Applied Energy 223 (2018) 69–81

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

# Photovoltaic systems coupled with batteries that are optimally sized for household self-consumption: Assessment of peak shaving potential

Wouter L. Schram*, Ioannis Lampropoulos, Wilfried G.J.H.M. van Sark

*Copernicus Institute of Sustainable Development, Utrecht University, 3584 CS Utrecht, The Netherlands*

## HIGHLIGHTS

- Optimal sizing of PV-coupled batteries from household's economic perspective.
- Batteries can be commercially viable with appropriate self-consumption benefits.
- Collaboration between different stakeholders economically attractive.
- Batteries that are optimally sized for self-consumption have a large peak shaving potential.
- Pre-charging of batteries is key to realize peak shaving potential batteries.

## ARTICLE INFO

*Keywords:*
PV self-consumption
PV-coupled batteries
Battery sizing
Peak shaving
Techno-economic analysis
Smart grids

## ABSTRACT

As the share of renewable energy sources in the energy mix is increasing, new challenges arise regarding the grid integration. This research focuses on a solution for one of these challenges, namely the employment of batteries to address the mismatch in electrical power between electricity supply from photovoltaic systems and household electricity demand. Herein, the optimal sizing of batteries for household self-consumption is combined with peak shaving at district level, whereas previous studies only looked at these questions in isolation. Our analysis makes use of a unique set of power measurement data from 79 households in the Dutch city of Amersfoort, in 295 evenly distributed days, with a resolution of 10 s. By using simulation of batteries and Net Present Value analysis, the average optimal storage size for self-consumption in the case of net metering abolishment for households with photovoltaic systems was determined to be 3.4 kWh. Large differences were observed between different households; photovoltaic system size, total net metered consumption and specific characteristics of load profiles resulted into optimal storage sizes in the range of 0.5–9 kWh. The impact of these optimally sized batteries on neighborhood peak demand was assessed and found to be limited, corresponding to a decrease of 5.7%. The peak shaving potential was further assessed under different control strategies of the batteries. Results show that the impact could be amplified to a decrease of 22% or 51% when the batteries are controlled by using heuristics or by assuming perfect foresight together with a power minimization algorithm, respectively. The findings of this paper emphasize the importance of collaboration between households and other stakeholders, such as distributed system operators and retailers in transitioning to a sustainable power system.

## 1. Introduction

One of the viable options to cut greenhouse gas emissions in order to combat climate change is to generate electricity from renewable energy sources. Photovoltaics (PV)[1] are expected to play an important role in this [1]. The global generation capacity of PV systems has increased from approximately 7 GW in 2006 to about 300 GW at the end of 2016 [2]. At the same time, a significant growth in electricity consumption due to electrification of the transport system and residential heating is expected [3,4]. As these trends will predominantly take place in the residential sector, this will pose challenges for the operation of low voltage (LV) electricity grids. Batteries installed in households could alleviate some of these challenges, by shaving peaks and filling valleys in the household demand profiles [5].

Several scholars have assessed the economic value that can be created by using storage in the smart grid context, i.e., by providing flexibility services to the electricity system, by addressing the power quality, reducing the negative effects of renewable energy, reducing the

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* Corresponding author.
*E-mail address:* w.l.schram@uu.nl (W.L. Schram).

[1] All abbreviations are included in a nomenclature, which can be found in Appendix A.

https://doi.org/10.1016/j.apenergy.2018.04.023
Received 10 October 2017; Received in revised form 5 April 2018; Accepted 6 April 2018

peak demand and system costs [6]. Furthermore, batteries can be used for market optimization; for instance by combining self-consumption with minimizing costs on the day-ahead market [7], or control battery operation on the day-ahead market and in the imbalancement settlement system in an economically optimal way [8]. Malhotra et al. [9] stated that demand charge reduction, residential solar integration and frequency regulation are the most attractive grid-connected applications, whereas load following, renewable energy integration and ancillary services are the most attractive island-mode and microgrid services [9]. Another review study on energy systems in island-mode reported that PV-diesel-battery systems were proven to be competitive, feasible and having positive environmental impact [10]. Collectively, these studies outline a critical role for batteries in the integration of PV-generated electricity. Increasing self-consumption of households can decrease the stress on the grid by limiting the maximum feed-in of PV-generated electricity [11,12]. Storage is reported to increase self-consumption by 13–24% for battery sizes of 0.5–1.0 kWh per kWp of PV system size [13]. With sufficient self-consumption incentives, the coupling of PV and batteries can become an attractive option from a households' economic perspective [14,15].

While using batteries to increase self-consumption limits the impact of PV-generated electricity to the grid, several other studies have investigated the role batteries in reducing the peak power demand of a household or neighborhood. For instance, in a fast-charging infrastructure for electric vehicles (EVs) batteries can allow for efficient fast-charging with reduced impact on the main grid [16]. In a DC microgrid, batteries are especially suitable as they can operate on DC, just like PV electricity production and EV charging [17]. Research on the exact peak shaving potential of PV-battery systems is still inconclusive. De Oliveira e Silva and Hendrick [18] found that the peak power consumption does not decrease when a battery is added to the PV system. This is in contrast to Fares and Webber [19], who found that peak power on neighborhood level can be reduced by 8–32%. The difference largely depends on geography: households in the United States [19], which have consumption peaks in summer due to the use of air conditioning versus households in Belgium [18], where consumption peaks occur in winter when there is much less solar irradiation. In different climatological conditions peak shaving can also occur in the winter [20]. Our research aims to present a generic solution by addressing also the peak shaving potential under low solar irradiation conditions.

There are several limitations in current literature about the coupling of PV systems with batteries. Firstly, many studies focus on single households [12,14,18], or small samples of households [11,21–23], regarding the consumption or PV generation profiles. A disadvantage of these approaches is that they lack the statistical power to determine the differences that exist between households. Furthermore, for peak shaving, aggregation of many households is essential as problems for grid operators mostly arise at neighborhood or district level. Secondly, most studies make use of synthesized generation or consumption profiles instead of measured data, and only a few studies [15,19] are exceptions to this. For PV generation profiles, sometimes solar irradiation is used as the only input [24], occasionally combined with temperature [25,26]. In practice, PV-generated electricity depends on many more factors, such as tilt and orientation of the PV system [27], and the output can be influenced by location-specific shadow impacts, especially in residential areas [28]. Thirdly, most studies use measurements with a resolution of 15 min to one hour. Beck et al. [29] found that these time resolutions could be insufficient: for households with large amounts of electricity consumption or production exceeding 2 kW, using 15 min resolution data results in substantial errors ($>5\%$) in determining self-consumption. Furthermore, for determining peak power demand, which plays an important role in this research, higher time resolutions are also preferred [13]. Lastly, all reviewed studies have a single focus, particularly maximizing self-consumption or minimizing household electricity costs, whereas our study is focused on whether batteries can be used for additional applications in support of multi-revenue business models.

The aim of this paper is thus to determine the economically optimal battery size for high self-consumption for a large variety of PV households in the Netherlands, while assessing the potential of these batteries for consumption peak shaving.

The novel contributions of this research address five aspects. Firstly, this study adds new results to the body of literature on optimal storage sizing by determining the influence of many different technical and economic factors. Secondly, we provide insight in the impact on optimal storage size due to differences between individual household production and consumption profiles by making use of a large set of 79 households. Thirdly, we assess the peak shaving potential by mutually combining optimal sizing of batteries from a household's economic perspective with peak shaving on neighborhood level, which reflects a realistic future use case. Fourthly, we present two novel pre-charging algorithms which are employed for determining both the minimum and maximum peak shaving potential. When grid assets are mainly dimensioned to transport PV-generated electricity, this leads to a low utilization rate of these assets [30]. Our approach of coupling a battery to a PV system and pre-charging the battery on days with low PV surplus (i.e. more production than consumption) leads to more efficient use of distribution grid capacity because of two separate factors: a lower distribution grid capacity is needed and the utilization rate of the distribution grid capacity is increased. Lastly, a unique empirical dataset of 79 households with PV systems and very high time resolution (10 s) of net power measurement data underlies all results.

The paper is organized as follows: in Section 2, the mathematical model is presented, followed by an explanation of how the battery size for optimal self-consumption is determined, a description of the pre-charging algorithms, an overview of battery technologies and possible impact of battery degradation, and a description of the input data and the assumptions underlying this research. Section 3 presents the results regarding the optimal storage sizing and the peak shaving potential, including a sensitivity analysis. The paper ends in Section 4 with conclusions and recommendations.

## 2. Methods

### 2.1. Model description

The simulation model was developed in MATLAB. Fig. 1 shows a simplified flow chart representing all steps that were undertaken in the model, for each household, and various storage sizes. It is similar to the model reported in Ref. [19], with the main difference being the input; net power ($P_{net}$) in this study compared to separate consumption and generation profiles in [19]. In case of either surplus production and a non-fully charged battery, or residual load (i.e. more consumption than production) and a non-empty battery, the battery can be used to prevent import from or export to the grid. Then, the resulting power from/to the grid ($P_{grid}$) is either zero or $P_{net}-P_{rated}$ (in case of battery power constraint violation). $P_{rated}$ is defined as the power of a battery charged or discharged with a C-rate of 1 (i.e. $P_{rated}$ is 1 kW per kWh of battery size), and is thus dependent on the battery size in kWh; $\eta$ is the one-way charging/discharging efficiency of the battery. The energy in the battery $E_{bat}$ at time $t$ can be calculated according to Eq. (1):

$$E_{bat}(t) = E_{bat}(t-1) - \begin{cases} P_{net}*\eta*\Delta t & \text{if } P_{net} \leqslant P_{rated} \\ P_{rated}*\Delta t & \text{else} \end{cases} \tag{1}$$

This is formulated for surplus production; in case of residual load $P_{net}$ is divided by $\eta$.

This model was used to first determine the optimal storage size. Storage sizes were stepwise increased at an interval of 0.5 kWh. Per household and per storage size, the energy consumed from the grid was determined. The benefits of storage could then be determined by