Applied Energy 229 (2018) 1140–1151

Contents lists available at ScienceDirect

Applied Energy

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

Interdependencies between self-sufficiency preferences, techno-economic drivers for investment decisions and grid integration of residential PV storage systems

J. von Appen[a,*,1], M. Braun[a,b,2]

[a] Fraunhofer Institute for Energy Economics and Energy Systems Technology IEE, Königstor 59, 34119 Kassel, Germany
[b] University of Kassel, Wilhelmshöher Allee 71-73, 34121 Kassel, Germany

HIGHLIGHTS

- Model of investment drivers of photovoltaic (PV) and battery storage systems (BSSs).
- Interdependencies between self-sufficiency, BSS incentive and PV grid integration.
- BSSs enable larger PV systems without providing a benefit for PV grid integration.
- Quantitative analyses show self-sufficiency and BSS subsidy foster larger PV systems.
- Network operators should adjust guidelines for PV BSSs and adopt feed-in limits.

ARTICLE INFO

Keywords:
Photovoltaics (PV)
Battery storage
Self-consumption
Self-sufficiency
PV grid integration
Distributed energy resources

ABSTRACT

The business case for residential photovoltaic (PV) systems in combination with battery storage systems (BSSs) is thriving in Germany. Next to an increasing spread between electricity prices and feed-in tariffs (FITs), the adoption of PV BSSs is fostered by a preference for higher self-sufficiency and a federal investment incentive for PV BSSs. Such an incentive subsidizes BSSs on the promise of facilitating PV grid integration. However, so far a comprehensive analysis of implications of self-sufficiency desire and investment incentive for PV BSS sizing and operation and their grid integration is missing. To enable the key stakeholders – PV BSS investors, distribution network operators and policy makers – to derive a better understanding of the underlying interdependencies between these drivers and the corresponding sizing and operation of PV BSSs, an optimization model is developed. The model includes all relevant cash flows for the business case of PV BSSs, e.g. surcharges on PV self-consumption, and an approach for adopting preferences for self-sufficiency. A case study-based analysis shows that the desire for self-sufficiency and the BSS investment incentive lead to larger PV systems. From a PV grid integration perspective, a grid-supporting BSS operation is contradicted by larger system sizes fostered by the investment incentive and self-sufficiency desires. Imposing stricter feed-in limits and adjusting the residential PV support mechanism entail chances to enable larger PV systems sizes while also limiting their grid impact.

1. Introduction

In Germany, around 80,000 photovoltatic (PV) systems in combination with battery storage systems (BSSs) were installed by the beginning of 2018 [1]. The majority of these BSSs is installed in the residential buildings with PV systems smaller than 10 kWp; meaning that almost every second new PV system in Germany is nowadays installed together with a BSS. Investment decisions into such systems are not only based anymore on collecting the feed-in tariff (FIT) and net metering, but also by desires to become self-sufficient – meaning reducing electricity consumption from the grid – and benefit from an investment incentive for BSSs [2,3]. The shift from refinancing small-scale, rooftop photovoltaic (PV) systems through feed-in tariffs (FITs) towards relying also on local PV self-consumption influences the sizing decision of such systems and their operation [4,5]. A rapid decline in BSS prices, the reliance of this business case on future developments of the electricity

* Corresponding author.
E-mail address: jan.vonappen@iee.fraunhofer.de (J. von Appen).
[1] J. von Appen leads the department for Energy Management and Energy Efficiency at Fraunhofer IEE (formerly known as IWES).
[2] M. Braun is a full professor at the University of Kassel and leads the department for department for Grid Planning and Operation at Fraunhofer IEE.

https://doi.org/10.1016/j.apenergy.2018.08.003
Received 3 May 2018; Received in revised form 18 July 2018; Accepted 1 August 2018

Nomenclature

Parameter

A^{PV}, A^{BSS} lifetime of PV system and BSS [a]
C^{E} electricity procurement price [€/kWh]
C^{Fit1}, C^{Fit2} feed-in tariff for PV grid feed-in for PV systems below or equal to and above 10 kWp [€/kWh]
C^{Sc1}, C^{Sc2} taxes and EEG surcharge on self-consumption [€/kWh]
$E^{L}_{j,t}$ electricity demand for HH j during each time step t [kWh]
$E^{PV}_{j,t}$ normalized PV energy for HH j during each time step t [kWh]
ERR expected rate of return [%]
I^{PV}, I^{BSSkWh}, I^{BSSkW} investment costs for PV system [€/kWp], for capacity of BSS [€/kWh] and for inverter of BSS [€/kW]
In^{PV}, In^{BSS} installation costs for PV system and BSS [€]
M^{PV}, M^{BSSkWh}, M^{BSSkW} yearly maintenance and operation cost for PV system [€/kWp], for capacity of BSS [€/kWh] and for inverter of BSS [€/kW]
PF^{HH} present value factor for HH cash flows
S^{PV}, S^{BSSkWh}, S^{BSSkW} max. size of PV system [kWp], of capacity of BSS system [kWh] and of of inverter of BSS system [kW]
Sub^{BSSkWh} percentage of BSS investment subsidy
TE^{Dep}, TE^{BSS}, TE^{Fit}, TE^{Sc} tax depreciation for investment in PV system [€/kWp], on BSS investment incentive [€/kWh], on PV self-consumption [€/kWh] and on PV feed-in [€/kWh]
W^{NPV}, W^{Self} weights for economic and self-sufficiency preference
$\eta^{BSSCh,}$, η^{BSSDis}, η^{BSSSd} charging, discharging and self-discharging efficiency of BSS
κ^{BSSCyc} available BSS cycles
κ^{BSSUc} usable capacity of BSS
κ^{PVLim}, κ^{IncLim} feed-in limit for PV feed-in without and with BSS incentive
τ adjusting simulation step to time steps

Decision Variables

z_j objective function for HH j
b^{PV}_j, b^{BSS}_j binary variable for installation of PV system and BSS for HH j
b^{BSSInc}_j binary variable for BSS investment incentive for HH j
$b^{BSSChdis}_{j,t}$ binary variable to avoid simultaneous BSS charging and discharging for HH j during time step t
b^{SkWp}_j binary variable for PV sizing threshold for HH j
$e^{GL}_{j,t}$, $e^{BSSL}_{j,t}$ load supply via grid or BSS for HH j during time step t [kWh]
$e^{PVL}_{j,t}$, $e^{PVG}_{j,t}$, $e^{PVBSS}_{j,t}$, $e^{PVC}_{j,t}$ direct PV consumption, PV grid feed-in PV BSS charging or PV curtailment for HH j during time step t [kWh]
r^{BSSInc}_j eligible BSS investment incentive for HH j [€]
s^{PV}_j, s^{BSSkWh}_j, s^{BSSkW}_j size of PV system for HH j [kWp], of capacity of BSS system for HH j [kWh] and of inverter of BSS system for HH j [kW]
$soc_{j,t}$ state of charge of BSS for HH j during time step t [kWh]

price and its tariff structure as well as a changing regulatory framework regarding PV feed-in behavior increase the complexity of planning such systems from a PV system owner's as well as from the distribution network operator's (DNO) point of view. Potential PV system owners strive to find the optimal balance between PV and BSS size depending on their personal preference (economics vs. self-sufficiency desire). DNOs require an understanding whether such preferences and different system configurations lead to adapted PV system sizes, which result in different grid planning assumptions, and whether BSSs provide an additional benefit for PV grid integration, as desired by the German investment incentive program [3].

Hence, this paper provides an optimization model for evaluating investment, sizing and operation decisions into PV systems and BSSs. It allows quantifying the impact of current investment drivers for PV BSSs from a residential investor's perspective, but also analyzing key performance indicators for other stakeholders, such as DNOs or policy markers. The interdependencies between the desire to increase self-sufficiency, the investment incentive program for BSSs and PV BSS sizing and operation are reflected on PV grid integration. Including such new drivers in modeling and performing corresponding case studies has previously not been done, but is necessary to retrieve a clearer picture to adjust grid and policy planning premises for such systems. The presented case studies analyze the implications of a wider PV BSS adoption using over 70 German household (HH) load profiles and simulating their PV BSS sizing and operation decisions for four different locations with each three PV system orientations.

1.1. Literature review

The business case for residential PV BSSs and PV grid integration have emerged as significant research topics. For this review, papers are selected that either contributed through models in the PV BSS context, discussed the potential of BSSs to facilitate PV grid integration on the low voltage (LV) level or evaluated the PV BSS business case.

Optimal sizes of PV systems and BSSs are mainly determined by using two different approaches (mixed integer linear programming i.e. MILP; or variation of fixed system sizes). In MILP implementations, the objective function consists out of PV BSS sizing variables, maintenance costs depending on system sizes, cash flow relevant operational variables, such as grid demand or revenue from PV feed-in. Typical constraints are energy balances ensuring that demand is met or equalities to model the state of charge of the BSS [6–9]. Certain papers introduce additional costs, such as one-time installation costs through binary variables [10], others adopt additional flexibilities, such as loads [11], electric vehicles [12,13], heat pumps [14–17] or combined power-heat systems [18–20], or only focus on storage sizing while PV system sizes are assumed constant [21].

In other PV BSS papers, the authors implement a simple rule-based operation strategy for BSS operation that only requires load and PV generation of the current time step as well as the BSS state of charge of the previous time step [22]. The best-fit PV BSS size is determined by simulating different PV and BSS sizes and calculating the system value afterwards. Analyses of the German business case for PV BSSs are performed in several studies, which typically differentiate in used assumptions for battery prices, electricity prices and load profiles [4,5,7,8,23–26]. Additionally, PV self-consumption and net metering with PV BSSs are discussed in country-specific contexts in different studies, e.g. for several European states [27], for different Australian states [28,29], for Spain [30], France [31], Italy [32,33], Portugal [34], Sweden [35] or Belgium [36]. Additional reviews are provided in [37,38]. With regard to modeling, these authors tend to neglect specifics related to sizing, such as taxes, which are crucial for the German business case. For example, PV self-consumption is taxed with 40% of the EEG surcharge (the surcharge based on the German Renewable Energy Act (EEG)), if the PV system is larger than 10 kWp. Additionally, preferences of PV BSS owners, such as self-sufficiency and contribution to the German energy transition, are not modeled, but are an investment driver [2].

Sizing related literature tends to neglect questions on PV grid integration and solely concentrates on the PV BSS owner's perspective