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Emergency power supply from photovoltaic battery systems in private households in case of a blackout – A scenario analysis

Peter Stenzel[a,c,*], Timo Kannengießer[a,c], Leander Kotzur[a,c], Peter Markewitz[a,c], Martin Robinius[a,c], Detlef Stolten[a,b,c]

[a]*Forschungszentrum Jülich GmbH, Institute of Energy and Climate Research – Electrochemical Process Engineering (IEK-3), D-52425 Jülich, Germany*
[b]*Chair for Fuel Cells, RWTH Aachen University, c/o Institute of Electrochemical Process Engineering (IEK-3), Forschungszentrum Jülich GmbH, D-52425 Jülich, Germany*
[c]*Jülich Aachen Research Alliance, JARA-Energy, Jülich, Aachen, Germany*

Abstract

The emergency power supply functionality of photovoltaic battery energy storage systems (PV BESS) is evaluated based on a case study, which comprises a single-family house in Germany with defined electricity load profile and installed PV BESS. Key factors, which influence the emergency power functionality, are: begin and duration of the blackout, electricity load and PV production profile during blackout and BESS state of charge at the beginning of the blackout. The backup functionality especially depends on the available electricity generation from the PV system and shows therefore a strong seasonal dependency. In case of a blackout, a PV BESS generally makes electricity available, which would not be available to a household without PV BESS. However, the complete coverage of longer blackout periods from PV BESS under the assumption of a normal load profile (100% autarkic system operation) is limited to only a few high PV production periods during the year. In this context, load reduction and load shifting by adapted user behavior during a blackout shows high potential to increase the backup supply functionality and the overall security of energy supply by extending the period during which the reduced household electricity load can be covered from the PV BESS.

Keywords: Photovoltaic battery storage systems, PV home storage systems, Emergency power, Backup power, Scenario analysis

* Corresponding author. Tel.: +49-2461-61-6556; fax: +49-2461-61-6695.
E-mail address: p.stenzel@fz-juelich.de

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1. Introduction

The increase of self-consumption from locally produced electricity of photovoltaic (PV) systems is getting increasingly attractive from an end-consumer perspective and is becoming a major application field of stationary battery energy storage systems (BESS). A high market growth for storage in the small scale/ residential PV storage sector is expected in the upcoming years e.g. by [1, 2]. From an economic perspective the pairing of BESS with PV systems to increase self-consumption is especially interesting in countries with high electricity tariffs and declining levels of remuneration (e.g. due to feed-in tariff) for grid feed-in of locally produced electricity. A high market growth can also be expected in the remote/ off-grid segment in regions with favorable solar conditions.

One of the early and currently one of the biggest markets for PV BESS in the residential sector (also called: distributed storage systems or home storage systems) is Germany. At the end of April 2017 approx. 61,300 PV BESS with a cumulated storage capacity of approx. 400 MWh have been installed in Germany [3]. This number grew to approx. 75,000 systems until the end of 2017 [4]. In 2016 almost every second PV system (46%) in the segment ≤ 30 kWp has been equipped with a battery [3]. Apart from the wish to contribute to the German energy transition ("Energiewende") and the protection against rising electricity prices also the emergency power/ backup supply functionality of PV BESS is one of the factors which are relevant for the customers [3]. That backup supply functionality of PV BESS to avoid blackouts and power outages is an important factor in the investment decision is also supported by a survey from Australia [5]. On international level, the backup functionality of PV BESS is especially interesting in countries with weak grids, which suffer from frequent blackouts. In these countries, the installation of a PV BESS can significantly improve the quality and the security of the electricity supply and can replace alternative backup power supply systems (e.g. diesel generators).

1.1. Literature review

The application of grid-connected PV BESS in the residential sector has been subject to numerous studies [6, 7]. Most of the studies focus on techno-economic aspects. Papers with a more technical focus cover a broad range of research questions and topics. One key aspect is the development and analysis of BESS operation strategies [8-12]. The effect of PV BESS on the distribution grid and possibilities to relief the grid by applying suitable battery operation strategies is subject of [13-18]. Another important point is the analysis of battery degradation and the impact on the battery lifetime under consideration of application specific aging for PV BESS [19-21]. The influence of the temporal resolution of PV production and consumer load profiles on the modeling of PV BESS is analyzed by [22-24]. A detailed technical PV BESS model is applied by [25] to quantify dynamic mismatch losses of grid-connected PV-battery systems in residential buildings. In [26] a detailed technical evaluation of PV BESS is presented based on field measurements. Different aspects regarding the design and sizing of PV BESS are covered by [27, 28].

Papers with a more economic focus are dealing with the development and application of optimization approaches and related profitability analysis of PV BESS [7, 29-36], country specific case studies [20, 37, 38] and the consideration of multi-use applications to increase the profitability of PV BESS e.g. [39]. The impact of the consumer load profile and the location on the techno-economic performance is investigated e.g. by [32, 40-42].

All mentioned papers focus on the normal standard operation of grid-connected PV BESS. The analysis of PV BESS operation as backup power supply system in case of a blackout has not been considered in the scientific literature so far.

1.2. Research objective

In focus of this contribution is the question to which extent a backup power supply of a single-family house from PV BESS is possible from a technical perspective. An economic evaluation of PV BESS as backup power supply system for single-family houses is not within the scope of this paper.

In a first step, the backup power supply functionality of commercial available systems is analyzed and differences between the systems are identified. In a second step, a case study is defined and the backup power supply functionality of a PV BESS is evaluated based on a scenario analysis. The case study comprises a single-family house in Germany with defined electricity load profile and installed PV BESS. Factors, which influence the backup power functionality, are: begin and duration of the blackout, electricity load and PV production profile during blackout and BESS state of charge at the beginning of the blackout. In a scenario analysis, these influence factors are quantified. As a result of the scenario analysis it can be calculated how much electricity is available from the PV BESS during the blackout and during what time period the load can be covered. The only factor determining the backup power supply functionality, which can be influenced, is the user/ end-consumer behavior. To account for this, also scenarios with adapted user behavior (load reduction during the blackout) are considered in the analysis.

1.3. Backup power functionality of home storage systems

The backup power supply functionality of commercial available PV BESS (home storage systems) varies significantly between the systems. In general, it can be distinguished between systems with and without backup functionality. The majority of commercial available PV BESS are equipped with backup functionality. Systems with backup functionality are able to provide backup power in case of a blackout to a certain extent. However, the extent of the technical functionality is rather diverse. In the following, a three level classification (level 1, level 2, level 3) is used to characterize the backup functionality.

- Level 1 (basic backup functionality)
  Storage systems in this category are able to provide only a basic backup functionality. This is typically realized by one or more power sockets, which are directly integrated in the BESS. In case of a blackout, plug based electrical devices (e.g. lamps, radio) can be connected manually via cables to the storage system. The supply of other devices without plug is not possible.
- Level 2 (advanced backup functionality)
  Storage systems in this category are fully integrated in the household energy system and are able to build up a grid-independent household electricity supply system in case of a blackout. This comprises a disconnection from the grid and the build-up of an island electricity supply system. However, the backup electricity supply is limited to the energy, which is available from the BESS. Battery charging from the PV system as well as direct electricity supply from the PV system is not possible during the blackout. This means, that backup power supply depends on the state-of-charge (SOC) of the BESS at the beginning of the blackout and is limited to maximum a couple of hours for typical system sizes.
- Level 3 (full backup functionality)
  Storage systems in this category provide full backup functionality. Additionally to the functionality of level 2 systems, battery charging from the PV system as well as direct electricity supply from the PV system during the blackout is also possible. Due to the battery charging possibility, level 3 systems are able to cover longer blackout periods depending on the PV electricity generation and the demand situation (consumer load profile).

For level 2 and level 3 systems, a further differentiation between single and three phase backup supply systems is relevant. In the case of a single-phase system, backup power supply in case of a blackout is limited to electric consumers, which are connected to the same phase as the storage system is connected to. A supply of the other two phases as well as the supply of three phase devices (e.g. oven/ kitchen stove) is not possible. These limitations do not occur for three phase systems which can be operated unsymmetrically and are able to supply all household electricity consumers in case of a blackout.

A parameter, which limits the backup power functionality of PV BESS, is the peak power of the battery storage system inverter. In case of a blackout, the supply of household electricity consumers is only possible if the household load is below the peak power of the inverter. If the load exceeds the peak power of the inverter, the system will automatically shut down and has to be restarted manually. In some cases, the peak power rating of PV BESS differs for the cases battery supply only vs. combined supply from PV and BESS (see Table 1).

Another point which influences the backup power functionality of level 2 and level 3 systems is whether the system switches automatically from standard operation (with grid-connection) to backup power operation (island system). The required switch-time varies from a few ms to several seconds. The additional (stand-by) electricity consumption, which is related to the automatic switch functionality, has to be considered in comparison to systems without automatic switch functionality. As an alternative, systems with manual switching are possible.

In the context of this paper, only PV BESS with full backup functionality (level 3) are considered. Table 1 provides technical data of selected systems.

Table 1. Technical data of selected commercially available PV BESS with full backup functionality (Level 3) [43-45]

System	Usable capacity [kWh]	Peak power [kW]	Continuous power [kW]	Type
Tesla Powerwall 2	13.5	7	5	single phase
E3/DC S10 E 12	4.6 / 6.9 / 9.2	12*	3	three phase
FENECON Pro 9-12	12	9	9	three phase

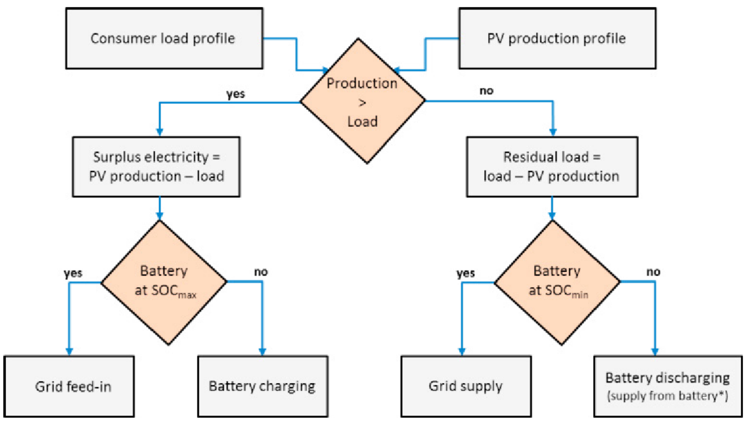
*: in combination with PV system only

2. Methodology and basis data

In the following chapter the methodology and the required basis data for the modeling and the simulation of PV BESS operation is described. In chapter 2.1 the chosen modeling approaches and packages for the simulation of PV BESS operation are presented. The analysis of the backup power supply functionality of a PV BESS is based on a case study which is defined in chapter 2.2 together with the required basis data. To evaluate the backup power supply functionality of a PV BESS scenarios are developed in chapter 2.3.

2.1. Modeling approach

To analyze the operation of a PV BESS in a private household, a simulation model has been developed and implemented in Python. The model is based on the energy balance of a household which is calculated for every time step according to Linssen et al. (2017) [41]. The electricity demand of the household is defined by the consumer load profile. The demand can be covered by electricity supply from the PV system, the BESS and the grid. The implementation of the PV BESS in the energy balance of the household is shown in Fig. 1.



*: in dependency from the load and the peak power of the PV BESS inverter, a combined supply from PV BESS and the grid is possible

Fig. 1: Implementation of PV BESS in the energy balance of a household (modified after [41])

Direct self-consumption of locally produced PV electricity is prioritized in the electricity supply concept. If direct consumption is not possible, the battery is charged (in the case of excess PV generation) or discharged (in the case of loads, which cannot be covered by PV generation). If both direct consumption and charging/discharging of the battery are not available, the public grid is used to cover the household’s demand or to feed-in excess PV electricity. [41]

The photovoltaic production profile is generated with the Python Package PV_LIB [46]. The PV_LIB Toolbox provides a set of functions for simulating the performance of photovoltaic energy systems based on time series of solar irradiation. The Perez-Model [47] is used for the diffuse irradiance calculation, and module temperature and photovoltaic performance are calculated with the Sandia Performance Model.

The electricity load profile is generated with a stochastic bottom-up demand model [48-50] that generates device-specific load profiles depending on the household equipment and behavior of the members of the household. For an automated workflow, it has been implemented as Python module. Furthermore, some minor adaptions have been made to the original model: the states between days have been coupled in order to get full annual time series, a four-state activity model has been integrated for a better heat load integration [51], and the original light bulb load has been updated to include besides bulbs a distribution of halogen and LED lamps [52].

The energy balance of the household (see Fig. 1) is used to calculate the degree of autarky (DA). The DA is defined as the ratio of energy generated by the PV system and directly used at the installation site ($E_{PV,used}$) to the total amount of energy used by the household (E_{load}) in a defined time period:

$$DA = \frac{E_{PV,used}}{E_{load}} \quad (1)$$

$E_{PV,used}$ results from the sum of PV electricity directly used ($E_{PV,direct}$) and the PV electricity used later after being stored in the battery ($E_{PV,indirect}$). Losses due to the charging/discharging efficiency of the battery are considered in the calculation. The DA is also used to characterize the backup functionality of a PV BESS. In this context, a DA of 100% means that the PV BESS can cover the complete load during the blackout. For values < 100%, the DA provides the share to which extent the load can be covered.

2.2. Case study and basis data

The selected case study comprises a single-family house in Germany with installed PV BESS. The house is located in Lindenberg, Germany (Latitude: 52.21, Longitude: 14.122). The house is equipped with a PV BESS. The technical parameters of the system are summarized in Table 2. For the AC coupled BESS system constant charging and discharging efficiencies are considered, which represents a simplification regarding the real power-dependent efficiency of PV BESS (see e.g. [53]). The constant efficiency approach overestimates the PV BESS performance for part load operation of the BESS inverter; however, the overall performance for longer periods is represented quite well.

Table 2: Overview of technical parameters of the PV BESS in the selected case study for the location Lindenberg, Germany

PV system		BESS	
Type	Rooftop PV	Type (phase supply)	3-phase
System size	6 kWp (24 modules)	Cell chemistry	Lithium-Ion
Tilt angle	30°	Storage capacity	8 kWh
Orientation	south	Battery inverter power*	6 kW
Module type	Hanwha HSL60P6-PB-1-250 (250 Wp)	Depth of Discharge (DoD)	80%
PV inverter type	ABB MICRO-0.25 (250 W)	Charging efficiency	95%
Other system losses**	10%	Discharging efficiency	95%
Specific solar yield***	1001 kWh/kWp	Backup functionality	Level 3 (see chapter 1.3)

*: Separate inverter for BESS (AC coupled system)
**: 10% system losses assumed due to soiling, mismatch, and DC wiring
***: Calculated with Python Package PV_LIB

The solar irradiation and the outdoor temperature time series are taken from the values measured in one minute resolution at the station Lindenberg operated by Germany's National Meteorological Service (Deutscher Wetterdienst - DWD) [54]. The resulting electricity production for a rooftop PV system is calculated in one-minute resolution with Python Package PV_LIB (see chapter 2.1). For the modeling of the output power of the PV system the albedo is set to 0.2. All other required parameters for the calculation of the PV output power are included in Table 2. To allow for maximum flexibility regarding the sizing of the PV system, it is assumed that each single module is equipped with a module inverter (micro inverter). The PV output power is calculated for the year 2007 as this year represents an average year regarding the location specific solar irradiation considering the time period 2000 to 2007 [54]. The resulting PV production profile is used for all following calculations and shown in Fig. 2.

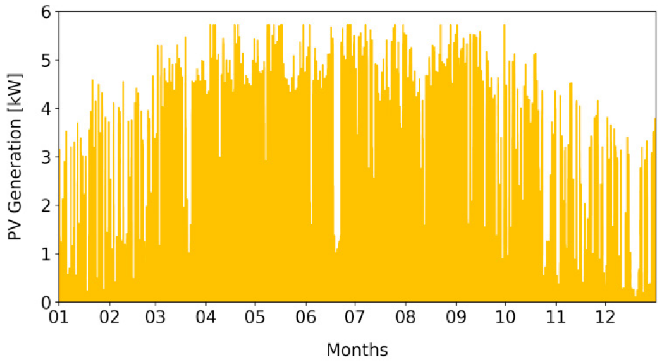


Fig. 2. PV production profile for the year 2007 for the location Lindenberg, Germany (own calculation with Python Package PV_LIB)

The PV production profile shows a typical characteristic for Germany with low PV production during the winter months and highest PV production during the summer months. The total yearly electricity production for the PV system defined in Table 2 sums up to 6,006 kWh.

The consumer load profile is calculated with the demand model (see chapter 2.1). For heating and hot water supply, a natural gas condensing boiler is applied. The electricity demand for the circulation pump is considered in the calculation of the household electricity load. It is assumed that the circulation pump is continuously operated at nominal load (20 W) during the heating period from September 1st to May 31st. It is further assumed, that natural gas and water supply infrastructures are not affected from an electricity blackout. As input data for the demand model the number of persons is required.

An exemplary day of the resulting electricity load profile of the selected four-person household is shown in Fig. 3.

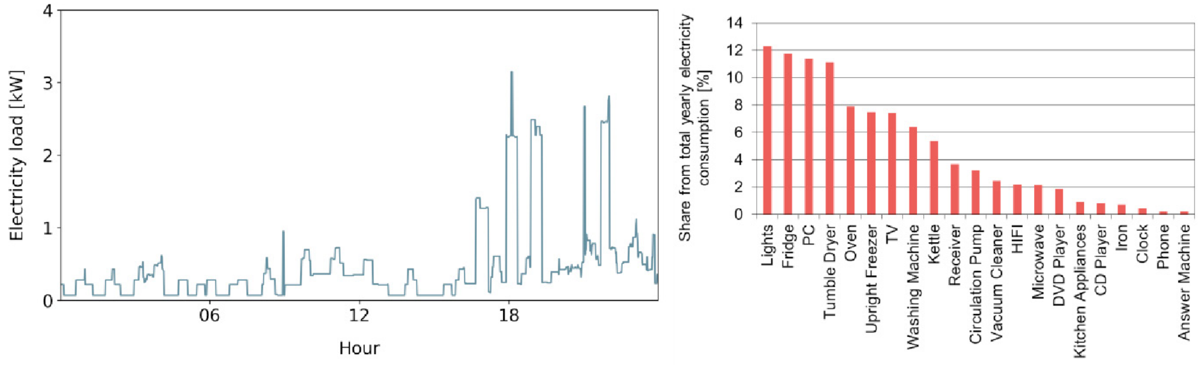


Fig. 3. Consumer electricity load profile (left: selected day: June 1st, 2007; right: share of electric devices from total yearly electricity consumption) for a single family house with a four person household located in Lindenberg, Germany

The total yearly electricity consumption sums up 4,071 kWh. The daily electricity consumption varies between 5.2 kWh (June 23rd) and 23.4 kWh (February 3rd) and is on average 11.2 kWh. The share of the electric devices, which are present in the modeled household, from total electricity consumption, is also shown in Fig. 3. The device categories “Lights”, “Fridge”, “PC” and “Tumble Dryer” have the highest share from total electricity consumption with a cumulated share of approx. 47% (see Fig. 3).

2.3. Scenario analysis

The backup power supply functionality of a PV BESS is evaluated based on a scenario analysis where it is distinguished in a first step between a summer and a winter scenario. The analysis is carried out for the year 2007. The summer scenario is related to the period June 1st to August 31st. The winter scenario is related to the time period December 1st to February 28th/29th. For each case (summer/winter), the week with the highest and the lowest electricity generation from the PV system is selected for the backup power supply functionality analysis. In the analysis it is assumed, that a blackout occurs during the selected weeks. The minimum duration of the blackout is one minute and the maximum duration of the blackout is the complete week. For the selected weeks, it is further distinguished between a normal load profile and an adapted load profile (adapted user behavior and related reduced electricity demand during the blackout).

The normal load profile is identical to the load profile for the case that no blackout occurs. For the adapted load profile it is assumed, that electricity consumption during the blackout is significantly reduced by limiting the electric devices, which are used during the blackout. The list of all electric devices, which are present in the household, can be seen from Fig. 3. In the case of a blackout, it is assumed that the members of the household change their user behavior by limiting the device usage to the kitchen equipment (fridge, upright freezer, oven, microwave, kettle, kitchen appliances), the use of lights and the use of basic information and communication technologies (clock, phone, HIFI). It is further assumed, that the circulation pump of the heating system remains in operation to guarantee heating supply to the household. All other electric devices are not used during a blackout. The device group which is not used during the blackout includes devices of which their usage can be postponed to the time period after the blackout (washing machine, tumble dryer, vacuum cleaner, iron) and further communication and entertainment technologies (PC, TV, receiver, DVD, CD player and answer machine).

For the defined cases, the development of the DA is analyzed. The DA serves as an indicator to which extent the load could be covered during the blackout. To analyze different blackout durations and blackout starting points, the DA is calculated in one-minute resolution for the selected weeks. As an additional indicator, the available energy from the PV BESS during the blackout is calculated. For the case of an adapted load profile, the SOC of the BESS at the beginning of the blackout is taken from a reference simulation of PV BESS operation for a complete year without blackout. The scenario approach is summarized in Fig. 4.

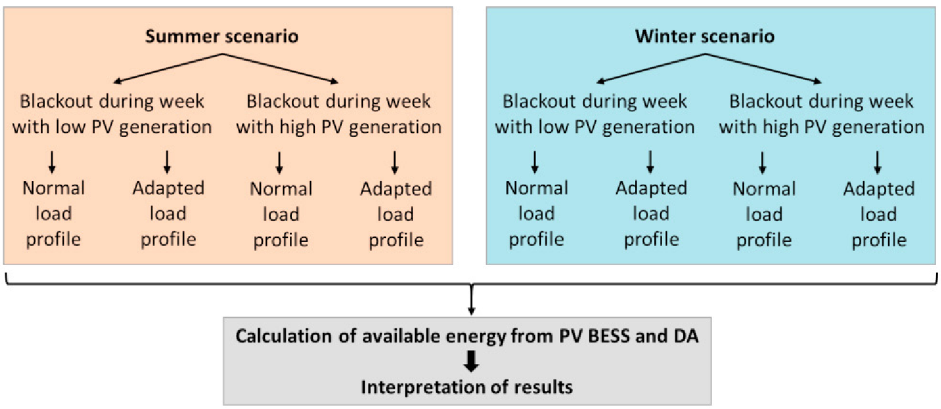


Fig. 4. Scenario approach for PV BESS blackout functionality analysis

In a second step an analysis of different blackout durations and starting points for a complete year is performed. Three different intervals representing the blackout duration (1 hour, 1 day, 1 week) are considered. The hourly blackout interval starts always at hh:00 and ends at hh:59. The daily interval starts always at 00:00 and ends at 23:59. The weekly interval starts at Monday 00:00 and ends on Sunday 23:59. The total number of intervals sums up to 8760 hours (hourly interval), 365 days (daily interval) respectively 52 weeks (weekly interval). The blackout functionality is analyzed by calculating the DA for each interval in a complete year. As a result, the numbers of intervals with a DA of 100% are evaluated on a monthly basis. In the analysis, it is further distinguished between the cases normal and adapted load profile.

3. Results and discussion

In chapter 3.1 and 3.2, the results of the summer and the winter scenario are presented. Chapter 3.3 shows the results of the analysis of different blackout durations and starting points.

3.1. Summer scenario

Fig. 5 shows the results of the backup functionality analysis for the summer scenario. The summer week with the lowest PV generation is week 28 (July 9th to July15th) with a total electricity production of 141.6 kWh. The electricity demand in week 28 varies between 72.5 kWh (normal load profile) and 35.0 kWh (adapted load profile). The summer week with the highest PV generation is week 24 (June 11th to June 17th) with a total electricity production of 191.3 kWh. The electricity demand in week 24 varies between 67.5 kWh (normal load profile) and 36.3 kWh (adapted load profile).

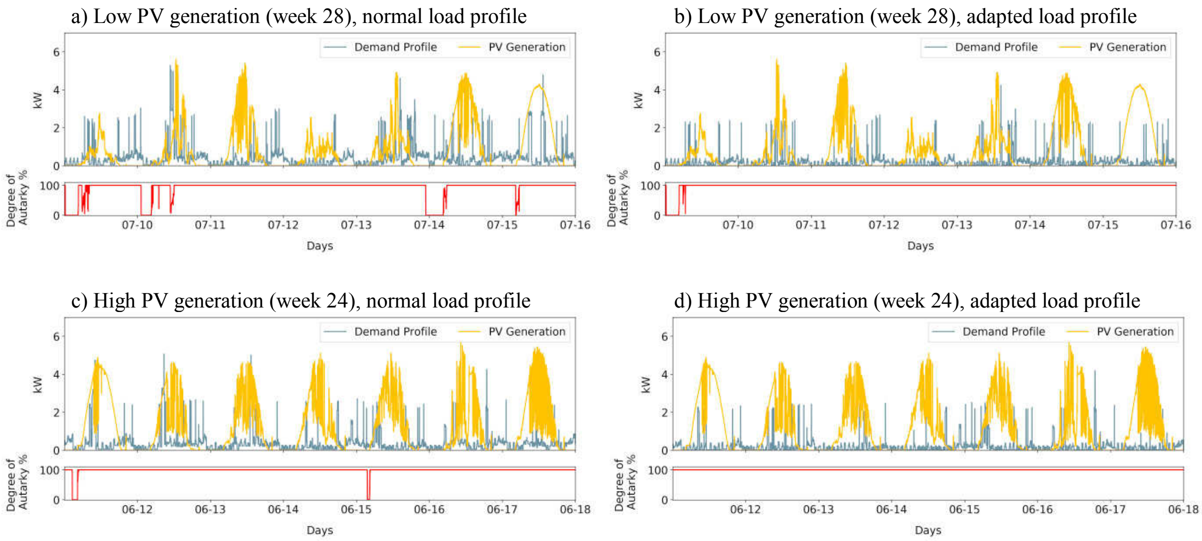


Fig. 5. Electricity demand profile, PV production profile and DA for selected summer weeks with high (c) and d)) and low (a) and b)) PV production for normal (a) and c)) and adapted (b) and d)) load profile

In Fig. 5 a), the development of the DA is shown for the selected summer week with low PV generation and normal load profile. The average DA in this week is 90.3%. During the selected week, the DA is mostly at 100% which shows a high availability of the PV BESS for full backup power supply. Some shorter periods occur during the nights / early mornings where the demand could not completely be covered from the PV BESS in case of a blackout. Under the assumption of an adapted load profile for the complete week (Fig. 5 b)), the average DA is increased to 97.4%. Only a short period occurs during the beginning of July 9th where the load could not be covered from the PV BESS in case of a blackout.

In Fig. 5 c), the development of the DA is shown for the selected summer week with high PV generation and normal load profile. The average DA in this week is 98.5%. During the selected week, the DA is with the exemption of two very short periods at 100%, which shows a high availability of the PV BESS for full backup power supply. Under the assumption of an adapted load profile for the complete week (Fig. 5 d)), the average DA is increased to 100%.

It can be stated, that during summer weeks respectively during weeks with relatively high PV production, the PV BESS backup functionality is generally good. Depending on the beginning and duration of a blackout, only shorter periods during the night could not be covered from the PV BESS. The influence of high and low PV generation weeks on the results is less pronounced.

3.2. Winter scenario

Fig. 6 shows the results of the backup functionality analysis for the winter scenario. The winter week with the lowest PV generation is week 1 (January 1st to January 7th) with a total electricity production of 16.1 kWh. The electricity demand in week 1 varies between 76.5 kWh (normal load profile) and 48.7 kWh (adapted load profile). The winter week with the highest PV generation is week 7 (February 12th to February 18th) with a total electricity production of 77.2 kWh. The electricity demand in week 7 varies between 83.1 kWh (normal load profile) and 53.0 kWh (adapted load profile).

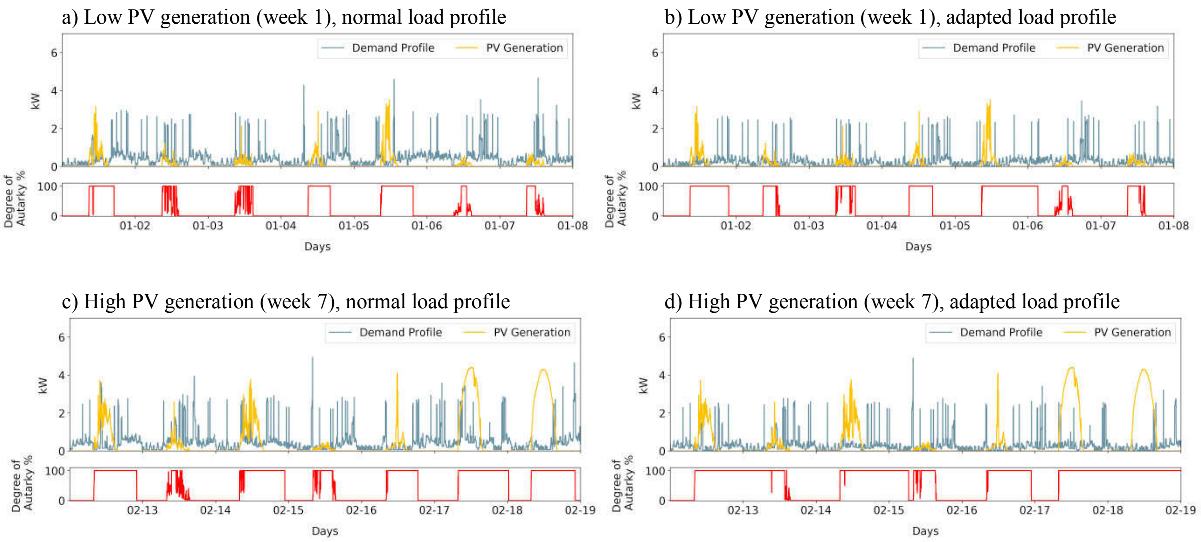


Fig. 6. Electricity demand profile, PV production profile and DA for selected winter weeks with high (c) and d)) and low (a) and b)) PV production for normal (a) and c)) and adapted (b) and d)) load profile

In Fig. 6 a), the development of the DA is shown for the selected winter week with low PV generation and normal load profile. The average DA in this week is 23.3%. During the selected week, the DA is only during shorter periods (during the day at sunshine and short after sunset) at 100%. On the one hand, this shows only a limited availability of the PV BESS for backup power supply. Especially the complete period during the night could not be covered from the PV BESS in case of a blackout. On the other hand, there are also 26 hours in the selected week during which the load could be completely supplied from the PV BESS.

Under the assumption of an adapted load profile for the complete week (Fig. 6 b)), the average DA is increased to 33.9%. However, the periods with a DA of 100% are extended only slightly and still mainly limited to periods during the day. Limiting factor is the low electricity generation from the PV system.

In Fig. 6 c), the development of the DA is shown for the selected winter week with high PV generation and normal load profile. The average DA in this week is 47.4%. During the selected week, the DA is during longer periods (during the day at sunshine and short after sunset) at 100%. This shows a high availability of the PV BESS for backup power supply during the day. However, the nighttime periods could still only to a short part be covered from the PV BESS in case of a blackout. Under the assumption of an adapted load profile for the complete week (Fig. 6 d)), the average DA is increased to 67.8%. In comparison to the normal load profile, the periods with a DA of 100% are extended and in several cases, also nighttime periods can be covered from the PV BESS in case of a blackout.

It can be stated, that during winter weeks respectively during weeks with relatively low PV production, the PV BESS backup functionality is mainly limited to periods during the day. Depending on the beginning and duration of a blackout, only very short time periods during the night could be covered from the PV BESS. There are also days with almost no PV electricity generation, which lead to longer periods with a DA of 0%, which means no backup supply functionality by PV BESS. The influence of high and low PV generation weeks on the results is higher than in the summer scenario and also the difference between normal and adapted load profile is stronger.

3.3. Analysis of different blackout durations and starting points

Table 3 shows the results of the analysis of different blackout durations and starting points for a complete year under the assumption of the normal load profile (see chapter 2.3).

Table 3: Number of intervals with 100 % DA and share from total intervals per month for different blackout durations (interval length) and normal load profile

Blackout duration (interval)	January		February		March		April		May		June	
	Number of intervals with 100% DA	Share from total intervals [%]	Number of intervals with 100% DA	Share from total intervals [%]	Number of intervals with 100% DA	Share from total intervals [%]	Number of intervals with 100% DA	Share from total intervals [%]	Number of intervals with 100% DA	Share from total intervals [%]	Number of intervals with 100% DA	Share from total intervals [%]
1 hour	208	28	263	39	467	63	638	89	681	92	653	91
1 day	0	0	0	0	1	3	11	37	15	48	13	43
1 week	0	0	0	0	0	0	0	0	0	0	0	0
Blackout duration (interval)	July		August		September		October		November		December	
	Number of intervals with 100% DA	Share from total intervals [%]	Number of intervals with 100% DA	Share from total intervals [%]	Number of intervals with 100% DA	Share from total intervals [%]	Number of intervals with 100% DA	Share from total intervals [%]	Number of intervals with 100% DA	Share from total intervals [%]	Number of intervals with 100% DA	Share from total intervals [%]
1 hour	658	88	680	91	435	60	392	53	207	29	144	19
1 day	12	39	17	55	0	0	1	3	0	0	0	0
1 week	0	0	0	0	0	0	0	0	0	0	0	0

The backup functionality of a PV BESS varies significantly for the three considered blackout durations (1 hour, 1 day, 1 week) and for the different months. For a blackout duration of 1 hour in approx. 90% of the hours during the months from April to August the complete blackout duration could be covered from the PV BESS without constraints. This value is significantly lower for the winter months. In December, e.g. for only 19% of the hours the complete blackout duration could be covered from the PV BESS. During the complete year, for 5,426 hours (62% from total hours) a backup power supply from PV BESS is possible.

Under the assumption of a blackout duration of 1 day, a complete coverage of the daily load from the PV BESS is possible for only approx. 40% of the days during the months from April to August. In the months October and March only one out of all days could be supplied completely from the PV BESS in case of a blackout. In all days of the months November to February, the DA is < 100% which indicates that an entire day could not completely be supplied from the PV BESS. For a complete year, a backup power supply from PV BESS is possible for 70 days (19% from total days).

A complete coverage of a blackout lasting an entire week from the PV BESS is not possible in the analyzed year. Even during the highest production weeks some short periods occur with a DA < 100%. The longest period, which could be covered during a week, is 5 out of 7 days.

Table 4 shows the results of the analysis of different blackout durations and starting points for a complete year under the assumption of the adapted load profile (see chapter 2.3).

Table 4: Number of intervals with 100% DA and share from total intervals per month for different blackout durations (interval length) and adapted load profile

Blackout duration (interval)	January		February		March		April		May		June	
	Number of intervals with 100% DA	Share from total intervals [%]	Number of intervals with 100% DA	Share from total intervals [%]	Number of intervals with 100% DA	Share from total intervals [%]	Number of intervals with 100% DA	Share from total intervals [%]	Number of intervals with 100% DA	Share from total intervals [%]	Number of intervals with 100% DA	Share from total intervals [%]
1 hour	233	31	289	43	500	67	647	90	687	92	659	92
1 day	1	3	0	0	7	23	21	70	23	74	22	73
1 week	0	0	0	0	0	0	3	60	4	100	3	75
Blackout duration (interval)	July		August		September		October		November		December	
	Number of intervals with 100% DA	Share from total intervals [%]	Number of intervals with 100% DA	Share from total intervals [%]	Number of intervals with 100% DA	Share from total intervals [%]	Number of intervals with 100% DA	Share from total intervals [%]	Number of intervals with 100% DA	Share from total intervals [%]	Number of intervals with 100% DA	Share from total intervals [%]
1 hour	669	90	688	92	463	64	414	56	236	33	166	22
1 day	20	65	24	77	2	7	2	6	0	0	0	0
1 week	4	80	1	25	0	0	0	0	0	0	0	0

The backup functionality of a PV BESS is generally increased for all considered blackout durations and for the different months for the case of the adapted load profile in comparison to the normal load profile. For a complete year, the number of intervals with a DA of 100% is increased from 5,426 hours (normal load profile) to 5,651 hours (adapted load profile) respectively from 70 days (normal load profile) to 122 days (adapted load profile). Due to the load reduction, also a complete coverage of a blackout lasting an entire week from the PV BESS becomes possible for in total 15 weeks in the period from April to August. Especially for longer blackout durations (1 day, 1 week) the effect of load reduction (adapted load profile) is more significant regarding the number of intervals with a DA of 100%.

4. Summary and conclusion

This paper presents a backup power supply functionality analysis of PV BESS for a single-family house in case of a blackout. In a first step, the backup power supply functionality of commercial available systems has been analyzed. Systems with backup functionality are able to provide backup power in case of a blackout to a certain extent. However, the extent of the technical functionality is rather diverse. To cope with that, a three level classification (level 1, level 2, level 3) is introduced to characterize the backup functionality. A key finding from this classification is that only level 3 systems are able to provide full backup functionality. Systems in this category are fully integrated in the household energy system and are able to build up a grid-independent household electricity supply system in case of a blackout. During a blackout, battery charging from the PV system as well as direct electricity supply from the PV system is possible. Further important parameters, which influence the backup power functionality, are the number of supplied phases from the PV BESS and the peak power rating of the inverter(s). For full backup functionality three phase PV BESS with a peak power rating of the inverter(s) which is greater than the peak demand during the blackout are required.

In a second step, a case study is defined and the backup power supply functionality of a PV BESS is evaluated based on a scenario analysis. The case study comprises a single-family house in Germany with defined electricity load profile and installed PV BESS. A model has been developed and implemented in Python to calculate the energy balance of the household and the degree of autarky (DA) for each time step. The DA is introduced as an indicator to characterize the backup functionality of a PV BESS. In this context, a DA of 100% means that the PV BESS can cover the complete load during a blackout. For values < 100%, the DA provides the share to which extent the load can be covered. The scenario analysis distinguishes between a summer and a winter scenario. For each case (summer/winter), the week with the highest and the lowest electricity generation from the PV system is selected for the backup power supply functionality analysis. In the analysis it is assumed, that a blackout occurs during the selected weeks. As the user behavior is the only factor, which can be influenced, it is further distinguished between a normal load profile and an adapted load profile where a load reduction by limiting the usage of certain devices is assumed during the blackout. For the different scenarios it is calculated how much electricity is available from the PV BESS during the blackout. Further, it is determined during what period the load can be covered.

As a result from the analysis, key factors which influence the backup power supply functionality have been identified. These are: begin and duration of the blackout, electricity load and PV production profile during the blackout and BESS state of charge at the beginning of the blackout.

For the analyzed case study it can be stated, that during (summer) weeks with relatively high PV production, the PV BESS backup functionality is generally good. During high PV production periods, the DA is frequently at 100% for several consecutive days. Even for very long blackout durations up to one week, only shorter periods during the night could not be covered from the PV BESS.

During (winter) weeks with relatively low PV production, the PV BESS backup functionality is mainly limited to shorter periods during the day. Depending on the beginning and duration of a blackout, only very short time periods during the night could also be covered from the PV BESS. There are also days with almost no PV electricity generation, which lead to longer periods (up to several days) with a DA of 0%, which means no backup supply functionality by PV BESS. Nevertheless, even for low PV production weeks a minimum electricity supply level from the PV BESS can be realized for longer blackout durations (several days).

The analysis of such periods in more detail regarding the development and analysis of a minimum load profile, which on the one hand offers basic electricity supply to the household and on the other hand can completely be covered by the energy available from the PV BESS is subject to future research. One possibility for longer blackouts during low PV production weeks could also be to time-shift the usage of certain devices (e.g. kitchen equipment) to periods when enough energy is available from the PV BESS. As indicator to determine time and length of periods with possible device usage, the SOC of the BESS in combination with a PV production forecast could be used. The time-shifted usage of electric devices is also subject to future research.

A conclusion from the seasonal and monthly analysis is that the backup functionality strongly depends on the available electricity generation from the PV system. In case of a blackout, a PV BESS generally makes electricity available to a household, which would not be available to a household without PV BESS. However, the complete coverage of longer blackout periods from PV BESS under the assumption of a normal load profile (100% autarkic system operation) is limited to only a few periods during the year. Under the assumption of a blackout duration of 1 day, for only 19% of the days (70 from 365 days) the PV BESS offers full backup power supply functionality. In this context, one general finding from the analysis is that load reduction and load shifting by adapted user behavior during a blackout shows high potential to increase the backup supply functionality and the overall security of energy supply by extending the period during which the reduced household electricity load can be covered from the PV BESS.

Apart from the analyzed case study, the backup functionality of a PV BESS respectively the energy which is available from such a system depends on the installed peak power of the PV system and the storage capacity of the BESS. For the future, it is planned to investigate this influence based on a parameter variation. Furthermore, the consideration of different countries and locations with significantly different load and PV production profiles is subject to future work.

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