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The effect of different working parameters on the optimal size of a battery for grid-connected PV systems

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Abstract

This work investigates the possibility of improving the economic performance of PV in Northern Europe. The PV system investigated in this study is assumed to be connected to the electricity grid. However, because there is a difference between the electricity tariff and feed-in electricity price, adding a battery to such a system improves its economic viability. But the application of a battery increases initial costs of the system. Therefore, it is especially of economic relevance to choose the optimal size of the battery. In this work, the optimal battery size was calculated under different parameters including electricity tariff, feed-in electricity price, and battery performance and price. For this purpose, an actual building located in Landskrona, Sweden was chosen as a case study. A computer model was built to simulate the PV system. The simulations show that the optimal battery size is strongly influenced by the local conditions especially the feed-in electricity price.

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Keywords: PV system; grid connected; battery size; optimization; computer modeling

1. Introduction

Renewable energy systems are needed to replace the fossil-energy resources with clean-energy resources to mitigate the anthropogenic contribution to the Greenhouse gas emissions. Solar energy is seen as a promising source of

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renewable energy that could contribute to achieve the EU targets for 2020, 2030 and 2050 [1,2]. The growing demand for photovoltaic (PV) systems in recent years led to an advanced manufacturing of solar cells and significant reductions in PV manufacturing costs [3]. These resulted in an increased amount installed globally [4]. In 2016, global solar demand reached 78 GW installed new capacity and the installed capacity in Europe has been increasing continuously [5,6]. The clear majority of all PV systems today in Europe are connected to energy utilities. In such system, the electric grid acts as a virtual storage system, which in return reduces the net costs of PVs. However, in several countries PV electricity subsidies are decreasing, which makes the feed-in price lower than the buying price. In such cases, reducing the PV power injected in to the grid may increase the profitability the systems [7]. On the other side, the battery technologies have been improving rapidly and their prices are reducing. Therefore, in recent years, the analysis of PV systems combined with batteries has been the objective of several studies [3,4,7-10]. Based on these studies, adding a battery to the system can obviously improve the economic viability of a PV system and the self-consumption. Self-consumption of a PV system in residential buildings means that the electricity generation of the PV system is directly used by the system owner on the site. It was shown that the installation of a battery of a sufficient capacity allows to increase the amount of self-used PV energy significantly [11]. Nyholm et al. defined the maximum capacity of a battery to be added to PV system to minimize the power injected in to the grid [4]. Yet, the economic viability of PV systems depends first and foremost on the up-front cost of the system. Thus, adding a battery to the system increases the up-front costs even more. This challenge is needed to be addressed to achieve a high economic performance of a PV system. Therefore, the determination of the optimal size of a battery is a crucial factor to enhance the economic performance. However, the size of the battery depends on many factors such as the difference between the feed-in price and the buying price. The study, therefore, focuses on two aspects. The first aim is to demonstrate the improvement of the economic performance to the PV system by adding the optimal size of a battery. The second aim is to investigate the impact of different parameters on the optimal size of a battery. In this study, electricity prices, feed-in price, battery prices and efficiency are considered as varying working parameters.

2. Methodology

The aim of this work was achieved through building a computer model simulating the performance of a PV system in an hourly resolution. The model was built in Excel environment and based on the best available relations [12-15]. The case study is a residential building in Landskrona, Sweden of total roof area of 2972 m^2. Figure 1 illustrates a real electricity consumption data, which taken form the utility grid database. The electricity consumptions is for lighting and different appliances. In order to define the size of the PV system, it was assumed that the owners of the building intend to install PV to self-produce 50% of their electricity consumption on-site, while keeping the power injected in to the grid at the minimum level by adding a battery. Certainly, the economic performance of the PV system depends on its size. However, the effect of the system size on the final results is expected to be ignorable. The metrological working conditions of the selected city were taken Ref. [16]. Solar World SW325XL (monocrystalline) was chosen as PV panel. Table 1 shows the specifications of the considered PV panel, which are fed to the model as input data.

Table 1. Specifications of the considered PV modules brand at STC.

fill factor (FF)	0.748	Nominal temperature (C)	46	open circuit voltage (V)	46.1
derating factor	0.891	nominal capacity (W)	325	Area (m^2)	1.995
short circuit current (A)	9.48	module price ($)	310	voltage temperature coefficient 1/C	0.304

To simulate the performance of the PVs, a few assumptions had to be made. In the current study the assumptions are based on current conditions and data collected from literature, the details are shown in Table 2 [17-26].

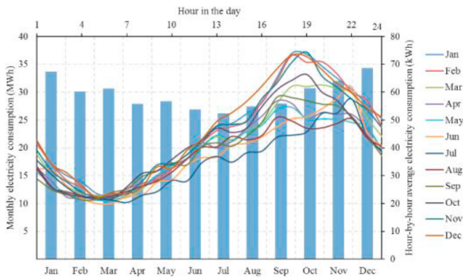

Figure 1. Hour-by-hour and monthly average electricity consumption of the case study.

Table 2. Assumptions made in the present work

inflation rate	0.79%	module degradation rate	1%/y	labor cost	18 $/kW
real interest rate	2.5%	battery degradation rate	1%/y	Operation/maintenance	10 $/kW·y
Elec. price	20.7 ¢/kWh	Inverter life time	10 y	Inverter efficiency	90%
Feed-in Elec. price	6.7 ¢/kWh	Battery life time	9 y	Battery efficiency	90%
Elec. price escalation rate	2.3%	Lifetime of the project	25 y	Wire efficiency	98%
Module price	Table 1.	Inverter price	322 $/kW	Battery price	128.3 $/kWh

The influence of adding a battery to the system on the economic performance were assessed in terms of the payback time of the system, which allows to combine all economic indicators in a single figure that can easily interpreted. The optimal size of the battery, in which the payback time of the system is minimized, was determined. The simulations were performed for different factors including (see Table 3): electricity price, feed-in electricity price, battery price and battery efficiency. By doing so, the impact of the considered working factors on the economic performance and the self-consumption share of the PV system was demonstrated.

Table 3. The considered working parameters and their range

Working parameter	Electricity price [¢/kWh]	Fee-in electricity price [¢/kWh]	Battery price [$/kWh]	Battery efficiency [%]
Range	15.5-25.9	0-20.7	96-160	80-100

3. Results and Discussions

The annual electricity demand of the considered buildings was found 356 MWh, as listed in Figure 1. The computer model was used to determine the hourly available solar energy, the required area of the solar panels to cover 50% of the annual electricity demand of the building, the optimal inclination and azimuth angles of the panels, and the optimal size of the battery, see Table 4. The hour-by-hour average and monthly available solar power is illustrated in Figure 2 (left). The electricity generation per square meter of a Solar World SW325XL panels with the resolution of one hour was computed. Figure 2 shows the hourly and monthly electricity output per square meter of the considered PV module.

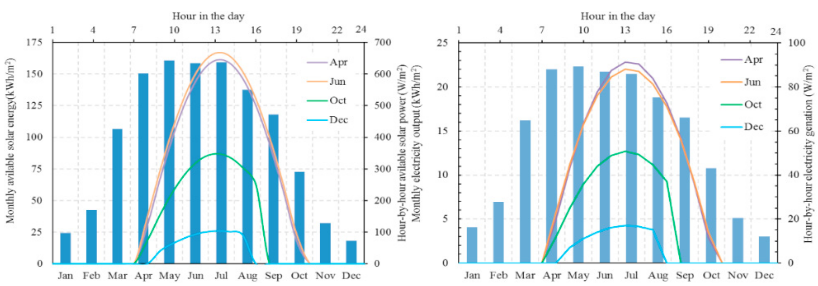

Figure 2. Hour-by-hour average available solar power and monthly solar energy (left) and electricity generation of PV module and monthly electricity output (right) per square meter of Solar World SW325XL panels on an inclined surface (50° inclination angle).

Table 4. Summary of technical calculations to achieve 50% saving

Optimal inclination angle	50	Plant capacity	190 (kW)
Optimal azimuth angle	204 clockwise from north	Investment cost of PV system	k$ 276
Annual available solar energy	1181 (kWh/m²)	Payback time	12.2 (y)

It is worth mention that the electricity generation of the PV panels depends on the ambient air temperature. Namely, during summer time the performance of the panels is lower. So, the electricity output in April is higher than in June. The simulation shows that the annual electricity output per square meter of the module is 149 kWh. With the results of the available solar power and the electricity output of the module in Figure 2, the annual average efficiency of the Solar World SW325XL panel was found to reach 14.3%. With the result of the annual electricity demand in Figure 1 and the electricity generation per square meter of the considered Solar World panel in Figure 2 (right), the required number of PV panels to achieve 50% of annual electricity consumption of the building of 356 MWh, is resulting to 610. Considering the electricity demand profiles over seasons in Figure 1 and the electricity output of the module in Figure 2 (right), there is periods when the output of PVs exceeds the electricity demand of the building or the other way around, see Figure 3. Since there is difference between feed-in price and buying price of electricity, adding a battery to the system results in an increased economic viability as well as self-consumption of the PV system.

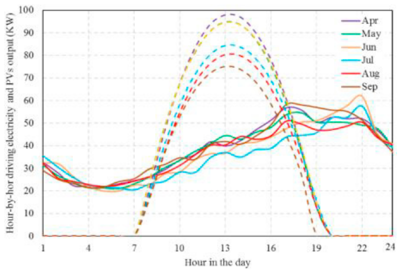

Figure 3. (▬) daily electricity consumption of the buildings and, (▬ ▬) daily electricity generation of PV system of 610 modules, on the 15th of the selected months.

As Figure 4 shows, adding a battery to the PV system increased the self-consumption economic. The latter was defined as the ratio of the PV electricity generation that consumed on the site to the total electricity generation. Since the feed-in electricity price is lower than the purchase price, increasing the self-consumption results in reduced PBT. However, use a battery increase the front cost of the system and, thus, there is an optimal capacity of the battery in which the PBT is minimized. As shown, the optimal size of the battery if 152 kWh. Table 5 shows the benefits gained from adding a battery to the system, in terms of improving the economic performance of the system at the nominal working conditions specified in Table 2.

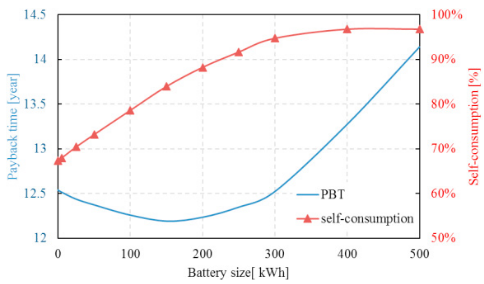

Figure 4. The impact of the battery size on the payback time along with the self-consumption of the PV system.

Table 5. Benefit of adding a battery to the PV system of to achieve the 50% saving energy target

	Without Battery	With Battery
Total cost (k$)	252	276
Self-consumption share (%)	67	83
Payback time (year)	12.4	12.2

However, the optimal size of the battery and the self-consumption level were calculated for different working parameters. As listed in Figure 5 (left side), increasing the electricity price leads to an increased optimal battery size and, consequently, increased the self-consumption share. This is due to the fact that an increasing electricity price, for a given feed-in price, results in an increased difference between the electricity buying price and the feed-in prices. Hence, to store the excessive PV generation in the battery to be used later is of more beneficial, although adding a battery to the system increases the up-front costs.

Figure 5 (right side) shows the effect of the feed-in price on the optimal battery size and self-consumption of the PV system. As show, for a higher feed-in price, the benefit of storing the excessive PV generation in the battery is reduced and, consequently, the self-consumption of the system is smaller.

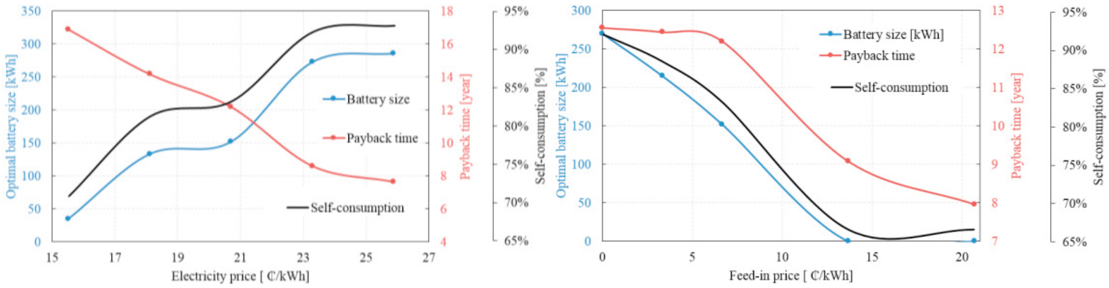

Figure 5. The impact of electricity price (left) and the feed-in electricity price (right) on the optimal battery size along with the self-consumption.

The simulations were performed to investigate the effect of the battery price on the required optimal size of the battery. As shown in Figure 6 (left side), increasing the battery price can overcome the benefit of storing the excessive PV electricity generated. Therefore, a higher battery price, a smaller optimal size of the battery is needed and, thus, the self-consumption of the system is reduced.

Finally, the impact of the efficiency of the battery on its optimal size was investigated by carrying out the simulation for different efficiencies. The results illustrated in Figure 6 (right side) show that a higher efficiency of the battery results in an increased optimal size of the battery. This is due the fact that increasing the efficiency of the battery means less energy losses of the battery during the storing period.

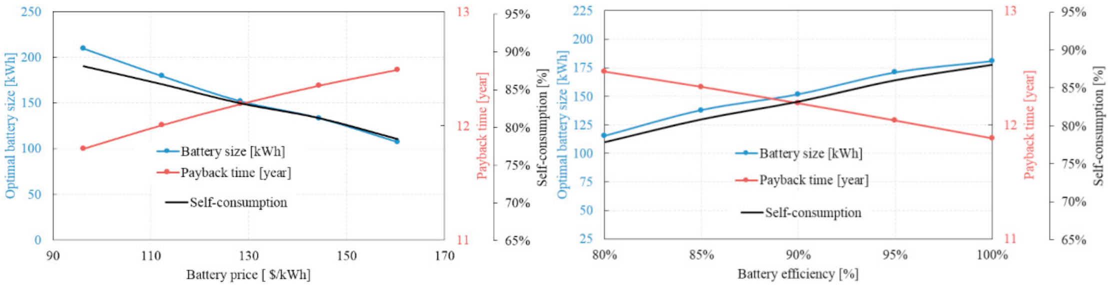

Figure 6. The impact of the battery price (left) the battery efficiency (right) on the optimal battery size along with the self-consumption

4. Conclusion

This work demonstrates that the optimal sizing of a battery for a multi-story residential building in the southern-western part of Sweden depends on different working parameters. The optimal size of the battery is defined as the size that results in a minimized payback time of a PV system. The considered working parameters are electricity price, feed-in electricity price, battery performance, and price. The results obtained show that the optimal size of the battery is strongly affected by the parameters considered. Among the selected working parameters, the calculations show that the electricity price has the highest impact while the battery performance turned out to have the lowest impact on the optimal size of the battery. Beside reducing the payback time of the system, adding a battery of the optimal size results in an increased the self-consumption share on the site, which is of primary importance for the economic viability of the PV system, especially at low feed-in prices. We find that the installation battery of the optimal size leads to increasing the of self-consumption share by 17% (i.e., from 66% to 83%) compared to a system without a battery.

Another important conclusion that can be drawn from the results achieved in this work is that the consideration of a battery with an optimal size helps to reduce the payback time of the PV system, even though the up-front costs of such a system is increased. The benefits obtained by adding a battery to the system depends on the subsidies, namely, the lower the subsidies the bigger the benefits from adding a battery. It is worth mentioning that an increases self-consumed share helps to reduce peak power, thus adding a battery to a PV system provides benefits for the electricity grid as well.

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