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Economic benefits of combining self-consumption enhancement with frequency restoration reserves provision by photovoltaic-battery systems

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HIGHLIGHTS

- Development and comparison of six battery storage dispatch strategies.
- Strategies applied on 48 residential and 42 commercial PV battery systems.
- Limited reduction of self-consumption combined with large increase in profitability.
- Provision of frequency restoration reserves is recommended for profitable investments.

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ABSTRACT

Residential and commercial photovoltaic (PV) battery systems are increasingly being deployed for local storage of excess produced PV energy. However, battery systems aimed at increasing self-consumption are not constantly put to use. Additional battery storage capacity is available for a second application to improve the profitability of an energy storage system. One of these options is the provision of frequency restoration reserves (FRR) to the electricity balancing market. This provision can be either negative to compensate for excess power supply, or positive to compensate for excess demand on the power market. This study assesses the benefits for residential and commercial PV-battery systems by combining PV energy storage for higher self-consumption with provision of FRR. Six battery storage dispatch strategies were developed and assessed on the technical and economic performance of 48 residential and 42 commercial PV-battery systems. These systems were modelled over their economic lifetime with a time resolution of 5 min and with historical energy consumption measurements and market prices. FRR provision results in a small drop in the self-consumption rate of 0.5%. However annual revenues are significantly increased. Using battery storage systems only for self-consumption is not profitable with the assumptions used in this study. Provision of negative FRR substantially reduces the electricity bought with the consumption tariff and increases investment attractiveness substantially. Prioritizing the provision of FRR over self-consumption enhancement results in even higher revenues, but significantly reduces self-consumption. We recommend FRR provision to economically investment in residential battery storage systems. Commercial systems need prioritization of both positive and negative FRR provision over self-consumption for a cost-effective investment. In conclusion, combining enhancement of PV self-consumption with the provision of frequency restoration reserves leads to profitable investments.

1. Introduction

Photovoltaic (PV) battery systems are increasingly deployed in urban areas to store excess PV energy for later use. In this way, the effect of intermittence of PV generated electricity on a low voltage network is reduced and self-consumption is increased [1]. Furthermore, CO_2 emissions from fossil-based backup power generation are reduced, particularly when curtailment of renewable energy generation is avoided [2].

The cost of stationary battery energy storage systems (BESS) is rapidly decreasing and this is expected to continue due to their current and future potential of deployment [3]. However, the benefits of storing PV produced electricity are limited, especially in areas with small differences between prices of consumption and feed-in tariffs [4]. The added value that can be generated for each kWh of stored PV energy is restricted. Also, battery systems only use part of their potential storage capacity, especially in locations with large seasonal difference in PV electricity generation. Stationary batteries can be used for a broad

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Nomenclature

Abbreviations

AC	alternating current
BESS	battery energy storage systems
BOS	balance of system
CEC	California Energy Commission
DC	direct current
DOD	depth of discharge
EPC	engineering procurement construction
FCE	full cycle equivalents
FCR	frequency containment reserves
FRR	frequency restoration reserves
PV	photovoltaics
SOC	state of charge
TSO	transmission system operator

Battery storage dispatch strategies

FRRO	FRR provision only
PFRR	prioritize FRR provision over self-consumption
PFRRN	prioritize providing only negative FRR over self-consumption
PSC	prioritize self-consumption over FRR provision
PSCN	prioritize self-consumption over providing negative FRR only
SCO	self-consumption only

Performance indicators

CF_{ET}	cash flow under the electricity tariffs [€]
CF_{FRR}	cash flow from frequency restoration reserves provision [€]
D_{BESS}	battery storage capacity degradation [%]
R_{BESS}	battery energy storage system revenues [€]
FRRSR	frequency restoration reserve storage ratio [%]
PBP	payback period [years]
PI	profitability index
SCCR	self-consumption contribution rate [%]
SUR	storage use rate [%]

Parameters

Δt	timestep of 5 min
$\Delta E_{B\,pot}$	battery charge or discharge energy potential [Wh]
ΔE_{B}	battery charge or discharge energy [Wh]
ΔE_{buy}	difference in bought electricity [Wh]
ΔE_{sell}	difference in sold electricity [Wh]
η_{charge}	battery charge efficiency [%]
$\eta_{discharge}$	battery discharge efficiency [%]
π_{cons}	consumption tariff [€/Wh]
$\pi_{feed\text{-}in}$	feed-in tariff [€/Wh]
π_{neg}	price for negative FRR provision [€/Wh]
π_{pos}	price for positive FRR provision [€/Wh]
$C_{B\,BOS}$	battery balance of system cost [€]
$C_{B\,EPC}$	battery engineering procurement construction cost [€]
$C_{B\,store}$	battery storage system cost [€]
CCF	cumulative cash flow [€]
D_{cal}	battery calendric degradation [%]
D_{cyc}	battery cycle degradation [%]
$E_{B,\,t}$	battery state of charge [Wh]
$E_{B\,max}$	maximum battery state of charge [Wh]
$E_{B\,min}$	minimum battery state of charge [Wh]
$E_{buy\,PV\text{-}B}$	electricity bought with a PV-battery system [Wh]
$E_{buy\,PV}$	electricity bought with a PV system [Wh]
$E_{sell\,PV\text{-}B}$	electricity sold with a PV-battery system [Wh]
$E_{sell\,PV}$	electricity sold with a PV system [Wh]
$f_{B\,OM}$	battery operation and maintenance cost factor [%]
I_{BESS}	battery investment cost [€]
L_{cal}	calendric lifetime [years]
L_{econ}	economic lifetime [years]
N_{FCE}	number of full cycle equivalents [#]
$P_{B\,charge}$	power charged to the battery [W]
$P_{B\,discharge}$	power discharged to the battery [W]
$P_{B\,from\,PV}$	PV power used to charge the BESS [W]
$P_{B\,inv\,max}$	battery inverter rating [W]
$P_{B\,inv}$	battery inverter load [W]
$P_{B\,pot}$	battery load potential [W]
P_{D}	electricity demand [W]
P_{neg}	power provided for negative FRR [W]
P_{pos}	power provided for positive FRR [W]
P_{PV}	PV power [W]
r	discount rate [%]
$S_{B\,inv}$	battery inverter size [W]
$S_{B\,store}$	battery storage capacity [Wh]
t	timestep
y	year

range of use cases and are therefore seen as a multi-purpose technology [5]. Combining multiple applications improves the financial attractiveness of these storage systems [6].

A potential additional application of PV-battery systems is offering power and energy to the balancing and ancillary services markets. Two balancing services can be distinguished that are traded on the imbalance markets for the Netherlands, namely frequency containment reserves (FCR) and frequency restoration reserves (FRR). FCR (also known as primary control reserves), are the first tier to balance the grid and are automatically activated. The balancing power capacity is contracted in blocks of one week and the reserved capacity is remunerated [7]. Moreover, the BESS has to be able to deliver the contracted FCR, otherwise the balancing service provider receives financial penalties.

FRR (also known as secondary control reserves) are provided to restore the FCR and to compensate for excess of power supply or an excess of demand. Provision of FRR can be either mandatory or voluntary. Mandatory contributors place bids of energy provision (positive) or energy subtraction (negative) capacities on a bid ladder. These are delivered in blocks of 15 min and can be proposed to the market up to one hour before dispatch. The bid ladder determines the minutely imbalance FRR price. Voluntary contributors observe the current imbalance price and determine if they want to deliver FRR. In case of mandatory contribution, all positive and negative energy delivered is remunerated within a block of 15 min. In case of voluntary contribution, only the energy provision is remunerated if all energy within a 15 min block is positive provision, or all is negative provision [8]. FCR and FRR are contracted and remunerated by the Dutch transmission system operator (TSO) TenneT, in the Netherlands.

1.1. Literature review

Few studies were found that assess the combination of self-consumption enhancement with provision of control reserves. The ones found can be distinguished between studies that combine self-consumption with FCR, or with FRR. Revenues of storage systems that combine self-consumption with provision of FCR are about three times