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Prescriptive analytics for optimal multi-use battery energy storage systems operation: State-of-the-art and research directions

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Abstract

This paper presents the state-of-the-art and latest advances in implementing multi-use practices on BESS applications to the power system grid. Representative papers on modeling and optimization methods were selected, most of them working with realistic use cases, but none reporting on real-world implementations. Some major findings from reviewing key representative papers are that current optimization methods were able to handle uncertainty related to prices and other parameters either in the look-ahead planning stage or real-time control for obtaining an optimal dispatch schedule, thus addressing previously pointed-out gaps. Further, a recommendation for future work is to implement current multi-use methods, found to be mature enough, to real-world BESS use cases for validation and gaining experimental experience. Furthermore, the multi-use performance can further be improved by joining the strong contributions from each paper's method. Current methods have shown great potential for bringing simultaneous benefits to the grid, as well as being economical for the owner. A continued exploration and inclusion of new future BESS applications in prescriptive analytics for BESS multi-use suggest robustness for future market changes. However, further assessments are needed to evaluate whether the technology is economical and green for each particular use case and also for a potential systematic upscaling of the technology as a means to facilitate the green shift.

Keywords: battery energy storage system; BESS ; power grid applications; prescriptive analytics; multi-use; value stacking; review;

Abbreviations			
BESS	Battery Energy Storage System	EA	Energy Arbitrage
BTM/FTM	Behind-/in-front-of-the-meter	RES	Reserve market regulation
SoC	State of charge (BESS energy)	FREQ	Frequency market
MI(N)LP	Mixed Integer (Non-)Linear Programming	PF	Power factor compensation
DDRO	Distributionally data-driven robust optimisation	DSM	Demand Side Management
CPSO	Constrained Particle Swarm Optimisation	SC	Self-consumption increase
		PS	Peak Shaving, energy shifting

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1. Introduction

Energy storage is gaining more importance for stationary applications in the power grid. Battery energy storage systems (BESS) are able to save, hold and release electrical energy with very quick response times. This makes them attractive for stationary applications for power systems. Power grids are facing the task of facilitating a rapid increase in power demand and increased flow complexity (two-way and volatile) due to higher-order trends such as electrification, continuing industrialization, and an increased share of variable renewable energy sources. Additionally, system operators are expected to operate the grid on tighter margins, meaning utilizing the current grid infrastructure more effectively, with the aid of digitization, research, new technology, and analytics tools. While the recent decrease in the cost of BESS is an important factor for the financial feasibility, another much important factor that this paper is focusing on is the recent advancements in methods for optimizing the battery operation for multiple applications. Using a BESS for multiple applications, if done properly, can maximize the value they are able to bring to the power system.

Battery energy storage systems (BESSs) are beneficial to the power grid and energy markets in various ways and forms. Firstly, installation takes a significantly shorter time than planning and building new line capacity. Secondly, BESS has applications for energy markFets and grid services. The defined overarching goal of a power grid system is to ensure efficient, secure, and reliable production and distribution of electricity resources. Within these terms lies transmission efficiency, cost efficiency, quality of power, number of outages, and more. Market-based power systems consist of regulations, various products, trading platforms, bilateral agreements, tariffs, fees, and so on that are intentionally designed such that the whole system of grid operators, consumers, producers, and others shall work together to strive for the overarching goal. Regulations tend to lag technological progress, exemplified by many years of market-wise and regulative barriers to multi-use BESS implementation [9]. On the other hand, methodologies for controlling and operating a BESS have seen huge advancements in the last few years [13] [11]. There weren't many optimization methodologies for multi-use in 2019, when the work in [22] showed that a rule-based BESS control algorithm outperformed at-the-time mathematical optimization approaches - leaving much more potential for using the full multi-capabilities of a BESS. This gives motivation for investigating multi-use optimization methods, that can increase the maximized benefits of the invested resources by reducing idle times and increasing lifetime. Similarly, a power grid line whose maximum capacity is reached only a few high-load hours of the year is underutilized, to which energy storage can offer a solution - BESSs in particular can flatten out high load peaks on short- and medium-term, whilst also offering other services with its leftover available energy and power capacity.

Utilization of the full BESS potential brings us to the main part of this review. The key contribution of this work is mainly two-fold: 1) highlighting the work of the most recent key representative papers within the field of prescriptive analytics applied to BESS multi-use in power systems, and 2) identifying research gaps and industrial challenges based on the reviewed literature and experience from a system operator in Norway, followed by recommended research directions for the scientific community.

The remainder of this paper is structured as follows. The rest of the introduction provides information about BESS applications, prescriptive analytics, and technical notes on BESS as a background for the reader to understand the paper. Section 2 explains the study design used to select papers and how the papers are classified. Then, section 3 presents the findings and insights from the state-of-the-art review. A table of the ten selected representative papers is listed along with the features according to the classifications mentioned in the study design. Further, the methods are presented according to their features. Section 4 summarizes the main challenges and weaknesses of the reviewed methods as well as a discussion on the challenges the industry faces based on a representative industrial actor in Norway. This is followed up by recommendations for future research directions in section 5, which is based on the identified gaps in the literature and industrial challenges. Last is the conclusion.

1.1. Services and prescriptive analytics

The use of BESSs has grown from single applications, such as backup power, to now being able to utilize their multi-use capabilities, with good reasons - multi-use methods have been shown to increase profitability by tapping into multiple revenue streams reducing their idle times [13]. Adaptable methods can also mitigate the uncertainty related to dependence on one revenue stream in case of changes. As briefly mentioned earlier, the BESS could support the grid. They can operate in a way that leads to loss minimization at the distribution level while helping in the balance of demand and supply at a transmission level. It is not always a clearly defined product or available revenue stream attached to all its potential applications. The applications that were provided in the reviewed methods are listed and explained below:

- EA: Energy arbitrage means buying low and selling high, regarding energy amounts, taking advantage of energy market price volatilities, through time and between different markets. It is a pure energy market application, FTM, also a favourable SoC recovery strategy after providing another application.
- RES: Reserve regulation, such as up or down-regulation for the system balance, an FTM application for trading up and down-regulation in a continuous manner for a controlled balanced transmission system frequency.
- FREQ: Frequency markets for fast reserves , also about maintaining system frequency, but much more rapidly. Such markets are recently developed [14] to deal with low-inertia situations in the grid in case of a critical component failure. Batteries can contribute to feed-in and feed-out power and are most effective when activated and injecting power just before a system frequency minimum [8].
- PF: Power factor compensation helps to compensate for some of the reactive power flow leading to losses with the reactive power from a BESS instead, thus reducing transmission losses and often also improving voltage quality. An FTM application using mainly reactive power, but active power will also contribute. Reactive compensation usually also improves voltage quality.
- DSM: Demand Side Management is a BTM application, and often involves reducing peak loads to save the cost of an end-user.
- SC: Self-consumption increase, a BTM application similar to peak shaving and DSM, but uses the BESS to help prosumers shift over-shooting production e.g. from photovoltaics to a timeslot such that as much of it is consumed BTM.
- PS: Peak shaving; either smoothing out the load at consumers (BTM), the production at producers (BTM), or the flow on a transmission line (bottlenecks, FTM) by storing and releasing energy so as to fill the valleys and shave the peaks of the power curve. This can enable a higher averaged power flow, and thus onboarding new load or production, which could defer grid investments. Another positive effect is weakly reduced transmission losses due to the loss being proportional to the square of the current (there are fewer high currents).

When the BESS dispatches positive or negative active power for an application, such as providing frequency services, its energy offset needs to be balanced in real-time, i.e. through bilateral contracts or through trading in the real-time markets. For frequency services, this cost was in a paper found to be negligible compared with FFR income [1]. When a prescriptive method plans to recover the BESS energy state (SoC) after dispatching active power for an application, this is referred to as SoC recovery energy cost. Another important aspect is degradation due to usage, and the associated costs can be modeled and off-traded against revenues. The degradation of electrochemical batteries when used for grid applications, such as lithium-ion ones, has been well-researched and more on this can be found in [20].

BESS offers many opportunities for prescriptive analytics. Since a BESS has a limited power conversion capacity, trade-offs need to be done regarding what service to prioritize and provide in real-time. Further, the limited energy capacity is another operational constraint, which introduces a temporal dependency between services throughout time. For example, discharging the BESS to its minimum energy level now take away future chances to discharge and could be stipulated as an opportunity cost and taken into consideration in the optimization problem. Prescriptive analytics, with foresight and mathematical optimization at its core, find an optimal schedule for charging and discharging, maximizing profit or minimizing costs, or optimizing other objectives, given the operational constraints and market requirements. There are several methods being researched for enabling the multi-use capability of BESS, such as machine-learning-based decision-making, whereas this paper focuses on mathematical optimization as the means to prescribe the optimal operation decision. The motivation is that mathematical optimization is successfully applied in other fields and the research for BESS multi-use has seen great advancements in the last years. Some major challenges are data uncertainty and availability, whereas others will be discussed later in this paper. Prescriptive analytics is an advancement from predictive analytics - excelling from descriptively analyzing what and why an outcome will or did happen to also prescribing how that certain desirable optimal outcome can be achieved, resulting in an optimized operational plan. Such a plan takes into account the modeled landscape of possible choices (decision variables) and likely scenarios (parameters) [17]. Prescriptive analytic frameworks can provide decision-making support for the short-term or near-real-time operational scale, but also on a longer-term investment assessment that considers optimizing on e.g. sizing and placement of a BESS. The latter is out of the scope of this review. Each application to the power grid system is often mathematically formulated separately and then combined in the final objective function. A successful prescriptive analytics implementation is the step before a fully automized operation, which means little to no intervention from humans that instead will monitor and tune the settings.

2. Study design

This section explains the method for reviewing the most recent scientific literature in the field of prescriptive analytics for BESS in power grids. The aim of the review is to identify key representative papers for gaining insights on current advancements, practices, and challenges in optimizing the operation of a BESS for multiple applications. With a main focus on mathematical optimization methods, the state-of-the-art is investigated and the findings from the review are presented in section 3. The main goal is to gather insights that can be used in a broad dialogue with the industry to discover research gaps and propose research directions for real-world industrial applications, which is presented in section 5. Ten representative papers have been identified as suitable for the purpose outlined above. The selection process is as follows. First, a search inquiry was made on google scholar with the search words: ”battery multi-use power grid optimization”. These key terms are believed to yield papers that fulfill the criteria in the bullet list right below.

- Authors developed a multi-use optimization framework or methodology for BESS operation,
- BESS is providing at least one in-front-of-the-meter (FTM) application of relevance to a system operator, and
- the paper is from 2020 or newer (with an exception for a 2019 paper).

Papers from the 10 first search result pages are considered, discarding those that do not satisfy the criteria scope. The aim is to encapsulate the great advancements made in the last three years for utilizing BESS' multi-use capabilities, as well as BESS applications that are of benefit to power grid operations. To limit the literature survey, 10 papers were finally selected, which were found to fulfill some features of interest to the industry, as well as representing a variety of complexity in approaches. We acknowledge that the final selection discards other more or less similar methods of relevance, however, we believe the selected 10 key papers provide a good insight foundation for making well-directed future recommendations in broad dialogue with the industry.

From the 10 selected papers, each of the paper's optimization methodologies are classified according to the following features, which also define the headings of Table 1:

- Problem formulation type: How is the planning model mathematically formulated: Mixed integer (non-) linear problem (MILP or MINLP for non-linear), Distributional data-driven robust optimization (DDRO), Continuous particle swarm optimization (CPSO),
- Solving approach: Is the approach of solving the problem deterministic, stochastic, robust or through simulations,
- Planning stage: A planning model involving a look-ahead time period whose optimization problem results in a planned BESS dispatch schedule,
- Real-time control: Does the methodology consider that future real-time values will defer from historical or forecasted values either by doing near-real-time (1 hour or less) recalculations of the optimization problem or with a dedicated in-real-time controller,
- Scale: Size of the energy and power conversion capacities of the battery being researched.
- Industrial use-case: Does the paper replicate a real-world use-case somewhere, for example by modeling the surrounding grid structure, using historical market or load data of that location,
- Degradation aware: Is the methodology considering degradation in its scheduling problem,
- Topology: Does the BESS provide services behind the meter (BTM) or in front of the meter (FTM)

- Applications: What services that the BESS provides (in the order of the table: Energy Arbitrage, Reserve market participation, Frequency market, Power Factor correction/Voltage regulation, Demand Response Management, Self-Consumption increase, Peak Shaving. See section 1 for further descriptions)

2.0.1. Some existing reviews

A few other reviews have been conducted on ongoing research and advances in the field of value stacking for batteries. The paper [23] from 2021 for example reviews papers on BESS in power grids until 2020 and classifies them based on their battery modeling and optimization methods, their level of detail, the problem type, and solution methods, (solving short-term operation OR also long-term planning, deterministic or stochastic, mathematical programming or other methods, a single application or multiple applications). They also review how battery life degradation is treated in the scheduling problem. The authors found that the majority of papers used loss-of-life models, whereas a few papers have used/developed full degradation models, however, none successfully prevented an early overuse of battery lifetime. They recommend future work on developing models that capture the future opportunity cost of ”spending” the battery lifetime now. The paper [11] reviews 15 papers from 2015 to 2021 and amongst other things provides an overview of the optimization objectives and constraints of the optimization problem of the planning stage. Authors of [21] give a comprehensive review of BESS usage in the grid, including storage technologies, optimization objectives/methods, and types of grid services.

3. Battery energy storage systems in the industry - state of the art of applied prescriptive analytics

This section presents a review of the optimization frameworks from 10 selected representative papers, which are listed in Table 1 showcasing their key features and classifications.

Table 1. Literature review table.

Ref.	Formulation type	Approach	Look-ahead planning model?	Real-time control?	Scale MWh / MW	Industrial use-case?	Degr. aware?	Topology	EA	RES	FREQ	PF	DSM	SC	PS
[10]	MILP	det	✓	✓	1,5 / 0,75	✓	no	BTM+FTM	✓	✓		✓			✓
[7]	MILP	det	✓	no	1,34 / 1,25	✓	✓	BTM+FTM	✓		✓			✓	✓
[2]	MINLP	stoch./piecewise	✓	✓	20,0 / 10,0	✓	✓	FTM	✓	✓	✓				
[19]	DDRO**	stoch	✓	✓	0,1 / 0,018	✓	✓	BTM+FTM	✓	✓	✓		✓		
[16]	MILP	det	✓	✓	20+ / 15	✓	no	FTM	✓*		✓				
[18]	MILP	det/sim	✓	no	1 / 1	no	no	FTM	✓		✓				
[3]	MILP	det	✓	no	1,1 / 0,8	✓	✓	BTM	✓				✓		✓
[12]	CPSO**	meta-heur	✓	✓	0,6 / 1,2	✓	✓	FTM	✓*		✓				
[4]	MILP	math-heur.	✓	no	2 / 4	no	no	FTM	✓		✓				
[6]	MILP	sim.	✓	✓	3,6 / 1,8	✓	no	BTM+FTM	✓		✓		✓		

** DDRO: Distributionally data-driven robust optimization, CPSO: Continous Particle swarm optimization.

* Energy arbitrage is not the main objective, but SoC recovery after the usage for another application is planned to optimal timeslots.

All of the papers present mathematical models that optimize the BESS’ decision variables according to an objective. One area in which they differ is how accurately they represent real-world conditions. As seen in Table 1, all the selected methods have a look-ahead planning model - an optimization problem spits out a timestep-by-timestep charging/discharging schedule ahead of the time of operation. Six of the methods also feature a subsequent (near-)real-time control module for readjusting to real-time parameters. For those who do not, a deterministic optimization model is run and gets input updates, even forecasts, every 8 hours [7], or once a day assuming perfect foresight [3]. The method in [4] is building probabilities of FFR-bid acceptances, and propagates probable outcomes through a deterministic optimization model. It minimizes the SoC recovery costs on the real-time market (energy arbitrage) but does not feature a real-time control although building a realistic scenario. The optimization model in [18] is quite similar, but gets inputs from an agent-based energy market simulation model.

The look-ahead planning models in [6] [10] [16] each output a preliminary optimal dispatch plan for a whole day, whereas the final dispatch is determined by a rule-based controller algorithm considering real-time parameters. In [12], day-ahead market commitments are made in a look-ahead planning model followed by simulating various real-time (online) control methods. Opposed to a rule-based approach, [19] and [2] implement a real-time optimization model that is run every hour (also referred to as model predictive control). It takes into account look-ahead commitments, and new data and executes the BESS dispatch for the coming hour along with a dispatch plan for the rest of the hours.

Despite the shortcoming of not having a real-time control in [18] their look-ahead planning problem does contribute to novel research regarding the uncertainty of bidding and market prices, involving agent-based simulations of market participators, including amongst others coal and gas for electricity generation. They used historical data and also simulated a 2030 scenario with reduced CO_2 emissions and increased intermittent renewable energy. Then a deterministic BESS planning model was solved to explore the BESS use-case. The method in [4] also brought novel research regarding markets, in their case evaluating the probability of frequency market bid acceptance applying a machine learning approach. Whereas many papers assume that bids are always accepted, their approach classifies probabilities of whether a BESS bid to the frequency market would be accepted and iteratively feed this through the BESS dispatch planning optimization problem, ergo a math-heuristic approach. The mixed integer non-linear problem (MINLP) formulation in [2] was solved with different techniques for handling the different types of parameter uncertainties, such as linearization and robustification. Their model was solved in 12 seconds, a feasible computation time for their rolling horizon approach updating the near-real-time optimization model every hour. For the papers that check off the ”industrial use-case” box, that means their methodology was replicating a real-world use-case somewhere, for example by modeling the surrounding grid structure, using historical market or load data of that location, or even by using real data from an installed BESS such as in [6] [12] [3] [7].

Many papers assess their methodological contribution in terms of performance improvements - usually economical, such as [3] [18]. The fact that the papers measure their method’s improvements differently, provides useful insights. [7] assessed all combinations of providing 4 applications down to single-use cases. Authors of [19] compared their developed heuristic multi-use approach to a deterministic approach. The method in [4] took into account that not all FFR bids are accepted, which resulted in a 28% lower expected income from FFR markets compared to the deterministic bid-always-accepted approach. Their results also indicated that the provision of FFR market services is a larger revenue source than energy arbitrage, for their case in Britain. Authors of [19] apply a data-driven robust optimization technique for making an operation plan for a BESS trading in the electricity market and doing demand side management. Through the use of so-called mean-risk portfolio management, uncertainties in market clearing prices are mitigated, by finding a best-case result during the worst-case outcome of uncertainties. Their results show that this method outperforms stochastic optimization and deterministic approaches when participating with a BESS in BTM services, and electricity markets (spinning reserves, regulation up/down). A downside is high computational complexity, likely non-suitable for online usage. Authors of [16] developed a multi-use optimization framework for both FTM and BTM applications, using historical data from real BESSs that have been operated since 2016 for frequency regulation services. Through backtesting, authors found operational efficiency and profit could have been improved by applying their developed multi-use optimization-based control strategy in-place. Their results showed that it was most profitable when combining peak-shaving with frequency regulation and arbitrage in the ID market as of 2022 in Germany.

There are various ways of considering degradation. Loss of lifetime due to degradation due to certain usage can be represented mathematically through a simplified linear and solvable technique. All of the degradation-aware optimization problems in the reviewed papers used a linear or piecewise linear ”cost of use” term in their objective function to avoid usage where degradation costs are bigger than the income. One method punished usage related to increased degradation, such as SoC below 20% or above 80% [5]. The optimized schedule is a result of valuing each application up against each other and the associated cost-of-life, however, none considers degradation-related opportunity costs past the model’s optimization horizon e.g. saving lifetime for future applications. Some of the papers chose to leave the degradation issue outside of the optimization problem. [3] is one of them, but what they do instead is to descriptively post-analyze how the various operation strategies impacted battery degradation, using the simulation tool SimSES.

As seen in Table 1, the papers differ in what applications they provide. The majority of the reviewed papers have chosen energy arbitrage and frequency market participation. Only one paper considered power factor correlation. In the work of [18], bids are generated to the reserve capacity market, based on calculated opportunity costs from not participating in the day-ahead market. The methodology in [10] mitigates uncertainties in both a planning stage and in a proposed real-time control, thus contributing to closing an identified gap related to real-time operation.

Another major contribution of the work is a framework that handles multiple time scales which arise from the different requirements of different services. This was done with a combination of linearization techniques and a robustification approach featuring an uncertainty budget. Their results show that their real-time control framework managed to peak-shave a high load that was not predicted in the look-ahead planning model. They constrained the SoC to always have 20% reserve capacity for backup power in the case of an outage.

The optimized schedule in [7] benefits from a clear distinction between BTM and FTM applications, on the physical level of the BESS inverter lever assuming 1 hour switching time. Their method solves a technical requirement to distinguish between FTM and BTM purposes in the physical BESS setup. In [12], the authors simulate optimized BESS operation using 4 years of real BESS data from Helsinki, Finland. Their contribution involves a detailed model of FFR market participation involving a bidding strategy and real-time control of the BESS. They put focus on optimizing the rebound recovery of SOC, whilst minimizing degradation-, energy- and balancing costs. Their results showed that by being highly active in the Finnish FFR market, battery lifetime was 8 years whilst payback time was 6 years. Though a positive business case, it might be worth exploring the economic assumptions and the environmental aspect.

4. Industrial challenges in BESS optimization

While there is a union agreement that multi-use frameworks is a key enabler for making BESS economically feasible for power grid applications, some recommendations for research directions and future work has been identified based on the reviewed papers and in dialogue with an industrial actor.

It was pointed out that the multi-use methodologies can benefit from including more services and new combinations of them, as well as adapting the methods to other countries [7] [3]. Authors in [2] recommended the same and also advised politicians to facilitate multi-use strategies in order to increase BESS investment attractiveness. Two more papers recommend exploring applications for more use cases, such as how various BESS locations put constraints on the BESS dispatch scheduling problem [10] and how the location and sizing of a BESS can be optimized under various multi-application combinations [7]. Sizing and location optimization is out of the scope in this paper.

Whereas some of the reviewed methods tackled or handled uncertain variables, some of the papers left this out either for simplicity or for future work, by for example assuming a perfect foresight of real-time market prices [3] [18]. A few of the papers mitigated price uncertainties in the planning stage, such as with robustification approaches including price quotas to represent other market participants [2]; or formulating a modified robust problem and solving it with sophisticated techniques for representing bid acceptance [19]; or machine learning for predicting likely bid acceptance probabilities [5] - however, their methods lack in one or other ways, for example by assuming that their bids are always accepted [2]; having too high computational time to work online (in this work their methods was applied offline) [19]; or neglect battery degradation [5]. [10] proposed a robust optimization approach with an uncertainty budget approach in their planning model which was further combined with a real-time controller, but neglected degradation - they suggested exploring more advanced battery models which entails degradation, with a reasonable trade-off between accuracy and computational time. Some of the methods did not take uncertainties into account when planning a schedule in advance but instead depend on the real-time controller to handle real-time parameters, such as in [16]. Further, they suggested carrying out a sensitivity analysis to assess how the forecast quality impacts the BESS operation performance, affecting the outcome of the look-ahead planning problem. Among the papers with frequency market participation, [16] recommends future work to develop their method such that it reassures that it does not cause any higher energy costs related to the operation. In [5], authors did evaluate such costs but not for updated real-time costs of frequency market participation, as well as exploring other energy arbitrage strategies - in which inspiration and approaches can be found in other papers' work. [12] recommends continuing to develop frequency market bidding strategies with methods with less computational complexity, as their continuous swarm optimization approach took 20 minutes to solve. Regarding the DDRO approach in [19], the authors recommend gathering more training data for building a proper probability distribution for their approach. However, their method is out-of-sample guaranteed, meaning it does not need a complete probability distribution such as other stochastic methods.

The handling of uncertainties and other previously identified gaps has indeed been addressed in the reviewed literature in quite realistic simulations. There is however still a lack of papers reporting on actual implementations of multi-use methodologies on real-world BESSs. This need is pointed out by for example in [16], who recommend tests on real BESSs in different time periods in order to validate their proposed BESS multi-use model. None of the papers reported applying their methods on BESS with real tests or implementations. At this point, current academic literature can only provide valuable insight into real-world operations through real-like simulations, to the author's knowledge. For the industry, it is relevant to explore whether the battery energy storage system technology is economically, environmentally, or society-wise better than other components or technologies for coping with the challenges they face. Reliability of the deliverance of a service is important for a system operator who might depend on it, stressing the importance of a working multi-use methodology. It would be interesting from a system perspective to assess whether a multi-use BESS can replace other components in the grid, thereby mapping the proper relative impact on resource use, area, environment, economy, and emissions. When it comes to environmental factors, such as emissions and area usage, the industry may soon in the future require full disclosure of this data from manufacturers, such as cradle-to-gate footprint data [1]. Amongst the papers in this review, none are optimizing systemic emissions and environmental footprint in the operational multi-use, and such work is left out of the scope of this paper.

Prescriptive analytics and multi-use BESS have become more widespread, lowering the bar for utilizing larger data quantities with more user-friendly interfaces. Similarly, these factors also pose a challenge for the industry - they need to learn what data to collect and ensure its quality is sufficient - from investing in sensors and making data available to teaching employees within prescriptive analytics. As an example, [10] assumes that the responsible system operator has already ensured enough hosting capacity in the grid for the installed BESS, meaning its max and min power will not lead to voltage violations or high fault currents. This might pose a challenge for voltage regulation and peak curve smoothing applications where a grid operator might be interested in using a BESS for onboarding more load to a radial line. BESS or energy storages in general are suggested as an alternative to grid reinforcements, meaning that the goal is to "exceed the grid capacity limit", only that it is the BESS who does the extra pushing to keep the physical grid flow within its limits. The reassurances needed for reliable operation are followed by some chances being taken and successfully adapting and implementing optimization formulations and constraints to real-world use cases. This requires proper data accessibility. The method in [10] assumes a reliable stream of data as close to the operation hour as possible - a challenge related to sensors and digital data handling which the power grid industry is currently working on.

As already mentioned, none of the methods reported any real-life test, leading to a lack of validation of the results. On one hand, multi-use BESS methods have been theoretically shown to be profitable in many studies, even when uncertainties are taken into account in real-like simulations. An owner of a BESS still faces uncertainties regarding the specific grid structure and the market design and regulations of the country of the evaluated site. Future operational conditions might also change. As [7] points out, a weakness of their method is assuming 2019 data for their use case, concluding this is not suitable for future use cases where markets and load profiles could change. Another point they made is that market saturation of more BESSs likely decreases profitability. This incentives implementation of multi-use frameworks that can utilize different and new arising applications. More BESSs in the grid system services might mitigate some of the risks associated with non-availability that the responsible grid operators face if depending on BESSs grid applications for more effective grid operations, or even to prevent blackouts. Another challenge for the industry is that regulations do not encourage system operators to take risks as the consequences fall on the customers, but they are still willing to take some risks.

5. Recommendations for future research directions

Based on the findings in this review and dialogue with the industry, the first notion is that more work is needed to close the gap between proposed theoretical frameworks and real-world implementations for optimizing multi-use BESS operations in a suitable way. Key papers indicate overall positive business cases for BESS multi-use, as well as advancements in handling uncertainties. Some papers provide very realistic simulation environments, which gives valuable insight. It is the authors' understanding that multi-use BESS methods are mature for real BESS implementation. Such exhaustive work must involve continuing to build on, adapt, and utilize currently available multi-use BESS frameworks with relevant applications to the area of relevance. The inclusion of regulatory frameworks, grid

[1] Impact from raw material, production till the product is delivered

settings, objectives, and markets needs special care for its use case but can take inspiration from current methods and formulas. The next step is to gather and share experimental experience from real-world applications to the scientific community, which enables further benchmarking of current methodologies. Then they can be further improved, and important experience for BESS owners and grid operators is gained. Another recommendation is to make it a normal practice to be on the lookout for new BESS application opportunities in a developing power system. The papers in this review were mainly focusing on improving the business use case for BTM and FTM services i.e. improving revenues from ancillary markets. None of the papers considered any non-renumerated services that still might be of benefit to a system operator operating the grid. Future research should consider further investigating new ways a BESS can prove beneficial for the grid, also including non-renumerated services in future optimization frameworks.

Based on the challenges mentioned in the previous section, one observation is that many of the papers bring novel methods thus filling some research gaps, for example via sophisticated uncertainty handling, or real-time control management, but that simplifications on other areas were made. A future research recommendation is to combine the novel or strong contributions from each of the various methods together into one improved method. An example is to combine the novel uncertainty inclusion of frequency market participation in combination with real-time optimization model considering services that other methods included. Exploring the ways that a contribution from one method can add to the performance of another method is left for future work, however, some indications may be drawn from the analysis of the weaknesses and contributions of the papers in section 4. The methodological advances in the reviewed papers where a comparison was provided, were shown to either improve the use case or bring a more realistic result. When on the topic of recommending methodological improvements, it is worth asking if even more advanced methods will improve the operation of BESS and of the system. A recommendation is to continue with comparative studies of new methods with benchmark methods. Novel approaches may also be needed in order to tackle the computational complexity. For the industry, methods that are simple in their usage lowers the bar to start utilizing the multi-use capabilities of BESSs.

A last recommendation for future research is exploring the effect of scaling up BESSs and multi-use, on the power grid operations in a long-term planning perspective. The general finding is that multi-use BESS has great potential to improve provide power grid operations through multi-use. More analyses are needed to explore in what use-cases they can contribute to the green transition and if an upscaling solves the power grid challenges more sustainably and ethically compared to other solutions. The next recommendation is based on the points from the previous section on lifetime and early overuse of battery lifetime and exploring other applications. Work is still needed to explore how longer term opportunity costs can be taken into account in the daily BESS operation in order to avoid early overuse which some work reported. A suggestion is to make such "future" scenario forecasts of revenue streams. Since they will be uncertain, they could be included in a similar way as other uncertain parameters, e.g. robustification approach for representation in a long-term assessment of a BESS. While on the topic, it might be relevant to ask the question of how the battery lifetime is valued now versus in 5 or 10 years, exploring the economic assumptions. The discontinuation principle as an example presumes the lifetime of a battery is economically worth more today than in the future, however, the resource and environmental footprint could be debated and need to be assessed. An explanation of how the discontinuation principle generally might not be compatible with long-term sustainable thinking and decision-making can be found in [15].

To summarize, four key recommendations are:

- Implement and research multi-use methods on real-world BESSs to validate current methods,
- Improve current methods by combining the strong contributions of each method,
- Explore new applications and use cases for multi-use BESS, and
- Assess the impact multi-use BESS has on system-level performance as a whole

6. Conclusion

This paper discussed the state of the art of prescriptive analytics methodologies for battery and energy storage systems (BESS) and their many applications to the power grid. Since none of the 10 reviewed papers reported any real-world implementations, the next step is to implement existing suitable methodologies to real BESSs. The current advancements in multi-use methods for BESS are showing promising results, namely a positive business case for the owner, and benefits to power grid operators. The reviewed papers did address previously identified gaps, such as a lack of real-time control approaches and handling of uncertain parameters, but in a somewhat fractioned manner. For improving on the methods, future research is recommended to combine the strong contributions from the different reviewed papers and evaluate further improvements. However, keeping the simplicity may lower the bar for the industry to take advantage of the multi-use capabilities of a BESS in an earlier stage and start building industrial knowledge. Adaptations to each use case are key, as well as sharing real operational experience from multi-use so that methods can be benchmarked against the theoretical use cases and further improved. Further, we recommend exploring how BESS with multi-use applications to the power grid compares with other solutions for enabling more efficient grid operations, in economical, environmental, and ethical terms.

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