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Techno-economic analysis of photovoltaic battery system configuration and location☆

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HIGHLIGHTS

- A techno-economic analysis of battery system at two different locations in Almeria (Spain) and Lindenberg (Germany).
- The impact of changing orientation on SC, DA and LCoE in Germany is investigated.
- The study is done at two different tilt angles, near to the optimum values for the two locations at south orientation.
- The higher load profile is found to play a key role in increasing SC.
- A trade-off still has to be made between increasing self-consumption and achieving cost reduction for the coming 20 years.

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ABSTRACT

The techno-economic analysis investigates first the impact of tilt angle and orientation on the production profile of a rooftop solar generator and the related performance of a photovoltaic battery storage system for single family houses at a specific location in Germany. Then, a technical comparison to a different location in Almeria in Spain is performed.

The calculations are model-based and take into consideration the consumer load profile, technical and economic photovoltaic battery storage system parameters as well as the framework of regulations for the case of Germany. The parameters “share of self-consumption”, “degree of autarky”, and “economic efficiency in terms of levelized cost of electricity” make up the focus of the modelling results. It is concluded that self-consumption and degree of autarky are strongly and inversely related. In terms of system design, a trade-off has to be made between aiming for high self-consumption and a high degree of autarky.

Key findings from the modelling results reveal that in Lindenberg in Germany, a south orientation gives the highest degree of autarky and the lowest levelized cost of electricity, but with the lowest share of self-consumption as well. For rooftops oriented towards east/west, an interesting possibility could be to split the total installed capacity (equally) between the two orientations. This makes it possible to benefit from the high self-consumption of the east orientation and the high degree of autarky of the west orientation. In general, it has to be considered that the optimum orientation strongly depends on the consumer load profile. The technical analysis shows that changing the location to Almeria increases degree of autarky and decreases share of self-consumption for south orientation with different magnitude that depends on the load profile. Finally, the results show opposite impacts that depend on orientation and location when switching from a tilt angle of 30° to 45°. For a south orientation in Almeria and Lindenberg, the degree of autarky is increased when approaching the optimum tilt angle, while for west and east orientations in Lindenberg self-consumption increases.

1. Introduction

The strong growth in the number of photovoltaic (PV) installations worldwide since 2010 [1] has shown that this technology has taken a major step towards positioning itself as a good alternative to conventional energy resources in order to lower CO_2 emissions and meet the increasing global energy demand. On the other hand, the intermittent nature of this resource raises the problem of how to balance the supply and demand of electricity. In the case of small-scale rooftop PV systems for private households, battery energy storage systems (BESS) offer the opportunity to match the PV energy supply with the respective consumer load profile and thus significantly increase the share of self-

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consumption (SC) and the degree of autarky (DA). These two parameters make it possible to assess the congruence of the PV generation profile and the electricity demand profile, as SC is defined by the ratio of PV directly used to the total amount of PV generated, and DA is defined as a ratio of PV directly used to the total consumption by the household [2].

The self-consumption of locally produced electricity is gaining popularity due to falling system prices for PV [3] and BESS [4,5], on the one hand, and increasing end-consumer electricity prices [6,7], on the other. If price trends continue, costs for generating electricity via PV BESS can be expected to reach grid parity in several countries in the near future.

The design and the optimization of PV BESS have been the subject of research in different studies [2,8–21]. For instance, the economic study [21] investigates the impact of adding BESS on cost-effectiveness for two different battery systems (Vanadium redox flow and Lithium-ion batteries) using irradiance data from one location at Johannesburg and a load profile of the national load data of Kenya. Pb-acid and Li-ion batteries were compared as well under three different retail tariff systems in combination with PV generation for a single home in Switzerland [18].

A cost optimization was also made under Portuguese regulations to investigate the cost reduction required to enhance self-consumption [19]. A same approach was applied using real measurement data of solar radiation in Aachen Germany and load profile in commercial application to investigate the influence of different PV system size, PV system cost and interest rates [20].

Most of the existing techno-economics studies investigate in common the impact of battery capacity and installed PV power on the performance (SC) and the impact of component cost and tariffs on reduction of PV BESS systems costs. The current study offers a different perspective of analysing the performance and the cost of PV BESS system by looking at the parameters that impact directly the PV output power.

In this paper the impact of tilt angle and orientation on the production profile of a rooftop solar generator and the related performance of a PV BESS for single family houses is analysed firstly for a specific location (Lindenberg, Germany, Fig. 1), focusing on the parameters SC and DA (Fig. 1). The impact of these two parameters on the PV power output has been the subject of different studies [22,23] promoting the south orientation as the optimal configuration independently from the location. Concerning the tilt angle, the location plays a key role for finding the optimal configuration. As an example, at Incheon Korea the optimal south tilt angle is found to be 60° [22] which is different from the optimal configuration used in the study at Lindenberg. Different seasons impact as well the optimal tilt angle. Changing the tilt angle of the photovoltaic array in the cold and hot season improves considerably the performance and uniformity of the power output of the photovoltaic array [23].

Based on the analysis of tilt angle and orientation, a techno-economic calculation is supplemented by an investigation of the cost-effectiveness in terms of levelized cost of electricity (LCoE).

To investigate the impact of consumption and changing location on SC and DA, a technical comparison with a different location in southern Europe (Almeria, Spain) is performed at south orientation for different tilt angles and different load profiles (Fig. 1).

2. Sustainable methodology and basis data

Two models were used to investigate the impact of the tilt angle, orientation and location on the performance of PV BESS. Section 2.1 presents a brief summary of the techno-economic model and Section 2.2 the PV output power model. Data and model input parameters are summarized in Section 2.3.

2.1. The BaPSi model

The BaPSi (Battery-Photovoltaic-Simulation) model [13] is a tool for the techno-economic analysis of battery-supported PV systems. With the simulation model it is possible either to calculate a fixed system configuration with defined PV system size and battery capacity, or to conduct an iterative parameter variation to determine the cost-optimized combination of the PV system size (power rating) and the nominal capacity of the battery. The battery is integrated into the energy balance of a household considering PV production and household consumption. Here, the direct self-consumption of PV electricity (simultaneous consumption and generation of PV electricity without storage) is always prioritized over storage in the battery and feeding into the electric grid. The energy balance is calculated for every time step. The internal resolution of the model depends on the resolution of the input data time series. The required input parameters for the model calculation are economic parameters, household load profile, and PV BESS data including technical parameters and costs (see Section 2.3). Output parameters are the cost-optimal system configuration with and without battery as well as technical parameters including SC and DA. The calculation of total costs for electricity supply is based on the net present value approach by considering all costs and revenues during the operation of the system to meet complete household electricity demand. Major cost components are the costs of electricity supply from the grid – to meet the remaining electricity demand after SC from the PV BESS – the investment costs for the PV BESS, and costs of system operation and maintenance. Revenues are generated from the feed-in of surplus electricity generation, which is compensated by a guaranteed feed-in tariff. For the cost calculation, the current regulatory framework and the taxation system in Germany are considered according to [15]. The resulting total costs are therefore costs after income tax. The optimization goal is the minimization of total costs of electricity supply. As a benchmark for PV BESS it is possible to consider either grid supply of electricity only, or grid supply in combination with a PV system (without battery). LCoEs are calculated by dividing the total costs of electricity supply by the total household electricity demand in the simulation period considered.

The economic analysis was limited to the case of Germany, as changing the location to Almeria is Spain will change the electricity prices and different support schemes (Feed-In-Tariffs and battery implementation support).

2.2. The PV output power model

PV output power depends on the time, location, tilt angle, and orientation of the PV module. For this reason, a model shown in Fig. 2 was developed to calculate the output power. This model is based on real horizontal irradiation data measured on site [24,25], and takes into account the different losses that occur during energy conversion from the module and the overall system.

Firstly, the global irradiation for a given location is calculated as a sum of the direct, diffuse, and reflected irradiation on a tilted surface of angle β at an arbitrary angle orientation α (Eq. (1)).

$$G_{\alpha,\beta} = B_{\alpha,\beta} + D_{\alpha,\beta} + R_{\alpha,\beta} \tag{1}$$

Direct beam $B_{\alpha,\beta}$ is expressed as a product of sun position incidence $cos\theta_s$ and the measured data of the direct beam on a horizontal surface B_n (Eq. (2)).

$$B_{\alpha,\beta} = B_n * \cos\theta_S \tag{2}$$

The sun position is the angle of incident rays (Eq. (3)) at a given position to the normal of a tilted surface at arbitrary orientation calculated from θ_z, Ψ_s,β, and α, respectively, sun zenith and azimuth angles, and surface tilt and orientations angles.

$$\cos\theta_s = \cos\theta_z * \sin\beta * \cos(\alpha - \Psi_s) + \sin\theta_z * \cos\beta \tag{3}$$

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