EMERGING PERFORMANCE ISSUES OF PHOTOVOLTAIC BATTERY SYSTEMS

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ABSTRACT: This paper sheds new light on the real energetic performance of grid-connected PV-battery systems for self-supply purposes in residential buildings. A novel simulation test for the performance assessment of residential PV-battery systems with the Storage Performance Index (SPI) is proposed. Two different systems are modelled and annual time series simulations are carried out with a temporal resolution of one second. The calculated Storage Performance Index of the AC- and DC-coupled PV-battery system under study amounts to 51% and 53%, respectively. In other words, the investigated PV-battery systems can realize about the half of the respective grid electricity cost saving potential of equivalent lossless PV-battery systems. Moreover, a detailed loss analysis reveals that the majority of the system losses are caused by the conversion losses in the power electronic components, followed by the losses due to the standby power consumption of the battery, converter and auxiliaries. The developed simulation test allows the evaluation of the energetic and economic performance of PV-battery systems of different sizes and system topologies. In this way, the comparability and transparency with regard to the performance of different products available on the market can be improved.
Keywords: PV-Battery Systems, Performance Assessment, Efficiency, Energy Losses, Loss analysis

1 INTRODUCTION

Due to the significant cost reduction of both PV systems and battery storage devices in the recent years, the market for grid-connected storage systems for residential applications has been growing rapidly. Until the end of 2015, more than 35000 small-scale battery systems have been installed in conjunction with grid-connected PV systems in Germany [1]. The main objective of such PV-battery systems in residential applications is to store surplus PV energy on-site in order to use it later to cover the electrical loads within the respective buildings [2]. In this way, the home owner´s self-sufficiency is increased and the amount of electricity that has to be purchased from the grid is reduced. In other words, the battery system is operated with the aim of reducing the energy procurement from the grid by adjusting the charging and discharging power according to the resulting power flow at the point of common coupling.

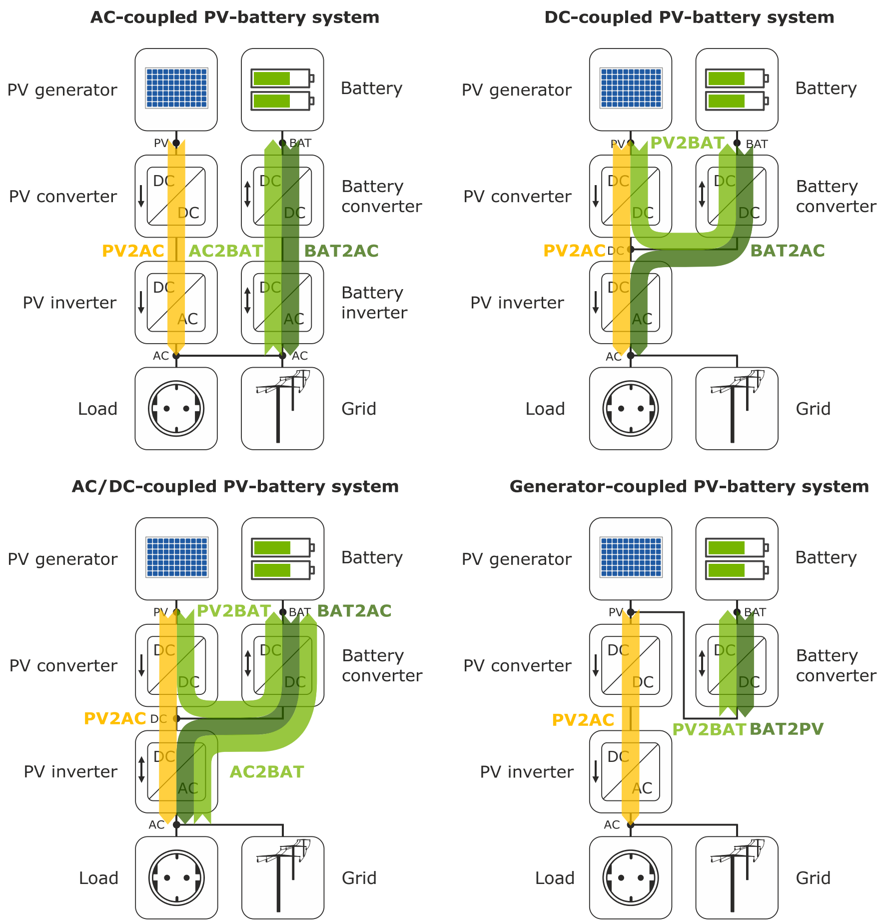


Figure 1 Schematic system configuration and relevant power flows of different topologies of PV-battery systems.

2 PV-BATTERY SYSTEM TOPOLOGIES

In general, a PV-battery system consists of a common PV generator, power electronic components, a battery device and a control unit. Today, there are numerous commercial PV-battery systems for the application in residential buildings available on the market [3]. One of the relevant distinctive characteristics between the products is the type of the connection between the battery storage and the PV system [4]. The system layouts of the most common topologies are illustrated in Figure 1. In AC-coupled systems, the PV inverter and the battery device with a bidirectional battery converter are linked to the AC-bus of the household. In contrast, the battery can also be linked to the PV inverter´s DC-side. In such a DC-coupled PV-battery system, the battery can only be charged by power from the DC-bus. AC/DC-coupled systems are equipped with bidirectional AC/DC converters, so that additionally power from the household´s AC-bus can be used to charge the battery. The battery unit can also be linked directly to the PV generator via a DC/DC charge regulator. Such generator-coupled battery systems supply the loads via the common PV inverter.

In order to provide a better understanding of the different system topologies, the relevant paths of energy flow are shown in Figure 1. The nomenclature of the paths is chosen with regard to the direction of the energy flows between the three points of reference on the PV generator side (PV), battery side (BAT) and AC-side (AC). The path PV2AC describes the conversion of DC-power from the PV generator to AC-power and is present in all system topologies. The charging path is described either by AC2BAT or by PV2BAT, depending on the topology. BAT2AC and BAT2PV are the discharging paths. The defined energy flow paths are required to characterize both modular system components as well as integrated systems appropriately.

3 CLASSIFICATION OF SYSTEM-RELATED LOSS MECHANISMS

Several loss mechanisms contribute to the overall energy efficiency and performance of grid-connected PV-battery systems. The different losses can be separated into four categories, which are as follows: conversion, standby, control and energy management-related losses. This section provides an overview of the various loss factors.

3.1 Conversion losses

Energy losses occur during the charging and discharging process within the battery mainly due to its internal resistance. The battery-related conversion losses can be specified with the battery round trip energy efficiency, which is calculated over one cycle that begins and ends at the same state of charge [5].

Apart from the internal battery losses, the distinct paths of energy flow depicted in Figure 1 are associated with conversion losses in the power electronic components. These converter-related losses can be separated into power-independent losses, voltage losses proportional to the power and resistive losses proportional to the square of the power [6]. At power levels of less than 20% of the nominal power, the characteristic drop in efficiency is mainly caused by the power-independent losses.

3.2 Standby losses

In addition to the losses associated with power conversion or energy storage, a standby power demand of the battery system occurs even when no power charges or discharges the battery. The standby consumption of the battery is caused by the battery management system (BMS), which observes the battery unit and fulfills safety functions. The standby consumption of the BMS can either be covered by energy stored in the battery or by energy drawn from the grid [7].

When the battery is not charging or discharging, the power electronic components remain in the idle or standby mode with respective losses. During completely discharged periods, this standby consumption has to be provided by the grid. At a fully charged state of the battery, the standby demand of the power converters is usually covered by PV generated electricity. On top of that, the additional energy consumption of the measuring devices and energy management system (EMS) has to be taken into account. It must be noted that the power demand of these components has to be supplied at all times and cannot be disregarded.

3.3 Control losses

The goal of the control unit is to balance the power flow at the point of common coupling by adjusting the charging and discharging power of the battery system. For reasons of data acquisition and signal processing, typical residential battery systems have an inherent response time of up to several seconds. Therefore, the power of the battery system cannot follow the strongly fluctuating electrical load demand and PV generation profile instantaneously. As a consequence, a mismatch between the residual power (PV output minus load) and the provided or absorbed battery power can be observed [8]. The mismatch in the power balance in buildings equipped with AC-coupled PV-battery systems is compensated by power fed into the grid or drawn from the grid. Due to the unidirectional path of DC- and generator-coupled PV-battery systems, the mismatch causes only a grid injection of such battery systems without any additional energy flows from the grid to the battery.

Further mismatch losses are related to the accuracy of the power measurements at the point of common coupling, as the control unit of a PV-battery system is usually subjected to error-prone measurements. Typical measuring devices are less precise compared to the calibrated energy meter which is relevant for billing purposes. Due to the lower measuring accuracy and the resulting control deviations, the battery power cannot be adjusted exactly according to the power flows within the building even under steady state conditions.

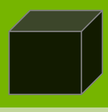
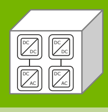
3.4 Energy management losses

With the introduction of the new market incentive program for small-scale battery systems in March 2016 in Germany, a limitation of the feed-in power to 50% of the rated PV power was introduced. If the PV-battery system is operated in a way that charges the battery as soon as excess PV power is available, the feed-in limitation is mainly realized by curtailing surplus PV power [9]. To avoid these unnecessary curtailment losses, the battery charging has to be scheduled based on forecasts of the PV generation and load consumption [10]. With such predictive energy management strategies, the grid feed-in can be increased due to the decline in the curtailment losses. However, the forecast errors can reduce the utilization of the battery system which results in an increase in the energy demand that has to be provided by the grid [11]. As a result, the energy management is associated with additional energy losses on top of the conversion, standby and control losses.

4 OVERVIEW ON SYSTEM PERFORMANCE TESTS

With the increasing market penetration of residential PV-battery systems, new aspects regarding the assessment of the energetic system performance are arising. Up until now, no standardized performance evaluation procedures for grid-connected PV-battery systems exist [12]. As a consequence, performance-related specifications are rarely stated in the data sheets of the products. From the end customer´s point of view, the comparability of the performance between different products is rather difficult as of yet [7]. This highlights the need to develop test procedures for performance evaluation purposes of residential PV-battery systems at both the component level as well as the system level. However, when assessing the performance of the entire PV-battery system, the interaction between the system components causes a range of phenomena that are difficult to quantify if studied in isolation [5]. As an example, the common round-trip efficiency determined by the ratio of the discharged energy to the charged energy does not take all of the aforementioned loss mechanisms into account, and is thereby not adequate to assess the overall performance of grid-connected PV-battery systems [13]. Table I provides an overview of the different methods to identify the performance of grid-connected PV-battery systems. The performance evaluation procedures are described and discussed in the following subsections.

Table I Overview on different performance evaluation procedures for grid-connected PV-battery systems.

Field tests	Black-box tests	White-box tests	Simulation tests
			
Characteristics			
• Long-term field tests by monitoring the real operational behavior over a period of at least one year	• Short-term application tests in a laboratory environment with reference profiles or at defined operating points	• Detailed characterization tests under laboratory conditions with the aim of characterizing the efficiency of each component or path of energy flow	• Model-based simulation tests parametrized with measurements from white-box tests and based on measured load and PV output profiles
Results			
• Average operating efficiency and load distributions of distinct paths of energy flow	• Use case-specific performance indicator obtained from measurements	• Measurements of efficiency curves, standby consumption, response behavior, etc.	• Use case-specific performance indicator obtained from simulations
Advantages			
• Real operational and long-term performance can be observed	• Short time period required and good comparability of the test results	• Detailed characterization of the components and overall system	• Fast test procedure and good reproducibility of the test results
Disadvantages			
• Long time period required • Results mostly available for outdated products • Identical test conditions are hard to ensure • Limited comparability of the test results from different systems	• Measurements are already affected by the predefined profiles • Test results are only applicable to the specific use case • General validity of the reference profiles has to be demonstrated	• No single performance indicator for the end-customer can be extracted from the test results • Expensive measurement equipment is required • Poor comparability between the results of different topologies	• Detailed characterization measurements are required • Accuracy of the test results depends on the level of detail of the simulation model • Not all loss mechanisms can be modelled exactly

4.1 Field tests

The most obvious way to analyze the performance of residential PV-battery systems is to monitor the relevant energy flows in the buildings equipped with such systems. As the performance of the systems may vary during the course of the year, a measuring period of at least one year is needed to derive meaningful evaluation results. One of the most comprehensive field tests is being conducted by the RWTH Aachen University in the framework of the scientific monitoring of the German federal funding program for PV-battery systems [1]. Both average operating efficiency values and energy content distributions with regard to the charging and discharging power levels are analyzed within the project based on field data. However, one of the drawbacks of long lasting field tests is that the systems under study are mostly outdated by the time of publication of the test results. Owing to the site-specific utilization of the battery systems in distinct buildings, the results gained from different systems are not fully comparable.

4.2 Black-box tests

Another approach is to accelerate the test procedure through short-term application tests in the laboratory, also known as black-box tests. Two types of application tests can be distinguished: reference profile-based and typical operating point-based black-box tests. An application test using a reference profile sequence of four days was developed by the Fraunhofer IWES [13]. From the proposed test procedure, three different performance indicators concerning the static and dynamic efficiency as well as the degree of self-sufficiency can be derived. Referring to the EU efficiency of PV inverters, a typical operating point-based black-box test determining an EU efficiency for residential PV-battery systems was proposed by [14]. Both types of black-box tests have the disadvantage that the measurement results are already affected by the predefined test profiles, thus the test results are only applicable for the specific use case. Moreover, the general validity of the chosen reference profiles and typical operating points have not yet been fully demonstrated.

4.3 White-box tests

The aim of white-box tests is to measure the performance-relevant characteristics of the system components under laboratory conditions. Such detailed characterization tests were developed and performed by several institutions [1], [7], [13]. Apart from measuring the efficiency curves as a function of the power throughput for the different paths of energy flow, the standby consumption of the system components and the system´s response behavior are measured. The experimental results obtained from such white-box tests allow the characterization of the performance-related system specifications. Despite the advantages, no single performance criterion for the end-customer can be extracted from the test results.

4.4 Simulation tests

By means of the experimental results obtained from white-box tests, detailed simulation models of PV-battery systems can be parametrized. Thus, it is possible to conduct model-based simulation tests in order to simulate the operational system behavior with realistic PV output and load profiles measured over a period of one year or longer. As a result, use case-specific performance metrics can be derived from the simulation tests. The simulation test approach allows the analysis of the relevance of various loss mechanisms separately. Other advantages of this approach are the fast test procedure and the fact that everyone can perform the tests if the underlying simulation models are freely available. However, the effort to develop and validate such universal simulation models is very high [15]. Moreover, the accuracy of the test results depends on the level of detail of the simulation models. For reasons of simplification, some loss mechanisms, such as the cell balancing of the battery unit, cannot be modelled in detail. On the other hand, once detailed performance models have been developed, the simulation results can also be used to optimize the system layout, system sizing and control algorithms.

5 PERFORMANCE EVALUATION WITH THE STORAGE PERFORMANCE INDEX (SPI)

In this section, a model-based simulation test is proposed and test results for two different PV-battery systems are presented. The goal of the simulation test is to determine the proposed Storage Performance Index (SPI).

5.1 Approach

The calculation of the Storage Performance Index aims to evaluate the performance of grid-connected PV-battery systems for self-supply purposes in residential buildings. To perform the simulation test, profiles of the PV output and electrical load demand with a 1-s resolution over a period of one year are used. In this study, the PV array’s output power is calculated based on meteorological measurements provided by the University of Oldenburg, Germany [16]. The DC-power output simulations are conducted for a PV generator with a size of 5 kWp by means of empirical models [17], [18]. The load profile of one household with an annual load demand of 5009 kWh is used for the simulation test. The chosen load profile (no. 31) is taken from a database with 74 domestic load profiles [19]. In accordance with the intention to establish a replicable simulation test procedure, all used input profiles are freely available as open data.

In a second step, the PV-battery system has to be modelled according to the respective system topology, as shown in Figure 1. In this study, two different lithium-ion based PV-battery systems are modelled and analyzed. The first one is a modular AC-coupled system with 5 kWh of usable battery capacity, which comprises the following components:

- SMA Sunny Boy 5000 TL (PV inverter)
- SMA Sunny Island 3.0M (battery inverter)
- Akasol neeoQube (battery unit)
- SMA Sunny Home Manager (EMS)
- SMA Sunny Remote Control (control unit)
- SMA Energy Meter (meter)

The second one is an integrated DC-coupled system with 2 kWh of usable battery capacity, which is composed of the following components:

- SMA Sunny Boy 5000 Smart Energy (integrated system with inverter, control and battery unit)
- SMA Energy Meter (meter)

Both PV-battery systems are modelled according to publicly available data and data provided by the manufacturer. The conversion losses of the different paths of energy flow are modelled with efficiency curves as a function of the power throughput. The standby power consumption of the battery, converters and auxiliaries are set to the provided values. To incorporate the transient behavior of the battery systems in the simulation test, a first-order time delay element with a dead time is implemented in the battery control unit. It must be noted that measuring inaccuracy incurred control losses and energy management-related losses are not depicted in the simulation model.

In a further step, the identical PV-battery systems without any losses are modelled considering the same usable battery capacity. The simulation results obtained from the lossless PV-battery systems serve as the benchmark for the performance evaluation of the real PV-battery systems. Note that the conversion paths of the ideal battery systems have no power restrictions, so that the utilization of the lossless battery system depends only on the specific battery capacity and is independent from the system topology. It is thereby ensured that the results of the performance evaluation can be compared between differently sized battery systems. As the DC-power profile of the PV generator serves as an input for the system simulation, losses induced by the PV inverter are included within the proposed performance evaluation procedure. Subsequently, the performance assessment results of different systems can be compared between the four distinct system topologies presented in Figure 1.

5.2 Energetic Performance Results

This subsection focuses on the energetic results of both PV-battery systems under study. The energetic performance is evaluated by analyzing the amount of energy exchanged between the residential building equipped with the respective systems and the grid. The results obtained from the power flow simulations of both PV-battery systems are represented in Figure 2. Without a PV-battery system, the residential building's load is completely supplied by the electricity grid and the amount of energy drawn from the grid is about 5009 kWh/a. If the building is equipped with an ideal PV system with a lossless inverter rated at 5 kWp, the grid supply is reduced by about 30% to 3474 kWh/a. In addition, the energy injected into the grid amounts to 3739 kWh/a. The results obtained from the ideal PV system with a lossless inverter serve as a reference.

Both the grid supply and grid feed-in drop when adding an ideal battery system without any conversion, standby and control losses. The higher the usable battery capacity, the lower the amount of energy exchanged with the grid. The 5 kWh lossless battery system reduces the grid supply and grid feed-in to 2007 kWh/a and 2272 kWh/a, respectively. As a result, about 60% of the electrical load demand is provided by the ideal PV-battery system. However, by considering all the modelled losses of both systems, the energy drawn from the grid rises while the energy injected into the grid declines. In total, the building equipped with the AC-coupled PV-battery system draws 2308 kWh/a from the grid and feeds 2017 kWh/a into the grid. In comparison with the results obtained from simulating the ideal 5 kWh battery system, the grid supply is increased by 15% and the grid feed-in is reduced by 11%. Similarly, the system losses of the DC-coupled PV-battery system are accompanied by an increase in the energy supply from the grid of 6% and a 5% reduction in the grid injection. As such, the overall energetic performance of grid-connected PV-battery systems is interpreted as the increase in grid supply and drop in grid feed-in in comparison with the identical lossless PV-battery system.

5.3 Economic Performance Results

As the primary goal of PV-battery systems is to reduce the energy costs, it is reasonable to evaluate the operational results from the economic perspective as well. The annual costs for the procurement of electricity from the grid C_{GS} are obtained by multiplying the annual amount of energy supplied by the grid E_{GS} with the retail electricity price p_{GS}:

$$C_{\mathrm{GS}} = E_{\mathrm{GS}} \cdot p_{\mathrm{GS}} \qquad (1)$$

The annual revenues R_{GF} from selling the PV energy E_{GF} for a specific feed-in tariff p_{GF} are calculated via:

$$R_{\mathrm{GF}} = E_{\mathrm{GF}} \cdot p_{\mathrm{GF}} \qquad (2)$$

In a further step, the net grid electricity costs C associated with the energy exchanged with the grid are obtained by subtracting the annual revenues R_{GF} from the annual costs C_{GS}:

$$C = C_{\mathrm{GS}} - R_{\mathrm{GF}} \qquad (3)$$

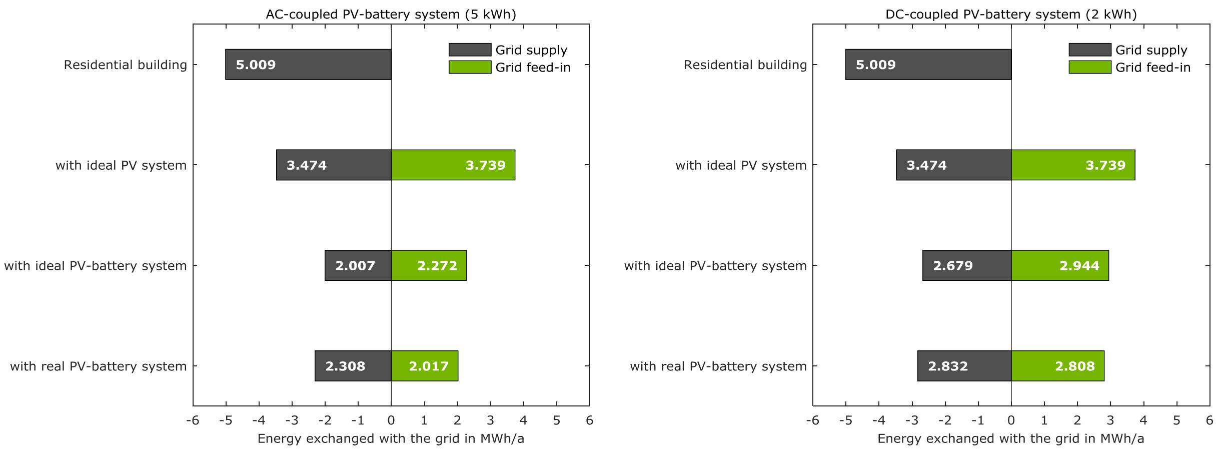


Figure 2 Annual energy balance of the reference building equipped with the AC-coupled (left) and DC-coupled PV-battery system (right).

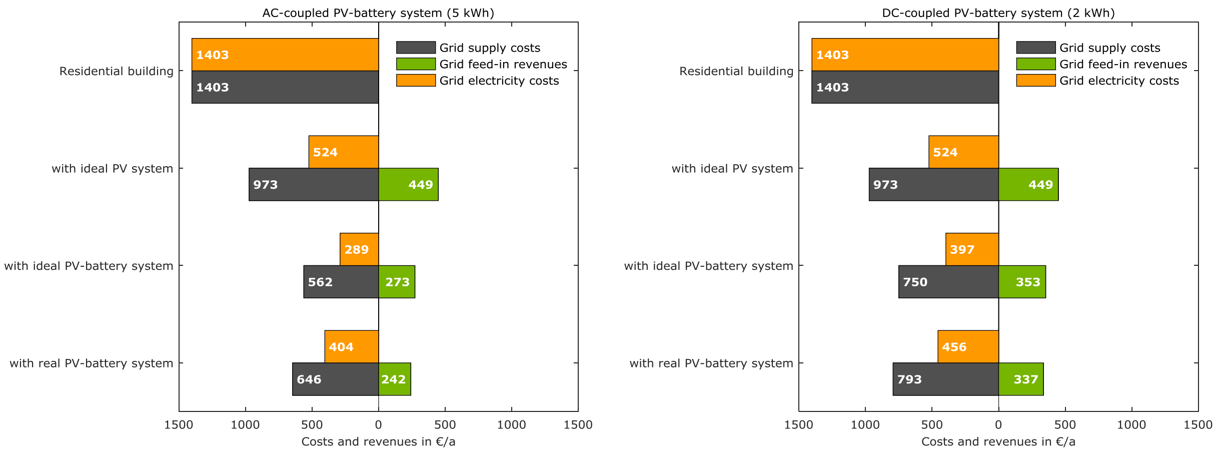


Figure 3 Annual costs and revenues associated with the energy exchanged between the grid and the reference building equipped with the AC-coupled (left) and DC-coupled PV-battery system (right).

In this way, the energy flows between the building and the grid are weighted with regard to their economic value. According to the current economic framework in Germany, the feed-in tariff is set to 0.12 €/kWh and the retail electricity price is valued at 0.28 €/kWh in this study.

The economic assessment results of both PV-battery systems are shown in Figure 3. The annual costs due to the procurement of electricity from the grid will be 1403 €/a, if neither a PV system nor a PV-battery system is installed. Owing to the revenues from the grid injection and the reduced expenses for the grid supply, the grid electricity costs are diminished to 524 €/a with the ideal PV system rated at 5 kWp. In the case in which the building is equipped with the lossless AC- or DC-coupled PV-battery system, the grid electricity costs are dropped to 289 or 397 €/a. As was to be expected, the system losses reduce the economic benefit of the battery systems and increase the grid electricity costs to 404 and 456 €/a for the AC- and DC-coupled system, respectively.

In order to enable a better comparability between the economic results of PV-battery systems of different sizes, the grid electricity costs are plotted as a function of the usable battery capacity in Figure 4 (left). The green line represents the grid electricity costs of the ideal PV-battery system, which serves as a benchmark. The yellow dot indicates the grid electricity costs of the PV system with a lossless inverter. As can be seen, the grid electricity costs of the real AC-coupled PV-battery system are increased by 115 €/a compared to the lossless system of the same usable battery capacity. For the DC-coupled PV-battery system, the losses increase the grid electricity costs by only 58 €/a. As the grid electricity cost saving potential of the ideal PV-battery system differs with the battery size, the increase in the grid electricity costs of systems with distinct usable battery capacities cannot be compared directly.

From the PV system owner´s point of view, the economic benefit of the battery system consists in the reduction of the grid electricity costs compared with the grid electricity costs obtained from a PV system without a battery. Thus, the purpose of the proposed Storage Performance Index *SPI* is to determine the ratio of the grid electricity cost savings of the real PV-battery system to the grid electricity cost saving potential of the lossless PV-battery system with the same usable battery capacity:

$$SPI = \frac{C_{\mathrm{PV,IDEAL}} - C_{\mathrm{PVBAT,REAL}}}{C_{\mathrm{PV,IDEAL}} - C_{\mathrm{PVBAT,IDEAL}}} \quad (4)$$

where $C_{\mathrm{PV,IDEAL}}$, $C_{\mathrm{PVBAT,IDEAL}}$ and $C_{\mathrm{PVBAT,REAL}}$ are the grid electricity costs of the ideal PV system (with a lossless inverter), ideal and real PV-battery system, respectively. For better comparability between different system topologies, the PV inverter related losses are incorporated within the economic assessment of the real PV-battery systems by taking the ideal PV system as the reference.

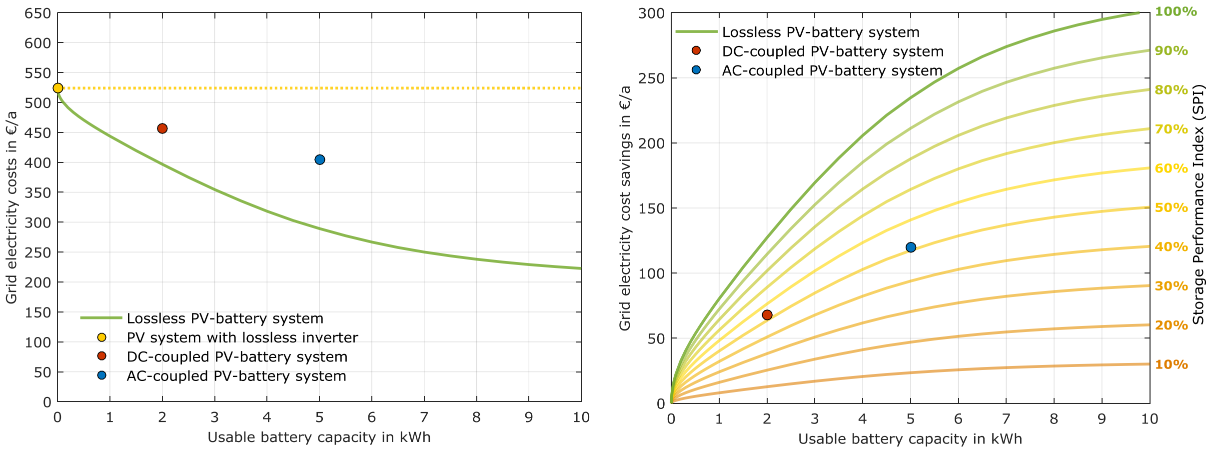


Figure 4 Grid electricity costs (left) and reduction of the grid electricity costs (right) as a function of the usable battery capacity.

In Figure 4 (right), the grid electricity cost savings of real PV-battery systems for varying Storage Performance Indices and usable battery capacities are shown. The lossless PV-battery system with a Storage Performance Index of 100% represents the upper limit. The grid electricity cost savings of the real PV-battery systems are reduced according to the specific Storage Performance Index. The results of the AC-coupled and DC-coupled PV-battery systems under study are also displayed. By comparing both systems, it can be noticed that the determined Storage Performance Indices of the AC- and DC-coupled PV-battery systems with 51% and 53% are in the same range. Taking into consideration that the layouts of both system topologies differ significantly from each other (compare Figure 1), this is a surprising result. However, due to the small battery size of the DC-coupled system and therefore low energy-related utilization of the battery conversion paths (PV2BAT and BAT2AC), the highly efficient charging path has only a small contribution to the overall system performance. This leads to the fact that the Storage Performance Index of small sized PV-battery systems is strongly affected by the PV conversion path (PV2AC). Furthermore, an identical standby power consumption has a higher negative impact on the Storage Performance Index of small-scaled PV-battery systems compared to systems with larger sized battery capacities.

For a better understanding of how the different loss mechanisms affect the Storage Performance Index, a detailed loss analysis of the systems under study is presented in Figure 5. In order to identify the contribution of each loss mechanism to the overall reduction of the Storage Performance Index, system simulations are carried out by isolating the distinct loss mechanisms from each other. The bars represent the reductions in the Storage Performance Index due to the various loss mechanisms. The first thing to note is that the biggest losses are associated with conversion in the power electronic components, which cause the Storage Performance Index to drop by approximately 26% in both systems. This is because the PV conversion path is the predominated path in both systems and the battery converter takes effect twice: during charging as well as discharging. Secondly, the reduction of the Storage Performance Index by the battery, converter and auxiliaries standby power consumption varies between 15% and 10% for the AC-coupled and DC-coupled system, respectively. Another point to note is that the energy losses occurred in the battery and the dynamic response related control losses only slightly affect the overall system performance. Because of the different sizing of the power electronics of the AC- and DC-coupled PV-battery system, the reduction in the Storage Performance Index due to the power rating of the converters varies for both systems. In this way, the contribution of each loss mechanism to the economically assessed system performance can be determined with the proposed performance evaluation procedure.

As it is a drawback of each economic assessment procedure, the test results are affected by the presumed economic input parameters. For this reason, the Storage Performance Index of both systems was calculated for a variety of feed-in tariffs and retail electricity prices. It was found that the Storage Performance Index depends only on the ratio of the feed-in tariff to the retail electricity price. Figure 6 illustrates the impact of this ratio on the Storage Performance Index of the AC- and DC-coupled PV-battery system. Without any feed-in remuneration, the Storage Performance Index is in the order of 80% and is equal to the ratio of the grid supply savings of the real PV-battery systems to those of the ideal PV-battery systems, both in comparison with the ideal PV system (see Figure 2). In such a case without a feed-in tariff, the losses in the grid feed-in do not lead to a reduction in the Storage Performance Index. For this reason, the higher the ratio of the feed-in tariff to the retail electricity price, the larger the impact of the feed-in losses on the Storage Performance Index. The results obtained for the reference case with a ratio of the feed-in tariff to the retail electricity price of 0.43 are already presented in Figure 4 (right). As soon as the feed-in tariff is larger than approximately 70% of the retail electricity price, the grid electricity costs of the real PV-battery systems are larger than those of the ideal PV system, which results in a Storage Performance Index below zero. As a consequence, the battery system cannot contribute to the reduction of the grid electricity costs. Summarizing, the calculation of the Storage Performance Index can be adopted to the economic circumstances of different countries.

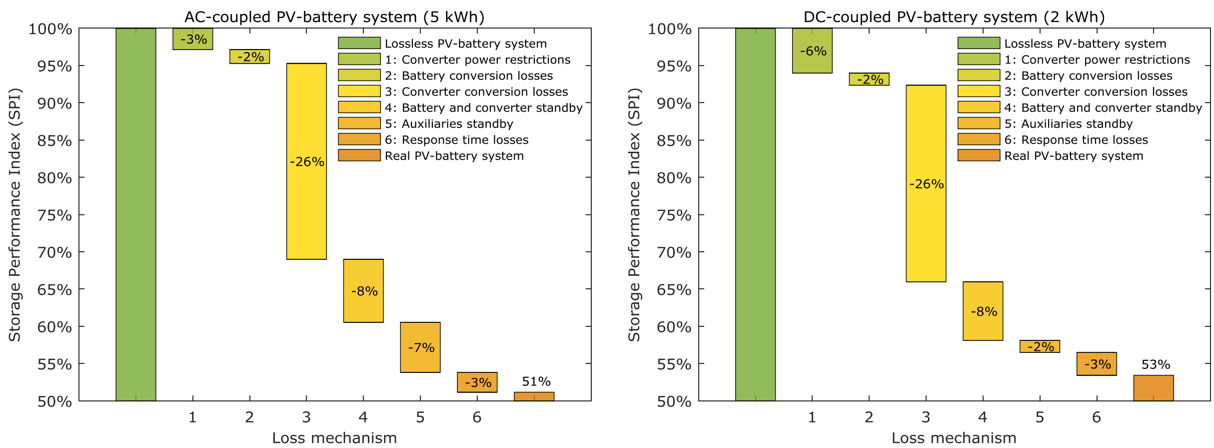


Figure 5 Contribution of different loss mechanisms to the reduction of the Storage Performance Index of the AC-coupled (left) and DC-coupled PV-battery system (right)

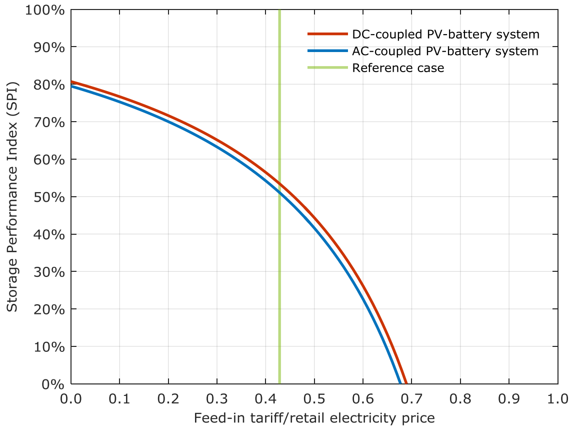


Figure 6 Variation of the Storage Performance Index of the AC-coupled and DC-coupled PV-battery system with the ratio of the feed-in tariff to the retail electricity price (reference case: feed-in tariff of 0.12 €/kWh and retail electricity price of 0.28 €/kWh).

6 CONCLUSIONS

In this paper, a novel simulation test procedure for assessing the energetic and economic performance of grid-connected PV-battery systems with the Storage Performance Index (SPI) is proposed. In a first step, the energetic behavior including the conversion, standby and control losses of two PV-battery systems are simulated and the specific annual amount of energy exchanged with the grid is determined. In a second step, the simulation results are compared with the results obtained from simulating lossless PV-battery systems of the same usable battery capacity. This comparison allows the determination of the energetic performance of the real PV-battery systems expressed by the increase in grid supply and the reduction in grid feed-in due to the system losses. In a further step, the energetic test results are assessed economically by weighting the energy exchange with the grid with the respective monetary values and calculating the grid electricity cost savings of the PV-battery systems compared with a reference PV system. The calculated Storage Performance Index of the AC- and DC-coupled PV-battery systems under study amounts to 51% and 53%, respectively. This means that the investigated PV-battery systems can realize about the half of the respective grid electricity cost saving potential. A detailed loss analysis reveals that the majority of the reduction in the Storage Performance Index is caused by the conversion losses in the power electronic components, followed by the losses due to the standby power consumption of the battery, converter and auxiliaries. The developed simulation test allows the minimization of the energy losses by improving the system layout, system sizing and control algorithms of residential PV-battery systems. Moreover, the energetic and economic performance of PV-battery systems of different sizes and system topologies can be assessed with the proposed Storage Performance Index. Further research will be carried out to evaluate the performance of more products available on the market and to improve the comparability between the products from the end customer´s point of view.

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