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Multi-Use of Stationary Battery Storage Systems with Blockchain Based Markets

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Abstract

This article proposes a basic concept for the multi-use of stationary battery storage systems with multiple stakeholders to improve the economic value of battery storage systems. An auction market is suggested, where segments of the energy storage system and rights of use are auctioned. The blockchain technology is incorporated to develop a generic, low-cost concept that enables distinct obligations between the stakeholders caused by the technical operation of the battery storage system. Smart contracts allow flexible sharing of the battery storage system and increase the system's utilization ratio in the presence of prediction uncertainties.

Keywords: auction market; energy storage; internet of things; microgrid; multi-objective; multi-purpose; operation strategy; sharing economy; smart contract; stacked services;

1. Motivation

Growing shares of intermittent, renewable energy sources (RES) and of electric vehicles introduce a number of issues for the electrical power system. Battery energy storage systems (BESS) are acknowledged as a key component for future, low-carbon power systems [1]. However, BESS face issues regarding their profitability because of their high costs [2–4]. Operating BESS for single, dedicated applications leads to low utilization [5], resulting in insufficient revenue that prevents widespread adoption and integration into the electricity grid.

In order to increase the stream of revenue and consequently improve the economic value of BESS, serving multiple applications (multi-use) has been proposed in the literature and shown to have promising potential [5]. However, only a few algorithms have been published and they exhibit some considerable weaknesses. The value of multi-use can only be reliably determined if interdepending and possibly conflicting effects of applications are taken into account [5, 6].

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Multi-use results in the dynamic dispatch of BESS and is not compatible with rather static electricity markets and regulations. Multiple applications within one system require a conciliating mechanism that maps the BESS efforts and resulting benefits to market-based obligations. This is especially relevant in deregulated energy markets, common in the European Union, where the ownership and operation of BESS need to be decoupled. This allows value generation of shared BESS across different market players.

The blockchain technology exhibits properties for trusting agreements, that may enable a more flexible and dynamic use of BESS in the future. Immutable proof of agreements and the utilization of so-called smart contracts hold the potential to enable local auction markets that are compatible with both business logic and flexible multi-use of BESS for optimized performance.

This manuscript proposes a basic concept that allows for technical flexibility of multi-use, yet enables a transfer to market logic for transparent revenue among multiple stakeholders.

2. Multi-Use

Synonyms for the multi-use of BESS in the literature include multi-objective, multi-purpose and stacked services. Multi-use generally describes the concurring execution of multiple applications. We roughly classify the existing approaches for multi-use into two categories: merging of objectives and stacking of applications.

We will assume for the remaining manuscript that each application belongs to a different stakeholder. Possible stakeholders are for example the grid operator, RES owner, system operator, consumer or BESS owner/operator.

2.1. Classification of Multi-Use

The literature review (Section 2.2) reveals two distinct types of multi-use of BESS. Firstly the merging of objectives, where timing and value of the output power determine the performance towards the set of applications. Secondly the stacking of applications, that leads to a distinct partitioning of the BESS resources (power, energy capacity, and energy stored). The latter allows a straightforward mapping of the BESS usage to market logic and is therefore proposed in this manuscript.

2.1.1. Merging of Objectives

The first type of multi-use is the merging of objectives. In this operating mode, the BESS meets several objectives by adapting the output power with regard to absolute value and timing. This multi-use operation results in the BESS to serve multiple objectives without being able to clearly assign battery power or energy capacity (the battery resources) to an objective. It may also be impossible to determine separate power profiles for each goal.

Examples of this multi-use type have been proposed by Weniger *et al.* [7] and Zeh *et al.* [8]. Both authors proposed the operation of photovoltaic (PV) home battery systems that would increase a household's self-consumption and at the same time reduce the peak feed-in of the PV unit during mid-day, in order to relieve rural distribution grids with high shares of RES.

Figure 1 illustrates how both goals are achieved, compared to the conventional direct charging behavior. The black line describes the net load of the household. The blue area shows the BESS charging (negative values) and discharging (positive values) behavior. The green area displays power exchanged with the grid. Negative values illustrate energy that is fed into the grid.

The direct charging operation strategy on top of the Figure stores an excess generated energy in the BESS immediately to maximize the self-consumption. The grid relieving operation on the bottom plot exhibits a smaller peak of the feed-in. Instead of immediately storing any surplus power, the charging time is shifted towards midday and the energy of the high generation period is stored instead of fed into the grid.

The operation strategy at the bottom of Fig. 1 pursues both goals of maximizing the self-consumption and at the same time decreasing the feed-in peak of the household, while the direct strategy does not aim at reducing the peak. Both operation strategies shown require the entire energy capacity of the BESS and the BESS resources cannot be distinctly allocated to the objectives.

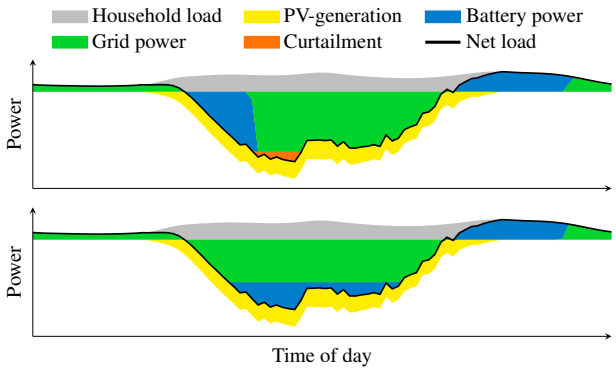

Fig. 1. Illustration of BESS operation strategies. The top plot shows the *direct charging strategy* of the BESS to increase the self-consumption of the household. The bottom plot shows the strategy which in addition reduces the peak feed-in of the household.

2.1.2. Stacking of Applications

The second type of multi-use of BESS is the stacking of applications. This multi-use type divides the physical energy capacity, nominal power, and state of charge (SOC) of the BESS into virtual segments and associates each segment to one specific application. Depending on the requirement predictions for the applications, the proportions of the BESS partitions can be adapted. Each application requires a certain power profile that can be independently assigned to a segment and the resulting physical output is the sum of the applications' output power.

Figure 2 illustrates this operation mode and displays the allocation of BESS resources to the applications *A* and *B* over time. The applications may only use these resources and cannot exceed the assigned resources. A redistribution of the resources is depicted twice in the Figure.

Fig. 2. Illustration of time-varying energy capacity distribution for two applications (AP).

A fixed partitioning of the battery segments would be the static case for this multi-use type, while a sequential alternation of applications represents the most dynamic case of application stacking.

The disadvantage of this operation mode is that the capability of the system may not be fully utilized, as the limits may lead to either under-utilization of the BESS or to the insufficient fulfillment of the application's objective. Any reduction of the assigned BESS resource for the application increases the utilization of that BESS resource but diminishes the performance for that application. The available BESS resources for the remaining applications, however, increase. This multi-use type is further discussed in this manuscript.

2.2. Literature Review

The concept of multi-use has been proposed in numerous publications, to improve the economic value of BESS. The majority of the reviewed manuscripts analyze specific sets of applications and propose particular solutions. The multi-use category, merging of objectives is more prevalent in the literature, as this problem can be solved by established multi-objective optimization, that has been proven to be effective on other topics. There are fewer publications that propose a stacking of applications and even less that explicitly describe the methodology.

Fitzgerald *et al.* [5] state that multi-use customer-sited BESS deliver maximum service and value to the customers and the grid. They claim that the value of applications cannot be generalized and that regulations are the main barrier

for the market participation of BESS since behind-the-meter assets are hindered by regulations to receive payment for deferral services, grid services, or wholesale markets. Their meta-study does not describe the necessary BESS operation to capture the value of multiple applications.

Another shortcoming of numerous papers is the assumption of perfectly known future profiles, such as load and renewable power generation. Their methods are not tested against forecast errors and likely to be sensitive to uncertainties. Some papers simulate multi-use of BESS but do not discuss conflicting applications [9, 10].

Tsakgou *et al.*[9] describe a stacking of services without reservation of BESS resources for the specific applications. They show an example, where the power requests do not occur at the same time.

Di Wu *et al.*[10] optimize the hourly output and the amount of balancing service of an energy storage system. They introduce optimality constraints to achieve a sequential order of the applications.

Other publications determine the optimal power output of BESS for several applications by means of numerical optimization algorithms but do not consider the presence of multiple stakeholders. While their approaches achieve good results, they are limited to cases with a single stakeholder, who attempts to serve several applications. If several stakeholders seek to serve different, potentially conflicting applications, by operating the BESS, the remuneration remains unclear with these methods. There is no apparent procedure to determine the financial obligations and to achieve mutual agreements on the operation of the BESS.

Megel *et al.* [11] suggest a time-varying stacking of two applications and the corresponding allocation of the energy capacity of the BESS. They have not looked into the issue of sharing the system among several stakeholders.

Stephan *et al.* [6] assessed the economic value of BESS with a variety of applications. They conclude that combining applications can improve the investment attractiveness substantially. Their analysis is limited to two applications at a time, where the primary application is given priority, while the secondary application is served only if sufficient idle capacity is available based on pre-known profiles.

Metz *et al.* [12] optimize multiple applications, considering perfect forecast of the BESS profiles. The benefits are summed up, but a single stakeholder is assumed and the resource splitting of the BESS among several stakeholders has not been considered.

Zeh *et al.* [13] propose a multitasking of BESS to provide both secondary control reserve and grid-friendly storing of PV-generated energy. They consider the strict separation of energy capacities as necessary, to avoid a clash of different storage tasks. They also mention that legal proof of delivery for certain applications requires the installation of measuring devices. Concepts for metering devices designed specifically for the multi-use of BESS have been proposed [14].

Hollinger *et al.* [15] describe a multi-use method for home BESSs that provide primary control reserve and increase the self-consumption of the household. The state-of-charge determines the power output for increasing the household's self-consumption. The introduced rules of operation modify the output for the second application and aim to keep the BESS capable of providing primary control reserve.

Auction markets for BESS have been proposed to allow a sharing of the BESS among multiple stakeholders [16, 17]. In order to propose a sound mathematical framework, their constraints and assumptions for the markets are rather strict.

He *et al.* [16] are the first to propose a business model that allows the systematic aggregation of several revenue streams of energy storage systems. They propose a series of auctions for the right to utilize the energy storage to ensure non-conflicting usage of the energy storage by different actors. The optimal composition of the stacking is determined with perfectly forecast power profiles. They set the constraint that the charged and discharged energy of each application is equal, to avoid conflicts of interest between the auctions. No consideration of prediction errors has been given.

Brijs *et al.* [17] propose the usage of auction markets, where storage owners can offer rights of physical storage usage. They introduce an aggregator for clearing the auction market. This limits the deployment of the proposed market to large-scale BESS with powers of several MW, as the aggregator adds further operating cost that can only be compensated by large-scale BESS with higher absolute revenue. The deployment of their concept excludes smaller BESS such as community BESS in distribution grids that would address the most severe challenges of RES [18].

Besides setting very strong constraints, both proposed auction market concepts require a clearing of the market by an additional party, the aggregator. This introduces another cost factor that impairs the added economic value of multi-use and in addition limits the application to larger BESS in order to be financially attractive. Another systematic

issue is the role of the aggregator. Holding the monopoly to market decisions automatically creates strong incentives to exploit market power, requiring complex regulations to remedy these incentives [19].

Even though multi-use has been proposed thoroughly, no concept has been proposed, that allows for both, optimal, technical operation and transfer to business logic with multiple stakeholders.

3. Blockchain for Operating Energy Storage

The blockchain is currently a much-noticed topic that is discussed in a variety of industries. It is mostly known in its application for cryptocurrencies, such as Bitcoin or Ethereum. The blockchain is a distributed database that allows every participant to verify the authenticity of any transaction, registered in the blockchain. Some blockchain projects exist in the energy sector, with the majority dealing with using the blockchain for trading transactions.

3.1. Blockchain Technology

The blockchain is a distributed database where each agent has an identical copy. The database comprises a chain of blocks. Any agent can generate blocks that store the block header, transactions, and smart contracts. The distributed nature, the cryptographic mechanisms, and the proof-of-work mechanism enable transparency and validity of the transactions. The blockchain technology is assumed to be independent of central authorities, yet ensures the agreement between all parties by peer to peer validation. [20]

Generating new blocks start with a new block header that includes a timestamp, a hash of the previous block in the chain, and the result of the proof-of-work that is generated by the mining mechanism. These elements protect the block and prevent a subsequent change of the database entries. Each generated block is broadcast in the blockchain network for validation by each individual agent, before they add that block to their own chain, leading to a synchronization of the distributed blockchains. [21]

Mining is the solving of a pre-defined problem to validate the generated block. Higher complexity of the problem raises the security of the mechanism, but also requires more time and energy to be solved.

A smart contract is a user-defined program in a block that specifies the rules of transactions. They can be reviewed by all blockchain-participants and serve as a substitute for written, legal contracts. [22]

3.2. Blockchain in the Energy Sector

The majority of blockchain related projects in the energy sector are concerned with using the blockchain for simple energy-trading and as proof of origin for low-carbon electricity. This allows for customized distribution of the carbon emission among the customers and adapted billing depending on individual customers' willingness to pay for a lower personal carbon footprint.

Using blockchain as data management for energy markets, emissions, green certificates, and maintenance [23] or for an energy trading system based on blockchain for peer to peer trading [20, 24] are among the more obvious ideas.

Industrial projects include the TransActive Grid and the ConsenSys grid. The former project utilizes permissioned ledger, while the latter utilizes a public ledger for its framework. Both projects currently enable peer to peer trading between consumers and RES. They expect to achieve load smoothing and financial reward of RES [25]. The Oxygen Initiative is a billing system based on blockchain for charging stations for electric vehicles [26].

Only a few concepts exist so far, that go beyond simple trading transactions and virtual redistribution of the carbon footprint. Following examples propose the use of blockchain to enhance the control of microgrids.

Danzi *et al.* [21] propose blockchain in microgrids to address voltage violation issues in the distribution grid. The utilized mechanism is the curtailment of RES generation during peak generation periods. The blockchain is facilitated to enable a fair distribution of the curtailment among all RES.

Munsing *et al.* [19] present an architecture for a peer to peer energy market in microgrids with RES. The architecture is shown to ensure fair payment and keeping of operational constraints without an aggregator, as trusted, central authority. The architecture determines an optimal schedule and allows automatic, secure, and transparent payments.

Kvaternik *et al.* [27] propose the blockchain for a peer to peer energy trading platform to maintain the stability of microgrids. They suggest smart contracts to keep track of energy and financial assets of the market. Both Munsing

and Kvaternik acknowledge that a parallel off-blockchain communication is required for performance, reliability, and privacy reasons.

Pop *et al.* [28] analyze the potential of blockchain with smart contracts to coordinate and manage the demand response of prosumers in smart grids. The smart contracts are used for expected energy flexibility levels, validation of RES agreements, and balance between energy demand and energy production. The demand response programs are controlled by distribution system operators. They acknowledge that the recording of energy transactions and the transfer into the blockchain (tokenization) remains an open research issue.

TenneT, a transmission system operator in Germany, announced two blockchain related projects. The first project is conducted together with sonnen, where excess wind power is stored in PV-home BESS to stabilize the power system and to avoid expensive redispatch measures. In the second project, where Vandeborn is their project partner, blockchain enables electric vehicles to participate in balancing the grid. The blockchain is used to document and verify the contribution of the market participants in both aforementioned projects. A permissioned blockchain type, developed by IBM, is used to reduce the electricity consumption caused by the mining of the blockchain. The companies claim to be the first ones to use blockchain for complex grid services instead of simple energy trading. [29]

Another commercial project is the Gridchain. The purpose is to provide a tool for coordination of the balancing power between transmission system operators, distribution system operator, aggregator, and generation units. Further information has not been published yet. [30]

4. Proposed Multi-Use Concept

We propose a basic concept that combines two promising topics: multi-use of BESS and blockchain technology. It allows a market-based multi-use of a BESS with several stakeholders while providing flexibility for real-time energy management. The concept consists of a two-layer architecture, combined with a blockchain to implement a business logic that determines the financial obligations. The first layer provides the cyclical (pre-)allocation of the BESS resources and determines the control parameters. The second layer serves the purpose of real-time re-allocation of the resources, triggered by the technical control algorithm. The formal introduction is given in this section. The concept is shown graphically in Figure 3. Comprehensible examples are outlined in Section 5

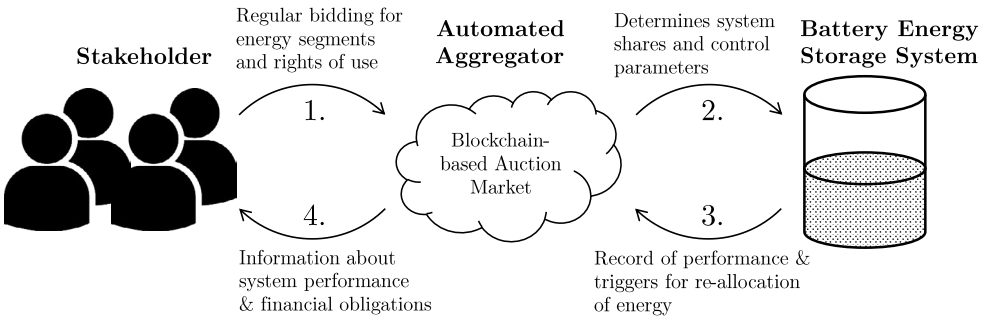

Fig. 3. Graphical illustration of the proposed multi-use concept. Multiple stakeholders bid on energy segments and rights of use. An automated aggregator clears the market and sets the operating parameters of the BESS. The behavior of the BESS is recorded and the financial obligations according to the terms agreed on at the bidding process are distinctly determined.

4.1. Time-Ahead Auction Market for Battery Resources

The first layer is the auction market where stakeholders bid for BESS resources and right of use (energy capacity, stored energy, priority power value, and rank), depending on their forecast needs. The distribution of the BESS resources among the bidders depends on the bidding prices, reflecting their willingness to pay.

This is the first allocation of the BESS resources for the different applications and goals. The terms for the second layer, i.e. triggers and (financial) consequences are also determined at this layer. The submitted bids are registered in the blockchain. The disclosure of all bids and the rules for the clearing process allow all blockchain participants to acknowledge and verify the results.

The virtual energy capacity segments E_k^C of the BESS are assigned to each stakeholder k. The sum of all n capacity segments is equal to the total physical nominal energy E^N of the BESS (Eq. 1). A segment that is not allocated to any application may exist. The physically stored residual energy E^r in the BESS is distributed among the applications and is associated to the state-of-charge (SOC) (Eq. 2). Consequently, the residual energy segments E_k^r may not be negative and must not exceed the corresponding energy capacity segment E_k^C (Eq. 3). The variables with a bottom index (k, A or B) denote the segments in general or the specific value for the according stakeholder.

$$E^N = \sum_{k}^{n} E_k^C \tag{1}$$

$$E^N \cdot SOC = E^r = \sum_{n}^{k} E_k^r \tag{2}$$

$$0 \leq E_k^r \leq E_k^C \quad \forall k \tag{3}$$

An illustration of the energy asset segmentation is shown in Figure 4. The physical reality of the BESS is shown on the left, while the virtual segmentation is depicted on the right of the Figure. The residual energy segment E_k^r is the energy stored in the according energy capacity segment E_k^C. The balanced energy segment $E_k^b = E_k^C - E_k^r$ represents the storable energy, until the segment is fully charged.

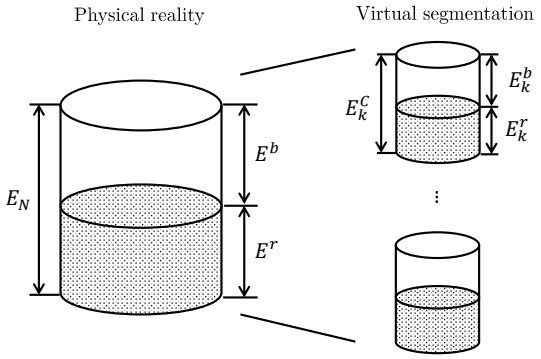

Fig. 4. Illustration of BESS segmentation and distribution according to the auction of the stakeholders.

Unlike energy, power is only limited by momentary values, instead of persisting system states. The constraints for the power distribution are therefore not as strict as the energy constraints. The sum of assigned power values determines the physical output of the BESS. Each application is given a rank R_k and yields a priority power value P_k^P.

Equations (4) to (7) describe how power is allocated to each application if the total requested reference power $\sum_k P_k^{\text{ref}}$ exceeds the nominal power P^N of the system. During the first distribution, a maximum of prioritized power value P_k^P is assigned.

Equations (4) to (6) are computed for each application sequentially in the order of their rank R_k. If physical power is available after assigning the powers $\tilde{P}_k$ for all applications in the first step, the unfulfilled reference powers $\tilde{P}_k^{\text{ref}}$ (Eq. 6) are met with the remaining BESS power capability P^{rem} (Eq. (4)). The ratios of the unfulfilled reference powers $\tilde{P}_k^{\text{ref}}$, after execution of Eqs. (4) to (6) for all applications, determine the allocation of the power for each application P_k (Eq. (7)). If the BESS reaches its power limit P^N at any step of the power assignment, the current value is set to maximize the output power. All following reference powers are then set to 0. An example of the power distribution

mechanism is elucidated in Section 5.3.

$$P^{\text{rem}} = P^{N} - \left| \sum_{k}^{n} \tilde{P}_k \right| \tag{4}$$

$$\tilde{P}_k = \begin{cases} \min\left\{P_k^{\text{ref}}, P^{\text{rem}}, P_k^{P}\right\} & \text{for } P_k^{\text{ref}} \geq 0 \\ -\min\left\{-P_k^{\text{ref}}, P^{\text{rem}}, P_k^{P}\right\} & \text{for } P_k^{\text{ref}} < 0 \end{cases} \tag{5}$$

$$\tilde{P}_k^{\text{ref}} = P_k^{\text{ref}} - \tilde{P}_k \tag{6}$$

$$P_k = \tilde{P}_k + \frac{\tilde{P}_k^{\text{ref}}}{\left|\sum_l^n \tilde{P}_l^{\text{ref}}\right|} \cdot P^{\text{rem}} \quad \forall k \tag{7}$$

4.2. Intra-Day Battery Resource Shifting for Real-Time Control

The purpose of the second layer is to allow re-allocation of resources in cases of prediction errors. Stakeholders may require obtaining additional resources to fulfill their objectives because of prediction errors. The control algorithm may detect the shortage of resources for each stakeholder individually during operation and trigger the request for more resources from another resource holder.

These new resources allow the receiving stakeholder to fulfill his objectives, while the resource provider may suffer performance losses and consequently financial losses. The compensation is registered in the smart-contract that is executed during the transfer if the BESS resources between the two stakeholders. The terms of the transactions that the parties agreed on in the first operation layer apply.

A general description and the associated constraints of the transactions and the implications on the BESS state are given in Eqs. (8) to (10). Energies (both energy capacity E_k^C or residual values E_k^r) may be changed at any time (Eq. (8)), given that any increase ΔE_k is taken from other segments (Eq. (9)). This ensures the overall energy balance (Eqs. (1) and (2)). The superscript star denotes the new value E_k^*, the superscript 0 denotes the previous value E_k^0. The redistribution is not limited to pairs of applications, but may include more parties (Eq. (10)). ΔE_{kl} denotes an energy transfer from application k to application l.

$$E_k^* = E_k^0 + \Delta E_k \quad \forall k \tag{8}$$

$$\sum_{k}^{n} \Delta E_k = 0 \tag{9}$$

$$\Delta E_k = \sum_{l}^{n} \Delta E_{lk} \quad \forall k \tag{10}$$

4.3. Suggested Properties of Blockchain

We suggest a permissioned blockchain, to ensure that only actual stakeholders that have a technical interest in operating the BESS may participate in the auction market. With a set of limited agents in the blockchain, the proof-of-work mechanism can be designed as a simple problem to consume only little energy and require only short computation. Even though this compromises the security against manipulation of the transactions, the limited access to the blockchain should reduce that risk.

The less elaborate proof-of-work enables reasonable mining without high-performance computers and is therefore possible for all or at least a large share of the market participants, to further minimize the risk of manipulation and reinforce the validity of transactions.

5. Illustration Examples

The first examples in this Section show the proposed behavior of the BESS with two stakeholders. Charging power is defined by positive power values. Negative power values represent a discharging. Suppose a BESS with following states and allocation of the properties to each stakeholder A and B.

The physical properties and states are the nominal energy capacity $E^N = 100\,\text{kWh}$, nominal power $P^N = 50\,\text{kW}$ and the stored (residual) energy $E^r = 5\,\text{kWh}$. The properties of application A and application B, as well as the total values are given in Table 1.

Table 1. Example values of the right of BESS-use and virtual states of applications.

Application k	Energy Capacity E_k^C	Residual Energy E_k^r	Priority Power P_k^P	Rank R_k
A	75 kWh	5 kWh	10 kW	2
B	25 kWh	0 kWh	20 kW	1
Total	100 kWh	5 kWh	30 kW	-

5.1. Negating Output Powers

Assume opposing power requests P_k^{ref} of the stakeholders' operation strategy. They negate each other and the residual power is executed by the BESS, if all relevant constraints are fulfilled. Suppose application A requires a power P_A^{ref} of 30 kW and application B requests a power P_B^{ref} of -25 kW, the resulting reference power is the sum of both reference powers (Eq. (11)).

$$\sum_k^n P_k^{\text{ref}} = 5\,\text{kW} \tag{11}$$

5.2. Energy Capacity Allocation

The next example illustrates how the allocated energy capacity segments E_k^C to stakeholder k limits the requested power P_k^{ref}. Suppose that both applications request a discharging power of both 10 kW (Eq. (12)). As application B has no energy left for discharge (Table 1), its residual energy is at the limit and the application must keep the energy constraint (Eq. (3)). Consequently application B does not discharge (Eq. (13)). The overall output power of the BESS is equivalent to the output of application A (Eq. (14)).

$$P_A^{\text{ref}} = P_B^{\text{ref}} = -10\,\text{kW} \tag{12}$$

$$P_B \geq 0\,\text{kW} \rightarrow P_B = 0\,\text{kW} \tag{13}$$

$$P = P_A + P_B = -10\,\text{kW} \tag{14}$$

5.3. Hierarchical Distribution of Power

If the sum of the requested power exceeds the nominal power (Eq. (15)), a priority based distribution of the BESS's nominal power to the requested output of each application is executed. Suppose the reference power of application A is $P_A^{\text{ref}} = 50\,\text{kW}$ and application B requires $P_B^{\text{ref}} = 30\,\text{kW}$. Application A is assigned power first, because it has a higher rank $R_A = 2$ than application B with a rank of $R_B = 1$.

In the first step, A receives its reference power up to a maximum of its prioritized power P_A^P or the remaining power P^{rem} (Eq. (16)). Since no power allocation has taken pace in this iteration yet, the remaining power P^{rem} equates to the nominal power P^N (Eq. (4)). $\tilde{P}_A$ is the preliminary power that is allocated in the first step according to Eq. (5). The remaining power P^{rem} (Eq. (17)) is then assigned to application B (Eq. (18)), with the same rules that the priority power P_B^P and remaining capacity P^{rem} limit the allocated power $\tilde{P}_B$ (Eq. (5)).

After assigning all preliminary powers $\tilde{P}_k$, the remaining power P^{rem} (Eq. (19)) is distributed among the residual $\tilde{P}_k^{\text{ref}}$ powers (Eq. (6)) according to their proportions (Eq. (7)) and the definite powers P_k are assigned to the applications (Eqs. (20) and (21)). Figure 5 graphically represents the Equations (16) to (19).

$$\sum_k^n P_k^{\text{ref}} = 80\,\text{kW} > P^N \tag{15}$$

$$\tilde{P}_A = \min\left\{P_A^{\text{ref}}, P^{\text{rem}}, P_A^P\right\} = \min\{50\,\text{kW}, 50\,\text{kW}, 10\,\text{kW}\} = 10\,\text{kW} \tag{16}$$

$$P^{\text{rem}} = P^N - \tilde{P}_A = 50\,\text{kW} - 10\,\text{kW} = 40\,\text{kW} \tag{17}$$

$$\tilde{P}_B = \min\left\{P_B^{\text{ref}}, P^{\text{rem}}, P_B^P\right\} = \min\{30\,\text{kW}, 40\,\text{kW}, 20\,\text{kW}\} = 20\,\text{kW} \tag{18}$$

$$P^{\text{rem}*} = P^{\text{rem}0} - \tilde{P}_B = 40\,\text{kW} - 20\,\text{kW} = 20\,\text{kW} \tag{19}$$

$$P_A = \tilde{P}_A + \frac{\tilde{P}_A^{\text{ref}}}{\left|\sum_k^n \tilde{P}_k^{\text{ref}}\right|} \cdot P^{\text{rem}} = 10\,\text{kW} + \frac{40\,\text{kW}}{50\,\text{kW}} \cdot 20\,\text{kW} = 26\,\text{kW} \tag{20}$$

$$P_B = \tilde{P}_B + \frac{\tilde{P}_B^{\text{ref}}}{\left|\sum_k^n \tilde{P}_k^{\text{ref}}\right|} \cdot P^{\text{rem}} = 20\,\text{kW} + \frac{10\,\text{kW}}{50\,\text{kW}} \cdot 20\,\text{kW} = 24\,\text{kW} \tag{21}$$

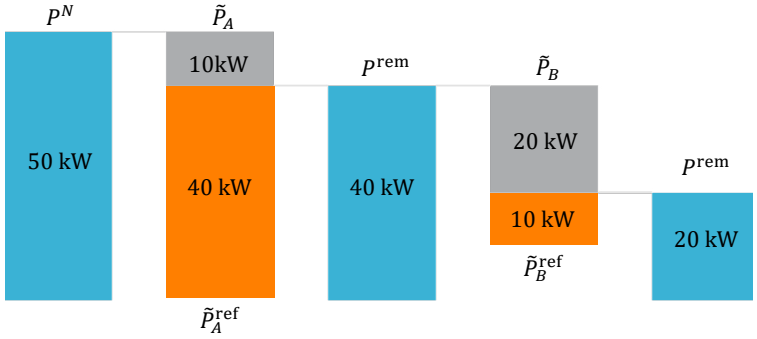

Fig. 5. Sequential assignment of available power to the power demands.

5.4. Shifting of Stored Energy

Equations (22) to (25) illustrate how residual energy is exchanged between two parties (Eqs. (24) and (25)), while the allocated energy capacities remain (Eqs. (22) and (23)). The superscript star denotes the new value E_k^*, the superscript 0 denotes the previous value E_k^0. This is a mere re-declaration of ownership. The equations ensure that the physical energy within the BESS remains identical to the assigned energy to their owners. This example procedure is intended to compensate for single-events where stakeholder A needs to shed energy ΔE_{AB}^r that stakeholder B is willing

to receive. The constraint of the redistributed energy (Eq. (9)) is fulfilled because $\Delta E_{AB} = -\Delta E_{BA}$.

$$E_A^{C*} = E_A^{C0} \tag{22}$$
$$E_B^{C*} = E_B^{C0} \tag{23}$$
$$E_A^{r*} = E_A^{r0} + \Delta E_{BA}^{r} \tag{24}$$
$$E_B^{r*} = E_B^{r0} + \Delta E_{AB}^{r} \tag{25}$$

The example is graphically illustrated in Figure 6. A redistribution of the residual energies E_k^r also changes the SOC of the application and generates a discontinuity in the graph. The amount of ΔE_{AB}^r is shifted from E_A^r to E_B^r. This way stakeholder A is able to store more energy in the future.

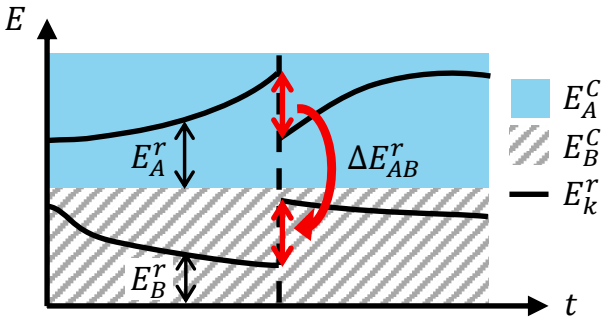

Fig. 6. Illustration of shifting residual energy E^r between applications triggered by short-term control outside of bidding.

5.5. Shifting of Energy Capacity

The next example illustrates a re-assignment of each stakeholder's auctioned energy capacity (Eqs. (26) and (27)), but the stored energy remains unchanged (Eqs. (28) and (29)). This transaction is intended for a more persistent increase of energy capacity for application A.

$$E_A^{C*} = E_A^{C0} + \Delta E_{BA}^{C} \tag{26}$$
$$E_B^{C*} = E_B^{C0} + \Delta E_{AB}^{C} \tag{27}$$
$$E_A^{r*} = E_A^{r0} \tag{28}$$
$$E_B^{r*} = E_B^{r0} \tag{29}$$

The shifting of the energy capacity is illustrated in Figure 7. A re-assignment is triggered, where E_A^C is increased by ΔE_{BA}^C. The graphical discontinuity of E_A^r is caused by the shifting of its bottom reference.

6. Discussion and Critical Review

The introduced market for BESS is suitable to handle dynamics in future electricity grids. The first auction layer enables a transparent allocation of BESS resources and some certainty for planning. The second auction layer introduces short-term flexibility and additional BESS buffer. Prediction uncertainties and emergency situations are covered, as well as general situations with a low probability could be covered by the second layer instead of completely occupying

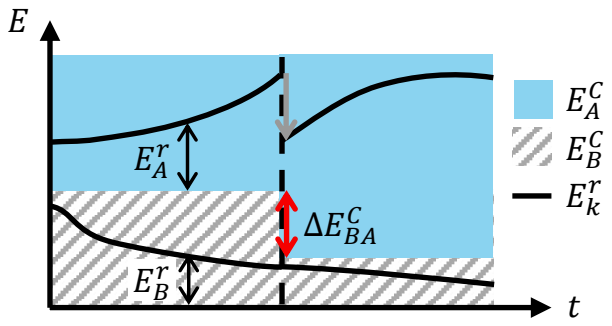

Fig. 7. Shifting of energy capacity E^C from stakeholder B to stakeholder A within the auctioned time period.

resources. As these short-term triggered events are expected to be more expensive, accurate capacity bidding is probably beneficial for all stakeholders. This short-term event and priority-based re-assignment allows the stakeholders to omit comprehensive hedging by liberally blocking large segments of the BESS resources. Yet, the added flexibility for the utilization does not exhibit ambiguity, because the explicit occurrence and value of obligations are pre-declared and the flexible BESS deployment is made accountable for all parties.

Brijs *et al.* [17] propose a promising concept that allows the sharing of BESS resources among several stakeholders. We extend the idea to consider prediction uncertainty by introducing a real-time modification mechanism for the energy segments and rights of use in-between bidding periods. In addition, blockchain is used for the market, which may be a catalyzing link between technical control and business logic. This extension avoids the need for an expensive aggregator, as automated algorithms are utilized instead. This enables the integration of the proposed multi-use concept for smaller BESS, such as community-scale BESS in the distribution grid. Consequently, the majority of applications for stationary BESS is covered [18].

The key-property of blockchain in the proposed multi-use concept for BESS is that all transactions (i.e. auctioned or triggered allocations of BESS resources) are registered in the blockchain and allow accountable actions and obligations between all stakeholders, without an added central authority [20].

A few conditions are necessary for the proposed concept to be feasible. First, all relevant stakeholders need to understand and adopt smart contracts and the consequences of the programming code included. Second, these smart contracts need to be legally effective and binding.

The proposed method relies on accurate state-estimation, in order to correctly assign the energies to the stakeholders. This includes physical issues, such as conversion losses, standby-consumption, and self-discharge that need to be taken into account, as these influence the available energy. We suggest the BESS owner has to (partially) compensate for losses caused by inaccurate state estimation. This creates the incentive for him to implement and further improve accurate estimation methods.

An essential issue that remains to be investigated in the according field is to guarantee the congruence of blockchain transactions and physical processes. The transfer between digital and physical world, the tokenization is a general issue of cyber-physical systems. Regulations today require approved measurement devices [13].

The concept is not strictly bound to the blockchain but could be operated with an independent aggregator instead. The benefits of blockchain seem to outweigh its complexity, as the cost for an additional aggregator renders the concept unattractive and creates incentives to exploit the market power [19].

7. Summary and Outlook

The contributions of this manuscript are a categorization and a formal, abstract definition of multi-use methods for BESS, as well as a concept that enables the multi-use with multiple stakeholders. We identified two types of multi-use methods, based on literature research: the first type is merging of objectives and the second type is stacking of multiple applications. The literature review also reveals, that no feasible concept for the multi-use of BESS, that considers multiple stakeholders and fits any BESS size, has been proposed, yet.

This paper proposes a concept that closes this research gap. The multi-use of BESS by stacking multiple applications is combined with blockchain technology to remedy the drawbacks of a conventional aggregator that coordinates the multiple stakeholders. We suggest a local auction market, where stakeholders bid for segments of a BESS and rights of use. The suggested blockchain-based aggregator is responsible for automated, computer-based market clearing, BESS execution, proof of delivery, and determination of financial obligations among the stakeholders. The properties of the blockchain technology presumably enable a generic, low-cost solution that can be applied to any BESS-size, down to small systems, such as community BESS with a few tens of kWh energy capacity.

Smart contracts are incorporated in the proposed concept to allow mechanisms that compensate for the intermittency of load and generation with the associated prediction uncertainties. The dynamics of the power grid are expected to increase with growing shares of RES and battery electric vehicles. Instead of adding energy buffer for each stakeholder during the auction, smart contracts allow more flexible sharing of the BESS within the auctioned periods. This consequently prevents oversizing of BESS, but increases their utilization ratio instead and eventually improves their economic value.

The proposed multi-use concept consists of two layers. The first layer is the time-ahead-layer, where the auction market determines the technical parameters: control algorithm, energy capacity, priority power, and rank. The second layer is the real-time-layer, where the control algorithm triggers the re-allocation of energy and priority power. This is transferred to the market via smart contracts to register the technical transaction and financial obligations in the blockchain.

Examples are presented in Section 5 to illustrate the proposed concept. Section 6 discusses the concept including its shortcomings. The uncertainty of external load and generation profiles are considered in the design of the concept. Accurate estimation of the state-of-charge is, however, assumed.

Future work includes the simulation of the proposed multi-use concept for demonstration and further improvement, based on the results. These also allow a quantification of the expected benefits compared to single-use. Especially the rules for power distribution need further elaboration for handling more than two applications. The impact of inaccurate state-estimation with regard to state-of-charge and aging needs to be analyzed and finally an extension to other units than BESS should be developed to obtain a general framework for the control of microgrids with multiple stakeholders.

Other distributed ledgers, such as tangle, may be more suitable for the proposed method, than blockchain [31]. A potential analysis of different technologies, as well as a comparison to the concept of a dedicated aggregator, is necessary for the future to prove the cost benefits claimed in this manuscript. We recommend further research on new methods that address security issues associated with tokenization, the transfer between physical reality and virtual data. This is not only beneficial for the proposed concept but concerns all fields, where tokenization is necessary.

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