Analysis of Operating and Positioning Strategies of Home and Community Storage Systems in Low Voltage Grids in a Sector-Coupled and Renewable Energy System

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Abstract. An energy system transformation is mandatory to reach a climate-neutral energy system. Several challenges within this transformation process have to be overcome. Due to the increasing sector coupling and renewable energy power plants on a decentralised level, new challenges arise. Photovoltaic systems, heat pumps, and electromobility can provoke higher power flows at the low voltage grid level, which results in voltage issues and overloaded transformers or power lines. Consequently, curtailment of photovoltaic power is necessary, or load outages may occur. Battery storage systems provide a promising solution to counteract these challenges and enable the energy transition. The influence of three operating and three positioning strategies of home and community battery storage systems on voltage stability, transformer and line load and on-site supply for low-voltage grids have been investigated in a highly renewable and sector-coupled energy system. Power flow simulations with five representative synthetic low-voltage grids have been conducted. The results show that without further measures, the safe operation of the equipment cannot be guaranteed in the representative grids. However, home battery storage systems can reduce grid issues, curtailment and increase the self-consumption of photovoltaic energy. Using digitally interconnected battery storage systems achieve the best results, as it can serve both the self-consumption and the grid. Home and community battery storage system prove to be equally suitable.

Keywords: Battery · Low-voltage grid · Residential · Storage · Sector-coupling · Renewable energy sources · Community storage · Home storage · Operating Strategies

P. Schossig et al. (Eds.): IRES 2022, AHE 16, pp. 215–234, 2023.
https://doi.org/10.2991/978-94-6463-156-2_16

1 Introduction

The United Nations Framework Convention on Climate Change states in the Paris Agreement that the global community shall limit the increase of the global average temperature to 1.5 °C to a maximum of 2 °C above pre-industrial levels [18]. A transformation of the energy system towards renewable energies in all sectors is mandatory to achieve this goal. In Germany a mix of renewable energy sources, especially photovoltaic (PV) and wind power, is targeted [34]. In the future, electricity will also be increasingly used in the transport sector for electric mobility and the heating sector for heat pumps (HPs), increasing electricity demand. Various studies assume that electricity demand will significantly increase in the future [38,41]. A higher electricity demand due to sector coupling requires higher expansion rates for renewable energies.

The transformation of the energy system to renewable energies and sector coupling is facing many challenges. For instance, in the past, the current distribution grids in residential areas were often only designed for the conventional household load. Due to the increasing number of prosumers and thus the increasing grid feed-in through PV and higher load peaks through sector-coupled consumers, the distribution grids are exposed to high stress and loading if no countermeasures are taken [31]. Thus, the respective voltage bands may be violated in the case of future higher grid supply or feed-in capacities [31].

The capacity of low voltage (LV) grids to integrate a high proportion of PV systems is considered problematic without appropriate countermeasures. In order to avoid grid loads, only 45 to 60% of the existing PV potential can be incorporated into LV grids [26].

Battery storage systems (BSSs) could contribute to solving this problem. They provide a balance between local electricity supply and demand [12], which may reduce the curtailment of renewable energies. In addition, home BSSs (HBSSs) and a limitation of the maximum permissible feed-in power of PV systems can contribute to the integration of PV into the energy system and can be used locally to maintain the specified voltage quality and permissible equipment load [25]. Furthermore, a HBSS increases the degree of self-sufficiency of a household [31] or the LV grid [42]. Up to 80% of the electricity demand of private households can be covered by PV and HBSSs [31]. Furthermore, PV and load forecasts support a grid-serving and self-supply-optimised operation of a HBSS [31].

Operating strategies for BSSs that serve the grid and operate without forecasts have been investigated in other studies [25,50]. It was demonstrated that feed-in damping could significantly reduce feed-in power and at the same time ensure a high share of self-consumption.

Despite of studies on HBSSs, studies on community BSSs (CBSSs), which connect several households, are coming more into focus. For example, the use of a CBSS to reduce PV feed-in peaks can be more economical and energy-efficient compared to HBSSs [49]. In addition, CBSSs, in contrast to HBSSs, can achieve a better balancing of the cumulative total load of a grid [20]. Furthermore, CBSSs can reduce grid congestion at the distribution grid level and significantly increase the grid capacity for renewable energy sources to the same extent as HBSSs [37,42].

Many studies exist on the impact of BSSs on LV grids. However, in these studies, BSSs are investigated in combination with relatively moderate PV power [13,29,30,51,52] or only HPs [11,15,30,39,43] or only battery electric vehicles (BEV) [16,19,24,28,29,35,36,51]. This paper investigates LV grids with a high share of PV systems and sector-coupling loads, such as BEVs and HPs.

In addition, many studies deal with BSSs in terms of balancing electricity supply and demand at the household level or village/town level but do not determine the exact impact on LV grids [43]. In this paper, load flow calculations using the open-source grid simulation tool pandapower [40] are performed on a minute basis to determine line and local power transformer (LPT) loading and voltage band violations.

Two studies deal with the specific positioning of CBSSs. They underline its relevance but come to different conclusions. Thus, one recommended a connection of the CBSS to the low voltage busbar (LVBB) of a transformer station (TS) [37], while the other preferred positioning with a high distance to the TS [42]. In this paper, the positioning of CBSS within LV grids is investigated.

This study examines the extent to which BSSs in the renewable and sector-coupled energy system can contribute to secure grid operation at the LV level and increase the capacity of the grids to integrate renewable energies. Five synthetic LV grids are being investigated. All grids consist of residential areas with single-family houses (SFHs). Each SFH has a BEV, HP and PV system that fully occupies the usable roof area. Storage units can be charged from the own PV system and the LV grid. The following research questions are investigated:

- What influence does the positioning of BSSs have on the grid equipment load and the local generation balancing of the LV grid?
- What influence do different modes of operation for HBSSs and CBSSs have on the grid equipment load and local generation balancing of the LV grid?
- How do positioning and operation differ in rural and suburban LV grids?

2 Methodology

Section 2.1 presents the research scenarios and evaluation criteria. The operating and positioning strategies for the BSSs are explained in Sects. 2.3 and 2.2. The assumptions made for modelling the BSSs are discussed in Sect. 2.4. Section 2.5 presents the grids under investigation and assumptions about consumers and PV systems.

2.1 Research Scenarios and Parameters

In addition to one scenario without BSSs (the reference scenario), three scenarios with HBSSs were investigated using different operating strategies. One of the operating strategies was applied to HBSSs and two different positioning strategies for CBSSs. Table 1 contains the reference and the five BSS scenarios with their abbreviations.

All scenarios are simulated with curtailment of loads and PV systems. The simulation periods are one week in spring, summer, autumn and winter. The weeks with the maximum negative and positive residual load were chosen as the summer and winter weeks. Energy generation and consumption are almost equal in the spring and autumn weeks. For all scenarios and weeks, a simulation interval of 1 min is chosen.

For safe operation of the grid, the apparent power at the LPT S_{LPT} must not exceed the nominal apparent power of the LPT $S_{\mathrm{LPT,n}}$. The current I in the power lines should be less than or equal to the nominal current I_{n}. The voltage at the grid nodes U must not deviate by more than 10% from the nominal voltage U_{n} of the LV grid. These load and voltage band limits are defined in Eqs. 1 to 3.

$$S_{\mathrm{LPT}} \leq S_{\mathrm{LPT,n}} \tag{1}$$

$$I \leq I_{\mathrm{n}} \tag{2}$$

$$0.9 \cdot U_{\mathrm{n}} \leq U \leq 1.1 \cdot U_{\mathrm{n}} \tag{3}$$

Load and PV curtailment is performed to avoid LPT and line overloads and voltage band violations. The evaluation criteria are the share CPV (curtailed PV energy) of curtailed PV energy $E_{\mathrm{PV,curt}}$ in generatable PV energy $E_{\mathrm{PV,gen}}$ and the share of curtailed load CL (curtailed load energy) as the ratio of curtailed energy $E_{\mathrm{load,curt}}$ to demanded energy $E_{\mathrm{load,demand}}$ (cf. Eqs. 4 and 5). The curtailed power indicates the absorption capacity of the power grid for the energy generated by the PV systems and the security of supply for household consumers.

Table 1. Research scenarios and methodology of comparison

Operating strategy (OS)	Positioning strategy (PS)	Scenario	Methodology for comparison		
-	-	Reference			Comparison of reference and BSS scenarios
Direct	HBSS	d-HBSS	Comparison of OS		
Preventive	HBSS	p-HBSS			
Preventive-curative	HBSS	pc-HBSS		Comparison of PS	
Preventive-curative	CBSS	pc-CBSS-LVBB			
Preventive-curative	CBSS	pc-CBSS-line			

$$CPV = \frac{E_{\mathrm{PV,curt}}}{E_{\mathrm{PV,gen}}} \tag{4}$$

$$CL = \frac{E_{\mathrm{load,curt}}}{E_{\mathrm{load,demand}}} \tag{5}$$

Further evaluation criteria are the degree of self-sufficiency DOS and the self-consumption rate SCR. They are used to evaluate the generation balancing within the LV grid. The DOS indicates to what extent the demand for electrical energy E_{demand} can be met by the electrical energy which is generated by the PV system and locally used $E_{\mathrm{PV,consumed}}$ (cf. Equation 6). The SCR represents the ratio of locally self-consumed PV energy and generatable PV energy $E_{\mathrm{PV,gen}}$ (cf. 7). The generatable PV energy includes the energy actually generated and the curtailed energy of the PV system.

$$DOS = \frac{E_{\mathrm{PV,consumed}}}{E_{\mathrm{demand}}} \tag{6}$$

$$SCR = \frac{E_{\mathrm{PV,consumed}}}{E_{\mathrm{PV,gen}}} \tag{7}$$

2.2 Operating Strategies

Three different operating strategies are compared: (1) the demand-oriented operating strategy ("direct"), (2) the grid-oriented operating strategy ("preventive"), which charges with reduced charging power, and (3) the grid-serving operating strategy ("preventive-curative"). In the latter, the BSSs are digitally interconnected with each other and the LPT. They act as a unit and can react to the grid states at the LPT. Due to the digital interconnection, the preventive-curative strategy is also applicable to CBSSs. Therefore this strategy is also used to compare the three positioning strategies (cf. Table 1).

2.2.1 Direct Operating Strategy

Direct charging corresponds to state-of-the-art and is most frequently used in practice. As soon as the PV system generates more electricity than the household consumes, the BSS is charged. If there is a surplus of load, the BSS is discharged. Limiting parameters for the storage operation are the maximum charging and discharging power, as well as the current state of charge SOC of the BSS. An advantage of this strategy is that the highest possible self-consumption is achieved. However, this strategy does not take the grid status into account. Thus, it can be disadvantageous for the grid if the BSS is already full in the morning and the midday PV-peak is fed in completely.

2.2.2 Preventive Operating Strategy

Using the preventive operating strategy, the BSS is charged at a time t with reduced charging power $P_{\text{ch,pre}}(t)$ (cf. Eq. 8).

$$P_{\text{ch,pre}}(t) = \frac{C_{\text{spare}}(t)}{\Delta t_{\text{ch}}(t)} = \frac{C_{\text{usable}} - C_{\text{stored}}(t)}{t_{\text{sunset}} - t - \Delta t_{\text{delay}}} \tag{8}$$

The charging power depends on the spare storage capacity still available for charging $C_{\text{spare}}(t)$ and the remaining time $\Delta t_{\text{ch}}(t)$. $C_{\text{spare}}(t)$ is determined as the difference between the usable storage capacity $C_{\text{usable}}(t)$ and the storage capacity already used for energy storage $C_{\text{stored}}(t)$. $\Delta t_{\text{ch}}(t)$ represents the period from time t to sunset t_{sunset}, minus a period Δt_{delay}. With each timestep, the charging power is updated to reach the highest possible SOC at sunset. With this strategy, BSSs are still available for charging at times of high PV feed-in, such as midday. This operation can serve the integration of the generation peaks and reduce the curtailment of PV systems. Δt_{delay} is calculated proportionally to the length of the day and thus takes seasonal differences into account concerning solar irradiation. Δt_{delay} corresponds to 12.5% of time between sunrise and sunset. Depending on the season, the discharging processes take place differently. In the summer half-year, discharging takes place "directly" in order to achieve the lowest possible SOC at sunrise. This way, more energy can be stored overall during the day. In the winter half-year, on the other hand, when the nights are longer than the days and grid consumption at night can cause equipment overloads and voltage band violations, the storage units are discharged according to Eq. 9 with reduced discharging power $P_{\text{dch,pre}}(t)$. $\Delta t_{\text{dch}}(t)$ corresponds to the time remaining for discharge until sunrise t_{sunrise}.

$$P_{\text{dch,pre}}(t) = \frac{C_{\text{stored}}(t)}{\Delta t_{\text{dch}}(t)} = \frac{C_{\text{stored}}(t)}{t_{\text{sunrise}} - t} \tag{9}$$

2.2.3 Preventive-curative Operating Strategy

The preventive-curative operating strategy builds on the preventive one. If no overload of the LPT occurs, the BSS is charged with reduced charging power. In contrast to the direct and preventive strategy, BSS charging and discharging do not depend on the energy flow at the respective grid connection point but on the residual load measured at the LPT. For all BSSs, the reduced charging power $P_{\text{ch,total,pc}}(t)$ is determined with Eq. 10 via the sum of the spare capacities of the individual BSSs i.

$$\begin{aligned} P_{\text{ch,total,pc}}(t) &= \frac{\sum_{i=0}^{n} C_{\text{spare,i}}(t)}{\Delta t_{\text{ch}}(t)} \\ &= \frac{\sum_{i=0}^{n}(C_{\text{usable,i}} - C_{\text{stored,i}}(t))}{t_{\text{sunset}} - t - \Delta t_{\text{delay}}} \end{aligned} \tag{10}$$

The discharging power in the winter half-year is calculated analogously to Eq. 10 with the total energy stored in the LV grid, i.e. the sum of the used storage capacities and the sum of all usable storage capacities. A share $x_{\text{reserve}} = 20\%$ of the usable storage capacity is kept as a reserve for the load peaks in the morning. The storage discharge in winter is thus determined according to Eq. 11.

$$\begin{aligned} P_{\text{dch,total,pc}}(t) &= \frac{\sum_{i=0}^{n} C_{\text{stored, reserve}}(t)}{\Delta t_{\text{dch}}(t)} \\ &= \frac{\sum_{i=0}^{n} (C_{\text{stored,i}}(t) - x_{\text{reserve}} \cdot C_{\text{usable,i}})}{t_{\text{sunrise}} - t} \end{aligned} \tag{11}$$

In the case of direct discharge in summer, the total discharging power of all BSSs is equal to the active power at the LPT if the current SOC allows it.

$$P_{\text{direct,total}}(t) = P_{\text{res}}(t) \tag{12}$$

The total active power is distributed among the BSSs such that they are used equally: The charging power for the individual BSSs is calculated proportionally according to the ratio of $C_{\text{spare}}(t)$ to the sum of all spare capacities. The discharging power is calculated analogously depending on the used capacities $C_{\text{stored}}(t)$.

If the nominal apparent power at the LPT is exceeded, the operating strategy explained so far is supplemented by feed-in damping. As shown in Eq. 13, for the new power due to feed-in damping $P_{\text{fid,total}}(t)$, the difference $P_{\text{overload}}(t)$ is added to the total charging or discharging power $P_{\text{BSS}}(t)$ that would have been set without the LPT overloads. $P_{\text{overload}}(t)$ in turn results from the current active power $P_{\text{res}}(t)$ and the maximum permissible active power $P_{\text{LPT,max}}(t)$ at the LPT (cf. Eq. 14).

$$P_{\text{fid,total}}(t) = P_{\text{BSS}}(t) + P_{\text{overload}}(t) \tag{13}$$

$$P_{\text{overload}}(t) = P_{\text{res}}(t) - P_{\text{LPT,max}}(t) \tag{14}$$

In the case of multiple BSSs (HBSSs or multiple CBSSs), the power to be charged or discharged $P_{\text{fid,total}}(t)$ is again distributed proportionally among the individual BSSs.

2.3 Positioning Strategies

The following three positioning strategies are compared: (1) one BSS per household (HBSS), (2) one CBSS at the LVBB, and (3) one or more CBSSs at a grid connection point within one or more power lines. For the latter strategy, the choice of lines and connection points is based on the maximum line overloads and voltage band violations that occur without BSSs. CBSSs were placed only in the network feeder where these network problems occur. The position was chosen so that both line overloads and voltage band violations can be counteracted as well as possible.

Table 2. Parameters of the battery storage system

storage efficiency	η_{BSS}	95.9% [32]
conversion efficiency ACDC	η_{ACDC}	95.3% [32]
conversion efficiency DCAC	η_{DCAC}	95.5% [32]
minimum state of charge	SOC_{min}	20%
maximum state of charge	SOC_{max}	80%
power/capacity ratio	$f_{\mathrm{P/C}}$	0.75 MW/MWh
start state of charge in spring	$SOC_{\mathrm{start,sp}}$	50%
start state of charge in summer	$SOC_{\mathrm{start,s}}$	75%
start state of charge in autumn	$SOC_{\mathrm{start,au}}$	50%
start state of charge in winter	$SOC_{\mathrm{start,w}}$	25%

2.4 Battery Storage System

AC coupled BSSs based on lithium-ion are assumed, which results in the BSS specifications selected for the simulations in Table 2.

A constant efficiency is determined for the entire BSS. In addition, the minimum and maximum state of charge SOC_{n} are defined in relation to the nominal storage capacity, thus considering limits for safe operation and long service life. The inverter of the BSS does not provide reactive power. This way, the influence of the different strategies can be investigated independently of the reactive power control.

2.4.1 Dimensioning

The usable storage capacities are selected as a function of the nominal power of the PV systems installed in the respective LV grid. This dimension approach ensures comparability of the research scenarios. Thus, the sum of the usable storage capacities remains constant across all positioning scenarios. A guiding value of 1 kWh usable storage capacity to 1 kW installed nominal PV power is often given, which corresponds to an adequate economic design [33]. Since this research is based on the assumption of a high PV expansion potential and the design with 1 kWh/kW can lead to oversizing [32], a ratio of 0.75 kWh/kW was applied. Each BSS inverter is dimensioned with a BSS inverter power to BSS capacity ratio of 0.75 (derived from [32]).

In the CBSS scenarios, the required total usable storage capacity is distributed among all CBSSs. Thus, in the case of a single CBSS, the CBSS holds the same amount of energy as all HBSSs combined. If multiple CBSSs are positioned in the lines, the distribution of storage capacity is based on the number of households in the respective line.

2.4.2 Efficiency

The energy losses are taken into account via an overall efficiency of the BSS η_{BSS}, an AC/DC conversion efficiency η_{ACDC} and a DC/AC conversion efficiency η_{DCAC} (cf. Table 2).

In the context of modelling, η_{BSS} is distributed between an efficiency for charging η_{ch} and an efficiency for discharging η_{dch} according to Eqs. 15 and 16.

$$\eta_{\mathrm{ch}} = \eta_{\mathrm{ACDC}} * \sqrt{\eta_{\mathrm{BSS}}} \tag{15}$$

$$\eta_{\mathrm{dch}} = \eta_{\mathrm{DCAC}} * \sqrt{\eta_{\mathrm{BSS}}} \tag{16}$$

2.5 Energy Cell Characterization and Modelling

The specifications used for modelling are presented below.

2.5.1 Low Voltage Grids

The synthetic SimBench grids [9], which represent today's LV grids in Germany, are examined. The analysis is limited to the three rural and two semi-urban LV grids. These radial grids differ in the number of lines and consumers, their line lengths and the nominal apparent power of the respective LPT (cf. Table 3).

2.5.2 Energy Supply and Demand

In the following, the assumptions for the energy supply of the PV systems and the electricity demand of the households, HPs and electric cars are specified.

PV generation: All roofs are equipped with a PV system. The roof areas are assumed to have sizes of 116 m^2 in suburban areas and 180 m^2 in rural areas [27]. The distribution of the different south and east/west orientations of the PV systems is set according to the distribution of the roof top orientation in Germany [10]. A specific power of the PV modules of 200 $\mathrm{W/m}^2$ is applied, which results in nominal power ratings of the PV systems for the rural LV grids of 18 kW for the south orientation and 36 kW for the east/west orientation. The nominal power ratings in the suburban LV grids are 11.6 and 23.2 kW. The

Table 3. Specifications of the representative low voltage grids

	Rural 1	Rural 2	Rural 3	Suburb 1	Suburb 2
LPT-Nennleistung	160 kVA	250 kVA	400 kVA	400 kVA	630 kVA
Abgangszahl	4	4	9	3	6
Leitungslänge (Gesamt)	0.56 km	1.47 km	2.35 km	0.746 km	1.79 km
Leitungslänge (Maximal)	137.22 m	75.00 m	139.52 m	60.00 m	98.00 m
Verbraucheranzahl	13	99	118	41	104

time series for the PV systems were generated using pvlib [21] and irradiance and temperature data based on measured data [2–8, 44–48]. The PV plants are modelled with a $Q(U)$ control [14].

Household electricity demand: Time series from the Berlin University of Applied Sciences (HTW Berlin) are used for household electricity demand [17].

Heat: A total heat demand of 8928 kWh/a per household is assumed. This heat demand comprises 6300 kWh/a heating demand and 2628 kWh/a domestic hot water demand. The thermal load time series of the households were also determined using measured temperature data [2–8, 44–48], and a thermal load profile generation methodology [1]. Each household is equipped with a HP. Heat is provided in 50% of the households by an air source HP and in 50% by a ground source HP.

Electric cars: It is assumed that every household owns an electric car. The data for the energy demand of the electric cars was generated with the simulation tool SimBEV of the Reiner Lemoine Institut (RLI) [23] and is based on the region data RegioStaR7 [22]. In this process, the rural communities were assigned the region data for small towns and villages in the rural region and suburban communities were assigned the data for small towns and villages in the urban region. SimBEV was used to determine BSS sizes of 30, 65 and 90 kWh for electric cars. The maximum charging power of electric cars is 11 kW.

Both the HP and the electric car cannot operate flexibly. There is no heat storage for a flexible operation of the HP. Each electric car charges with the maximum charging power as soon as it is connected to the wall box.

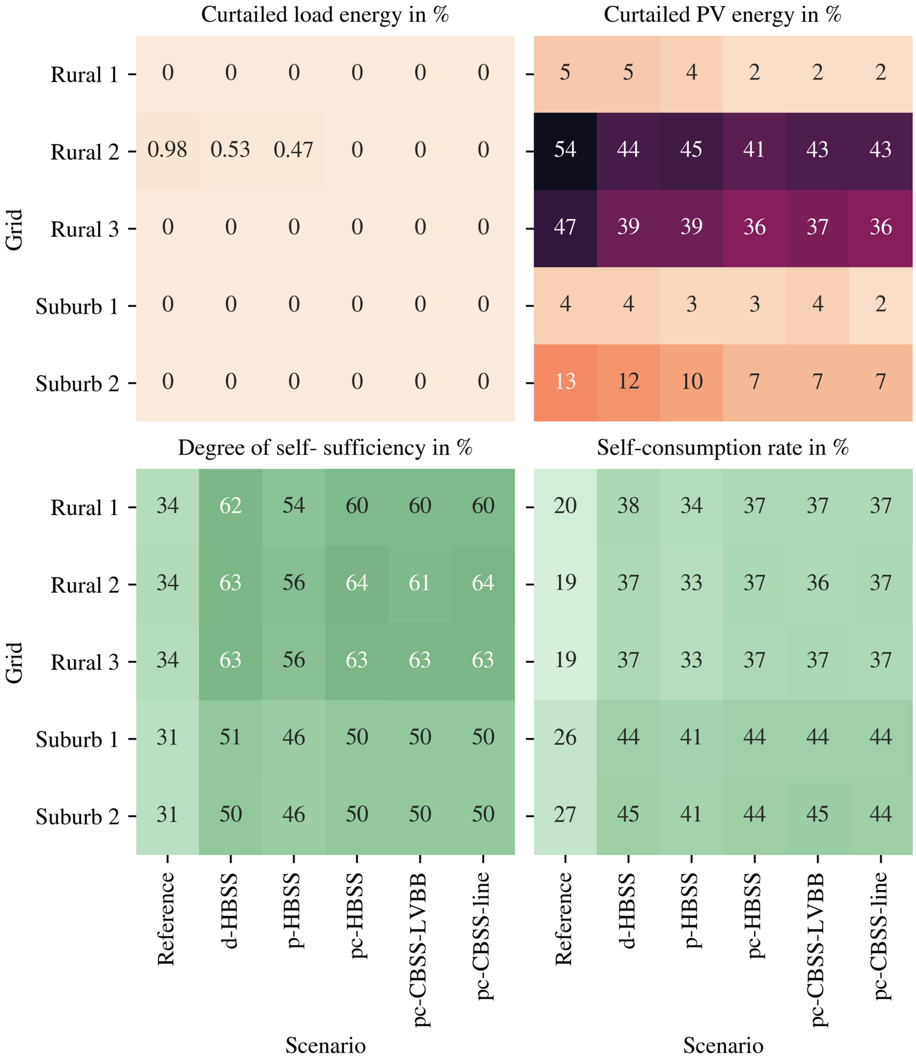
3 Results

Section 3.1 shows the results for the reference scenario without BSSs. Section 3.2 investigates the contribution of the BSSs concerning curtailment losses, self-sufficiency and PV self-consumption.

3.1 Reference Scenario

Figure 1 shows the share of curtailed energy consumption (top left) and curtailed PV energy (top right), as well as the degree of self-sufficiency (bottom left) and the self-consumption rate (bottom right). The respective left column shows the reference scenario. The overall results of all four weeks are given for each LV grid and scenario.

PV energy is curtailed in all five grids if no other countermeasures are taken. Especially large rural grids are affected since they have huge rooftop area potentials for PV, and the nominal apparent power of the LPT is relatively low compared to the number of households. The need for curtailment arises primarily from LPT overloads, but line overloads in long lines also lead to PV curtailment. Due to the $Q(U)$ control of the PV systems, there are no voltage band violations.



Curtailed load energy in %

Grid	Reference	d-HBSS	p-HBSS	pc-HBSS	pc-CBSS-LVBB	pc-CBSS-line
Rural 1	0	0	0	0	0	0
Rural 2	0.98	0.53	0.47	0	0	0
Rural 3	0	0	0	0	0	0
Suburb 1	0	0	0	0	0	0
Suburb 2	0	0	0	0	0	0

Curtailed PV energy in %

Grid	Reference	d-HBSS	p-HBSS	pc-HBSS	pc-CBSS-LVBB	pc-CBSS-line
Rural 1	5	5	4	2	2	2
Rural 2	54	44	45	41	43	43
Rural 3	47	39	39	36	37	36
Suburb 1	4	4	3	3	4	2
Suburb 2	13	12	10	7	7	7

Degree of self- sufficiency in %

Grid	Reference	d-HBSS	p-HBSS	pc-HBSS	pc-CBSS-LVBB	pc-CBSS-line
Rural 1	34	62	54	60	60	60
Rural 2	34	63	56	64	61	64
Rural 3	34	63	56	63	63	63
Suburb 1	31	51	46	50	50	50
Suburb 2	31	50	46	50	50	50

Self-consumption rate in %

Grid	Reference	d-HBSS	p-HBSS	pc-HBSS	pc-CBSS-LVBB	pc-CBSS-line
Rural 1	20	38	34	37	37	37
Rural 2	19	37	33	37	36	37
Rural 3	19	37	33	37	37	37
Suburb 1	26	44	41	44	44	44
Suburb 2	27	45	41	44	45	44

Fig. 1. Comparison of the curtailed load and PV energy, the degree of self-sufficiency and the self consumption rate in different LV grids and scenarios.

The greatest need for PV curtailment is during the summer week. In the rural grids, curtailment has to be performed in each of the four weeks examined.

Load curtailment is comparatively small and occurs only in one rural grid. In Rural 2, less than 1% of consumption has to be curtailed. Most of this curtailment takes place in the winter week but also in the spring and autumn week. The need for load curtailment is caused by the high HP load combined with the household load and the charging demand of the electric cars in the morning and evening hours. Even though the need for load curtailment is comparatively small, it is

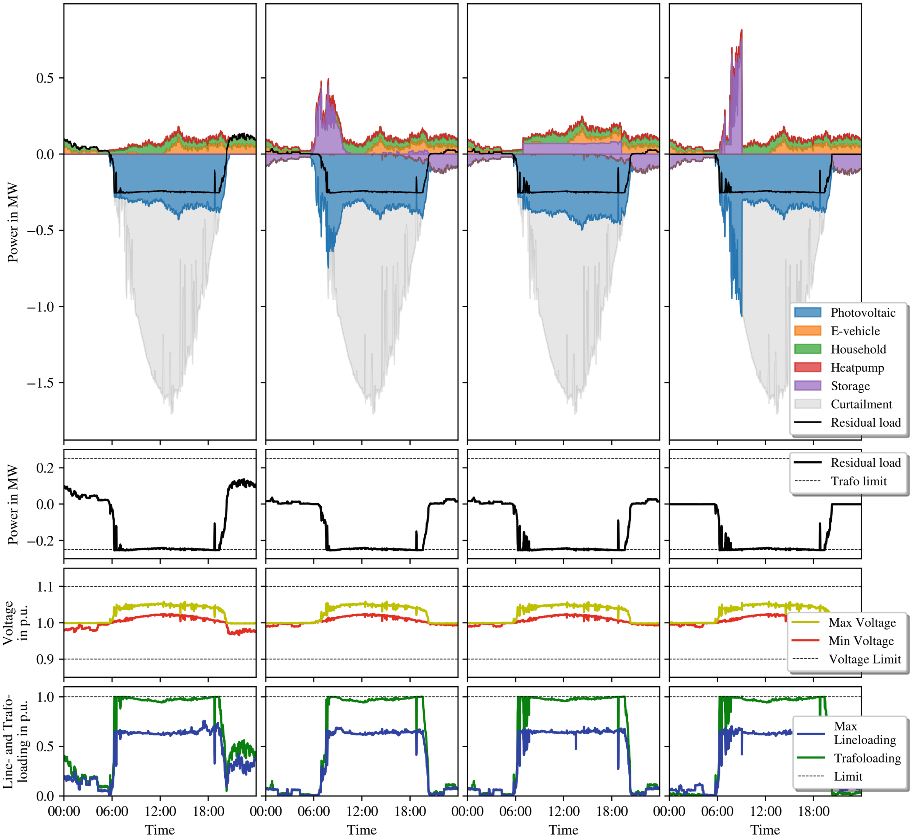


Fig. 2. Comparison of the reference scenario with three HBSS scenarios operated differently (from left to right: Reference, d-HBSS, p-HBSS, pc-HBSS): Time course of the cumulative power, residual load, voltage and equipment load during 24 h in summer in a rural LV grid.

more critical than the curtailment of PV systems since the curtailment of the load means a power outage for the affected households.

Consumption and PV generation are unevenly distributed both seasonally and during the day. The Figs. 2 and 3 show the generation and load curves over time, as well as system perturbations of an example day in Rural 2 in summer and winter. The left of the four graphs depicts the reference scenario. The seasonal differences are significant. In summer, for example, around six times more energy is generated than consumed. Whereas in winter, about twice as much energy is consumed as generated.

Nevertheless, also during the day, generation and consumption behave acyclically. The highest PV power is usually generated in the middle of the day, while consumption peaks occur mainly in the morning and evening, which argues for using BSSs. The results for the BSS scenarios are presented in the next section.

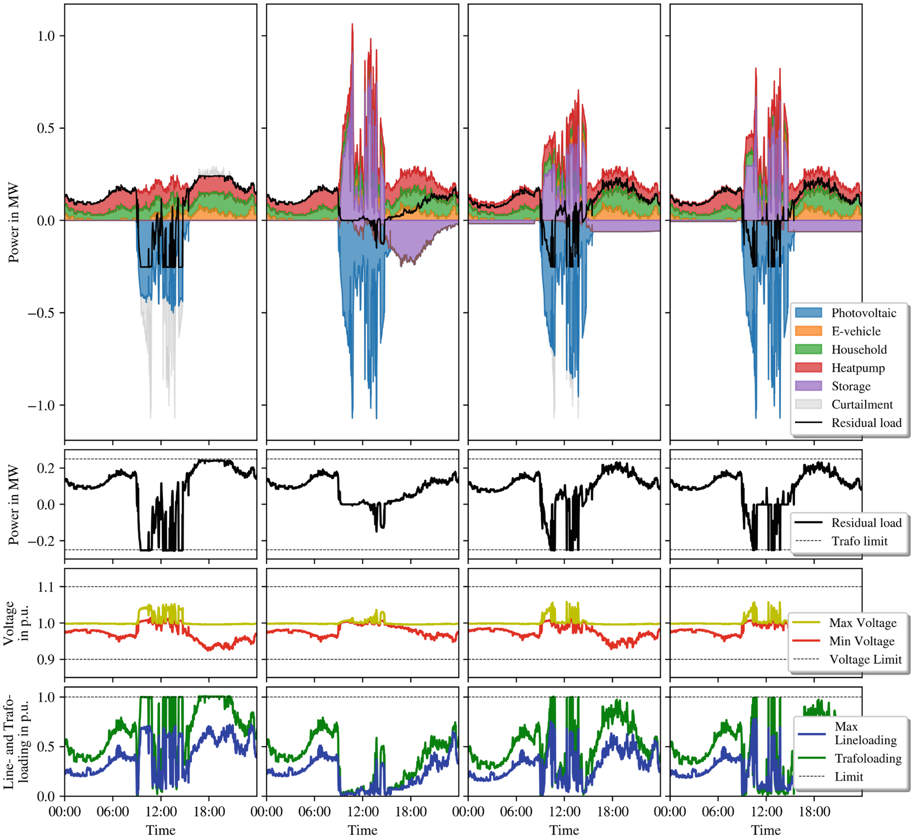


Fig. 3. Comparison of the reference scenario with three HBSS scenarios operated differently (from left to right: Reference, d-HBSS, p-HBSS, pc-HBSS): Time course of the cumulative power, residual load, voltage and equipment load during 24 h in winter in a rural LV grid.

3.2 BSS Scenarios

This section presents the impact of BSSs with the different operating and positioning strategies on curtailment, self-sufficiency, and PV self-consumption in all five LV grids (see Fig. 1). In addition to the reference scenario, Figs. 2 and 3 show the three BSS operating strategies for HBSSs on an example day in Rural 2 in summer and winter.

3.2.1 Curtailment of PV Systems and Load

By using BSSs, less PV energy is curtailed in all grids. However, the curtailment of PV systems cannot be completely avoided in any grid. Rural 2 and 3 continue to be particularly affected by PV curtailment, with 41 to 45% and 36 to 39%, respectively. 2 to 12% of PV energy is curtailed in the remaining grids.

Direct charging reduces the curtailment of PV systems in most grids. In Rural 2 and 3, the influence of BSSs is particularly evident. The curtailment of PV energy is reduced by about 8 to 10% points. The preventive operating strategy results in a further but smaller reduction in curtailment. HBSSs achieve the lowest losses due to curtailment with the preventive-curative operating strategy. Similar to preventive charging, the BSSs have, on average, a larger spare storage capacity in the middle of the day due to reduced charging compared to direct charging. However, since they can also respond to LPT overloads, the feed-in peaks are damped more than within the preventive charging strategy.

Load curtailment in Rural 2 can only be entirely avoided by operating strategies in which BSSs actively respond to LPT overloads. In direct and preventive charging scenarios, load curtailment can only be reduced.

Compared to HBSSs with the preventive-curative operating strategy, a CBSS at the LVBB may result in slightly increased curtailment of PV energy because the positioning at the LVBB cannot reduce or prevent line overloads. With CBSSs in the power lines, line overloads may be increased or even newly created compared to the HBSS scenario. For example, cross-feeder energy exchange can cause line overloads. Nevertheless, the CBSSs essentially correspond to those of the HBSS scenarios.

3.2.2 Self-sufficiency and Self-consumption

The use of BSSs causes an increase in SCR and DOS in the BSS scenarios compared to the reference scenario. With BSSs, almost twice the amount of PV energy can be consumed locally, resulting in less PV energy being fed into the grid. A maximum SCR of 37 to 38% in the rural grids is achieved with BSSs. In semi-urban grids, the maximum SCR values are 44 and 45%. The lowest SCR are found in the rural LV grids, especially in Rural 2 and 3, since PV generation is comparatively high. Rural LV grids have DOS ranging from 54 to 64%, which is consistently higher than suburban grids at 46 to 51%.

Due to high storage utilisation, direct charging achieves some of the highest DOS and SCR. Preventive charging reduces SCR and DOS values by about 4–7 percentage points compared to direct charging since the BSSs do not always reach the highest possible SOC at the end of the day and are therefore less well utilised. The preventive-curative operating strategy results in only a slight change of about ±2% points compared to direct charging. On summer days, the preventive-curative charged BSSs are almost as well utilised as when they are directly charged. In winter, the BSSs can be used even better by charging power from the LV grid that other PV systems have provided.

Since the three positioning strategies are based on the same operating strategy, they have similar self-sufficiency and self-consumption values. The DOS and SCR in all LV grids with CBSSs are mostly the same as in the HBSS scenario.

4 Conclusion

In the renewable and sector-coupled energy system, a high degree of curtailment is required to avoid equipment overloads and voltage band violations in LV grids. Mainly LPT overloads are responsible for the high demand of curtailment. However, even in long power lines with a high number of households, line overloads can occur if no curtailment is performed. The greatest need for curtailment arises from high PV feed-in. Especially rural grids with considerable roof area potential and comparatively low nominal power of the LPT are affected. In winter, load curtailment may also occur. Load curtailments are equivalent to power outages and therefore more critical than curtailments of PV systems. However, load curtailments occur much less frequently.

HBSSs can reduce the need for curtailment and significantly increase the degree of self-sufficiency and the self-consumption rate. A direct, exclusively demand-oriented operation of HBSSs achieves the highest degree of self-sufficiency and self-consumption rate. However, it is least able to counteract the necessary curtailments compared to the other operating strategies. In contrast, a preventive operating strategy with reduced charging power results in lower curtailment losses. However, the poorer storage capacity utilisation reduces the self-sufficiency and self-consumption of PV energy.

HBSSs and CBSSs, with operating strategies that actively respond to grid states, can increase both local generation balancing and network efficiency within the LV grid. In contrast to the direct and preventive operating strategy, the preventive-curative operating strategy with digitally interconnected BSSs can serve the grid without affecting self-consumption. A CBSS at the LVBB cannot counteract line overloads, which leads to a slightly higher need for the curtailment of PV systems. Also, with CBSSs in the power lines, line overloads may increase compared to the HBSS scenario. However, these are lower than for the CBSS at the LVBB. The self-consumption corresponds to that of the HBSS scenario.

In all analysed LV grids, the operation of the BSSs has a more significant impact on curtailment, self-sufficiency and PV self-consumption than positioning. In this respect, the positioning of HBSSs and CBSSs shows only marginal differences. More relevant is whether BSSs respond to grid states instead of pursuing an exclusively demand-oriented strategy.

It could be shown that BSSs in LV grids can contribute to integrating PV systems, HPs and electric cars in the energy system. However, the digitalisation of distribution grids must be advanced to exploit the potential of BSSs in distribution grids fully.

In addition to the energy and electrical engineering aspects, other factors such as the business model might play a significant role. Congestion mitigation and grid security are the responsibility of the distribution system operator, whereas HBSSs are owned and operated by private customers. Today, there are no incentives for these customers to take on additional efforts or disadvantages that could be associated with grid-serving storage operations. Consequently, the regulatory framework needs to be adapted, and business models need to be developed to bring grid-serving operating strategies for BSSs, as presented in this work, into practice. Also, due to the lower investment costs per kWh storage capacity for CBSSs compared to HBSSs, with a similar impact on the grid and self-consumption, CBSSs may be advantageous in the future. These, as well as digitally interconnected HBSSs, also have a broader range of applications, i.e. the provision of ancillary services. This broader applicability could additionally be used to increase the economic efficiency of BSSs on the one hand and to contribute to the security of supply in the electric energy system beyond the respective LV grid on the other hand.

As a follow-up to this research, other BSS scenarios could be investigated. For example, a combination of interconnected HBSSs or CBSSs in the power lines with a CBSS at the LVBB could be interesting. Also, an economic analysis could be added to provide a more holistic view of the scenarios. Due to the work conditions and the scarcity of resources for lithium-ion batteries, further research concerning other electricity storage technologies for use in PV storage systems is needed. A part of this research could be done with the used Python model by adjusting the parameters of the storage system and making appropriate extensions.

Apart from investigations with the present model, seasonal storage should also be investigated more strongly in order to be able to use the solar generation peaks in summer to cover the energy demand in winter. Since seasonal and daily storage should not compete but complement each other, this opens up a broad field of research. For example, various storage technologies and coordinated operating strategies can be combined in further research. Among other things, it would be conceivable to divide the work of the storage systems by distinguishing between storage systems that cover the base load and store PV energy with reduced charging power and those used to cover peak loads and store generation peaks. Similar to the presented preventive-curative operating strategy, these could charge or discharge the share of energy that would overload the LPTs or power lines.

Credit Author Statement

Tabea Katerbau Conceptualisation, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review and editing, Visualisation, Funding acquisition

Ricardo Reibsch Conceptualisation, Methodology, Software, Validation, Formal analysis, Writing - original draft, Writing - review and editing, Visualization, Project administration.

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Acknowledgments. This paper was written in the framework of the research project 'Netz_eLOG', which the Federal Ministry for Economic Affairs and Climate Action (BMWK) finances. Furthermore, we would like to thank the Reiner Lemoine Foundation for its support, primarily through the creation of the PhD Graduate School and for co-financing this research work.

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