Solar Energy 159 (2018) 375–389

Contents lists available at ScienceDirect

Solar Energy

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

Minimizing storage needs for large scale photovoltaics in the urban environment

S. Freitas[a,*], C. Reinhart[b], M.C. Brito[a]

[a] Instituto Dom Luiz, Faculdade de Ciências, Universidade de Lisboa, 1749-016 Lisboa, Portugal
[b] Building Technology, Massachusetts Institute of Technology (School of Architecture + Planning), 77 Massachusetts Avenue, Cambridge, MA 02139, USA

ARTICLE INFO

Keywords:
Aggregated demand
community BIPV
Net load variance
Electricity storage

ABSTRACT

The rising popularity of PV has prompted the creation of urban community solar projects. This study evaluates the combined effect of aggregating demand, photovoltaic generation and electricity storage, on-site consumption of PV and its impact on the grid. Data sets with real aggregated electricity demand from grid distribution transformers were used and the PV potential of building façades and rooftops was estimated. The amount of PV in each orientation in the façades and rooftops was optimized maximizing self-sufficiency and minimizing net load variance. Two storage management strategies were investigated: one for maximizing self-consumption and the other to reduce net load variance. We show that the aggregation of the demand and PV potential from different building surfaces in the urban context translates into a better demand-supply match, therefore minimizing storage needs. Higher storage capacities with proper management strategy are needed for mitigation of unmanageable net load variance and consequent costs for the grid operator.

1. Introduction

In 2015, almost 54% of the world's population was living in cities and the average electricity consumption was higher than 3.1 MW h/person/year (The World Bank, 2017). Cities have become hot spots for electricity demand, which has to date been mostly covered by fossil fuel combustion in utility scale power plants. However, this form of supply directly contributes to global warming and should be avoided by an energy source that could be commissioned locally, with use of local resources and owned by the users. It has gradually been acknowledged that solar photovoltaic (PV) energy is the fittest candidate to tackle this challenge. Decreasing prices, market availability and technological improvements in terms of building integration are the main reasons for the emerging interest in urban PV where both rooftop and façade integration have become more popular (Biyik et al., 2017).

The commissioning of building integrated PV (BIPV) installations contribute to bringing buildings one step closer to the Net Zero Energy Buildings (NZEB) concept (Karlessi et al., 2017). Since a perfect demand-supply match is difficult to accomplish, the grid still serves as a sink for surplus PV production and a backup for periods of insufficient PV generation. Although it depends on the particular legal framework (Comello and Reichelstein, 2017), from the point of view of the end-user this, in general, means a high valorisation of the self-consumed electricity and a penalty for the exported electricity. Hence it is important that a PV system configuration allows for the maximization of self-consumption (Luthander et al., 2015). On the other hand, from the perspective of the grid operator, high PV penetration could be a technical challenge associated with voltage and frequency regulation (Obi and Bass, 2016) and demand/feed-in ramping rates, i.e. net load variance, (Grueneich, 2015) - the rates of change in the power that is required from the grid to satisfy abrupt increase/decrease in load demand, or the rapid increase in prosumer exports to the grid. Hence, there seem to be mutual excluding interests for prosumers and grid, which may ultimately set a limit for maximum feed-in power from households (Golden and Paulos, 2015), although this curtailment would entail a loss of production and, consequently, loss of revenue for the prosumer.

Although PV could – in principle – be installed according to a larger plan that ensures that the resulting solar electricity generation matches the demand profile of the PV host buildings, this is a challenging task to realize because the consumer behavior cannot be trivially inferred. Actual household consumption profiles are complex, featuring high variability and many spikes, which are difficult to grasp and model in a fully reliable way (Gouveia and Seixas, 2016; Grandjean et al., 2012). Yet, as one aggregates different profiles, the result is a smoother profile whose shape will match better the PV generation profile shape. When complemented with storage technologies and management strategies, the resulting overall system might be able to control the net load

---

* Corresponding author at: Instituto Dom Luiz, Faculdade de Ciências, Universidade de Lisboa, Campo Grande, Ed. C8 (8.3.33), 1749-016, Portugal.
E-mail address: srefreitas@fc.ul.pt (S. Freitas).

https://doi.org/10.1016/j.solener.2017.11.011
Received 8 September 2017; Received in revised form 10 October 2017; Accepted 6 November 2017

Nomenclature

Parameter/index	Description
A_f [m^2]	areas of PV modules installed in the façade
A_r [m^2]	areas of PV modules installed in the rooftop
A_s [m^2]	area of surface s
B_{bat} [kW h/kW$_{pv}$]	storage capacity
B_{exp} [kW h]	electricity stored in the battery that was exported to the grid
B_{sc} [kW h]	electricity stored in the batteries that supplies for the loads
$B_{soc,f}$ [kW h]	ending of cycle battery energy state of charge
$B_{soc,i}$ [kW h]	beginning of cycle battery energy state of charge
b [-]	block index
C_0 [€]	initial investment cost
C_{bat} [€/kW h]	unitary cost of the battery
C_{om} [€]	operation and maintenance costs
$C_{pv,f}$ [€]	cost of the PV installation for the façade
$C_{pv,r}$ [€]	cost of the PV installation for the rooftop
C_{rate} [kW/kW h]	charging rate relative to maximum battery capacity
C_{rep} [€]	replacement costs of the storage
C_y [€]	cash flow in year y
dg [%/year]	degradation rate for PV
E_{dem} [kW h]	electricity demand
E_{imp} [kW h]	electricity purchased from the grid
e_p [€/kW h]	grid single tariff
e_s [€/kW h]	retail electricity market prices
GI_s [kW h/m^2]	hourly global irradiation in the plane of surface s
h [h]	hourly time step
i [%]	inflation rate
L [years]	system lifetime
L_{bat} [years]	battery lifespan
N_b [-]	total number of surfaces in block b
$NOCT$ [°C]	nominal operating cell temperature
n_{bat} [-]	number of batteries
$PPVS$ [€/kW h]	Profit from PV System (value of the PV electricity)
PR [%]	performance ratio
PV [kW h]	PV generated electricity
PV_{bat} [kW h]	PV produced electricity that charges the storage bank
PV_{exp} [kW h]	PV produced electricity that was exported to the grid
PV_{sc} [kW h]	self-consumed PV generated electricity
p_{PV} [kW/m^2]	PV peak power density
$RMSD_{NLV}$ [kW/h]	root mean squared deviation of the net load variance
r [%]	opportunity cost of capital
NLV [kW/h]	hourly net load variance
SC [%]	self-consumption rate
SOC_{max} [%]	maximum state of charge relatively to the nominal battery capacity
SOC_{min} [%]	minimum state of charge relatively to the nominal battery capacity
SS [%]	self-sufficiency rate
s [-]	surface index
T_a [°C]	hourly ambient temperature
y [year]	yearly time-step
Δ_η [%]	temperature coefficient for efficiency
η_c [%]	charge efficiency
η_d [%]	discharge efficiency
η_{inv} [%]	inverter efficiency
η_r [%]	average reference efficiency for c-Si solar panels

variance and enhance self-consumption and -sufficiency.

Several studies have addressed the effect of the **aggregation of demand** profiles on self-consumption and -sufficiency rates of distributed solar PV systems, with and without community electricity storage. Parra et al. (2015) used real demand data from a single home to a 100-home community to obtain the optimum community energy storage in 2020 and a zero-carbon year. This approach achieved a cost reduction by 37% and 66% for a single home. Lopes et al. (2016) introduce the concept of a Cooperative Net Zero Energy Community, extending the discussion to the enhancement of load matching at a wider community level. The simulations employed stochastic load profiles with time resolution of 1 min, and the results point out an increase in the self-sufficiency up to 21% and the self-consumption up to 15%. Nyholm et al. (2016) uses real data from 2000 households in Sweden as input to a model that minimizes the amount of electricity purchased from the grid. Different combinations of PV installation sizes and battery capacities were studied, demonstrating that a self-consumption increase between 20% and 50% is possible with storage, but it strongly depends on the load profile of the dwellings.

It is equally interesting to assess the effect of **aggregation of photovoltaic generation**. If most systems are placed on rooftops with similar orientations, high net load variance are expected at sunrise and sunset times for those orientations. This effect could be mitigated by making use of the variety of orientations and inclinations (Hartner et al., 2015) available in buildings, such as building façade area (Martínez-Rubio et al., 2016; Martín-Chivelet and Montero-Gómez, 2017), which help widen the peak production throughout the day and providing electricity in the morning and late afternoon, as shown in Brito et al. (2017).

The effectiveness of battery storage systems implemented with PV has been widely documented in literature. Battery costs have been decreasing and their reliability improved, but most authors agree that electricity storage is still an unprofitable option for many users, except in very particular conditions or applications (Weniger et al., 2014; Naumann et al., 2015; Merei et al., 2016; Cucchiella et al., 2016; Camilo et al., 2017; Vieira et al., 2017). On the other hand, the effect of **aggregation of electricity storage** has only been discussed in few publications. For instance, Santos et al. (2014) assess the relevance of having distributed electricity storage capacity at the residential level, side by side with the consumption and generation devices. It is demonstrated that storage could be essential for the grid management for higher penetrations of PV generation in the residential sector by reducing the annual maximum power flow values. However, the effect of storage is strongly influenced by its sizing and operating strategy. In (Parra et al., 2017) the performance, economic benefits and optimum battery capacities for community electricity storage systems were quantified as a function of the size of the community. The optimization algorithm features demand load shifting strategies based on PV and load forecasts. It is shown that optimum storage capacity should ensure fully discharge during the peak period.

This study explores the combined effect of aggregating building demand, photovoltaic generation and storage on the self-consumption of PV and its impact on the grid. In particular, its main goal is to evaluate to what extent the building integration of PV alone avoids costs of extra storage while remaining profitable for users and innocuous for the grid. For this purpose, real aggregated electricity demand data from grid distribution transformers was employed; the amount of PV installed in each orientation in the façades and rooftops was optimized through a genetic algorithm aiming for the minimization of net load variance and maximization of self-sufficiency; and two storage management strategies were employed, one for maximizing the prosumer profit and the other to reduce net load variance.

Section 2 provides a detailed explanation of the Methods employed, followed by Results, Discussion and Conclusion in Sections 3–5.