Applied Energy 183 (2016) 148–159

Contents lists available at ScienceDirect

Applied Energy

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

# Solar photovoltaic-battery systems in Swedish households – Self-consumption and self-sufficiency

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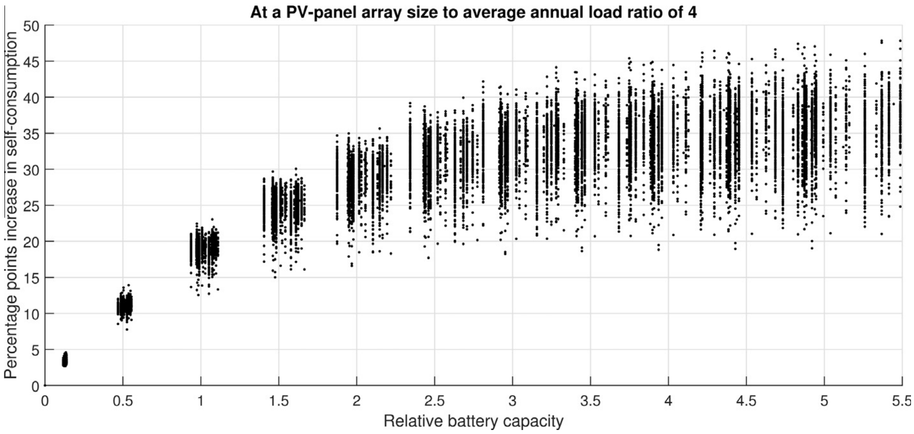
## HIGHLIGHTS

- A model for operation of batteries in household PV systems is developed.
- 2104 different Swedish households are analyzed.
- Batteries can help increase self-consumption by 20–50 percentage points.
- Batteries can help increase self-sufficiency by 12.5–30 percentage points.

## GRAPHICAL ABSTRACT



## ARTICLE INFO

*Article history:*
Received 1 June 2016
Received in revised form 12 August 2016
Accepted 28 August 2016

*Keywords:*
Solar photovoltaics
Batteries
Self-consumption
Self-sufficiency
Households

## ABSTRACT

This work investigates the extent to which domestic energy storage, in the form of batteries, can increase the self-consumption of electricity generated by a photovoltaic (PV) installation. The work uses real-world household energy consumption data (measurements) as the input to a household energy consumption model. The model maximizes household self-sufficiency, by minimizing the amount of electricity purchased from the grid, and thereby also maximizing the level of self-consumption of PV electricity, i.e., the amount of PV-generated electricity that is consumed in-house. This is done for different combinations of PV installation sizes (measured in array-to-load ratio; ALR: ratio of the PV capacity to the average annual electric load of a household) and battery capacities for different categories of single-family dwellings in Sweden (i.e., northern latitudes). The modeling includes approximately 2000 households (buildings).

The results show that the use of batteries with capacities within the investigated range, i.e., 0.15–100 kW h, can increase the level of self-consumption by a practical maximum of 20–50 percentage points (depending on the load profile of the household) compared to not using a battery. As an example, for a household with an annual electricity consumption of 20 MW h and a PV installation of 7 kW$_p$, this range in increased self-consumption of PV-generated electricity requires battery capacities in the range of 15–24 kW h (actual usable capacity), depending on the load profile of the specific household. The practical maximum range is determined by the seasonality of PV generation at Swedish latitudes, i.e., higher levels of increased self-consumption are possible, however, it would require substantially larger batteries than

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http://dx.doi.org/10.1016/j.apenergy.2016.08.172

the up to 100 kW h investigated in this work. Thus, any additional marginal increment in battery capacity beyond the range investigated results in a low level of utilization and poor additional value. Furthermore, our results reveal that when a battery is used to store PV-generated electricity in-house, self-sufficiency increases (as compared to not using a battery) by 12.5–30 percentage points for the upper range of the investigated PV capacities (ALR of 6).

## 1. Introduction

The falling cost of solar photovoltaic (PV) panels, as well as subsidy schemes to promote the installation of panels has resulted in increased worldwide deployment of solar PV, with a total of 180 GW being installed globally as of Year 2014 [1]. In addition, the cost of batteries is falling at a higher rate than predicted [2]. Due to their modular nature, both solar PV panels and batteries are well suited for distributed deployment and therefore represent a possible investment for individual households. Investment in a battery system would allow a household to increase self-consumption of its PV-generated electricity, and thus enhance independence from the grid (i.e., reduced need to purchase electricity from the grid). For instance, for the individual household there could be an economic benefit to increasing self-consumption as shown by Mulder et al. [3]. Given a high enough electricity price there can be a significant value in reducing the amount of electricity the household purchases from the grid. An increase in the amount of self-consumed electricity can also be beneficial for the surrounding electricity system. From the perspective of the operator of the distribution grid (DSO) the batteries can help reduce peak power, reducing the need for grid expansion, and help with voltage regulation [4]. This paper investigates how solar PV and battery installations can be combined within Swedish households so as to maximize PV electricity self-consumption (i.e., usage of the PV electricity generated in-house) and self-sufficiency (the fraction of electricity used by the household that is not purchased from the grid).

Luthander et al. [5] performed an extensive review of the available literature concerning PV electricity self-consumption in buildings. They have proposed definitions of the concepts of PV electricity self-consumption and self-sufficiency: PV electricity self-consumption is defined as the share of PV-generated electricity that is consumed in-house; and self-sufficiency is defined as the fraction of consumed electricity that is not bought from the grid. Luthander et al. [5] concluded that while it is obvious that batteries have the potential to increase PV electricity self-consumption, the extent to which this can be achieved varies considerably across the reviewed papers. Widén and Munkhammar [6] and Thygesen and Karlsson [7] have investigated the potential to increase PV electricity self-consumption in a Swedish context. Widén and Munkhammar [6] studied several battery and PV combinations for a Swedish household. They found that a 5 $kW_p$ PV installation coupled with a 3 kW h battery (actual usable energy capacity) increased PV electricity self-consumption by 614 kW h/year. Furthermore, they showed that doubling the battery size increased PV electricity self-consumption by only an additional 358 kW h/year. Thygesen and Karlsson [7] investigated the use of battery installations with capacities in the range of 5–24 kW h (actual usable energy capacity), together with a PV installation of 5.2 $kW_p$ in a Swedish building. For the extreme cases of batteries with capacities of 5 kW h and 24 kW h, PV electricity self-consumption increased by 18 percentage points and 33 percentage points, respectively, relative to not using a battery, indicating a reduced marginal benefit of the additional increase in battery capacity. Weniger et al. [8] investigated a German household and showed that for a PV installation of 1 $kW_p$/MW h, where MW h refers to the annual household consumption, PV electricity self-consumption of 30% and self-sufficiency of 28% were reached. With the installation of a battery with capacity of 1 kW h/MW h, the PV electricity self-consumption and self-sufficiency increased to 59% and 56%, respectively. Mulder et al. [9] investigated seven Belgian households and showed that the optimal storage size (based on their own definition and given in kWh storage per annual PV electricity in MW h) was in the range of 0.4–1.5. Pötzinger et al. [10] modeled a household PV system coupled with hydrogen storage in Germany and showed that for a PV installation of 8.6 $kW_p$, 8 kW h of storage would increase PV electricity self-consumption by 35 percentage points. Several other studies have also presented results concerning self-consumption and self-sufficiency of PV-battery system for German and Belgian households, e.g., Linssen et al. [11], Beck et al. [12], Johann and Madlener [13], de Oliveira e Silva and Hendrick [14], Braun et al. [15], and Schreiber and Hochloff [16]. There are also studies with a non-Northern European focus, e.g., Khalilpour and Vassallo [17] investigated the technical and economic potential of a PV-battery system for a household in Sydney, Australia. They showed that an increase in self-sufficiency by 50 percentage points, resulting in final self-sufficiency of around 90%, is possible given a PV installation of 20 $kW_p$ and a battery size of 15 kW h. Huang et al. [18] investigated the prospect of residential PV-battery systems in California, USA. They showed the reduction in the amount of electricity purchased per day given a PV-panel size of 4 $kW_p$ and battery sizes ranging from 0.5 kW h to 10 kW h. For 0.5 kW h, 7 kW h, and 10 kW h batteries the daily reduction in purchased electricity is 0.79 kW h, 7.13 kW h and 9.14 kW h, respectively. Thus, the reduction in purchased electricity per installed kWh battery diminishes with increasing battery capacity. Castillo-Cagigal et al. [19] studied a prototype of self-sufficient solar house in Spain with a 5.55 $kW_p$ PV installation and a battery capacity of 5.4 kW h. They also simulated several other batteries capacities together with the PV-panel and the house load. The 5.4 kW h battery improved the PV electricity self-consumption by 41 percentage points during a one week measurement, from 31% to 72%. From the simulations they showed that a battery capacity equaling the daily electricity consumption of the house results in a self-consumption of almost 90%. Osawa et al. [20] investigated a 3.4 $kW_p$ PV system together with a 24 kW h lithium-ion vehicle battery given a typical residential load profile in Tokyo, Japan. They concluded that the battery has the potential to increase self-consumption by 38 percentage points, from 41% without battery to 79% with a battery.

In summary, the above-mentioned studies indicate that the ability of batteries to increase PV electricity self-consumption and self-sufficiency decrease with increased battery capacity. However, the different investigations have yielded different results with respect to the extents to which batteries can increase PV electricity self-consumption and self-sufficiency. Furthermore, all of the previous studies investigated a limited number of households and applied different methods. Therefore, there is a need for a systematic approach that use a sufficiently large sample of buildings to give a reasonable representation of a true building stock, such as that for a country. There are also considerable differences between the level of self-consumption and self-sufficiency reached