Battery Energy Storage Systems as an Alternative to Conventional Grid Reinforcement

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ABSTRACT

The upcoming transformation from internal combustion vehicles to electric vehicles in the private transport sector, together with the increasing demand for electricity, leads to challenges such as over-loading for the power grid. This study shows an economic analysis to what extent storage systems can be an alternative to conventional grid reinforcement. Current and predicted costs for storage systems are compared with the costs for cable replacement in the mediumvoltage grid and correlations are derived. Accurate cosimulations of storage systems and the distribution grid allow these cost scenarios to be applied to use cases. The results show that the energy related costs for storage systems decrease about 38.5 % from 468 \$/kWh to 288 \$/kWh from 2020 to 2030. This leads to scenarios, mainly in urban distribution grids, where storage systems are an alternative to conventional grid reinforcement.

Keywords: battery energy storage, grid reinforcement, grid integrated energy storage, energy management system, lithium-ion battery, economic analysis

NOMENCLATURE

Abbreviations			
BESS	battery energy storage system		
e ^{rate}	energy rate of the battery energy storage system		
LIB	lithium-ion battery		
LV	low voltage		
MV	medium voltage		
open_BEA	open battery models for electrical grid applications		
SimSES	simulation of stationary energy storage systems		

Parameters & symbols			
C _{BEES}	specific energy costs in \$/kWh		
CGrid	specific grid reinforcement costs in \$/km		
Сар	maximum economic capacity in kWh		
сар	length-specific capacity in kWh/km		
d	discount factor		
fit _{1,} fit ₂	fitting parameters		
	length of grid reinforcement in km		
r	discount rate		
t _{BESS}	depreciation period of the BESS		
t _{inv}	year of the investment		
t _{inv,c}	year of the investment, corrected		
t _{Grid}	depreciation period of the cables		

1. INTRODUCTION

Increased electricity demand, mainly caused by electric vehicles and heat pumps, together with new generator units such as wind and solar power plants poses new challenges for the distribution grid [1]. While in rural areas, the increased share of renewable energies, resulting in over voltages is the main cause of grid reinforcement, in urban distribution grids, it is forecasted that over-loading will be the main driver therefore [2].

In the literature, various approaches exist to avoid grid reinforcement. Especially in the field of electric vehicles, a number of researches deal with controlled charging strategies or Vehicle-to-Grid approaches [3,4]. Battery energy storage systems (BESSs) are seen as an alternative without influencing owners of electric vehicles [5]. Due to the decreasing costs of lithium-ion

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batteries (LIBs), this opportunity might be even more interesting in the future [6].

However, in the past stationary BESSs had been often used in behind-the-meter applications to avoid over-loading, such as buffer storage for electric vehicle charging stations [7]. This study evaluates the possibility of integration BESSs as an active part of distribution grid planning, which allows the grid owner to manage the energy flow of the storage system.

The use of energy storage is compared economically with conventional grid reinforcement. First, a cost model for current and future BESS prices is developed and compared with the costs for cable replacement in the medium-voltage (MV) grid. Second, these cost scenarios are applied to use cases in a test grid together with a detailed analysis of the BESS. This detailed analysis allows an estimation of additional revenues for the BESS. A graphical representation can be found in Fig. 1.

1.1 Outline of this study

The remainder of this paper is structured as follows: Configuration of the grid modeling tool as well as the simulation settings for the BESS are described in Section 2. Section 3 describes the methodology of this study including a data and graphical representation of the economics. Section 4 shows some use cases, where the cost scenarios are applied, while Section 5 gives an outlook and concludes the paper.

2. SIMULATION FRAMEWORK

2.1 Grid modeling

The holistic open-source simulation tool open_BEA expanded as part of this study enables BESSs to be integrated into MV grids as well as low-voltage (LV) grids in order to analyze the effects of the various operating strategies. The source code is programmed in Python and the framework has been used in a former publication [8]. The main characteristic is the ability to assign individual time series to the various actors in the grid, such as residential or industrial consumers.

Furthermore, electric vehicles charging parks can be integrated at various nodes to investigate the effects of increasing the share of electric mobility. One of these effects is the need of grid reinforcement. With open_BEA, conventional grid reinforcement can be compared with the usage of BESSs.

2.2 Simulation of stationary energy storage systems

To analyze the behavior of the BESS in various operation modes a detailed simulation is necessary [9]. In this study, the storage system is used to avoid conventional grid reinforcement. For the analysis of the BESS, a simulation tool of stationary energy storage systems (SimSES) is used.

SimSES is a holistic simulation framework specialized in evaluating energy storage technologies technically and economically [10]. With a modular approach, SimSES covers various topologies, system components such as



Fig. 1. Graphical overview of the test scenario where the cost model for battery energy storage system and grid reinforcement is applied. The test grid includes a medium voltage grid with several underlying low voltage grids. The storage system is modeled in detail as shown in the blow-up.

power electronic units, and storage technologies embedded in an energy storage application. SimSES is used in this contribution to gain insights about the stress of the storage system operating to reduce the peak load and consequently avoid grid reinforcement. As a result, lifetime forecasts for the storage system in this operation mode can be obtained, for example.

3. ECONOMICS OF BATTERY ENERGY STORAGE SYSTEMS AND GRID REINFORCEMENT

In this section, the economic correlation of LIB based BEESs and conventional grid reinforcement is investigated. After defining the cost components, a data research gives an overview of the current and future costs. To consider different assumptions and cost prognosis, the data is organized in cost scenarios by functional expressions.

3.1 Battery energy storage systems

With the focus to an economic comparison of the BESS and conventional grid reinforcement, the data research only includes investment costs. Issuances for operation and maintenance are neglected.

In case of the BESS, the specific energy costs are declared on system level, containing all costs for the storage section, power electronics and additional equipment for grid coupling and system balance [11]. Due to an impact of the BESS design and dimensioning on the specific costs, requirements on the data quality are needed [12]. In this publication, we focus on BESSs with an e^{rate} of one. With an integration in the MV-grid, the storage capacity ranges between an industrial- and large-scale system with a few 100 kWh up to some MWh [13].

In addition to the BESS specifications, each publication gives a cost development with at least three data points between 2016 and 2040. Linearly interpolated, the data set splits up in three scenarios. While scenario *base* with a moderate cost development is defined by the mean values, the scenarios *low* and *high* represent optimistic and conservative prognosis in the 95 % confidence interval. To describe each scenario by a cost function, curve-fittings are performed. As a result, the hyperbola in Eq. (1) returns the specific energy costs C_{BESS} depending on the year of the investment t_{inv} . The fitting parameters fit₁ (\$/kWh) and fit₂ are dependent on the cost scenarios.

$$c_{\text{BESS}} = \frac{\text{fit}_1}{t_{\text{inv}} + \text{fit}_2} \tag{1}$$

Fig. 2 depicts the cost functions with the data points of the publications. Between 2020 and 2030 the specific energy costs decrease about 38.5 % from 468 \$/kWh to 288 \$/kWh in the scenario *base*.



Fig. 2. Specific energy costs of the battery energy storage system depending on the year of the investment. Data points and resulting cost functions for the scenarios base, low and high are based on [12,14–20].

3.2 Grid reinforcement

The approach of conventional grid reinforcement is to avoid grid congestions by extending or replacing the equipment. In this economic comparison, the parallel installation of MV-cables is used to reinforce the grid. Therefore, the cable from type NA2XS2Y, 3x1x185 mm², which is common in German distribution grid, is set as standard equipment for the following data research. In this, the material as well as the installation costs are considered [21].

Moreover, because of the higher installation costs for compressed surface, the specific costs are classified by rural and urban areas. Due to the limited data situation, the resulting costs do not show a development trend and include no information concerning the future. Therefore, the costs for the scenarios *base*, *low* and *high* are determined with the current data. Table 1 shows the specific grid reinforcement costs for these scenarios.

Table 1. Specific grid reinforcement costs in medium voltage-grids for cable extension in rural as well as urban areas. The data for the various scenarios are based on [21–29].

	specific costs in \$/km			
scenario	low	base	high	
rural	116 000	133 000	150 000	
urban	151 000	177 000	203 000	

3.3 Economic correlation of battery energy storage systems and grid reinforcement

In the following, an economic correlation between the BESS capacity and the length of the grid reinforcement is defined, with the purpose to determine the maximum capacity that allows an economic use case for the BESS at a specific cable length. Under consideration of the cost functions, it is the point at which the discounted costs of the BESS are equal to those of the grid reinforcement. In Eq. (2), the maximum economic storage capacity Cap is described by the discount factor d, the length-specific capacity cap, the correction on the year of the investment $t_{inv,c}$ and the length l.

$$Cap = cap \cdot t_{inv,c} \cdot d \cdot l \tag{2}$$

With:

 $cap = \frac{c_{Grid}}{fit_1}$ $t_{inv,c} = t_{inv} + fit_2$ $d = (1 + r)^{(t_{BESS} - t_{Grid})}$

For extension lengths of 40 km in rural areas and 20 km in urban regions, the capacities, for which the discounted costs of the BESS are lower than for a conventional grid reinforcement, are displayed in Fig. 3. In addition, the capacities are compared for a year of the investment in 2020 and 2030. For this, the discount rate is assumed with 6 % and the depreciation periods for the BESS and the MV-cable are set with 10 years and 40 years [21,30].



Fig. 3. Economic capacity of the battery energy storage system depending on the length of grid reinforcement in a) to c) for rural areas and d) to f) for urban areas.

4. ECONOMIC COMPARISON OF BATTERY ENERGY STORAGE SYSTEMS AND GRID REINFORCEMENT

The theoretical economic correlation of BESSs and grid reinforcement is applied to some use-cases in this section. After defining the scenario and the simulation settings, the storage sizing and the energy management strategy are described. Finally, the results of the use cases are discussed.

4.1 Simulation setting

In order to compare the economics of BESSs and grid reinforcement, a test distribution grid is selected consisting of a MV grid and 146 underlying LV grids [31]. The simulation and evaluation is performed with the simulation tools described in Section 2. The various load profiles for the industrial as well as residual consumers are based on an previous publication [9].

The mean annual consumption of the residual consumers is set to 6113 kWh, according to a predicted future demand [32, 33]. Resulting from the future demand four cables in the MV grid are beyond their limits and must be reinforced. The lengths of these cables vary from 6.66 km to 17.62 km.

4.2 Storage sizing and energy management strategy to avoid grid reinforcement

To avoid grid reinforcement, a BESS is integrated for each cable extension in the simulated MV grid. For sizing the BESSs, an iterative procedure is implemented in open_BEA. With the aim of avoiding the cable extensions, the BESS capacities are determined in a range between 100 kWh and 2 MWh for MV-level with a 100 kWh discretization.

Since each BESS is allocated to an extended cable, the grid positions of the BESSs equal to those of the grid reinforcement. At these positions, a state-of-the-art peak shaving strategy is performed by the BESS to reduce the grid load [34]. Table 2 shows the configuration of the four positions including the associated peak shaving limits.

Table 2. Parameters of all needed battery energy storage systems to avoid grid reinforcement.

Positions	Capacity	Peak Shaving	Cable length
	in kWh	Limit	in km
BESS 1 - (x)	1400	0.68	17.62
BESS 2 - (o)	1100	0.78	6.66
BESS 3 - (□)	100	0.95	12.45
BESS 4 - (+)	100	0.95	15.37

4.3 Results and Discussion

The four cables in the MV grid, which are beyond their limits, are relieved with a BESS and economically assessed. The results are showed in Fig. 4 for rural areas (a-c) as well as for urban areas (d-f).

BESS 1 (x) with a capacity of 1400 kWh is only competitive in a few cases, despite the long distance (17.62 km) of cable reinforcement that it avoids. Especially in urban areas this scenario only appears when storage costs are falling rapidly and grid reinforcement costs are high. If both remain in the base scenario, this BESS would only be worthwhile in 2030.

BESS 2 (O) with a capacity of 1100 kWh, on the other hand, is not competitive with conventional grid reinforcement. This is because the distance of the cable to be extended is only 6.66 km. Even in urban areas and in the best case for storage (year 2030, subplot d) the costs are identical.

The two storage systems with the least capacity required, BESS 3 (\Box) and BESS 4 (+), are in all cases competitive with conventional grid expansion. Due to the low capacity (100 kWh each) and the relatively long cable distances (12.45 km and 15.37 km), these BESSs are cheaper even with slightly decreasing storage costs and in rural areas.



Fig. 4. Classification of the four battery energy storage systems avoiding grid reinforcement in the economic correlation. Subplots a) to c) for rural areas and subplots d) to f) for urban areas.

5. CONCLUSION AND OUTLOOK

This study shows an economic analysis to what extent storage systems can be an alternative to conventional grid reinforcement. Current and predicted costs for storage systems are compared with the costs for cable replacement in the MV grid and correlations are derived. Accurate co-simulations of storage systems and the distribution grids allow these cost scenarios to be applied to use cases.

An economic analysis of storage systems is conducted for BESSs capacities in a range between a few 100 kWh up to some MWh. Three scenarios are derived from the available data. The results show that between 2020 and 2030 the specific energy costs decrease about 38.5 % from 468 \$/kWh to 288 \$/kWh in a base scenario. To describe each scenario by a cost function, curvefittings are performed.

The four investigated cases of cables extensions can be avoided by integrating BESS with a peak shaving strategy in the distribution grid. Therefore, the storage capacity is determined with an iterative procedure considering the loads at the positions with grid reinforcement.

The results show, that mainly in urban areas, BESSs can be competitive with conventional grid reinforcement now and even more in 2030. Especially, if small storage capacities are necessary to avoid grid reinforcement, grid operators should consider the possibility of a BESS integration.

5.1 Outlook

In future studies, ancillary services, such as frequency containment reserve, can be assigned to the BESS with the aim of making it more competitive. In addition to an economic analysis, an ecological assessment would allow a more precise investigation of the differences between conventional grid reinforcement and BESSs installation.

Furthermore, smart charging strategies or the potential of Vehicle-2-Grid at residential as well as public charging locations can be used to reduce the stress on the distribution grid resulting from a high EV-share. The simulation tools presented in this study might be used to investigate the effect of these strategies on the distribution grid.

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AUTHOR CONTRIBUTIONS

Daniel Kucevic: Conceptualization, Methodology, Software, Investigation, Writing - Original Draft Rebecca Meißner: Methodology, Software, Formal analysis, Writing – Original Draft, Visualization Andreas Jossen: Writing - Review & Editing, Supervision Holger Hesse: Methodology, Writing - Review & Editing, Supervision

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