Electricity Storage Systems in Medium- and Low-Voltage Networks

Dipl.-Ing. Andreas Becker[2], Hauke Loges M.Sc.[1], Dipl.-Wirt.-Ing. Stefan Kippelt[3], Dipl.-Wirt.-Ing. Alexander Gitis[4], Ghada Merei M.Sc.[4], Dr. Ing. Dipl. Wirt.-Ing. David Echternacht[5], Marcus Müller M.Sc.[6], Dipl.-Ing. Alexander Zeh[7] Dr.-Ing. Martin Kleimaier[8], Dr. rer. nat. Matthias Leuthold[4], Dr. Holger C. Hesse[6], Univ.-Prof. Dr.-Ing. Hans-Peter Beck[2], Prof. Dr.-Ing. Bernd Engel[1], Univ.-Prof. Dr.-Ing. Andreas Jossen[6], Univ.-Prof. Dr.-Ing. Albert Moser[5], Prof. Dr.-Ing. Christian Rehtanz[3], Univ.-Prof. Dr. rer. nat. Dirk-Uwe Sauer[4], Univ.-Prof. Dr.-Ing. Rolf Witzmann[6]

[1]Institut für Hochspannungstechnik und Elektrische Energieanlagen, TU Braunschweig, Germany
[2]Energie-Forschungszentrum Niedersachsen (EFZN), Technische Universität Clausthal, Germany
[3]Institut für Energiesysteme, Energieeffizienz und Energiewirtschaft (ie3), TU Dortmund, Germany
[4]Lehrstuhl für Elektrochemische Energiewandlung und Speichersystemtechnik, Institut für Stromrichtertechnik und Elektrische Antriebe (ISEA), RWTH Aachen University, Germany
[5]Institut für elektrische Anlagen und Energiewirtschaft (IAEW), RWTH Aachen University, Germany
[6]Lehrstuhl für Elektrische Energiespeichertechnik (EES), Technische Universität München, Germany
[7]Professur für Elektrische Energieversorgungsnetze (EEN), Technische Universität München, Germany
[8]Energietechnische Gesellschaft im VDE, Germany

This paper presents the results of the ETG (Energietechnische Gesellschaft) Task Force “Energy Storage in Distribution Networks”.
The principle result of the former ETG study “Energy Storage for the Energiewende – Need for Storage Systems and Impacts on the Transmission Network in Different Scenarios until the Year 2050” [2] is, that due to energy economic reasons, storage systems are only needed in the transmission system for a very high penetration of renewable energy sources. The research – and therefore the mentioned conclusion – is limited to the application field of balancing the fluctuating power feed-in from renewables and demand. Other fields of application for electricity storage systems, such as the provision of ancillary services or services for private and commercial customers, have not been analyzed. Therefore, the ETG Task Force “Energy Storage in Distribution Networks”, which started working in March 2013, was dealing with the arising new questions and challenges. The final report has been published in June 2015 [4]. Some of the main results are presented in this paper.

1 Application cases

The Task Force starts with describing all potential and technically feasible fields of application, differentiating between applications in responsibility of transmission system operators, distribution system operators, balancing group managers, power generation, electricity-sales as well as private and commercial customers. By using an expert survey the most promising utilizations have been figured out as followed:

- Increasing the rate of self-consumption of private and commercial customers by using a combined photovoltaic (PV) storage system.
- Provision of primary control reserve.
- Provision of secondary control and minute reserve in combination with ordinary energy trade.
- Supply of off-grid customers.
- Avoidance / deferment of necessary grid expansions.

Taking into account the mentioned selection of utilizations lithium-ion- (Li-Ion-) as well as lead-acid-batteries seem to be most suitable and therefore analyzed within the study. In this paper presented results will focus on Li-Ion-batteries. To perform necessary simulations and to ensure comparability between different utilizations, common assumptions on costs for battery systems have been used.
Due to increasing production capacities (especially in Asia), competition and market size, both capacity-rated as well as performance-rated prices are decreasing rapidly. The following table lists the made assumptions that are based on metastudies and an expert assessment available at ISEA RWTH Aachen.

Table 1: Cost Assumptions for Li-Ion-Batteries

Cost type €/kWh	2015	2025
Li-Ion-Cell	190-380	110-180
Li-Ion-System e-mobility	300-500	140-220
Li-Ion-System MW-scale	450-600	150-250
Li-Ion-System PV-Battery	750-1250	250-500
Cost type €/kW	2015	2025
Power electronics	100-150	60-90

The results are presented in the following chapters.

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1.1 Self consumption in households

About 15000 PV-battery-systems were installed in private households in Germany until the end of 2014. The main reason for these installations is to increase self-consumption, as the self-generated energy from PV may be cheaper than the energy from the grid that is burdened with taxes and fees (so-called "grid parity"). Despite the current promotion of these batteries they can usually not be operated profitably today. The use of batteries increases the independence from the electricity grid and, thus, influences the purchase decisions of customers significantly.

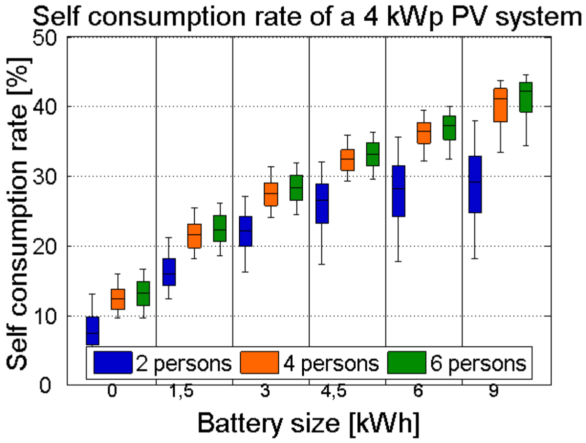

Figure 1: Self consumption of a 4 kWp system

In figure 1, the achievable self-consumption rates are illustrated for a 4 kWp PV system, depending on the size of the household and installed storage capacity. A four-person household with an annual consumption of 4200 kWh, a PV system with 4 kWp and no use of battery is able to consume on average about a quarter of the electricity produced in the household. The grid supply is therefore reduced to approximately 3300 kWh. If a battery with a capacity of 3 kWh is used, the self-consumption can increase up to 55 %, which is equivalent to approximately 2000 kWh per year. In this case, the energy needed from the public electricity network is reduced to 2200 kWh per year. Using an 8 kWp PV system without battery, the energy needed from the public electricity network can be reduced to approximately 3100 kWh. If a battery with a capacity of 3 kWh is used, the self-consumption increases by 31%. The energy needed is significantly reduced to 1900 kWh per year. The typical range of variation of the self-consumption for four- and six-person households is around 15 %.

Within the reference case, an inflation-adjusted increase of the electricity price of 2 % per year is assumed until the year 2025. At this time a value of 0.36 €/kWh will be reached and assumed to stay constant afterwards.

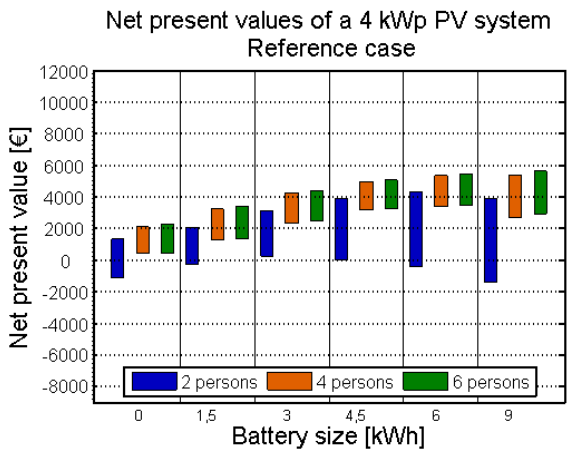

Figure 2 Net present values of a 4 kWh PV system – Reference Case

For small PV systems the best net present values can be achieved with battery sizes between 3 and 6 kWh. For the two-person household, there is no economic use in every case. Combined with a large PV-system, small batteries and particularly the PV-system with no use of battery are only partly economic. It turns out that the best net present values can be achieved with a ratio of battery capacity to PV system performance of 1:1 [kWh/kW$_p$].

1.1.1 Grid relieving self-consumption in households

The integration of BESS in electricity grids to support renewable energy power sources can be done in a beneficial way for both the grid and the end user. A typical operation strategy of a household BESS tries to charge to battery systems as soon as possible after sunrise and supply energy to the owner directly after sunset. Privately owned BESS are thus applied mostly to serve for a maximum benefit of its owner in line with the current law situation in Germany. This operation strategy has no grid relieving effect. Grid relieving can be understood as first of all reducing the maximum feed in power to a certain limit in order to relieve grid elements, as transformators and cables. The main achievement of a grid relieving operation strategy is the reduction of grid expansion and grid reinforcement costs. To achieve a grid relieving operation of a household BESS, there are a few options of which one is presented deeper in the following. Feed-in damping stores the surplus of energy throughout the whole daytime and thereby ensures a maximum SoC of the battery. Therefore a nearly constant charging power has to be implemented. This is done by dividing the spare battery capacity C_{spare} for every time step by the predicted remaining time until sunset t_{re} .[7]

$$P_{batt,ch,c}(t) = \frac{C_{spare}(t)}{t_{re}(t)}$$

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In case the feed-in power is still larger than the desired maximum value $P_{grid,max} = f_{max}$, where f_{max} is a fix maximum feed-in power [8] given by the grid, $P_{batt,ch}$ is calculated by

$$P_{batt,ch|P_{grid}>f_{max}} = P_{grid} - f_{max}$$

A feed-in damping operation strategy was applied on a 4 person household with a yearly energy consumption of 4.300 kWh and an 8 kWp PV-system. The simulation was done with a 9 kWh BESS, see Figure 3. Environmental framework data is same as all through the VDE study on BESS in low- and mid-voltages grids and chapter 1.1. [4] According to the KfW Förderprogram 275 the feed-in limitation lays at 60% of the maximum peak of the installed solar system. Known by former simulations, this feed-in limitation, the cutoff, was set here to 40% in order to show the ability of feed-in damping operation strategies.

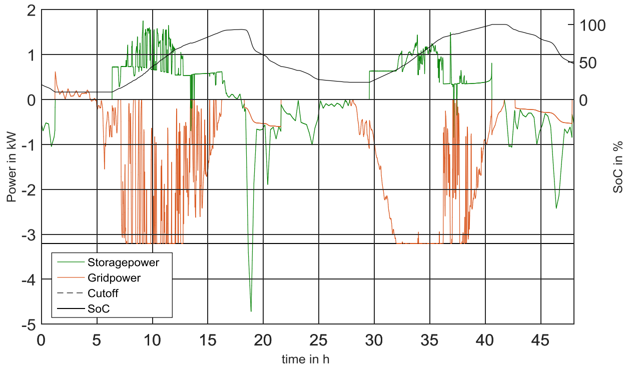

Figure 3: Operating a 9 kWh household BESS with a grid relieving operation strategy

Figure 3 shows the feed-in damping operation strategy with a 9 kWh household BESS. The system starts to store PV surplus energy after sunset, uses the pre-calculated c-rate, successfully stores any surplus over the cutoff rate of 40% and reaches 94% SoC before sunset.
The results of the aforementioned simulation data show, that a grid relieving operation strategy has only a small influence on loss in revenue for fed-in energy. Only about 1% in self-consumption rate (SCR) is lost, which can be seen in Figure 4, compared to the conventional operation strategy which was outlined.

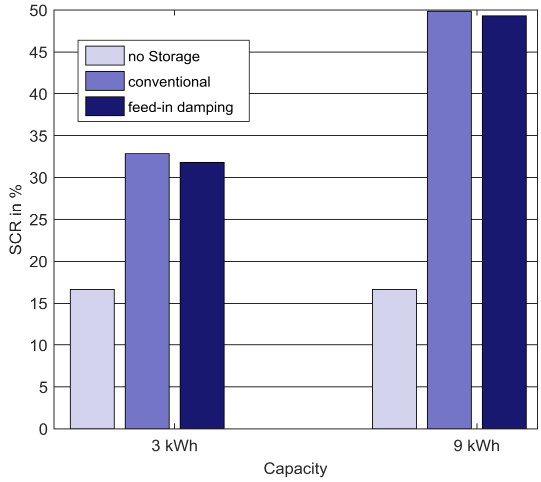

Figure 4: Self-consumption rate over different operation strategies

The simulations show, that the losses due to grid relieving operation strategies for private household BESS owners are very low. The lower curtailment loss rate in case of feed-in damping strategy is reasoned by the constant applied c-rate of the BESS. The c-rate in case of feed-in damping is calculated for each day according to environmental inputs and forecasts and is adapted online during the day when additional PV surplus is fed in the grid. Nevertheless the maximum feed-in limitation has to be calculated for each systems setup of PV and BESS in order to avoid high curtailment loss rates. The maximum available capacity of a household BESS is in consequence essential for a grid relieving BESS. Basically the capacity shortage is an individual problem by sizing household BESS reasoned by the differences in summer and winter operation and PV penetration of grids. The theoretical available energy content of household BESS in neighborhoods can thus not been used completely at any time. Compared to one large BESS installed in the rural grid itself, the shared use of many BESS with the same theoretical capacity could release even more potential to increase as well self-consumption rate, self-supply-rate as decrease curtailment losses.

1.2 Self-consumption by commercial customers

Commercial customers are a promising target group for local PV installations for self-consumption. Many of them have the space on the roof to install photovoltaic panels. Furthermore, the electricity purchase price for small and medium enterprises lies around 20 €ct/kWh, which is higher than the electricity from the solar panels (9 - 11 €ct/kWh). Additionally, their load profile correlates strongly with the generation profile of solar energy.
In this study, a dimensioning and assessment tool was developed for techno-economic analyses for PV-battery systems. For this purpose, a model of a PV-generator and a lithium-ion battery storage system was implemented in MathWorks SIMULINK, using real solar and load data measured in the field. The analyses show the influence of

different PV costs, battery sizes, battery costs and interest rates on the total system costs and, therefore, on the energy costs.

As a typical example, a PV-storage-system for a supermarket with a yearly electricity consumption of 250 MWh has been analyzed. The simulated system consists of 100 kWp PV and different sizes of li-ion batteries (0 to 50 kWh) to increase the self-consumption. For the electricity feed into the grid a feed-in tariff of 10 €ct/kWh was assumed.

In Figure 5, the economic impact of applying battery storage in the PV system is demonstrated for assumptions typical for 2015. As can clearly be seen, the installation of a PV system reduces the yearly electricity costs by about 10%. However, the installation of a battery storage system does not decrease the yearly costs further, but rather increases the costs again and therefore reducing the cost reduction achieved with the PV-system. It shows that even for very low battery price of 200 €/kWh, batteries are still not able to reduce the yearly costs of electricity. This is due to the fact that it is more economical to collect the feed-in tariff of 10 €ct/kWh than operating a battery for the increase of self-consumption.

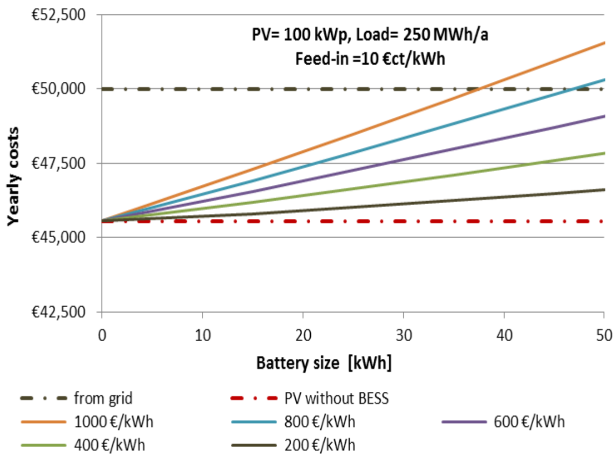

Figure 5: Yearly costs of the needed electricity for PV-battery system with different sizes and costs of the battery storage under the cost assumptions in 2015. Feed-in tariff = 10 €ct/kWh

1.3 Provision of primary control reserve

Primary control reserve (PCR) is essential for a stable and save operation of an energy supply system. Anytime soon in the course of the German “Energiewende” the PCR could be provided by large scale battery energy storage system (BESS). Within the scope of the study, a BESS model was developed and implemented in the MathWorks MATLAB environment. Both lithium-ion and lead-acid batteries were technically simulated and economically compared.

All system variations were specified with 10 MW feed-in/-out and different energy capacities of 5, 7 and 10 MWh. For the designed system an advanced energy management system (EMS) was developed, which autonomously maintains the state of charge (SoC) of the battery in an optimized window. Therefore, buy and sell orders on the EEX Intraday market are generated automatically as a function of the SoC deviation from the set value. The EMS was designed to guarantee a 100 % operation availability of the BESS providing PCR and minimize the battery aging.

To evaluate the energy management strategy and for the technical assessment, the BESS model was simulated using historical load time series, which were generated from historic frequency data with utilization of the standard PCR control characteristics. The simulated period was 3.5 month long. For the economical assessment, the investment and the operation costs for the different BESS variations were calculated. Afterwards, the net present value of the total costs and the yearly annuity were deduced and compared with the typical profit situation on the German PCR market in the last years. Also, a high price and a low price scenario for batteries were considered.

In figure 6, the results of the economical assessment of the lithium-ion BESS with a life cycle of 15 years are presented. In the simulation the calendric aging was dominating due to cyclic stability of the lithium-ion battery.

The investment costs of the converter, transformer, grid connection and the DC-battery-system were estimated. Maintenance and recharge costs have been considered as operation costs. Nevertheless, additional costs such as civil construction, trading fees and data connection could not be appraised because of various uncertainties.

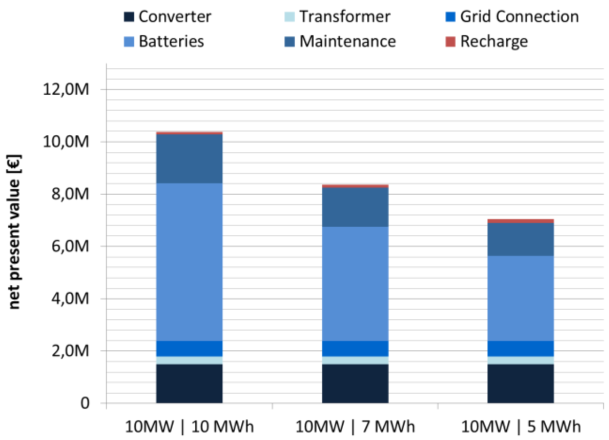

Figure 6: Net present value of investment and operation cost of a lithium-ion BESS for providing PCR

The results show that the recharge costs can be neglected in the economical assessment. The most expensive part is still the DC-battery-system, followed by the converter. The costs for the transformer and the grid connection are also relative low. The net present value is in the range between approx. € 7M and € 10M. Comparing the calculated costs with the profit potentials on the German PCR market, which are more specified in the study, the BESS for PCR are at the threshold of profitability.

1.4 Marketing storage systems on spot- and reserve-power-markets

The German transmission grid operators are responsible for frequency control and are procuring primary, secondary and tertiary reserve capacities over a special market platform [*regelleistung.net*]. Storage system operators can prequalify their system to provide services on this platform. Furthermore they can market their system on intraday and day-ahead spot-markets. Thereby, the day-ahead market allows trading of hourly and block products for scheduled generation and consumption as well as portfolio optimization on the day previous to the fulfillment. On the intraday market however 15 minutes and hourly contracts can be traded in order to optimize prediction errors and short-term deviations until 45 minutes previous to fulfillment.

Whereas the day-ahead market is a single clearing price market, the intraday market relies on pay as bid auctions. On the markets for secondary and tertiary reserve a two-step approach is used in which each vendor makes an offer for the capacity and energy price. Based on the increasingly ordered capacity prices, the offers are selected and paid by bid by the TSOs until the necessary capacities are reached (around 2000 MW for secondary reserve and 2800 MW for tertiary reserve). If reserve power needs to be activated the activation is executed based on the energy prices starting with the lowest one. For tertiary reserve the tendering period is daily with a minimum lot size of 5 MW (pooling of smaller units possible) whereat positive and negative reserve can be offered for six 4-hour time slices. The tender period for secondary control reserve is one week and offers for positive and negative reserve can be made separately for workdays between 8 am and 8 pm or the rest of the week.

In order to analyze the profitability of a storage system being marketed on spot- and reserve-markets, a yearly simulation of the contribution margins is performed utilizing a trading support tool presented in [1]. As the minimum lot size for secondary and tertiary reserve markets is 5 MW a battery storage system of this size is being simulated. The capacity of the simulated system amounts to 21 MWh as the TSO demand at least an energy capacity for 4 hours for prequalification. The simulation of the intraday and day-ahead spot-market is based on perfect foresight whereas the offers for secondary and tertiary reserve are based on average weighted historic prices for capacity as well as for energy prices from the year 2013.

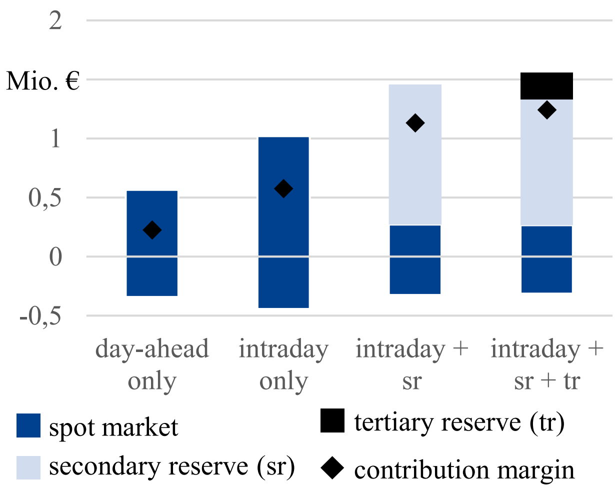

Figure 7: simulated contribution margins in 2013 for a 5 MW/21 MWh storage system

The results of the simulations are displayed in figure 7. It can be seen that a storage system which is being marketed on the intraday market can reach a higher contribution margin compared to a marketing on the day-ahead market due to a higher volatility on the intraday market. When being additionally marketed on reserve markets the system's contribution margin can be almost doubled. Nevertheless the contribution margin of the system is below its annual cost, which amount to around € 2M, so that there is no profitability for this application. Further simulation indicates that profitability could be increased if the prequalification requirements are eased and the required storage capacity would be reduced.

The future spot- and reserve-market prices cannot be predicted reliably, therefore a simulation for future points in time is not performed within the scope if this study. Based on the assumption of constant market prices, the costs for battery storage systems need to drop significantly in order to reach profitability when marketing the system.

1.5 Supply of off-grid customers

Off-grid installations are a huge worldwide market in countries with low security of electrical power supply. It is the most cost effective choice, especially for homes or businesses, such as telecommunication base stations, which are located in places beyond the reach of power lines. However, also in Germany off grid systems are a small but valuable market such as mountain huts and summer houses.

In this analysis, a holistic simulation model with PV-diesel system using lithium-ion or lead-acid battery storage was developed. Two use cases have been considered: telecommunication base station and alpine hut. The model was implemented in MathWorks SIMULINK [5]. One of the major challenges was an adequate consideration of the battery aging. Also, an advanced energy management system (EMS) was conducted to control the power flow among the system components. Moreover, EMS should satisfy the load needs with the minimal energy costs.

The whole system was simulated and optimized with real load profiles over many years. Afterwards, the economic

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assessment of the investment and operation costs was presented.
Figure 6 shows the cost analysis of the optimization results for three different scenarios: PV + diesel generator, PV+ diesel generator + lead-acid battery, PV+ diesel generator + li-ion battery.

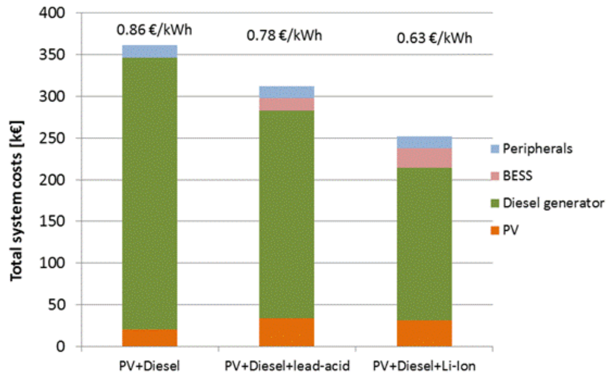

Figure 8: Total system costs, components costs and energy costs for three scenarios

As can be seen, the most cost effective solution is combining photovoltaic with li-ion batteries and using diesel generator as a back-up system. In this case energy costs of 0.63 €/kWh can be reached. The energy costs of the system using lead-acid battery storage can reach down to 0.78 €/kWh. The most expensive solution is the system without using energy storage. This can be explained by the long operation time of the diesel generator, and the consequently high fuel consumption. Thus, the biggest cost share in the three scenarios is causes by diesel backup system.

1.6 Avoidance of grid expansion measures

The increasing amount of renewable feed-in can, depending on the individual grid situation, causes a high demand for grid expansions. Especially the high penetration of PV-units in rural areas results in violations of the distribution grid's boundary conditions even today. Typically, the DSO (Distribution System Operator) encounters this development by conventional grid expansions. Lately, more and more innovative equipment such as tab-changing transformers, power electronic-based voltage controllers or the curtailment of PV feed-in are considered in the grid planning process. Furthermore, battery storage systems can be an additional measure for a substitution of conventional grid expansions.
In this analysis, an economic comparison between battery storage systems, conventional grid expansion and innovative approaches is done by an assessment of typical grid congestions in low- and medium-voltage grids. In this context, single stub lines with a varying length are investigated. Since the line length has a high impact on the later results, the typically occurring line lengths in German distribution grids is investigated in a first step. It appears that the 99 % quantile of line lengths is 1.6 km for the low voltage, 9.8 km for 10 kV voltage level and 32 km for the 20 kV voltage level. This length is further regarded as the maximum of the analyzed lines.
In a next step, each regarded line is simulated over one year in a resolution of 15 minutes. In this simulation, the lines are stressed with typically occurring loads and feed-in time series. For the low-voltage level, the load is generated by a stochastic load model (based on the findings of [6]) and for higher voltage levels using standard load profiles. The PV feed-in is generated by use of a weather data model [3] and is varied from 120 % to 250 % of the line's maximum capacity. This induces a line overloading and thus need for action for the DSO. The analysis considers the following four action alternatives:

- *Conventional grid expansion*: The existing line is extended with an identic parallel line. Load and feed-in are shared on both lines equally.
- *Feed-in curtailment*: In order to resolve the grid congestion, the PV feed-in is curtailed. The costs of curtailment are equal to today's average feed-in tariff for domestic PV-units.
- *Voltage Control*: By installation of tab-changing transformers (low voltage level) or active voltage controllers (medium voltage level), violations of the voltage range can be encountered.
- *Battery storage*: By simulation of the load flow on the resp. line, a storage system is fitted to the congestion situation of each investigated power line. By determination of the required power and capacity, the system's costs can be estimated.

The different action alternatives are further compared by means of today's typical acquisition costs. Due to their different cost structures, the annuity of each alternative over its individual life span is used for a cost comparison. The analysis thus considers the substitution of grid expansion as the only revenue of the storage system.
Figure 9 shows the analysis' results for a 1.6 km low-voltage line. It is obvious, that the annuity of the alternatives *Battery Storage* and *Curtailment* highly depends on the individual PV penetration of the regarded line. Therefore, the optimal decision for the DSO varies with the line length and the PV penetration. Storage systems generally show better competitiveness with increasing line length and decreasing voltage level. However, they are in none of the regarded combinations of line length and PV penetration a cost efficient alternative for the DSO. These findings hold true for the all examined voltage levels.

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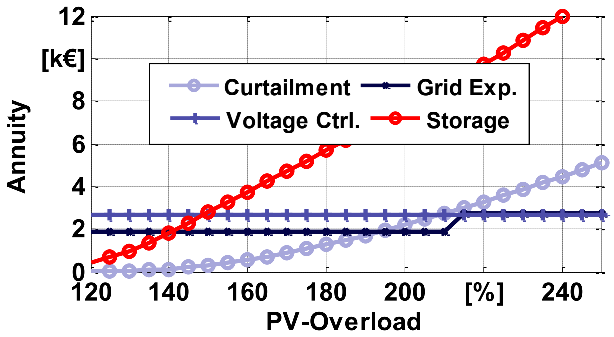

Figure 9: Annity of alternatives for a 1.6 km low-voltage line

The analysis focusses on battery storage systems at today's acquisition costs. Nevertheless, even an assumed cost reduction for battery storage systems of over 60% (see Table 1) until 2025 does not lead to a decision in favor of storage systems in any investigated scenario. However, the analysis regards the substitution of grid expansions as the only economic benefit of storage systems. Additional applications such as the provision of reserve control might affect the DSO's decision towards the storage systems. However, this combination can, depending on the DSO's location, collide with the applying regulatory framework.

2 Conclusion

Energy storage systems in medium and low voltage networks have a good technical potential for a large number of applications. Some of the most promising applications have been analyzed in use-cases and special simulation tools have been applied. Especially battery systems like the lithium-ion but also the lead-acid technology are well suited for the analyzed applications.

In the case of the supply of remote sites which are not supplied by the grid, PV-panels combined with battery storage systems are a well suited option in order to reduce the fuel and maintenance costs of a conventional diesel gen-set.

Currently, battery systems in the context with a PV-plant attract high interest also for grid-connected customers with the aim to increase the self-consumption rate. In the case of decreasing costs for battery systems together with increasing electricity prices, this can become an economic option for household customers in the future. Nevertheless, an individual consideration will remain necessary, taking into account the size of the PV-system and the expected load-profile of a given customer in order to find the best suited capacity for the battery. This holds true especially for commercial customers as no economic application could be identified for the customer load profiles analyzed in the present study.

It should be also mentioned that these storage systems at customer site do not automatically contribute to a decrease of the PV-loading on the grid as it may happen that the battery is already fully charged before the PV-peak at noon arrives. For the purpose of a grid-friendly operation, special charging strategies need to be adapted for these customer owned storage systems. The simulations show that in such cases the curtailment losses due to grids relieving operation strategies for the BESS owner are very low.

Grid based battery storage systems are discussed in the literature to be an option avoiding conventional grid expansion. The assessment of storage systems as an alternative to grid expansions shows, that conventional and innovative expansion measures are considerably advantageous. However, the use of storages in congested distribution grid shows a high potential for combined applications.

The use of energy storage at low and medium voltage level is not limited to applications at distribution level but can also provide ancillary services for the transmission grid, e.g. control power at different time domains. Taking into account the past bidding prices, the application of battery systems for the provision of primary control power appears to be an interesting market for battery systems in Germany. For other ancillary services, the use of battery storage systems does not show an economic business model at present. The spot- and reserve-market prices are highly fluctuating. Therefore a prediction of the economic benefits of battery storage systems in these markets is not reliable.

The combination of different applications can presumably increase the economic attractiveness of battery storage systems. However, the combination can be in contradiction with the existing regulatory framework [4] [9].

Battery storage systems in medium and low voltage grids show quite a number of interesting applications but only a few of them are actually also economical solutions.

Although the prices for batteries are expected to decrease, especially driven by the use in the transport sector, stationary battery storage systems will remain in competition with other solutions, conventional or innovative ones.

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