Use of Energy Storage Systems in Low Voltage Networks with High Photovoltaic System Penetration

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Abstract—The objective of this study is to analyze the influence of electrochemical energy storage systems on low voltage grids with high penetration of renewables (RES), mostly photovoltaic power stations (PV). Furthermore, it compares the integration of energy storage systems (ESS) with other alternative solutions economically. It also presents the simulation results for a German power network in a suburban area of Bavaria. In the case study, the ESS are used to reduce overloading of electrical equipment (e.g. power cables and transformers) caused by fluctuating generation of integrated RES. The simulation results reveal that economic use of energy storage to support the grid is feasible when it is accompanied by a specific incentive. The storage tariff necessary for this is comparable with the initial Renewable Energy Act tariff for renewables, thus making this a realistic method for facilitating the use of EES that benefits the grid.

Index Terms—cost-benefit analysis, electrochemical energy storage, electrical grids, renewable energy sources.

I. INTRODUCTION

The development of smart grids and the increasing integration of RES in the electrical grid have intensified present and future need for ESS, thus making ESS a priority research topic worldwide. Basic research [1]-[5] has specified the technical attributes of different ESS and this has been used to identify the pros and cons for typical use cases and fields of application. In addition, [6] provides a summary of lithium-ion batteries. After analyzing different ESS, [7] concentrates on typical use cases for them. These include voltage control, power flow management, restoration, network management and participation in the energy market. Most research projects on low voltage grids focus on two use cases. On the one hand, voltage stabilization is a typical use case of ESS. This is analyzed in [8]. An overview of potential uses of ESS owned by end customers for voltage stability is provided in [9] and a method for optimal parallel operation of ESS and tap changing transformers is presented in [10]. On the other hand, balancing the generation of fluctuating RES is an important application of ESS, which is described in detail in [11]-[14]. This range of potential uses makes EES important for the operation of future smart and micro grids since they can effectively contribute to their stabilization.

Unlike previous studies, this paper concentrates on an economic comparison of ESS and alternative solutions. Their use to relieve load on equipment is examined more closely. This study is additionally intended to analyze the conditions under which the use of EES beneficial to the grid is also economically feasible.

II. GRID STRUCTURE MODELING

A. Power Grid Structure

This study focuses on a low voltage distribution grid in a suburban area in the German state of Bavaria. Bavaria has a large proportion of renewables, primarily photovoltaic, in the low voltage power grid and thus offers optimal conditions for this study. Figure 1 shows the per capita installed PV capacity for different suburban areas in Bavaria, thus making clear why this low voltage grid and this region were selected. The selected location has an installed PV capacity of 2.4 kW/cap and thus represents the top 8.94% of all suburbs considered. Since this region is not an isolated case and nevertheless has a high proportion of renewables, it can consequently be used for this study.

Figure 1. Installed PV capacity per capita in suburbs [15], [16]
Once a suburb had been selected, a single low voltage grid in this location had to be selected and modeled. Selection of a low voltage grid was based on grid structure data from the distribution system operator [17] from which typical mean parameters for low voltage grids in the region were determined. Then, the selected region was clustered. Assuming that the population of every cluster is identical and factoring in the average parameters identified, a possible low voltage grid was selected. Since suburban low voltage grids are generally characterized by a rural structure [18], the substation was integrated in the center of the area selected and the different lines were laid parallel to the existing infrastructure. The final low voltage grid (see Figure 2) consists of four individual lines with a total of fifty-seven households and two farms.

![Figure 2. Structure of the low voltage grid selected](image)

**B. Electrical Grid Parameters**

Cables and transformer are dimensioned on the basis of simulation results for the year 2012, which were obtained by assuming that the maximum utility load was between 60% and 80%. This allowed using a 400 kVA transformer and NAYY-J 4*70 mm² cable.

**C. Integration of PV Power Plants and Electrical Loads**

The basic scenario (2012) incorporates the PV power plants in operation in 2012. They were selected from master data taken from the German Renewable Energy Act [15]. These data make it possible to assign power plants directly to actual household connections. The 2013 Network Development Plan and its scenarios B2023 and B2033 for Bavaria were used [19] to forecast future PV penetration in the low voltage grid. The resulting development factors and the installed PV capacity are presented in Table I. A randomized algorithm that distributes individual systems among household connections without PV power plants in 2012 was used to allocate the additional PV capacity of the future scenarios set in 2023 and 2033 to household connections. The installed power per PV power plant is based on the average installed power per power plant in the existing low voltage grid. The Max Planck Institute for Meteorology’s REMO climate model [20] was used to generate supply profiles for every scenario. This model contains time series of sunlight in different regions from which the incoming supply from PV power plants can be determined on the basis of generation curves.

### Table I. Installed PV Capacity in Bavaria and Development Factors for Several Years [19]

<table>
<thead>
<tr>
<th>Year</th>
<th>PV Capacity [GW]</th>
<th>Development Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012</td>
<td>9</td>
<td>1</td>
</tr>
<tr>
<td>2023</td>
<td>15.1</td>
<td>1.68</td>
</tr>
<tr>
<td>2033</td>
<td>15.8</td>
<td>1.76</td>
</tr>
</tbody>
</table>

A difference was made between the electrical load of households and of farms. The load profiles of households were produced by a load generator, which varies the number of residents and the appliances used in a household according to a normal distribution to produce an individual synthetic load profile for each household. The electrical load of farms, on the other hand, is modeled using the standard load profile L0 [21] and the installed power is based on the average installed power per farm in Germany.

III. ESS Modeling

A. Selection of ESS

The voltage level analyzed and power and capacity required make it possible to use electrochemical ESS in this study. They have short response times and are easily scalable. Lead acid batteries were selected as the electrochemical ESS because of their high level of development [22].

B. ESS Model

The use of ESS is intended to reduce cable overloads. The power generated by PV, which exceeds the electrical load in the low voltage grid significantly, results in substantial exported power. This exported power causes grid overloads, which can be reduced by charging the ESS. The first section of cable of every line is utilized to maximum capacity, e.g. in L01 und L30 in Figure 2, since it absorbs the power generated by PV and exports it through the distribution transformer to the primary voltage level. In order to use this model, a measurement must be taken on the first section of cable of every line. The resulting ESS model is presented in Figure 3.

Once the transferred active power of the first section of cable (z. B. L30) has been imported, the necessary storage capacity can be determined. The ESS is regulated by a $P_{\text{ESS}}(P_{\text{Line}})$ curve (see Figure 4), i.e. the moment the maximum cable load is exceeded the ESS stores energy to relieve the electrical grid. The charged energy can be used to cover the electrical load in the evening and at night. This is possible because the peak loads occur at defined times.

![Figure 3. ESS Model](image)
The ESS model is built so that it can output the necessary ESS parameters as a function of the incoming line load $P_{\text{Line}}$. To do so, the necessary ESS capacity is determined in the first step using the $P_{\text{ESS}}(P_{\text{Line}})$ curve. Then, the ESS capacity can be modeled incorporating the efficiency. Since the limits of overcharging and overloading are disregarded, the potential state of charge is between 0…100 % of ESS capacity. The capacity must be adjusted by a scale factor as a function of the storage system technology employed.

![Diagram](image)

**Figure 4.** Power characteristic of the peak shaving ESS

A twenty-four hour storage system was also modeled. Rather than being fixed, the value $P_{\text{Line,max}}$ in this ESS model is calculated as a function of the daily maximum line load, thus reducing the line load to a specific percentage utilization every day. An exact forecast is, therefore, required in order to use this model. To be able to compare these two ESS models, the maximum percentage utilization on one day was determined so that the maximum line utilization is equally high when both models are applied.

IV. DEFINED SCENARIOS

TABLE II presents an overview of the simulation scenarios defined. First, three scenarios, without methods to support grid operation, e.g. network expansion or ESS, are analyzed. These scenarios allow quantifying the development of grid utility loads, which result from the greater impact of energy incoming from PV, until 2033. The scenario for 2033 is subsequently used to analyze ESS use and demand for network expansion and reduction of PV capacity. In the final step, these three methods are compared with each other.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-2012</td>
<td>scenario 2012 without actions</td>
</tr>
<tr>
<td>B-2023</td>
<td>scenario 2023 without actions</td>
</tr>
<tr>
<td>B-2033</td>
<td>scenario 2033 without actions</td>
</tr>
<tr>
<td>S1-2033</td>
<td>scenario 2033 with peak shaving ESS</td>
</tr>
<tr>
<td>S2-2033</td>
<td>scenario 2033 with twenty-four hour storage system</td>
</tr>
<tr>
<td>N-2033</td>
<td>scenario 2033 with grid expansion</td>
</tr>
<tr>
<td>P-2033</td>
<td>scenario 2033 with PV reduction</td>
</tr>
</tbody>
</table>

V. SIMULATION RESULTS

A. Development of Grid Utilization

Expansion of the installed PV capacity increases grid load significantly as a result of the substantial power exported. This affects line loads and node voltages. The development of these parameters for every single line and scenario is presented in Figure 5. The additional generation affects primary lines 2 and 3, causing cable overloads. A rise in maximum voltage is identifiable in both lines, too, but the limits of DIN EN 50160 are not exceeded. Methods of voltage regulation are not given further consideration in this study.

![Graphs](image)

**Figure 5.** Maximum line currents (left) and node voltages (right) per line and scenario

Figure 6 also shows annual profiles of current load in the most critical cable section (L30) and voltage in the most critical nodes (K49). The significant influence of PV capacity on grid load is evident since they are typical seasonal and daily profiles. What is more, maximum loads occur infrequently over a year. Intervention in grid operation was necessary only 1 % of any time in 2023. This will increase to 4 % in 2033. Ensuring reliable grid operation will necessitate a reduction of generation from renewables by at least 0.38 MWh in 2023 and by at least 3.34 MWh in 2033. This can be achieved by using ESS or directly reducing PV power plants’ production. What is more, grid operation can be sustained by expanding it. This would require expanding five cable sections in 2023 and eight in 2033.

![Graphs](image)

**Figure 6.** Year profiles of cable section L30 (left) and node K49 (right)

B. Use of Energy Storage

Given the high loads in the electrical grid, use of ESS in 2033 was analyzed. In this scenario, maximum consumption occurs in lines 2 and 3, thus requiring the integration of at least one separate ESS in each line. The positioning of the ESS can be explained by Figure 7, which provides an overview of the maximum line current in every single cable section of line 3. Since the first six cable sections of line 3 are overloaded, the ESS has to be positioned after these cable sections in order to relieve complete line. The effect is
optimized when energy storage is integrated in the last section of the line. This reduces loading of other cable sections and the ESS additionally contributes to voltage stabilization.

![Possible energy storage position](image)

Figure 7. Maximum line current of every cable section in line 3 for scenario B-2033

The effect of using ESS on the load of cable section L30 is shown in Figure 8. This underscores the exact design of both ESS since the maximum line capacity is 1.0 pu. In addition, since both ESS are charged only during peak generation, the maximum ESS power and capacity necessary are directly contingent on the duration and magnitude of the maximum peaks. The difference between the ESS models is that the ESS is charged to shave peaks only when the exported power exceeds the maximum load limit and the twenty-four hour storage system is charged even when generated capacity is low. This is evident in the low number of full load cycles (n) for the ESS to shave peaks (see TABLE III). The storage system parameters necessary to fully relieve the grid are thus only utilized in a small part of the year. The twenty-four hour storage system, on the other hand, has a significantly longer utilization period. Furthermore, the table reveals that this use case requires high capacity and comparatively little ESS power.

![Year profile of line current of cable section L30 with and without ESS](image)

Figure 8. Year profile of line current of cable section L30 with and without ESS

### TABLE III. ESS PARAMETERS

<table>
<thead>
<tr>
<th></th>
<th>S1-2033</th>
<th>S2-2033</th>
</tr>
</thead>
<tbody>
<tr>
<td>E [kWh]</td>
<td>20</td>
<td>14</td>
</tr>
<tr>
<td>P [kW]</td>
<td>10</td>
<td>104</td>
</tr>
<tr>
<td>n</td>
<td>14</td>
<td>10</td>
</tr>
<tr>
<td>E [kWh]</td>
<td>28</td>
<td>39</td>
</tr>
<tr>
<td>P [kW]</td>
<td>10</td>
<td>131</td>
</tr>
<tr>
<td>n</td>
<td>104</td>
<td></td>
</tr>
</tbody>
</table>

C. Alternative Solutions

This study employs two alternative methods of resolution to relieve the electrical grid, which can be used to compare the use of ESS. On the one hand, different network expansion methods can be used. An overview of these methods is provided in Figure 9. Option var 2 (parallel line) is used in the cost efficiency analysis below.

![Network expansion methods](image)

Figure 9. Network expansion methods

This option is the most affordable and simplest method of grid expansion. 193 m of additional cables have to be laid to ensure reliable grid operation in scenario 2033. This corresponds to a grid expansion requirement of 0.64 m/kW per installed PV capacity. This value is relatively high in comparison with other studies, the reason being that only one generic grid model, which does not reproduce mean parameters for Germany exactly, was analyzed in this study. The effect of network expansion on grid utilization is presented in Figure 10. As a whole, the load on the cable sections influenced by grid expansion is reduced significantly, thus generating new potential for PV power plants in this line.

![Maximum line current of every cable section in line 3 for scenario N-2033](image)

Figure 10. Maximum line current of every cable section in line 3 for scenario N-2033

On the other hand, the generation of renewable energy sources can be reduced. At present, such so-called grid reliability management is implemented by incrementally reducing the power generated to 60 %, 30 % or 0 % of the rated output [23]. This discrete reduction of production means that more power is always disconnected than is required. The power really disconnected differs from the findings presented in section V-A. Therefore, generation has to be decreased by 4.34 MWh instead of by 3.34 MWh in scenario 2033.
D. Economic Comparison

Use of ESS beneficial to the grid is only feasible when appropriate financial incentives exist. This means that either the cost of ESS use is lower than grid expansion or the use of ESS beneficial to the grid is compensated so that private storage system operators are also able to make a profit.

The first step entails analyzing the costs incurred under current conditions. TABLE IV presents the assumptions made. The use of grid reliability management generates costs equal to the Renewable Energy Act tariff, which a system operator has to pay to operators of PV power plants. In this study, the Renewable Energy Act tariff is assumed to be €0.1/kWh. This would generate the static costs presented in Figure 11. Since both models have virtually identical costs, only one method of ESS use is presented in the figure. The total costs incurred clearly reveal that use of ESS beneficial to the grid is infeasible under present conditions. The relatively little power that must be disconnected in the grid analyzed makes the use of grid reliability management actions the most cost effective alternative that assures reliable grid operation. Since grid expansion and the use of ESS constitute the only options to increase the percentage of renewables in power production, these two methods are examined more closely.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity price</td>
<td>€200/kWh</td>
</tr>
<tr>
<td>Power price</td>
<td>€160/kWh</td>
</tr>
<tr>
<td>Useful life</td>
<td>10 years</td>
</tr>
</tbody>
</table>

TABLE V presents the assumptions made. The use of grid reliability management generates costs equal to the Renewable Energy Act tariff, which a system operator has to pay to operators of PV power plants. In this study, the Renewable Energy Act tariff is assumed to be €0.1/kWh. This would generate the static costs presented in Figure 11. Since both models have virtually identical costs, only one method of ESS use is presented in the figure. The total costs incurred clearly reveal that use of ESS beneficial to the grid is infeasible under present conditions. The relatively little power that must be disconnected in the grid analyzed makes the use of grid reliability management actions the most cost effective alternative that assures reliable grid operation. Since grid expansion and the use of ESS constitute the only options to increase the percentage of renewables in power production, these two methods are examined more closely.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cable</td>
<td>€8/m</td>
</tr>
<tr>
<td>Cable trench</td>
<td>€80/m</td>
</tr>
<tr>
<td>Installation (with cabinet)</td>
<td>€1000</td>
</tr>
<tr>
<td>Useful life</td>
<td>30 years</td>
</tr>
</tbody>
</table>

Even if future prices of ESS were to drop to the lowest prices according to [24], the use of ESS cannot compete with grid expansion. The total costs incurred even under these optimal conditions would still be €40,000 (peak shaving) or €50,000 (twenty-four hour storage system).

The only alternative that encourage the use of ESS beneficial to the grid is, therefore, a storage system tariff that creates incentives for independent storage system operators. Figure 12 and Figure 13 plot the necessary storage system tariffs for ESS for peak shaving and twenty-four hour storage systems as a function of different storage system costs. The area of future ESS costs according to [24] is indicated in the figures.

Since the electrical ESS has a relatively lower power requirement than capacity, the reduction of inverter costs would have only a slight impact on the storage system tariff. This makes a drastic reduction of ESS costs in and of themselves essential. Factoring in the ESS prices possible in the future, the tariff for ESS for peak shaving would be between €0.45/kWh and €0.60/kWh and, under optimal conditions, the tariff would be €0.33/kWh. Increasing the period of use and, thus, the energy converted as well would reduce the necessary tariff. Thus the tariff for twenty-four hour storage systems would be between €0.20/kWh and €0.30/kWh and, under optimal conditions, the tariff would be €0.15/kWh. These values are comparable with the initial Renewable Energy Act tariff for wind turbines and PV power plants. The introduction of a storage system tariff to encourage the use of ESS beneficial to the grid is, therefore, a realistic approach.
VI. CONCLUSION

This study analyzed the use of ESS in comparison with alternative technologies and established that the use of ESS to support the grid is technically feasible. On the other hand, the use of ESS is economically in feasible under certain conditions. Only an appropriate storage system tariff will effectively encourage the use of ESS beneficial to the grid. The storage system tariff necessary is contingent on the period of use and the cost of the ESS.

Furthermore, this study did not analyze the effects on higher voltage levels. Only grid expansion can help relieve the low voltage grid itself, and the exported power supplied by PV power plants increases the load in the medium voltage level, thus making grid expansion necessary in this voltage level, too. Conversely, the use of ESS also affects the medium voltage grid since it reduces the exported power directly. Factoring in the reduced load on the medium voltage grid partly relativizes the high costs of ESS in comparison to the costs of grid expansion in the low voltage grid. These effects will have to be analyzed in another study.

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