,¹⁰ is assumed.

[Figure 1](#) illustrates the PI development of the scenarios, with clear clusters emerging for single-use, multi-use with two, and multi-use with three applications. The most attractive single-use application is FCR, due to its high profitability and long lifetime. Nonetheless, the single-use applications are in a similar PI range of 0.04–0.18, with positive values reached only in the 9th (SMT), 12th (FCR), and 14th years (PS) following the initial investment. Considering the uncertainty of revenue earning potential in the future of each application, establishing multi-use capability should be a high priority for any stationary BESS stakeholders operating in single use.

The positive contribution of application stacking is clearly illustrated by the significantly higher PI range of 0.63–1.24, with positive values attained significantly sooner (during 4th and 5th/6th year of operation with three and two applications, respectively). In any scenario with SMT, an accelerated battery degradation is observed, due to the application's increased energy throughput. By considering the cycles' opportunity costs in the model, only the most profitable trades are scheduled and cyclic degradation is reduced (see [Experimental Procedures](#)). The two most attractive application combinations, PS + FCR + SMT and PS + FCR, both require the clear distinction between BTM and FTM to satisfy the regulatory requirements.^{17,24,25} When comparing these scenarios, the assumed discount rate plays a significant role, due to the longer lifetime of the latter scenario. For instance, without discounting annual profits, the scenarios' PI would equal 1.94 and 1.93, respectively. The convex shape of the PIs over time is explained by the decreasing usable energy capacity and the greater discounting effect further into the future. The results make a strong case for the dynamic stacking of multiple stationary applications on a single utility-scale BESS, because synergies between applications lead to better utilization

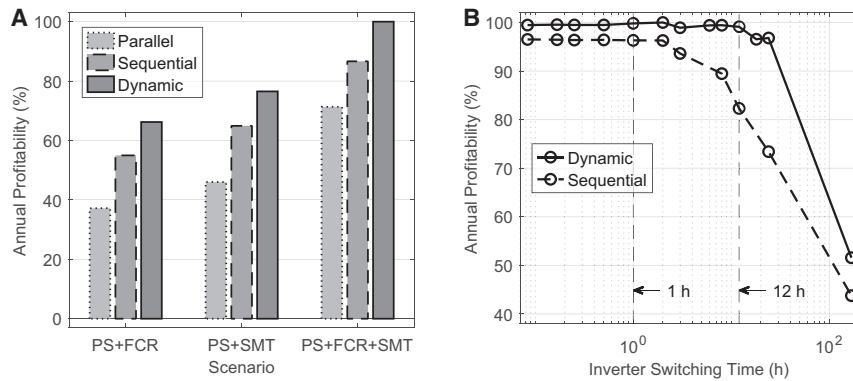


Figure 2. Profitability Comparison of Parallel, Sequential, and Dynamic Multi-use Approaches

(A) Comparison of parallel, sequential, and dynamic multi-use for the applications peak shaving (PS), frequency containment reserve (FCR), and spot market trading (SMT) as well as an inverter switching time of 12 h. Parallel multi-use is characterized by a constant allocation of storage capacity, whereas the sequential operations serve the behind-the-meter (BTM) or front-of-the-meter (FTM) partition exclusively. The dynamic multi-use approach yields the highest profit, as it combines the advantages of its two predecessors.

(B) Annual profitability for the dynamic and sequential multi-use approaches over inverter switching time. Inverter switching time determines the frequency with which battery energy storage system capacities can be reallocated. The relative profitability is illustrated for the PS + FCR + SMT scenario, with inverter switching times from 5 min to 7 days.

without a noteworthy lifetime contraction. By spreading dependence from a single revenue stream to multiple sources, multi-use also diversifies risks due to uncertain future price developments of the respective applications. This is an important factor for current and potential BESS stakeholders to consider.

Economic Impact of Different Multi-use Approaches

The matter of how limited battery energy and power capacities are allocated is an important consideration when implementing a multi-use strategy (see [Experimental Procedures](#) and [Figure S3](#) for further details on the three multi-use approaches). The inverter switching time is defined as the frequency with which the power reallocation can take place. Although this article focuses on the merits of a multi-use approach using dynamic capacity allocations, the economic impact of the alternative, sequential and parallel, approaches is also presented (see [Figure 2A](#)). Dynamic multi-use demonstrates superior profitability. The parallel strategy is the least preferable economically, despite the fixed allocations between BTM and FTM being optimized beforehand in our implementation. The higher profitability of the sequential strategy reveals that the subsequent switching between applications is more effective than the parallel sharing of capacities. Dynamic multi-use has the advantage of simultaneously serving both BTM and FTM applications, in contrast to the sequential strategy. This ability makes the profitability of the dynamic strategy more stable against longer inverter switching times (see [Figure 2B](#)). Thus, if it is not possible to implement a dynamic multi-use approach, then we recommend the sequential strategy over the parallel allocation of BESS capacities.

Dynamic Multi-use Optimization Framework

The developed multi-use optimization framework can be integrated into a state-of-the-art EMS, enabling a dynamic multi-use operation strategy on a real-world system, while upholding detailed technical and regulatory requirements. For an illustration of how this real-world implementation is executed, including feedback loops between the EMS and the physical BESS, see [Figure S4](#).

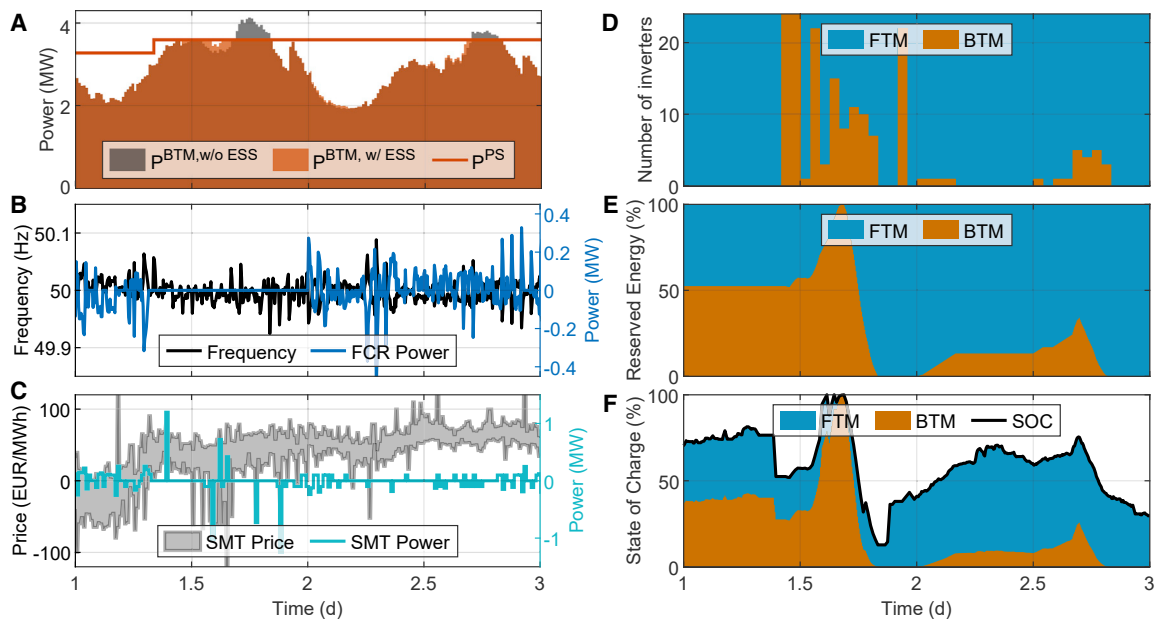


Figure 3. Optimization Framework Outputs of a Dynamic Multi-use Operation Strategy with Peak Shaving (PS), Frequency Containment Reserve (FCR), and Spot Market Trading (SMT)

A 2-day excerpt is shown for (A) the residual load on the behind-the-meter (BTM) partition and the respective PS threshold; (B) grid frequency input profile and the FCR power provided by the battery energy storage system (BESS); (C) price corridor on the intraday continuous market and the power traded by the BESS; (D) BTM and front-of-the-meter (FTM) power allocation; (E) BTM and FTM energy content allocation; and (F) state of charge (SOC) of the BESS and the respective energy allocation.

This framework makes several unique contributions, including the unprecedented consideration of power capacity as well as energy allocation and the technical implementation of distinct BTM and FTM partitions, which allows both application types to be served simultaneously. Central to this detailed technical consideration is the BESS topology (see Figure S5), which enables implementation in compliance with technical and regulatory conditions (e.g., through its distinction between BTM and FTM). Although the optimization is deterministic, a rolling horizon is implemented with successive input information updates, which increases the robustness of the results against forecast uncertainties (see Figure S6 for illustration). Furthermore, the model is degradation aware, meaning that the opportunity costs due to battery degradation losses are considered in decision making about the optimization tool (see Experimental Procedures and Figure S7).

Figure 3 demonstrates the behavior of the three applications (Figures 3A–3C) and the power and energy allocation (Figures 3D–3F) under the implemented dynamic multi-use operation strategy. In this article, the model parameters are based on a real-world stationary BESS located in Germany. Due to data availability, the model assumptions are designed around German regulatory and technical constraints. The depicted scenario shows characteristic results (see Table S1 for input profile and parameter assumptions), which we validated by conducting over 400 scenarios with varying sensitivities (see Figures S8–S12). Results of the sensitivity analyses show that profit variation subject to different input profiles is significantly more robust in a multi-use scenario (see Figures S9 and S11). Figure 3A demonstrates how the PS threshold, above which residual load is compensated for by the BESS, is adjusted upward, depending on the height and area of the foreseen peaks and the available capacities of BESS. This occurs repeatedly during the simulation period as new information becomes available, until the optimal PS threshold is determined (see Experimental Procedures). No FCR is provided by the

BESS (Figure 3B) while the peak is being shaved, because most of the energy content is reserved for the BTM partition (Figure 3E). Figure 3D and 3E demonstrate how the allocation of power and energy capacities differ notably in a dynamic multi-use implementation. Using a parallel multi-use approach, these reserved power and energy capacities would be constant over time. Whereas Figure 3E shows the partitioning of energy by BTM and FTM relative to the total reserved energy content, Figure 3F depicts the reserved energy content relative to total energy content, or the SOC of BESS.

The implemented model ensures that power and energy capacity allocation is optimal, depending on the input profiles, to maximize applications' operating profits in a degradation-aware manner while upholding necessary constraints (see [Experimental Procedures](#)).

DISCUSSION

Our results show that a dynamic multi-use operation strategy yields substantially higher profitability than any single-use operation. The application combinations of PS + FCR and PS + FCR + SMT generate especially attractive results for investors, with swift payback periods and high positive NPVs. Based on these findings, stationary BESS stakeholders have a strong incentive to adopt a dynamic multi-use approach. Based on our findings, the main barrier to BESS deployment—its lack of attractiveness to investors due to high initial investment costs—can be removed by maximizing its earning potential through application stacking. Policy makers interested in accelerating energy storage deployment to facilitate a sustainable energy system transformation should note that multi-use operation has the potential to substitute the need for costly deployment subsidies.¹⁸ The dynamic multi-use framework presented here is being implemented on a real-world stationary BESS. The authors are highly confident that once evidence from successful multi-use operations is available, private sector investment in this area will be expedited further. We recommend that policy makers draft policy to facilitate the proliferation of multi-use operation strategies. In addition, an effort should be made to remove remaining regulatory barriers to the deployment of energy storage at large, such as a lack of a clearly defined role for energy storage in the electricity grid and market designs that are not technology neutral.^{9,18,37,38}

The presented model makes a unique contribution to the literature, especially in its focus on the detailed technical capabilities required for a real-world dynamic multi-use operation, such as the BTM and FTM distinction and separate power and energy capacity allocation. Nevertheless, several assumptions are made, which need to be discussed to accurately interpret the presented results and to identify areas for further research. First, it is assumed that all bids on the frequency regulation and intraday continuous market are completed. Second, input data from 2019 are used for the full lifetime of the modeled BESS, which disregards the significant uncertainty regarding future load profile and market developments. For the SMT application's profit, the average value of the best- and worst-case scenarios is calculated as a realistic midpoint, using the high-low and weighted average price profiles, respectively. In addition, since the greater deployment and participation of stationary and mobile BESSs in the FCR and spot markets can lead to market saturation,²⁶ ensuing revenue generation is likely to decrease due to falling prices and smaller price spreads, respectively. Strongly falling FCR market prices in recent years,^{24,39} which severely reduced the revenue potential of this use case, demonstrates the danger of depending on a single revenue stream. By acquiring multi-use capability, dependence on a single revenue stream is avoided and the risk of future earning uncertainty is diversified over multiple

revenue sources. Thus, regardless of future market developments, a stationary BESS technically capable of addressing multiple applications, in various points in the electricity value chain, is better placed to make use of newly arising opportunities than one locked into a single-use case.

In our implementation, the E:P ratio and sizing of the BESS are based on data from a real-world lithium-ion battery in Germany. From this starting point, the optimal power and energy allocation under various single- and multi-use scenarios is determined and analyzed. In future research, the sizing and E:P dimensioning for the stationary storage could be optimized depending on given application combinations. In addition, the developed framework can be extended to include new applications to explore further combinations,⁴⁰ as well as the implementation of a more detailed efficiency model on the inverter level. Also, adjusting the model's input parameters and profiles to reflect the different conditions in other countries would illustrate to which extent results differ across nations.

EXPERIMENTAL PROCEDURES

Resource Availability

Lead Contact

Further information and requests for resources and materials should be directed to and will be fulfilled by the Lead Contact, Stefan Englberger (stefan.englberger@tum.de).

Materials Availability

This study did not generate new unique materials.

Data and Code Availability

The datasets generated in this study are available from the Lead Contact on request.

Performance Indicators

In this work, four primary performance indicators are used to analyze the techno-economic effectiveness of multi-use operation strategies: operating profit, EFCs, SOH, and PI. Total operating profit is the sum of each application's profit (Equation 1). The profit from the PS application, \mathbb{P}^{PS} (Equation 2), originates from the reduced costs for power-related surcharges. Thus, it equals the difference between power costs with ($C^{\text{PS,w/BESS}}$) and without ($C^{\text{PS,w/oBESS}}$) a BESS used for PS. Likewise, the profit from SCI, $\mathbb{P}_t^{\text{SCI}}$, represents the cost savings for energy-related charges to the end consumer with a BESS increasing self-consumption (Equation 3). Operating profit from FCR, \mathbb{P}^{FCR} , represents the revenue earned on the frequency regulation market. SMT profit, \mathbb{P}^{SMT} , is generated using price spreads at the intraday continuous market, whereby energy is sold at high prices and purchased when the price is low.

$$\mathbb{P}^{\text{Total}} = \mathbb{P}^{\text{PS}} + \mathbb{P}^{\text{SCI}} + \mathbb{P}^{\text{FCR}} + \mathbb{P}^{\text{SMT}} \quad (\text{Equation 1})$$

$$\mathbb{P}^{\text{PS}} = C^{\text{PS,w/oBESS}} - C^{\text{PS,w/BESS}} \quad (\text{Equation 2})$$

$$\mathbb{P}_t^{\text{SCI}} = C_t^{\text{SCI,w/oBESS}} - C_t^{\text{SCI,w/BESS}} \quad (\text{Equation 3})$$

The SOH of the BESS is the quotient of the remaining energy capacity, $E_t^{\text{remaining}}$, and the nominal energy content (Equation 4). For each 5-min time step, t , the remaining energy capacity results from the integrated degradation model, originally published by Schmalstieg et al.²¹ It differentiates between cyclic and calendar degradation while considering parameters such as depth-of-discharge, cumulative charge throughput, temperature, and voltage level. The EFC of the BESS is calculated by halving the absolute change in SOC from $t - 1$ to t (Equation 5). In turn, the SOC

is defined in Equation 6 as the actual energy content of the BESS, E_t^{actual} , divided by its remaining energy capacity.

$$\text{SOH}_t = \frac{E_t^{\text{remaining}}}{E^{\text{nominal}}} \quad (\text{Equation 4})$$

$$\text{EFC}_t = \frac{|E_t^{\text{actual}} - E_{t-1}^{\text{actual}}|}{2 \times E^{\text{nominal}}} \quad (\text{Equation 5})$$

$$\text{SOC}_t = \frac{E_t^{\text{actual}}}{E_t^{\text{remaining}}} \quad (\text{Equation 6})$$

Investment attractiveness is evaluated using the PI (Equation 7), which equals the NPV of the operation strategy, normalized over the capital expenditures of the BESS, C^{invest} . According to Equation 8, the NPV is defined as the discounted operating profits, P_n^{Total} , until the EOL of the BESS is reached, minus the initial investment.

$$\text{PI} = \frac{\text{NPV}}{C^{\text{invest}}} \quad (\text{Equation 7})$$

$$\text{NPV} = -C^{\text{invest}} + \sum_{n=1}^{\text{EOL}} \frac{P_n^{\text{Total}}}{(1+i)^n} \quad (\text{Equation 8})$$

Multi-use Approaches and Their Implementations

The three types of multi-use presented in this article differ in their approach to how the energy and power capacities of the BESS are allocated to the multiple applications (see Figure S3 for illustration). Parallel multi-use applies a fixed allocation, whereas the sequential approach serves one application exclusively, switching between applications over time. Dynamic multi-use combines the benefits of both.

In this work's implementation, the allocation occurs not on an application basis but on the distinction between BTM and FTM partitions. This means that the limitations of the parallel and sequential approaches do not apply to multiple applications within the same partition. Thus, in the sequential strategy with PS + FCR + SMT, the two FTM applications are combined dynamically. In the model, the default inverter switching time is 1 h. To guarantee comparability between the strategies, the optimal allocation values, on average, of the dynamic multi-use strategy are used as the input for the fixed fractional partitioning of the parallel strategy.

Dynamic Multi-use Optimization Formulation

To model the real-world problem, a mixed-integer linear programming framework is established in MATLAB. To reduce the computation time for each optimization, we use the Gurobi solver.⁴¹ The optimization objective, given in Equation 9, maximizes the operating profit from FCR provision and SMT, P_t^{FCR} and P_t^{SMT} , and minimizes the energy and power costs for the end consumer, $C_t^{\text{BTM,E}}$ and $C_t^{\text{BTM,P}}$. The opportunity costs of battery cycles, C^{cycle} , are also minimized and calculated using Equation 10, whereby the capital expenditures of the BESS are divided by a conservative estimate of total EFCs over the lifetime of a BESS, $\text{EFC}^{\text{expected}}$. The resulting estimated capital expenditures per cycle are multiplied by the cycles per time step. This ensures that only activities that generate higher profitability than the cycle opportunity costs are executed. By limiting less profitable cycles, degradation is reduced and degradation awareness is thereby introduced to the model.

$$\max z, z = \sum_{t=1}^N (P_t^{\text{FCR}} + P_t^{\text{SMT}} - C_t^{\text{BTM,E}}) - C^{\text{BTM,P}} - C^{\text{cycle}} \quad (\text{Equation 9})$$

$$C^{\text{cycle}} = \sum_{t=1}^N \left(EFC_t \times \frac{C^{\text{invest}}}{EFC^{\text{expected}}} \right) \quad (\text{Equation 10})$$

In the following, the model constraints of the optimization problem are introduced, first for the implementation of the power and energy partitioning of the storage and then the respective storage applications examined in this work: PS, SCI, FCR, and SMT.

Energy and Power Allocation

The battery topology, which includes the cells, inverters, busbar, electricity meters, EMS, thermal management system, and battery management system, is central to enabling the power and energy allocation implemented in this article (see [Figure S5](#) for the detailed topology). To enable the distinction between BTM and FTM, the physical storage system is divided into two BTM and FTM partitions.²⁵ It is essential that the energy flow between the BTM and FTM partitions is prohibited, for regulatory reasons (i.e., unbundling laws that denote the separation of different parts of the electricity value chain).¹⁸

In the following, the constraints governing the energy and power characteristics of the storage are outlined. To calculate the actual energy content of the two storage partitions and to operate the BESS within a technically feasible area, [Equations 11](#) and [12](#) are introduced. These consider the actual energy content of the respective storage partition at the previous point in time, E_{t-1}^{act} , the energy charged, E_t^{CH} , and energy discharged, E_t^{DCH} during the time step t . The in-going and out-going energy flows are calculated considering the efficiency values of the system components during charging, η^{CH} , and discharging, η^{DCH} . The usable energy content, E_t^{use} , of the storage partitions can be understood as reserved energy per partition, and the self-discharge, E_t^{SD} , is weighted proportionally for each partition, based on the reserved energy content.

$$E_t^{\text{act,BTM}} = E_{t-1}^{\text{act,BTM}} + E_t^{\text{CH,BTM}} \times \eta^{\text{CH}} - E_t^{\text{DCH,BTM}} \times \frac{1}{\eta^{\text{DCH}}} - E_t^{\text{SD}} \times \frac{E_t^{\text{use,BTM}}}{E_t^{\text{use}}} \quad (\text{Equation 11})$$

$$E_t^{\text{act,FTM}} = E_{t-1}^{\text{act,FTM}} + E_t^{\text{CH,FTM}} \times \eta^{\text{CH}} - E_t^{\text{DCH,FTM}} \times \frac{1}{\eta^{\text{DCH}}} - E_t^{\text{SD}} \times \frac{E_t^{\text{use,FTM}}}{E_t^{\text{use}}} \quad (\text{Equation 12})$$

Due to battery cell degradation, the usable energy content on the system level declines over time. [Equation 13](#) ensures that the BTM and FTM partitioning is upheld for the usable energy content. The actual energy content is required to calculate ongoing processes on the physical BESS level, such as the calendar and cycle degradation losses. Since the actual energy content per partition may move within the reserved or usable energy range, this is considered in the mathematical formulation using the inequalities in [Equations 14](#) and [15](#), where $E_t^{\text{act,BTM}}$ and $E_t^{\text{act,FTM}}$ are defined as the respective actual energy contents of the storage partitions.

$$E_t^{\text{use}} = E_t^{\text{use,BTM}} + E_t^{\text{use,FTM}} \quad (\text{Equation 13})$$

$$E_t^{\text{act,BTM}} \leq E_t^{\text{use,BTM}} \quad (\text{Equation 14})$$

$$E_t^{\text{act,FTM}} \leq E_t^{\text{use,FTM}} \quad (\text{Equation 15})$$

In addition to the energy-related component of the storage system, the power electronics is the decisive factor for the system's power and consist of several inverters. [Equation 16](#) ensures that all of the inverters of the BESS x_t are allocated to either the BTM or FTM partition, where x_t^{BTM} and x_t^{FTM} represent the integer number of

allocated inverters for the two partitions. Hence, unlike the allocation of energy capacity, which is continuous, the power capacity allocation is discrete (see Figures 3D and 3E).

$$x_t = x_t^{\text{BTM}} + x_t^{\text{FTM}} \quad (\text{Equation 16})$$

Peak Shaving

The inclusion of power-related costs in electricity billing creates an incentive to reduce peak power demand.¹⁰ Although the electricity tariff structures differ by country, power-related costs are generally implemented at least for a portion of electricity consumers, with the highest peak power within a billing period, typically of 1 year, being multiplied by the power surcharge. In Germany, electricity consumers with an annual consumption >100 MWh are required to pay a power surcharge in addition to the grid tariff for consumed energy.⁴² The power price and grid tariff (energy charge) depends on the consumer's residual load profile.⁴² For a detailed listing of assumed parameters, see Table S1. The network charges, which consider the costs for upstream grid levels, grid infrastructure, provision of system services, and the coverage of transmission losses, are reflected in the energy and power surcharges.

The PS application is particularly interesting with regard to stationary energy storage,⁴³ because with this flexibility, high power peaks can be covered by the BESS, which is recharged at times of low load. Value is created by decreasing the maximum power peak in the billing period, \hat{P}^{BTM} , which when multiplied by the power surcharge, $p^{\text{BTM,P}}$, results in lower power-related expenses, $C^{\text{BTM,P}}$ (Equation 17):

$$C^{\text{BTM,P}} = p^{\text{BTM,P}} \times \hat{P}^{\text{BTM}} \quad (\text{Equation 17})$$

The prediction quality of the power peaks is significant. Here, not only the height of the peak but also its energy content is relevant, since the integral of the power needs to be covered by the BESS. Thus, considering the residual load, it is essential to define an effective PS threshold above which the power is provided by the storage system. In the multi-use operation of a BESS, an appropriate PS threshold is even more vital. If the peak shaving limit is too low, a high amount of energy and power is reserved for the PS application, which can limit or prevent the service of other applications.

The residual load profile used is selected from a sample set of commercial and industrial profiles, resulting in some sample bias (see the input profile information in the Supplemental Experimental Procedures and Figures S10 and S11 for the effect on the profitability of different residual load profiles).

Self-Consumption Increase

In general, decentralized renewable generation is incentivized using feed-in tariffs or other demand-pull policies,¹⁰ whereby the producer receives a remuneration price for energy injected into the grid. Typically, the purchase price, or grid tariff, is higher than the remuneration offered, leading to an incentive to maximize self-consumption.^{28,29} If the generated power exceeds the load, then a BESS can be used to reduce the supply demand gap. In Germany, where the incentive to self-consume is very pronounced for households, the SCI application is cost-effective.⁴⁴ The baseline sample set shows only rare occasions of negative residual load, meaning that the generated power is generally lower than the demand. Thus, there is little to no excess power for the energy storage to buffer, resulting in limited added value from this application. Under different scenario conditions

(i.e., with greater dimensioning of the renewable generator), this application would be more appropriate.

For a prosumer of renewable generation, net electricity costs (energy charge), $C_t^{\text{BTM},E}$, in a self-consumption scenario are calculated by subtracting the electricity revenues from the electricity purchase expenses (Equation 18), whereby $E_t^{\text{BTM},\text{sell}}$, $E_t^{\text{BTM},\text{purch}}$, $p^{\text{BTM},E,\text{purch}}$, and $p^{\text{BTM},E,\text{sell}}$, are the energy sold, purchased, grid tariff, and feed-in tariff remuneration, respectively. See Table S1 for assumed values.

$$C_t^{\text{BTM},E} = E_t^{\text{BTM},\text{purch}} \times p^{\text{BTM},E,\text{purch}} - E_t^{\text{BTM},\text{sell}} \times p^{\text{BTM},E,\text{sell}} \quad (\text{Equation 18})$$

Frequency Containment Reserve

Within the ENTSO-E transmission grid, three products for electricity balancing exist: FCR, frequency restoration reserve, and replacement reserve.⁴⁵ These three products of the load-frequency-control structure in turn contain several processes. The primary control reserve, which is assigned to the FCR product, is the most economically interesting process for BESSs in central Europe, and therefore also in Germany. Within the FCR provision, the Austrian, Belgian, Dutch, French, German, and Swiss transmission system operators purchase the FCR service in a common market. The provided FCR must be offered in 1-MW increments. From July 2020, the duration of product delivery was reduced from daily to 4-h blocks.⁴⁵ The greater flexibility of the 4-h provision blocks is implemented in this model.

For the stable provision of FCR, a BESS must be designed to provide the allocated FCR power at any time for an extra 15 min.⁴⁶ Also, the BESS should guarantee 25% additional reserve power to cover scheduled transactions on a spot market, keeping the SOC in the permitted range during a full unilateral FCR call.⁴⁶ Hence, for the provision of 1 MW FCR power, the rated power of the storage system must be at least 1.25 MW, whereby the 0.25 MW reserve is also available for the SMT application. The usage of this reserve power by BTM applications is not permitted since the constraint for FCR reserve power would be violated.

During an active FCR period, the EMS of the BESS must react without delay to any frequency fluctuation. This means that the FCR active power is a function of the grid frequency with certain degrees of freedom. One of these degrees of freedom is the overfulfillment of FCR power, by up to 20%. Within the frequency dead band of ± 10 mHz from the nominal grid frequency of 50 Hz, the technical rules for providing FCR are less strict.⁴⁶

Value is generated from FCR provision through the price awarded per MW, p_t^{FCR} , multiplied by the total FCR power, $P_t^{\text{FCR},\text{alloc}}$ (Equation 19). However, a portion of this generated value can be shared with an aggregator.

$$P_t^{\text{FCR}} = P_t^{\text{FCR},\text{alloc}} \times p_t^{\text{FCR}} \quad (\text{Equation 19})$$

In our model, an aggregator provides flexibility in the FCR application, allowing the battery operator to participate in the market with smaller power portions than the 1 MW requirement. For this service, the aggregator is allocated a portion of the remunerated power, which is linearly dependent on the bid size. The smaller the bid size, the greater the risk and portion of remunerated power received by the aggregator. Equation 20 shows the linear relationship between the power remunerated for the FCR provision, $P_t^{\text{FCR},\text{rem}}$, and the bid power, where k is the slope and d the y-intercept (see Equations S1 and S2 for the mathematical definition of k and d). With an increasing k , the incentive for the battery operator to participate in the FCR market

with high power bids also increases, so as to minimize the relative surcharge paid to the aggregator. (See Table S1 for the assumed values applied to the FCR application.) It turns out that with the resulting incentive to bid with 1 MW when possible, the aggregator is not strictly necessary, and the FCR profitability potential would be higher without an aggregator. Still, we chose this implementation as it is more realistic for small players who are otherwise unable to participate in the FCR market and are thus willing to pay for the provided flexibility.

$$P_t^{\text{FCR,rem}} = \begin{cases} P_t^{\text{FCR,alloc}} \times k + d, & P_t^{\text{FCR,min}} \leq P_t^{\text{FCR,alloc}} \leq P_t^{\text{FCR,max}} \\ 0, & \text{otherwise} \end{cases} \quad (\text{Equation 20})$$

Spot Market Trading

Another FTM application for BESSs is energy trading on spot markets. In Germany, the three markets day-ahead auction, intraday auction, and intraday continuous market are of interest for the participation of BESSs.⁴⁷ Since BESSs have particularly short response times and are generally designed for a short temporary storage of energy, it is economically advantageous to have high price differences within short time spans.²⁶ With high price spreads, the economic result of arbitrage trading improves.

Three price signals from the intraday continuous market are used: weighted average price, low price, and high price. The first demonstrates only meager price variations, whereas the latter two represent the maximum variation possible. Thus, profits are calculated for both the weighted average and high–low price signals, representing the worst- and best-case results, and then their average is presented as a realistic midpoint (see Figure S12). Depending on several factors, including the sophistication of the intraday continuous price forecast and response time of communication equipment, the real-world implementation of the SMT application will generate higher or lower profits than the assumed midpoint.

To ensure that power is not purchased and sold during the same time step, Equation 21 is introduced, where $a_t^{\text{FTM,purch}}$ and $a_t^{\text{FTM,sell}}$ are binary variables.

$$a_t^{\text{FTM,purch}} + a_t^{\text{FTM,sell}} \leq 1 \quad (\text{Equation 21})$$

According to existing market regulations, the purchased and sold power, $P_t^{\text{FTM,purch}}$ and $P_t^{\text{FTM,sell}}$, must meet the minimum order requirement, $P^{\text{SMT,MIN}}$, of 100 kW⁴⁷ (Equations 22 and 23). The minimum offer duration period of 15 min is also maintained in our model.

$$a_t^{\text{FTM,purch}} \times P^{\text{SMT,MIN}} \leq P_t^{\text{FTM,purch}} \quad (\text{Equation 22})$$

$$a_t^{\text{FTM,sell}} \times P^{\text{SMT,MIN}} \leq P_t^{\text{FTM,sell}} \quad (\text{Equation 23})$$

Thus, value generation through the SMT application, $\mathbb{P}_t^{\text{SMT}}$, occurs with the realization of arbitrage opportunities (Equation 24), where high selling prices, $p_t^{\text{SMT,sell}}$, and low purchase prices, $p_t^{\text{SMT,purch}}$, are used to generate profit.

$$\mathbb{P}_t^{\text{SMT}} = \Delta t \left(P_t^{\text{FTM,sell}} \times p_t^{\text{SMT,sell}} - P_t^{\text{FTM,purch}} \times p_t^{\text{SMT,purch}} \right) \quad (\text{Equation 24})$$

In our model, for each transaction on the spot market, the physical delivery is also executed.

SUPPLEMENTAL INFORMATION

Supplemental Information can be found online at <https://doi.org/10.1016/j.xcrp.2020.100238>.

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AUTHOR CONTRIBUTIONS

S.E., A.J., and H.H. designed the study. S.E. developed the model and optimization algorithm. S.E. and H.H. carried out the data search. S.E. and H.H. carried out the analyses. S.E., A.J., and H.H. wrote the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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REFERENCES

- Jacobson, M.Z., Delucchi, M.A., Bauer, Z.A., Goodman, S.C., Chapman, W.E., Cameron, M.A., Bozonnat, C., Chobadi, L., Clonts, H.A., Enevoldsen, P., et al. (2017). 100% Clean and Renewable Wind, Water, and Sunlight All-Sector Energy Roadmaps for 139 Countries of the World. *Joule* 1, 108–121.
- Obama, B. (2017). The irreversible momentum of clean energy. *Science* 355, 126–129.
- Culver, W.J. (2010). High-Value Energy Storage for the Grid: A Multi-Dimensional Look. *Electr. J.* 23, 59–71.
- Denholm, P., and Hand, M. (2011). Grid flexibility and storage required to achieve very high penetration of variable renewable electricity. *Energy Policy* 39, 1817–1830.
- Lott, M.C., Kim, S.I., Tam, C., Houssin, D., and Gagne, J.F. (2014). Technology Roadmap - Energy Storage (International Energy Agency).
- Gallo, A.B., Simões-Moreira, J.R., Costa, H., Santos, M.M., and Moutinho dos Santos, E. (2016). Energy storage in the energy transition context: a technology review. *Renew. Sustain. Energy Rev.* 65, 800–822.
- Kittner, N., Lill, F., and Kammen, D.M. (2017). Energy storage deployment and innovation for the clean energy transition. *Nat. Energy* 2, 17125.
- Schmidt, O., Hawkes, A., Gambhir, A., and Staffell, I. (2017). The future cost of electrical energy storage based on experience rates. *Nat. Energy* 2, 1–8.
- Bhatnagar, D., Currier, A., Hernandez, J., Ma, O., and Kirby, B. (2013). Market and Policy Barriers to Energy Storage Deployment (US Department of Energy).
- Battke, B., and Schmidt, T. (2015). Cost-efficient demand-pull policies for multi-purpose technologies – the case of stationary electricity storage. *Appl. Energy* 155, 334–348.
- Bruff, W.A., Mueller, J.M., and Trancik, J.E. (2016). Value of storage technologies for wind and solar energy. *Nat. Clim. Chang.* 6, 964–969.
- Nykvist, B., and Nilsson, M. (2015). Rapidly falling costs of battery packs for electric vehicles. *Nat. Clim. Chang.* 5, 329–332.
- Zame, K.K., Brehm, C.A., Nitica, A.T., Richard, C.L., and Schweitzer, G.D., III (2018). Smart grid and energy storage: policy recommendations. *Renew. Sustain. Energy Rev.* 82, 1646–1654.
- Malhotra, A., Battke, B., Beuse, M., Stephan, A., and Schmidt, T. (2016). Use cases for stationary battery technologies: a review of the literature and existing projects. *Renew. Sustain. Energy Rev.* 56, 705–721.
- Aneke, M., and Wang, M. (2016). Energy storage technologies and real life applications – a state of the art review. *Appl. Energy* 179, 350–377.
- Davies, D.M., Verde, M.G., Mnyshenko, O., Chen, Y.R., Rajeev, R., Meng, Y.S., and Elliott, G. (2019). Combined economic and technological evaluation of battery energy storage for grid applications. *Nat. Energy* 4, 42–50.
- Fitzgerald, G., Mandel, J., Morris, J., and Touati, H. (2015). The Economics of Battery Energy Storage: How Multi-use, Customer-Sited Batteries Deliver the Most Services and Value to Customers and the Grid (Rocky Mountain Institute).
- Stephan, A., Battke, B., Beuse, M., Clausdeinken, J.H., and Schmidt, T. (2016). Limiting the public cost of stationary battery deployment by combining applications. *Nat. Energy* 1, 16079.
- Lombardi, P., and Schwabe, F. (2017). Sharing economy as a new business model for energy storage systems. *Appl. Energy* 188, 485–496.
- Keil, P., Schuster, S.F., Wilhelm, J., Travi, J., Hauser, A., Karl, R., and Jossen, A. (2016). Calendar Aging of Lithium-Ion Batteries: I. Impact of the Graphite Anode on Capacity Fade. *J. Electrochem. Soc.* 163, 1872–1880.
- Schmalstieg, J., Käbitz, S., Ecker, M., and Sauer, D.U. (2014). A holistic aging model for Li(NiMnCo)O₂ based 18650 lithium-ion batteries. *J. Power Sources* 257, 325–334.
- Eyer, J., and Corey, G. (2010). Energy storage for the electricity grid: benefits and market potential assessment guide. A Study for the DOE Energy Storage Systems Program. February 2010, SAND2010-0815. <https://www.sandia.gov/ess-ssl/publications/SAND2010-0815.pdf>.
- Sioshansi, R., Denholm, P., and Jenkin, T. (2012). Market and Policy Barriers to Deployment of Energy Storage. *Econ. Energy Environ. Policy* 1, 47–64.
- Englberger, S., Hesse, H., Hanselmann, N., and Jossen, A. (2019). SimSES Multi-Use: A simulation tool for multiple storage system applications. Proceedings of the International Conference on the European Energy Market 16, 1–5.
- Truong, C.N., Schimpe, M., Bürger, R.U., Hesse, H., and Jossen, A. (2018). Multi-Use of Stationary Battery Storage Systems with Blockchain Based Markets. *Energy Procedia* 155, 3–16.
- Braeuer, F., Rominger, J., McKenna, R., and Fichtner, W. (2019). Battery storage systems: An

- economic model-based analysis of parallel revenue streams and general implications for industry. *Appl. Energy* 239, 1424–1440.
27. Litjens, G., Worrell, E., and van Sark, W. (2018). Economic benefits of combining self-consumption enhancement with frequency restoration reserves provision by photovoltaic-battery systems. *Appl. Energy* 223, 172–187.
 28. Pena-Bello, A., Burer, M., Patel, M.K., and Parra, D. (2017). Optimizing PV and grid charging in combined applications to improve the profitability of residential batteries. *J. Energy Storage* 13, 58–72.
 29. Parra, D., and Patel, M.K. (2019). The nature of combining energy storage applications for residential battery technology. *Appl. Energy* 239, 1343–1355.
 30. Tian, Y., Bera, A., Benidris, M., and Mitra, J. (2018). Stacked Revenue and Technical Benefits of a Grid-Connected Energy Storage System. *IEEE Trans. Ind. Appl.* 54, 3034–3043.
 31. Schuster, S.F., Bach, T., Fleder, E., Müller, J., Brand, M., Sextl, G., and Jossen, A. (2015). Nonlinear aging characteristics of lithium-ion cells under different operational conditions. *J. Energy Storage* 1, 44–53.
 32. Ecker, M., Nieto, N., Käbitz, S., Schmalstieg, J., Blanke, H., Warnecke, A., and Sauer, D.U. (2014). Calendar and cycle life study of Li(NiMnCo)O₂-based 18650 lithium-ion batteries. *J. Power Sources* 248, 839–851.
 33. Naumann, M., Karl, R., Truong, C.N., Jossen, A., and Hesse, H. (2015). Lithium-ion Battery Cost Analysis in PV-household Application. *Energy Procedia* 73, 37–47.
 34. Tsiropoulos, I., Tarvydas, D., and Lebedeva, N. (2018). Li-Ion Batteries for Mobility and Stationary Storage Applications. Scenarios for Costs and Market Growth (Publications Office of the European Union).
 35. Ralon, P., Taylor, M., Illas, A., Diaz-Bone, H., and Kairies, K.P. (2017). Electricity Storage and Renewables: Costs and Markets to 2030 (International Renewable Energy Agency).
 36. Lazard Frères & Co. (2019). Lazard's Levelized Cost of Storage Analysis (Lazard Frères & Co.).
 37. Ruz, F.C., and Pollitt, M.G. (2016). Overcoming Barriers to Electrical Energy Storage: Comparing California and Europe. *Compet. Regul. Netw. Ind.* 17, 123–149.
 38. Castagneto Gisse, G., Dodds, P.E., and Radcliffe, J. (2018). Market and regulatory barriers to electrical energy storage innovation. *Renew. Sustain. Energy Rev.* 82, 781–790.
 39. 50Hertz Transmission GmbH; Amprion GmbH; TenneT TSO GmbH; TransnetBW GmbH (2020). Datacenter FCR/aFRR/mFRR. <https://www.regelleistung.net/apps/datacenter/tenders/>.
 40. Pearre, N.S., and Swan, L.G. (2015). Technoeconomic feasibility of grid storage: mapping electrical services and energy storage technologies. *Appl. Energy* 137, 501–510.
 41. Gurobi Optimization (2020). Gurobi Optimizer. <https://www.gurobi.com/>.
 42. German Federal Ministry of Justice and Consumer Protection (2005). Verordnung über die Entgelte für den Zugang zu Elektrizitätsversorgungsnetzen (Stromnetzentgeltverordnung - StromNEV); StromNEV. <https://www.gesetze-im-internet.de/stromnev/BJNR222500005.html>.
 43. Oudalov, A., Cherkaoui, R., and Beguin, A. (2007). Sizing and Optimal Operation of Battery Energy Storage System for Peak Shaving Application (IEEE PowerTech).
 44. Comello, S., and Reichelstein, S. (2019). The emergence of cost effective battery storage. *Nat. Commun.* 10, 2038.
 45. European Commission (2017). Electricity balancing guideline (EB GL). https://www.entsoe.eu/network_codes/eb/.
 46. 50Hertz Transmission GmbH; Amprion GmbH; TenneT TSO GmbH; TransnetBW GmbH (2019). Präqualifikationsverfahren für Regelreserveanbieter (50Hertz Transmission GmbH, Amprion GmbH, TenneT TSO GmbH, TransnetBW GmbH). https://www.regelleistung.net/ext/download/PQ_Bedingungen_FCR_aFRR_mFRR.
 47. epexspot (2019). Market data. <https://www.epexspot.com/en/market-data>.