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Sizing of Battery Converters for Residential PV Storage Systems

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Abstract

With the increasing number of domestic PV (photovoltaic) installations connected to battery energy storage systems for self-supply purposes in Germany, new research topics such as the sizing of the required system components have emerged. In this paper, the impact of the rated battery converter power on the utilization of PV-attached battery systems in residential buildings is discussed. First, the ratio between the battery converter rating and the storage capacity is analyzed for a variety of residential battery systems available on the market. Thereafter, simulations with a temporal resolution of 1 s are performed in order to identify how the rated battery converter power affects the energy throughput of the battery system taking account of the characteristic conversion efficiency curves. The results show that battery converter sizes in the range of 4 to 5 kW are optimal in terms of maximum discharged energy for the most system configurations under study. However, battery converters rated between 30 to 50% of the optimal power rating are sufficient to provide more than 95% of the maximum dischargeable energy from the battery system. Based on these findings, it can be concluded that small-sized battery converters rated at 1.5 to 2 kW are sufficient for residential self consumption applications.

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Keywords: Battery storage; photovoltaic; PV battery; Self-consumption; Sizing; Battery inverter

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1. Introduction

The market for grid-connected battery storage devices attached to residential PV systems is growing continuously. In countries like Germany, the installation of such PV-battery systems in private households is aimed at increasing the self-consumption of the PV energy on-site and thereby the home owner´s self-sufficiency. In the past, such battery storage devices usually comprised of lead-acid batteries. However, a growing percentage of newly installed PV-battery systems is equipped with lithium-ion batteries in Germany [1]. Depending on the connection of the PV system and battery storage, one can distinguish between AC- and DC-coupled PV-battery systems [2]. AC-coupled battery systems are attached to the residential building´s AC-bus and PV system via bidirectional AC/DC converters. In DC-coupled systems, the battery unit is linked either to the DC-side or to the intermediate circuit of the PV inverter via bidirectional DC/DC converters. As a result, the rated power of the AC/DC or the DC/DC converter restricts the capability of the battery system to store surplus PV power and to supply the loads. In other words, the charging and discharging power is limited to the power rating of the battery converter.

Several previous studies have investigated the sizing of the battery system with regard to optimal storage capacity based on techno-economic analyses [2]–[4]. However, there is a lack of studies analyzing the sizing of the power electronic components in grid-connected PV-battery systems for residential self-supply applications. In general, converter sizing recommendations are relevant either for the manufacturer or installer, depending on whether the battery system is preassembled or modular.

For a better understanding of how the battery converter sizing affects the benefit of the battery system, a typical efficiency curve of a bidirectional AC/DC converter rated at 3.3 kW is depicted in Figure 1 (a). The shown conversion efficiency represents the ratio between the AC- and DC-power during the discharging process and in a first approximation vice versa during the charging process. The converter efficiency usually varies with the power throughput due to different loss mechanisms. In general, it can be separated into power-independent losses, voltage losses proportional to the power and resistive losses proportional to the square of the power [5]. At low power levels, the reduced efficiency is mainly caused by the power-independent losses. The converter under study reaches its peak efficiency of 95% at about 27% of the power rating (0.9 kW). By increasing the power throughput, a decline in the efficiency down to 91.5% at full load due to higher resistive losses can be observed. It must be noted that the shape of the efficiency curve may vary from converter to converter and depends on the specific converter topology.

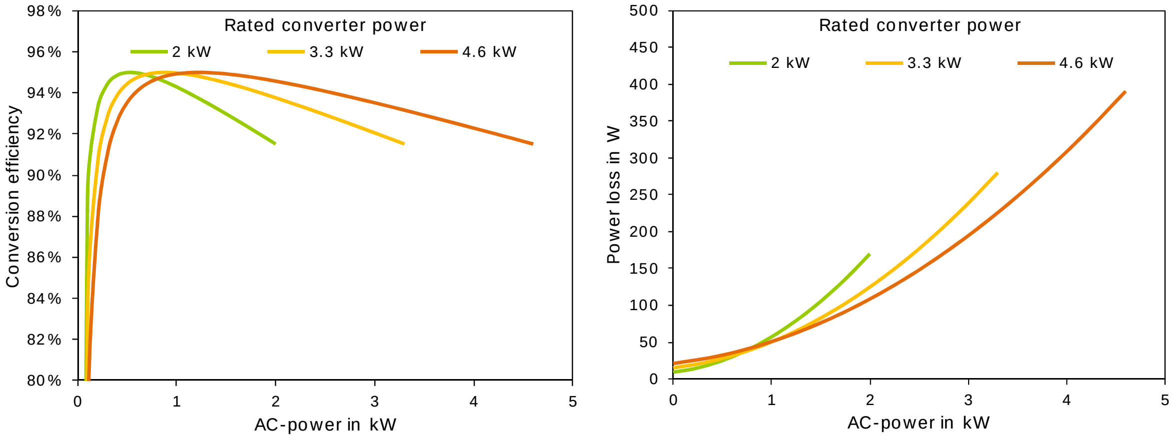


Figure 1 Typical efficiency characteristic (a) and the corresponding power losses (b) of a bidirectional AC/DC battery converter scaled to different supposed converter ratings (data: conversion efficiency at nominal voltage of the converter SMA Sunny Island 4.4M with 3.3 kW of rated power)

To reveal the meaning of the nominal power of the converter, the presented efficiency curve was scaled to different power ratings, as shown in Figure 1 (a). Correspondingly, the efficiency as a function of the AC-power varies with the power rating of the converters. Compared to the 3.3 kW rated converter, higher conversion efficiencies can be achieved by using a small-sized converter rated at 2 kW at AC-power levels of up to 0.8 kW. Nevertheless, at AC-power levels above 1.2 kW the highest efficiency levels can be achieved with the large-sized converter rated at 4.6 kW.

The corresponding power losses as a function of the AC-power for the three converter ratings are illustrated in Figure 1 (b). The power losses follow an approximately parabolic increase with respect to the AC-power. The intersections between the efficiency curves will lead to identical power losses. By comparing the curves, it becomes apparent that the differences in the power losses below 1 kW of AC-power are marginal compared to those above this threshold. This is due to the fact that a drop in efficiency by one percentage point causes higher absolute power losses at higher AC-power levels. Hence, considerable differences in the power loss emerge at AC-power levels above 1 kW due to the decline in the efficiency at power levels close to the converter rating. When 2 kW of AC-power are provided or absorbed by the battery converters, the power loss varies between 110 and 170 W for the 4.6 and 2 kW rated converter, respectively. In circumstances in which the AC-power amounts to 0.5 kW, the discrepancy in the power loss between the converters is less than 10 W. At those power levels, the gain in efficiency by using a smaller converter is almost negligible due to the relatively low AC-power, and thereby low power losses.

Apart from taking the efficiency characteristic into account, the converter size has to be chosen with regard to the size of the battery. The relation between the nominal converter power and the battery capacity of distinct commercially available AC- and DC-coupled battery systems is shown in Figure 2. The usable battery capacity of the systems under study varies between 2 and 6.4 kWh and the rated converter power varies between 1.5 and 3.3 kW. With increasing battery capacities, there is a tendency towards larger sized battery converters. For reasons of better comparability, the ratio between the nominal converter power and the usable battery capacity is termed converter sizing ratio in the following. The colored lines represent different converter sizing ratios ranging from 0.25 to 0.75 kW/kWh. Only two battery systems have a converter sizing ratio of less than 0.5 kW/kWh. The bulk of the depicted battery converters is rated at 0.5 to 0.75 kW/kWh.

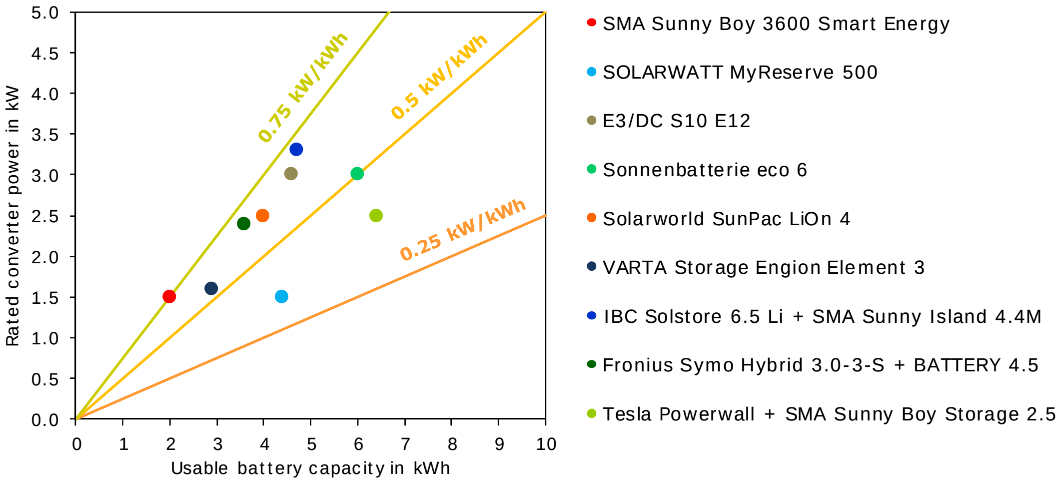


Figure 2 Rated battery converter power and usable battery capacity of different AC- and DC coupled systems (data: datasheet specifications of the manufacturer or system provider)

2. Methodolgy

For the purpose of quantifying the impact of the battery converter size on the annual energy throughput of the battery system, power flow simulations are performed for an AC-coupled PV-battery system. This section provides an overview of the input data and models of the simulation study.

2.1. Input profiles

The power output of the PV system is calculated using a weather data set provided by the University of Oldenburg, Germany [6]. The data set contains 1-s resolved measurements of the irradiance (diffuse as well as global) and ambient temperature recorded over the course of the year 2014. Within this period, the horizontal global irradiation amounts to 1065 kWh/m².

The demand curve of a single-family household is represented by a 1-s resolved load profile (no. 31) selected from a database with 74 domestic load profiles [7]. The load profiles are generated through load profile synthesis by means of merging two measured load data sets with temporal resolutions ranging from 1 s to 15 min. In this way, the typical fluctuating characteristics of a household´s load demand with pronounced peaks and steep ramps is preserved. The annual sum of the chosen load profile amounts to about 5 MWh.

2.2. PV-battery system model

First, the irradiance profile on the plane of the south oriented and 35° declined PV array is determined based on the measured global and diffuse irradiance using geometric relations and the Klucher model [8]. The power output of the PV generator is modelled as described in [9] by taking the ambient temperature and irradiance on the titled array into account. Additional generator losses are considered with empirical factors obtained from monitoring data [10]. The conversion efficiency of the PV inverter is depicted by the model proposed by Schmidt and Sauer [5]. The maximum power output of the PV inverter is limited to 1 kW/kWp. In a further step, the resulting power output of the PV system is scaled to 5 kWp of nominal PV power in the reference case.

The profiles of the PV power output and load demand are used to calculate the residual power (PV output minus load), which can potentially be absorbed or provided by the AC-coupled battery system. The lithium-ion batteries are modelled by a simplified approach, assuming a constant round trip efficiency of 0.95 [2]. The power loss of the bidirectional battery converter with regard to the residual power normalized to the rated converter power is modelled by a quadratic function fitted to the power loss curve of the SMA Sunny Island 4.4M converter at nominal voltage, as shown in Figure 1 (b). It is assumed that the conversion efficiency and the rated converter power are identical during the charging and discharging process.

Moreover, the battery converter is assumed to be switched off in periods without usage. Therefore, no standby consumption is taken into account. As the power flows are aggregated over all three phases, restrictions due to the maximum allowable asymmetry of 4.6 kVA between two external conductors are neglected (cf. [11]). The battery system is operated with a control strategy aimed at maximizing the battery throughput. Consequently, the battery system is charged as soon as the PV power output is higher than the load demand, until the maximum state of charge is reached. In the reference case, the battery converter is rated at 5 kW and the usable battery capacity is set to 5 kWh.

3. Results

This section aims at analyzing the power flows and energy throughput of PV-attached battery systems with regard to their rated battery converter power by means of simulations. Figure 3 (a) visualizes the calculated power flows of the PV-battery system under study with 5 kW of rated battery converter power in the course of one exemplary day. The PV output (sum of the positive power flows) is either directly consumed by the load, used to charge the battery system or fed into the grid. The sum of the negative power flows is covered either by power discharged from the battery system or by power drawn from the grid and is equal to the residual power. As the residual power neither exceeds the maximum charging nor the maximum discharging power, the rated battery converter power of 5 kW does not constrain the power flows absorbed or provided by the battery system on this particular day.

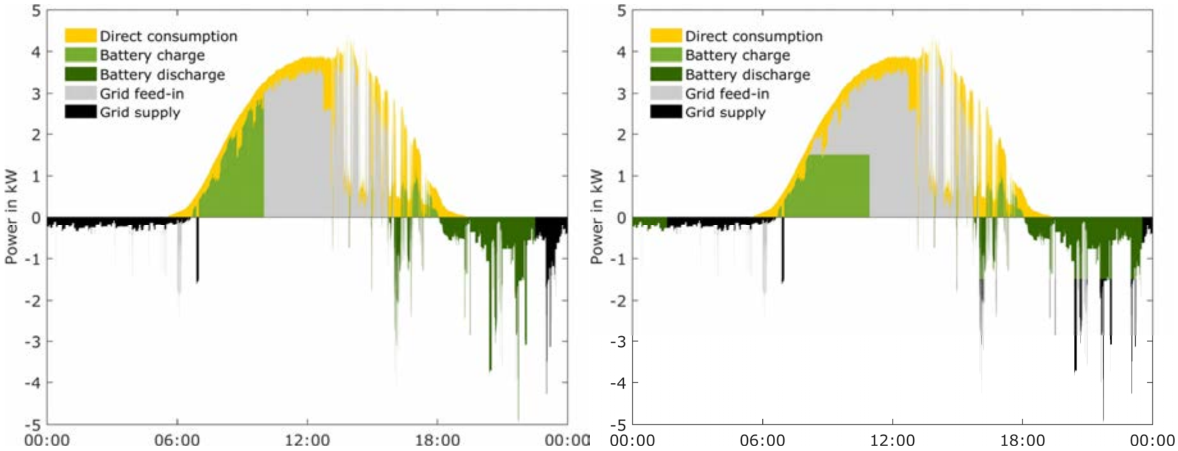


Figure 3 Power flows of a residential PV-battery system with 5 kW (a) and 1.5 kW (b) of rated battery converter power in the course of one exemplary day (rated PV power 5 kWp, usable battery capacity 5 kWh).

If the battery converter is rated at 1.5 kW, the lower nominal converter power will affect the charging and discharging process, as shown in Figure 3 (b). On the one hand, the charging power is limited to 1.5 kW and thereby, the battery reaches the fully charged state at a later point in time. On the other hand, load peaks greater than the rated converter power are only partially supplied by the battery system. Consequently, the minimum battery system´s state of charge is reached later at night. On this particular day, no power rating related losses in the battery system´s energy throughput incurred by the smaller sized battery converter are visible. However, the losses associated with the nominal power of the converter are strongly affected by the daily course of the PV production and demand curve. Thus, the impact of the battery converter size on the power flows has to be analyzed over longer periods of one year or more.

Figure 4 (a) shows the annual energy content distribution with regard to the charging and discharging power levels for the reference configuration with 5 kW of converter rating. For a better comparability, the sign convention of the battery power during the charging and discharging process is neglected. Each bar represents the share of the specific charging and discharging power levels on the annual amount of charged and discharged energy, respectively. By comparing both distributions, it is evident that the charging power is distributed more evenly compared to the discharging power. The battery charging power only occasionally reaches power levels above 4 kW. In contrast, the battery system is discharged at full load more frequently, which can be attributed to load peaks that exceed the nominal converter power. Nevertheless, about 60% of the annually discharged energy is provided at power levels of less than 1 kW, as demonstrated by the cumulative distribution curve in Figure 4 (b). The cumulative sum of the charged energy increases almost linearly up to 3 kW and is further below the cumulative sum of the discharged energy up to this threshold. It is worth noting that the shape of such energy content distribution curves may vary depending on the system configuration and the coincidence between the PV output and load demand.

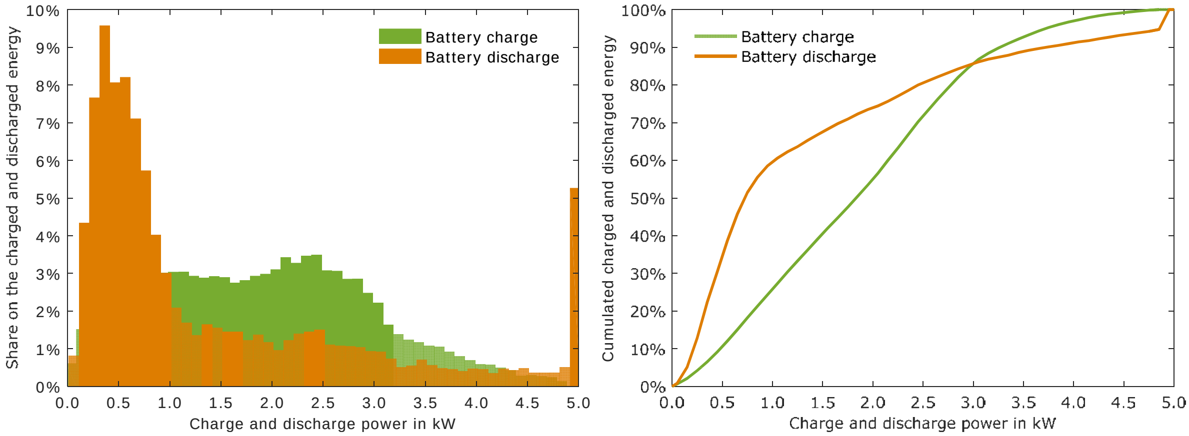


Figure 4 (a) Distribution of the energy content charged and discharged at different power levels as a percentage of the respective annual amount of energy (100 W step width); (b) Cumulative sum of the annual amount of charged and discharged energy as a function of the battery power (rated PV power 5 kWp, usable battery capacity 5 kWh, rated battery converter power 5 kW, annual load demand 5 MWh).

Moreover, the annual operational results in terms of charged and discharged energy were determined for various battery converter sizes. From an economic perspective, the amount of discharged energy (substituted grid supply) is valued higher than the amount of charged energy (reduced grid feed-in) in Germany. Therefore, hereinafter the annual amount of energy provided by the battery system serves as a benchmark.

Figure 5 (a) illustrates how the discharged energy changes with varying converter sizes between 1 and 5 kW. The simulation results are normalized to the maximum amount of discharged energy of 1294 kWh obtained with a 4.1 kW rated battery converter. If the rated converter power differs from its optimum, the discharged energy will vary slightly over a broad range of battery converter ratings. Hence, there is a pronounced plateau in the discharged energy around its maximum. On the one hand, a moderate decrease in the discharged energy for converter sizes larger than the optimum can be found. This is related to the efficiency characteristic and reduced conversion efficiencies at low specific power levels (see Figure 1). On the other hand, using a 2.5 kW rated converter instead of a 4.1 kW rated converter leads to a loss in the discharged energy of only 1%. A battery converter rated at 1.6 kW enables the provision of about 95% of the maximum withdrawable energy. Note that this loss corresponds to an increase in the amount of energy that has to be supplied by the grid of about 60 kWh per year for the system configuration under study. From an economic point of view, the increased grid supply is partially compensated by the higher grid feed-in, as the amount of energy used for charging the battery system also decreases by approximately the same value.

To determine whether the converter sizing related energy losses are incurred rather by restricting the charging or by restricting the discharging process, a sensitivity analysis was conducted by varying the rated charging and the rated discharging power independently from each other. In Figure 5 (b), the discharged energy normalized to its maximum is plotted as a function of the charging and discharging power rating. The peak of discharged energy amounts to 1296 kWh and is achieved with 3.5 kW of rated charging power and 4.25 kW of rated discharging power. Hence, the optimal rated power during discharging is larger than that during charging for the reference configuration. At rated power levels above approximately 1.5 kW, the amount of discharged energy is more sensitive to the rated discharging power. Below this threshold, a reduction in the rated charging power drops the discharged energy more significantly compared to a reduction in the rated discharging power.

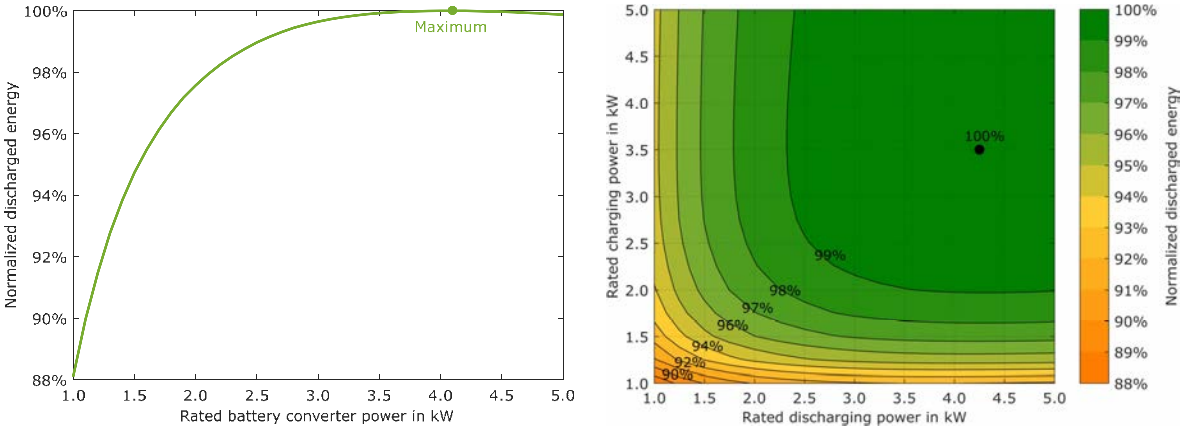
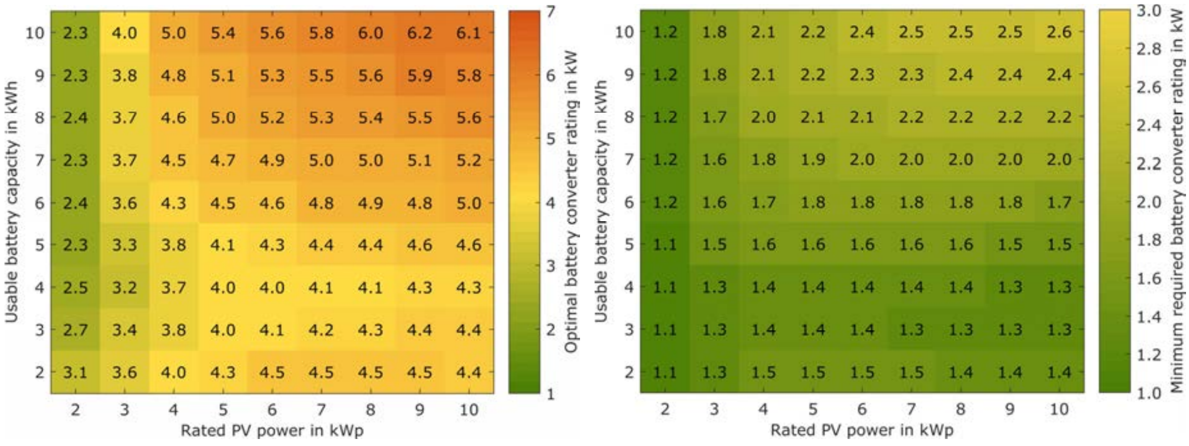


Figure 5 (a) Percentage of the maximum amount of discharged energy per year as a function of the rated battery converter power (a) as well as rated charging and rated discharging power (b) compared to the corresponding maximum (rated PV power 5 kWp, usable battery capacity 5 kWh).

In addition, simulations were carried out for various system configurations in terms of rated PV power and usable battery capacity in order to determine the optimal battery converter sizing. From an energetic point of view, the converter size that allows discharging the maximum amount of energy for a certain system configuration can be regarded as the optimal converter rating. Figure 6 (a) shows the calculated optimal rated battery converter power with varying PV array and battery sizes of up to 10 kWp and 10 kWh, respectively. The first thing to note is that there is a general tendency towards larger optimal battery converters when increasing the size of the PV system and storage device as well. An optimal battery converter size of 4.1 kW was determined for the reference configuration with 5 kWp of installed PV power and 5 kWh of usable battery capacity (cf. Figure 5 a). If both system components are twice as large, a battery converter rated at 6.1 kW will be the optimal choice.

Moreover, the optimal converter size may decrease when solely enlarging the PV system or battery system size. However, due to the plateau in the discharged energy around its maximum (cf. Figure 5 a), the losses in the discharged energy of converter sizes that slightly differ from the optimum are in the order a few kWh per year. Consequently, specific events in the load profile may cause such irregularities in the calculated optimal converter size.



	2	3	4	5	6	7	8	9	10
10	2.3	4.0	5.0	5.4	5.6	5.8	6.0	6.2	6.1
9	2.3	3.8	4.8	5.1	5.3	5.5	5.6	5.9	5.8
8	2.4	3.7	4.6	5.0	5.2	5.3	5.4	5.5	5.6
7	2.3	3.7	4.5	4.7	4.9	5.0	5.0	5.1	5.2
6	2.4	3.6	4.3	4.5	4.6	4.8	4.9	4.8	5.0
5	2.3	3.3	3.8	4.1	4.3	4.4	4.4	4.6	4.6
4	2.5	3.2	3.7	4.0	4.0	4.1	4.1	4.3	4.3
3	2.7	3.4	3.8	4.0	4.1	4.2	4.3	4.4	4.4
2	3.1	3.6	4.0	4.3	4.5	4.5	4.5	4.5	4.4

	2	3	4	5	6	7	8	9	10
10	1.2	1.8	2.1	2.2	2.4	2.5	2.5	2.5	2.6
9	1.2	1.8	2.1	2.2	2.3	2.3	2.4	2.4	2.4
8	1.2	1.7	2.0	2.1	2.1	2.2	2.2	2.2	2.2
7	1.2	1.6	1.8	1.9	2.0	2.0	2.0	2.0	2.0
6	1.2	1.6	1.7	1.8	1.8	1.8	1.8	1.8	1.7
5	1.1	1.5	1.6	1.6	1.6	1.6	1.6	1.5	1.5
4	1.1	1.3	1.4	1.4	1.4	1.4	1.4	1.3	1.3
3	1.1	1.3	1.4	1.4	1.4	1.3	1.3	1.3	1.3
2	1.1	1.3	1.5	1.5	1.5	1.5	1.4	1.4	1.4

Figure 6 Optimal rated battery converter power (a) and minimum required rated battery converter power to provide 95% of the maximum dischargeable energy (b) as a function of the PV system and battery storage size (annual load demand 5 MWh).

Finally, the smallest battery converter size that facilitates the provision of at least 95% of the maximum dischargeable energy of each system configuration is shown in Figure 6 (b). This minimum required rated battery converter power varies between 1.1 and 2.6 kW depending on the system size. Consequently, battery converters rated at about 30 to 50% of the optimal converter rating are sufficient to ensure that the converter sizing related energy losses in the discharged energy are less than 5%.

4. Conclusion

The aim of this paper was to investigate the impact of the battery converter rating on the energy throughput of PV-attached storage systems. The results gained from 1-s resolved simulations reveal that the battery converter size affects the battery charge and discharge behavior, and thereby, the annual amount of stored PV energy. For the bulk of the system configurations under study, a sensitivity analysis shows that battery converters rated at 4 to 5 kW are optimal in terms of the maximum discharged energy. However, in most cases a battery converter rated at 1.5 to 2 kW is sufficient without losing more than 5% of the optimum discharged energy. Consequently, the rated battery converter power can be sized significantly smaller than the rated PV power in residential buildings.

Apart from the energetic point of view, there are several additional aspects which have to be taken into account within the scope of the converter dimensioning. Small-sized converters will operate at nominal power more frequently, which may reduce the life-expectancy of the converter due to electronic component stress [12]. Moreover, the capability for peak-shaving proposes and ancillary services might be restricted for small-sized battery converters. However, smaller converters are usually less cost-intensive. As a result, a trade-off between the maximum energy throughput and the costs is required and has to be identified in future research. In order to proof the validity of the sizing recommendations presented in this paper, further investigations should be carried out with various PV generation and load profiles.

Acknowledgments

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