Cost-Benefit Analysis of Battery Energy Storage in Electric Power Grids: Research and Practices

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***Abstract*—This paper provides an overview of methods for including Battery Energy Storage Systems (BESS) into electric power grid planning. The general approach to grid planning is the same with and without BESS, but when BESS is included as an alternative, other methods are necessary, which adds significant complexity to the planning problem. Although recent research literature proposes a wide range of methods and models for Cost-Benefit Analysis (CBA) of BESS for grid applications, these are to a little extent applied in practice. For the research-based methods to be suitable for grid planning, they should handle timing of installations as well as sizing and siting of BESS. Moreover, they must capture long-term developments in load and generation. Finally, the CBA methods need realistic modelling of the operational benefits of BESS, taking into account multi-period AC power flow, battery degradation, and utilization for multiple grid services.**

Keywords—Battery storage, cost-benefit analysis, electric power grid, power system planning

I. Introduction

Battery Energy Storage Systems (BESS) have recently gained tremendous attention and are anticipated to make up an essential part of future power systems. BESS can be used for a range of applications (and combinations thereof), such as load levelling, balancing of variable renewable energy sources (VRES), provision of various ancillary services, and transmission and distribution grid reinvestment deferral [1-3]. For the latter application, BESSs can be deployed at strategic locations in the transmission and distribution grid and perform active and reactive power control for better utilization of the existing grid, as a (temporary) alternative to costly grid reinvestment. This usage of BESS is relevant for areas with expected growth in demand, bottlenecks, power quality issues and/or integration of a large amount of VRES. However, since such uses of BESS are still in the early stages of deployment, there exist yet no consensus on recommended computational methods for performing cost-benefit analysis (CBA) of BESS as alternative to grid reinvestment, or for other grid services.

In general, the starting point of a long-term grid planning process is the identification of a problem or a need in the grid over a defined planning horizon. These needs can be due to growth in demand, new generation, or ageing grid with high failure rates (now or in the future). The next step is defining the set of grid planning alternatives, traditionally grid expansion, reinvestment and reinforcement, to meet these needs. Traditional grid planning methods currently used by grid companies employ a variety of well-established techniques such as load duration curves, maximum loading scenarios and static AC power flow simulations to assess the benefits of grid alternatives. When BESS is included as an alternative, the general approach to grid planning is the same, but other methods are necessary to capture the operational strategy and constraints of the BESS and how this influences the potential benefits. This adds significant complexity to the planning problem. Especially in grids with large amounts of VRES, the storage dynamics increases system complexity and thereby requires more advanced computational methods for grid planning than presently employed in practice.

Adding to the complexity is the lack of clarity and certainty related to ownership and operation of BESS. According to Article 36 in Electricity Directive, “DSOs shall not be allowed to own, develop, manage or operate energy storage facilities” [4, 5], but in [6] EDSO for Smart Grids argue that distribution system operators (DSOs) should be able to use storage for technical purposes to solve local grid constraints (in emergency situations, reactive power control, and maintaining voltage limits) when a market solution is not possible. But regardless of the ownership and business model, it is still necessary for grid companies to be capable of analysing the costs and benefits of BESS in power grids.

In recent research literature, numerous advanced studies have been reported which to a varying degree have performed a CBA including BESS. Different approaches are used for solving the grid planning problem with BESS and VRES, with respect to storage modelling, AC power flow and/or other technical constraints, possible multiple (conflicting) BESS objectives, non-linear BESS characteristics such as degradation, VRES uncertainty, and so on. Existing computational methods also differ in how they account for the various forms of uncertainty present over both operational time scales and over the long-term planning horizon.

The lack of established computational methods for including BESSs in grid planning is a barrier for taking published research-based models into practice. This paper aims at giving an overview of relevant computational methods reported in the literature, as well as a selection of relevant real-world applications involving CBA of BESS. First, real-world BESS projects and studies are presented in Section II. Then, results from a review of the research literature are presented in Section III, and findings on the use of CBA methods in practice are presented in Section IV. Section V then discusses i) the gaps between current research-based methods and the requirements for grid planning and ii) proposes some recommendations to be able to apply such methods in practice. Finally, some concluding remarks are offered in Section VI.

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II. Use of BESS for Grid Applications

For decades, BESS has been used in autonomous (off-grid) systems and as back-up generation. Recently, the interest for using BESS in power system applications has rapidly increased, mainly driven by the breakthroughs in Li-ion battery technology and cost reduction [7]. As outlined in Section I, BESS has a broad range of grid applications. These applications are already described in numerous papers and reports, see e.g. [1-3] for good overviews. Reference [1] moreover includes a comprehensive overview of real-world applications of BESS in power grids, and ISGAN presents a comprehensive analysis of European case studies, demonstration projects and real-world applications of storage technologies and other flexibility options in [8]. The latter overview takes primarily a grid perspective, summarizes lessons learned from the projects, and aims to analyse the economic benefits of the storage applications. However, as discussed in more detail in Section V, none of these publicly available sources contain much information about CBA for real-world BESS applications.

The benefits of BESS for real-world grid applications are assessed in several ongoing and recent research projects. For instance, the EU-project InterFlex [1] demonstrated the added value of storage at different scales (single/multiple users) and different systems (electrical/cross-energy-carrier storage). This includes small distributed batteries' contribution to increase the hosting capacity of distributed generation units in low-voltage grids for the case of residential storage. For centralized storage, shared large-scale batteries enhance collective self-consumption, relieve grid constraints for the local grid (with significant electric vehicles and renewable energy development in the future), and increase resilience or improve the reliability of power supply.

Another relevant example is the FlexNett project [2] which focused on flexibility in the future smart distribution grid and included several case studies. The case "Prosumers in neighbourhoods/ regions with different locations of batteries" [9, 10] developed scenarios for the benefits with different locations of BESS, such as household level (prosumers, small scale distributed), community owned (medium scale) and grid company owned at MV/LV substation level (large scale). These BESS solutions were evaluated as an alternative to grid reinvestments and investigated for their impact on both the distribution grid (peak load) and self-consumption. The case study showed that a battery located at household level reduced the peak demand more than located in community and at substation.

Two BESS-related projects have currently (2020) been initiated at the Danish island Bornholm. These are the national project BOSS [3], and the European H2020 project InsulaE [4] [11]. The two projects benefit from the accumulated experience gathered in many previous research projects executed at the island Bornholm. The BOSS project aims to establish a BESS featuring the size 1MWh/1MW and to use the platform to demonstrate new and innovative business cases. In particular grid services supporting the frequency (Frequency Containment Reserves - FCR) will be explored as well as stacked services and mixed use. Depending on the hardware configuration other opportunities are also planned e.g. examining how the BESS can support integration of e-mobility, solar photovoltaic (PV) and wind power. Further, the power capability of the BESS is designed to be in the range of a few percent of the magnitude of the consumption. This means that the BESS potentially can impact the frequency directly if Bornholm is islanded. For both the new BESS projects, CBA aspects of the BESS installation and operation will be pursued, taking into account the constraint of being an island system.

III. Computational Methods for CBA in the Research Literature

This section summarizes the main results from a literature review of computational methods for including BESSs in grid planning, focusing on considering BESS as an alternative to grid reinvestment. The full review is available online as a working paper [12] and as a spreadsheet with supplementary details [13]. For previous reviews with a broader view on applications, benefits and optimization of BESS in electric power grids, we can refer to e.g. [14-19].

A CBA including BESS as grid planning alternatives can conceptually be considered to comprise a) an *investment model* as the upper layer of the analysis and b) an *operational model* as the lower layer. The investment model considers investment costs of grid planning alternatives as well as long-term scenarios for uncertain parameters such as demand growth and VRES development over the planning horizon, as described in more detail in Sec. III.B. To perform the CBA it is necessary to calculate the operational benefits of BESS for each planning alternative by taking into account short-term variability in demand and power output from VRES, BESS storage dynamics, degradation mechanisms, other BESS modelling details, grid topology, and so on. These operational modelling aspects are described in more detail in Sec. III.C. In order to consider the operational benefits of BESS in the long term relevant for power grid planning, there must be some coupling between the operational and investment modelling. Different coupling approaches are reviewed in Sec. III.D. First, however, the combined evaluation of costs and operational benefits of alternatives is described in Sec. III.A.

A. Cost-benefit evaluation

Evaluation of alternatives entails quantifying costs and benefits and calculating performance parameters. These are typically financial performance parameters, and most commonly, all costs and benefits are monetized and combined in a single objective function corresponding to the total cost. Some methods do not monetize e.g. reliability benefits but consider them in a multi-objective framework [20]. Technical constraints enter the evaluation as hard constraints (disqualifying alternatives with constraint violation) or probabilistic constraints (chance constraints allowing violations with a certain probability, e.g. as in [21]; cf. also [22]). Some methods instead use soft constraints in which technical constraint violation or technical performance is monetized in separate terms of the objective function (e.g. as technical performance costs [23-27]), but it is often not stated how the cost factors needed in such terms can be derived.

Net Present Value (NPV) of grid planning alternatives is the financial parameter most commonly used in the literature. NPV calculation implies discounting of the cash flow (monetized costs and benefits) over the planning horizon

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[1] https://interflex-h2020.com/
[2] https://www.sintef.no/prosjekter/flexnett/
[3] https://boss-project.com/
[4] https://www.euislands.eu/insulae-kickoff

considering interest rates and inflation rates. Methods considering an investment decision without an extended planning horizon often annualize future costs and benefits using similar financial modelling techniques. Alternative financial modelling techniques and performance parameters such as Return on Investment [28], Internal Rate of Return (IRR) [28-30], payback time [28, 30, 31], option values [31, 32], Weighted Average Cost of Capital, or benefit/cost ratio [30, 33] are rarely used in the literature.

The reviewed references primarily consider the expected value of the performance parameters for the alternatives that are evaluated. This means that the risk associated with uncertainties in costs or benefits are usually neglected in the evaluation and comparison of the alternatives. Exceptions include [34], which considers modified risk-adjusted cost ratios, and [35], which quantifies the Conditional Value at Risk using probabilistic simulations. Furthermore, the sensitivity of the cost-benefit results to uncertain input parameters is rarely considered systematically as an integrated part of the CBA methodology. Exceptions include [29] and [36], which visualize the dependence of the performance parameters (such as IRR) on key input parameters (such as BESS investment costs and market prices for BESS services).

B. Investment model

Relevant decision variables for investment decisions of BESS alternatives include energy and power capacity (sizing), placement (siting), the type of BESS technology, and timing of investments. The expected BESS economic lifetime (typically assumed to be around 10 years in the reviewed literature) is much lower than the technical lifetime of traditional grid assets (typically multiple decades). One must therefore expect that BESS assets have to be replaced during the long-term (grid) planning horizon. A majority of the reviewed references focus exclusively on BESS as grid planning alternatives and only some [28, 37-41] explicitly consider both grid reinvestment and BESS alternatives. Often it is not explicitly described whether BESS is considered as a temporary solution to postpone grid reinvestments [38, 42] or as a more permanent solution.

The investment models considered in the literature can be broadly categorized as a) simulation-based models or b) mathematical optimization models. In the former, planning alternatives are evaluated (simulated) individually. In a minority of the reviewed references, the analyst has to select a (typically) small set of alternatives. In others, the evaluation of alternatives in the defined solution space is guided by a meta-heuristic optimization method, e.g. based on Genetic Algorithms or Particle Swarm Optimization methods. The investment models in category (b) formulate and solve the investment problem using mathematical programming, e.g. as a Mixed Integer (Non-)Linear Program.

The investment model often considers a long-term planning horizon (i.e. several years). Thus, it often also considers long-term scenarios that capture the development, variability and uncertainty in input variables that exist over such time horizon. This includes development (typically growth) of load demand and VRES generation, typically by some annual growth factor. The most common modelling approach is to consider a single scenario for e.g. load growth. This approach neglects the uncertainty in the development of input parameters, and some methods therefore employ techniques for stochastic optimization, e.g. scenario trees [41]. However, several published works neglect long-term scenarios entirely, and perform the CBA based on one representative year. Development (degradation) of the technical condition of grid assets is not considered in the reviewed literature.

C. Operational model

The operational modelling in the CBA needs to emulate BESS operation (e.g. the charging/discharging schedule over the day). One key challenge that must be considered is the inter-dependency of operational (charging/discharging) decisions at different time steps: Simply put, the capability to discharge the BESS at one time step is dependent upon the decision to charge the BESS at an earlier time step. Static grid planning methods are thus of limited value in the presence of BESS. Common approaches to modelling operation are i) simulation using some heuristic model of the BESS operational strategy or ii) using an optimization model. The latter approach is typically represented by some variant of a Multi-Period Optimal Power Flow (MPOPF) model to capture the storage dynamics and the temporal inter-dependencies of operational decisions. Reference [36] also applies a Model Predictive Control (MPC) approach to MPOPF. If the same BESS is to provide multiple (stacked) services, the trade-off between these must be represented in the operational model.

The operational modelling needs to consider some short-term scenario for input variables such as load demand, VRES generation, electricity prices, etc. A typical modelling approach is the use of daily profiles, e.g. representative 24-hour load or PV time series with hourly resolution. For a more probabilistic approach, capturing a wider range of typical variability, some models use several representative profiles (e.g. for different seasons [25, 41] or from clustering [27, 43]) or full yearly time series. In addition, probability density functions may be considered for each hour, in some models [21, 25] combined with probabilistic load flow calculations. Stochastic optimization models could also be considered to capture short-term uncertainty, but this modelling approach does not seem to be common in state-of-the art CBA methods.

D. Coupling of investment and operational models

Operational modelling can be embedded in a single (bi-level) mathematical programming model in the form of sub-problems of a master investment problem. Alternatively, models for the two time scales can be more loosely coupled by running the operational model in the inner loop of a simulation-based investment model. Some works [27, 36, 44] use Benders Decomposition to decompose the optimization model. Others [38, 45] decouple the investment and operational model and speed up computations by first generating tables of operational benefits and/or costs in a pre-processing phase before using these in the investment model. The operational and investment time scales are in principle also coupled through BESS degradation [36]: In reality, BESS lifetime can depend strongly upon how the BESS is operated, and thus operational modelling can affect the timing of BESS disposal or reinvestment in the investment model.

IV. COMPUTATIONAL METHODS FOR BESS IN PRACTICE

In this section, the use of CBA methods is discussed in light of the real-world BESS applications introduced in Section II. In their review of economic viable use cases of energy storage systems, Ref. [1] analyses the use cases of 612 real-world storage projects, but they do not report on analysis of economic viability or CBA analysis for these. Likewise, Ref. [46] presents a review of real-life applications of energy storage systems but do not comment on analyses of the economic viability of any of the real-life projects that are reviewed. Among the real-word projects reported on in [8], a cost-benefit analysis is outlined for three BESS systems installed by the Korea Electrotechnology Research Institute and applied to demand side management. However, this analysis is based on operational data and could not have been carried out prior to the investment decision for the project.

A recent project which focus on CBA of BESS is the EU-project StoRES [5], where the CBA provides guidance and advice for residential BESSs connected to roof-top PV systems. In this project, the applied CBA framework was based on the JRC Reference Report, which provides guidelines for conducting a CBA of smart grid projects [47]. The main stages followed in the CBA of the StoRES project is: 1. Review and description of technologies, elements and goals of the project; 2. Quantify costs; 3. Map assets onto functionalities; 4. Map functionalities onto benefits; 5. Establish the baselines; 6. Monetize benefits and identify beneficiaries; and 7. Compare costs and benefits. After the implementation of these steps, the outcome of the CBA of this study are refined through a sensitivity analysis, whose primary aim is to identify the range of the critical variables of the project for which the net present value is positive.

So, with a few exceptions, little information is publicly available on how CBA analyses are performed for actual BESS installations, whether the BESS is planned to be used for grid services, price arbitrage, self-consumption of PV or other purposes. Where statements of economic viability or favourable CBA results are found, this is rarely substantiated by quantitative analysis or reference to the (computational) methods employed in the CBA. One obvious reason that many real-world BESS projects have been at the demonstration stage, which does not need to justify selecting a BESS alternative by a CBA. In other cases, e.g. for grid-scale and commercial storage projects, cost-benefit information may not be publicly available. On the other hand, the research literature on the same topic is vast, but to very little extent applied in practical cases.

V. Observations and Recommendations

Considering the utilization of BESS as an alternative to grid reinvestment, several important observations can be made on the gap between the requirements of grid companies and the state-of-the-art CBA methods presented in the research literature: The scope of most methods is limited to cover only parts of the overall grid planning process, and they do not always explicitly address which needs BESS are considered to meet. Many methods do not consider other alternatives than BESS to meet these needs (e.g. grid reinvestment) in their solution space. The underlying perspective of the methods (e.g. taking a grid operator or BESS operator perspective) depends on market and regulation assumptions, but these are rarely spelled out clearly in the literature. It is often not stated explicitly what the planning horizon is, which affects which long-term uncertainties are relevant and how they should be handled. In the evaluation of different alternatives, the methods often do not provide information about the uncertainties and risks associated with the alternatives.

For research-based methods to be suitable for grid planning, we can make the following recommendations based on these observations: The methods should handle timing of installations as well as sizing and siting, especially for cases where BESS can be a temporary solution. Moreover, they must capture long-term development in the need triggering the grid planning process (e.g. growth in load demand or PV) and preferably also the associated uncertainty. Furthermore, the use of BESS for long-term grid planning introduces new risks associated with short-term operational uncertainties [40], e.g. the availability of BESS services provided by a third-party BESS operator, and these are rarely considered in the research literature. In practice, putting the CBA in a broader, multi-criteria decision making framework is necessary to properly account for new risks associated with BESS as alternatives to traditional grid alternatives. Finally, the CBA methods need a realistic modelling of the operational benefits of BESS. This comprises models that captures multi-period AC power flow with acceptable computation times, representative variations of load and generation over the year, realistic modelling of lifetime of the batteries, and last but not least multiple services and the trade-off between these services.

VI. Concluding Remarks

BESS is increasingly considered as a viable asset in the grid for a range of uses, such as VRES balancing, grid reinvestment deferral, and various grid services. The research literature has proposed a large number of different methods for cost-benefit analysis of using BESS as an alternative to grid reinvestments. But these methods have to very little extent been adopted by grid companies and other relevant actors, and there is a significant gap between research and practice. An obvious reason is that grid use of BESS is still on an early stage of development and most installations so far are used for demonstration purposes. However, this will probably change in the near future since BESS costs are expected to continue to decrease. It will be crucial for the grid companies to be able to include BESS in their planning processes in a proper way, whether they are allowed to install BESS themselves or will rely on other actors to provide grid services.

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