Optimal Battery Storage Sizing for Residential Buildings with Photovoltaic Systems under Consideration of Generic Load and Feed-In Time Series

Björn Uhlemeyer, James Garzon-Real, Heiko Schroeder, Alexander Hobert, Markus Zdrallek
Chair of Electrical Power Systems Engineering
University of Wuppertal
Wuppertal, Germany
bjoern.uhlemeyer@uni-wuppertal.de

Abstract—**Battery energy storage systems (BESS) can be used in electrical distribution grids to avoid violations of grid's operational limits and to reduce residual photovoltaic (PV) peaks. For customers such as households with PV systems, the use of BESS is particularly interesting, as they can increase their electrical self-sufficiency degree (SSD) and reduce the costs of their electricity purchasing. This paper deals with the optimal sizing of BESS for residential buildings with PV. The analysis considers 175 buildings located in a real suburban neighborhood, consisting mainly of detached and semi-detached houses.**

Keywords—battery energy storage system, cellular energy supply, photovoltaik, self-sufficiency-degree

NOMENCLATURE

BESS	Battery energy storage systems
BSSD	Balance-self-sufficiency degree
EV	Electrical vehicle
MECS	Multi energy carrier system
MILP	Mixed integer linear programming
oemof	open energy modelling framework
PV	Photovoltaic
RES	Renewable energy sources
SOC	State of charge
SSD	Self-sufficiency degree

Parameters

C_h	Battery capacity
h	Number of the residential building
c_b	Specific cost in EUR per kWh
$c_{h,b}$	Cost of the BESS for the building h
E_D	Energy demand of a household
E_{RES}	Renewable energy generation of a household
$E_{RES,G}$	Part of E_{RES} which is feed into the grid
PV_{max}	Maximum PV power of the district
r_{BESS}	Rate of reduction of the PV surplus by BESS
$S_{n,T}$	Apparent power of the medium-voltage transformer

Optimisation

T	Amount of time steps
E	Amount of edges
N	Amount of nodes
$c_{s,e}$	Specific costs of edges
c_n	Specific costs of nodes
$w_{s,e}$	Specific power of edges
v_n	Specific power of nodes
τ	Period of time

I. INTRODUCTION

A further expansion of renewable energy sources (RES) and in particular of photovoltaic (PV) systems is necessary in order to reduce the consumption of climate-harmful energy sources. In summer, this expansion can cause a local electricity surplus, which, fed into the distribution grids, can lead to grid's equipment overloads and voltage limits violations. In the future, distribution grid's performance fluctuations caused by RES will be compensated by energy storage –such as battery energy storage systems (BESS)–, load management, sector coupling and other measures [1] [2]. In Germany, a big amount of PV systems for residential buildings are currently installed with BESS [3]. These storage systems lead to a higher electrical self-sufficiency degree (SSD) allowing a further reduction of households' energy costs due to the difference between the low remuneration of the PV energy and the high electricity purchasing costs.

This paper presents a comparison between a BESS sizing for PV in residential buildings considering a grid-supporting operation mode and an economical optimal sizing. The investigation takes into account the *cellular energy supply concept*.

II. CELLULAR ENERGY SUPPLY SYSTEM MODEL

A. Cellular Energy Supply System

In the sense of the cellular energy supply concept [4], the aim of an *energy cell* is to reach an energy balance at the lowest possible level [5]. As the lowest energy balancing level is considered here a *residential energy cell*. In this regard, if a residential building is equipped with a PV system, the installation of BESS may have advantages from the point of view of the economics and of the energy balance [6].

Exemplary components of an energy cell are shown in Fig. 1. The cell is constituted by the electricity, gas and heat sectors (blue, green and orange areas). Energy generators, such as PV, biogas or solar thermal, and energy consumers like households or electrical vehicles (EV) are found in the cell. Sector coupling allows an optimal use of the benefits of the energy forms. Surplus electrical energy can be converted into heat by using *power to heat* or into gas by means of *power to gas* systems. A residential building is an example of an energy cell.

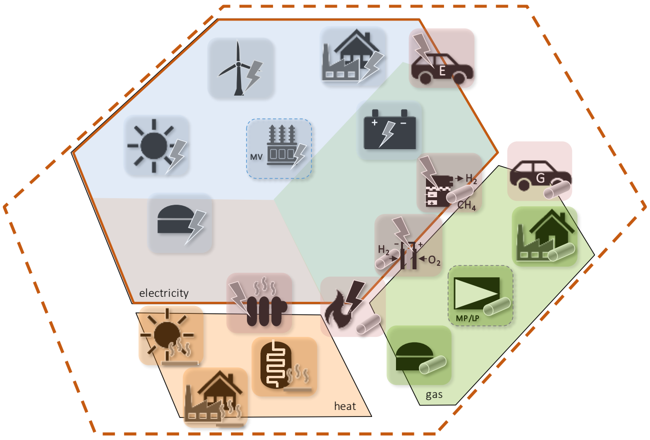

Figure 1: Cellular energy system [7]

A residential energy cell consists for instance of the electrical and thermal household load as well as from a PV system, a BESS, a heat pump (HP) and an EV. Additionally, the building has a connection to the power distribution grid. The consideration of a residential building as energy cell is used as basis for the investigations of this paper.

B. *Assumptions of the investigation*

In order to investigate the grid supporting operation mode and the economically optimal sizing of the BESS were time series for the following components of the energy cell elaborated:

- Households' electrical demand, based on typical behaviour depending on the type of day and the number of inhabitants.
- Households' heat demand, based on the year of construction of the buildings and on their size.
- PV systems, based on the size and the orientation of building's roof.
- EV, based on typical driving behaviours and technical values of current EV models

The assumptions for the elaboration of the time series are explained in more detail in [8]. A specification was drawn up for each building taking into account real data of the electricity consumption, heat demand and mobility requirements. Specific costs with an amount of $563\ EUR/kWh$ [9] –as a linearized function– were assumed for the economical optimal sizing of the BESS

C. *Definition of self-sufficiency degrees*

Essential parameters for the description of energy cells are the self-sufficiency degree (SSD) and the balance-self-sufficiency degree (BSSD) [10]. The SSD is defined as shown in Eq. (1), where E_{RES} is the generated renewable energy in the energy cell, $E_{RES,G}$ is the energy from RES, which is fed into the grid and E_D is the total energy demand within the energy cell. The SSD can be located in the range between 0 % and 100 %. The BSSD is defined as the relation between the generated renewable energy of the energy cell and the total energy demand (see Eq. (2)). If there are no RES in the energy cell the SSD and BSSD is zero. The SSD and the BSSD can be split up into the sectors electricity, heat and mobility.

$$SSD = \frac{E_{RES}-E_{RES,G}}{E_D} \tag{1}$$

$$BSSD = \frac{E_{RES}}{E_D} \tag{2}$$

D. *Modelling of the energy system*

Simulation are carried out using the *open energy modelling framework* (oemof) [11]. The software allows the simulation of multi energy carrier systems (MECS), such as energy cells, considering a simplified system of nodes and edges. At the nodes, energy can be fed in, fed out or stored depending on the case. The edges represent the connection between nodes. As general rule, the balance of energies at each node is equal to zero. A modelling and calculation of power, gas or heat grid states is not considered. Simulations of the residential energy cells were carried out for the period of one year in quarter-hour steps. These use the elaborated time series for household's electricity demand, EV's charging and PV feed-in.

The objective function of the optimisation is in this case the minimization of the overall cost of the residential energy cell. It is also possible to have environmental targets as objective function such as the minimization of the equivalent CO_2 emissions. The time-dependent power flows of the edges $w_{(s,e)}$ and the nodes v_b were multiplied by the variable costs $c_{(s,e)}$, c_n from all nodes and edges and the time step τ are represented within the objective function. The time-independent costs of the nodes and edges are also included there. The time-independent costs represent the capital expenditures (CAPEX), and the time-dependent costs the operative expenditures (OPEX). The nodes are represented for example by the household load and the PV systems. In each time step, a power value *w* is multiplied by the costs *c* and the result is added and minimized over all elements (see Eq. (3)) [12].

$$\begin{aligned} min:\ &\overbrace{\sum_{t\in T}\left(\sum_{(s,e)\in E} c_{(s,e)}(t)\cdot w_{(s,e)}(t)\cdot\tau\right)}^{time-dependent\ parts\ of\ the\ edges} + \\ &\overbrace{\left(\sum_{(s,e)\in E} c_{(s,e)}\cdot w_{(s,e)}\right)}^{time-independent\ portions\ of\ the\ edges} + \\ &\overbrace{\sum_{t\in T}\left(\sum_{n\in N} c_n(t)\cdot v_b(t)\cdot\tau\right)}^{time-dependent\ parts\ of\ the\ nodes} + \\ &\overbrace{\left(\sum_{n\in N} c_n\cdot v_n\right)}^{time-independent\ parts\ of\ the\ nodes} \end{aligned} \tag{3}$$

E. *Operating performance of PV systems*

Fig. 2 shows a PV power profile referenced to the nominal PV peak power. The profile is based on average data of the roof of the buildings of the investigated district in middle west Germany for an average weather year. The calculation of the solar radiation is based on [10].

For the further analysis, the amount of energy generated per day per kW of installed PV power is considered. Fig. 3 shows the proportion of days on which a certain amount of energy is generated by a PV system. For example, at least 1 kWh of energy per day per kW installed is generated on approximately 74 % of the days. 2 kWh per kW are generated by the PV on approximately 50 % of the days.

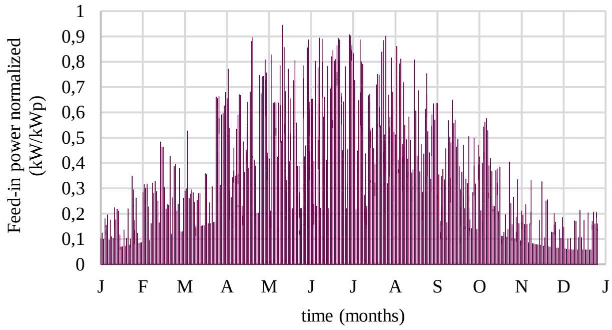

Figure 2: Feed-in power of a PV during the year

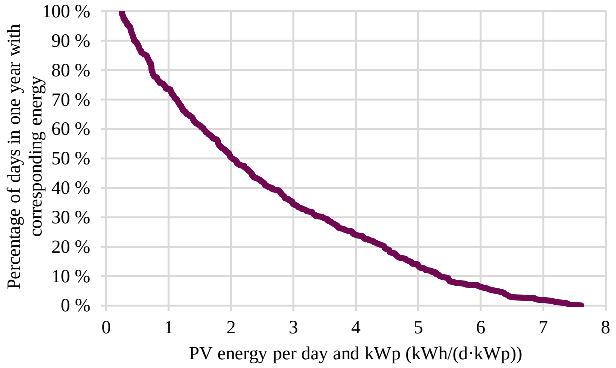

Figure 3: Percentage of days with a specific amount of PV generated energy

III. GRID SUPPORTING OPTIMISATION OF THE BESS

A. *Using BESS to avoid operational limits violations of the power distribution grid*

At the moment, there are no incentives for small PV with BESS, for a grid supporting mode of operation. However, under certain conditions, a grid supporting mode, such as peak shaving, leads to a considerable reduction of the power grid loading [13].

To avoid violations of the operational limits of the power distribution grid, BESS could store for example all energy above 0,5 kW per kW nominal power shown on Fig. 2. This reference value is exceeded only in the months from March to October, where a high power generation takes place. The necessary storage capacity to store the whole energy above the reference value of 0,5 kW, depending on the reduced feed-in power, is shown in Fig. 4. The figure shows that with for example 2 kWh storage capacity it is possible to reduce the feed-in PV power above until 50 %.

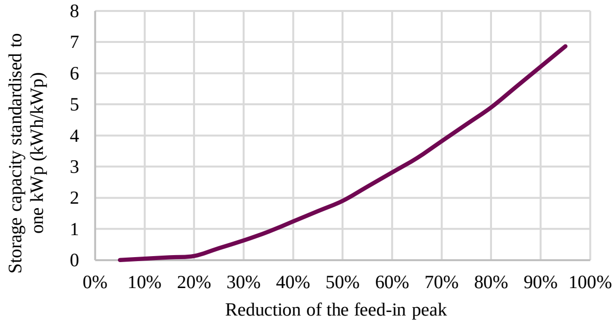

Figure 4: Reduction of the feed-in power of a PV-system during a year with a certain BESS

B. *Profile of the electrical power of the district*

Fig. 5 shows the profile of the electrical power of the whole district exemplary for three days in July. A maximum PV generation provides more energy than the district needs mainly in the middle of the day. The BESS ensure that the nominal power of the medium voltage transformer is not exceeded. This can be noticed for example at the 3rd July, where the BESS charges during the day with the energy of the PV and the medium voltage transformer does not exceed his nominal power of 630 kVA. This can be reached for instance by means of the communication between the battery management system of the BESS and a smart grid system of the local power distribution grid, which monitors the transformer's burden. Thus, the BESS can store energy at times, which would otherwise lead to an overload of the power transformer.

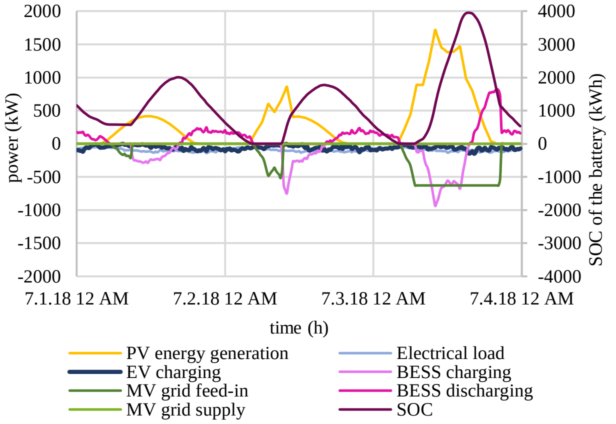

Figure 5: Load flow of the district and SOC

C. *Optimised grid support*

In the investigated district the medium-voltage transformer has a nominal power of 630 kVA. The nominal power of all PV systems amounts to 1750 kW$_{peak}$. A reduction of the maximum PV power to 630 kVA, considering no load, would imply a rate of 64 %. Fig. 4 shows that for a reduction rate of 64 % a BESS with a capacity of $(3 \cdot 1750\, kW) = 5.250\, kWh$ would be necessary. The BESS capacity obtained from the optimisation, which includes –opposite to Fig. 4– the load in the district, comes to a value of ca. 4.000 kWh. This implies that 2,28 kWh BESS capacity per kW of PV is necessary to avoid violations of the operative limits of the medium/low voltage power transformer. The optimal BESS size for a grid-supporting mode depends on the characteristics of the local power distribution grid.

IV. ECONOMIC OPTIMISATION OF THE BESS

An economic optimisation is carried out considering the simultaneity between electricity consumption and PV generation, the cost of the BESS and the residual power of the PV, which can be used for BESS charging. A BESS is especially interesting for new PV with low subsidies or old PV with expiring subsidies, when the difference between the purchasing and sales price of electrical energy is large. It is essential for the economic use of a BESS that the installed capacity is used as much as possible. As Fig. 3 shows, there are few days with high PV energy production and many days with low energy production. The degree of utilization of the BESS is high in the summer and low in the winter.

A. *Self-sufficiency degree of the buildings*

For the simulation, 173 of the 175 investigated residential buildings were equipped with a PV system. Fig. 6 shows the SSD of each building. Shown is the SSD of the residential buildings with only the PV and with a BESS additionally. The size of the BESS is optimised considering economic parameters. The SSD caused by the PV systems are located in a range from 14 % to 50 %. With an optimal sized BESS, the range raises from 15 % to 88 %. The average SSD increases from 29 % to 50 %.

B. *Optimised invest in the BESS*

The optimisation of the BESS capacity of the 173 buildings shows that –under the assumed conditions– BESS have economic viability up to a maximum of 0,85 kWh per kW_{peak} of PV. Fig. 7 shows the economical optimised BESS capacities per kW installed of PV power for each building. The optimised value summed up in the district comes to approximately 1.000 kWh of BESS capacity. Regarding Fig. 4, the entire energy of the PV system can thus be temporarily stored on approx. 25 % of the days. On 75 % of the days, however, only a part of the energy can be temporarily stored. Regarding Fig. 5, the feed-in capacity of the PV system cannot be reduced through the economic optimised capacities shown in Fig. 7 by more than 30 %. With the expected reduction in BESS prices, the curve on Fig. 7 would shift to the right and the reduction of feed-in power would continue increasing.

Considering the total costs of power supply over 20 years for four exemplary buildings, it can be seen that BESS first leads to a slight costs reduction (see Fig. 8). If the BESS capacity increases, the costs rise after a value of 5 kWh. It is noticeable that the building with the highest BSSD has by far the lowest costs.

The dependence between the BESS capacity and the SSD was investigated. It turns out that with a low BSSD, the increasing BESS capacity only results in a slight increase in the SSD (see Fig. 9). When the BSSD is higher, the self-sufficiency degree increases faster.

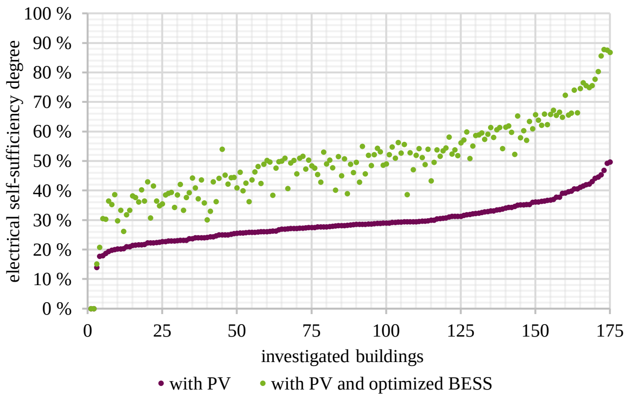

Figure 6: Self-sufficiency degree of 175 investigated buildings

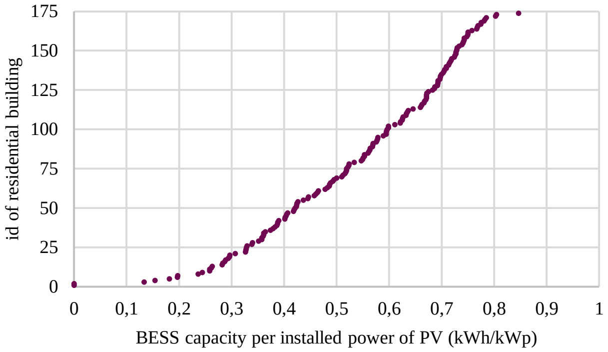

Figure 7: Economically optimised BESS capacity for each investigated building

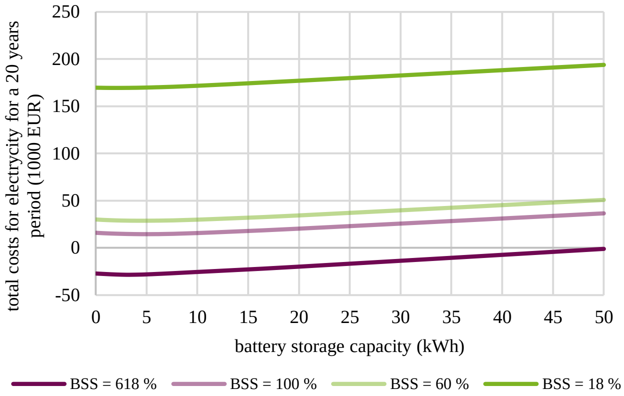

Figure 8: Total cost of the electrical energy supply of four buildings in dependence of the battery storage capacity

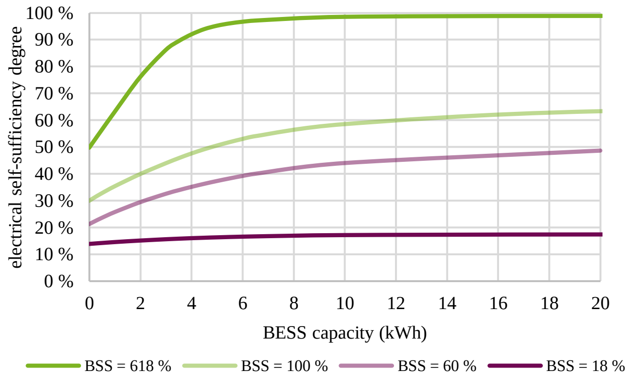

Figure 9: Electrical SSR of four buildings in dependence of the battery storage capacity

V. CONCLUSION

The results for the optimal BESS size considering a grid-supporting operation mode in the residential district show on average an optimal BESS capacity of 2,28 kWh per kW of installed PV power. The results for an economic optimisation of BESS' size show on average an optimal BESS capacity of 0,54 kWh per kW of installed PV power. This BESS capacity per installed PV power would increase due to decreasing BESS prices and subsidies. With the low value of 0,54 kWh, the storage can still show a high degree of utilization even with the low solar radiation of the winter months.

A comparison between the grid oriented and the economical optimisation of BESS' size show that –under the assumed conditions– the BESS from the private owners could not be used to avoid violation of the operative limits of gird’s power transformer in all cases. Although the BESS could be used to reduce the need for grid reinforcement. Further research works will investigate the impact of heat pumps with thermal storages on the BESS sizing.

Summarizing, the results show that the power transformer could profit from an optimal sizing of the BESS. The grid support operating mode represents a minor restriction for the customers. For the grid operator this has advantages especially in areas with a high concentration of PV.

VI. ACKNOWLEDGEMENTS

GEFÖRDERT VOM

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VII. REFERENCES

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