Applied Energy 215 (2018) 356–370

Contents lists available at ScienceDirect

Applied Energy

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

# Projecting battery adoption in the prosumer era

Edward Barbour[a], Marta C. González[a,b,c,*]

[a] Department of Civil and Environmental Engineering, MIT, USA
[b] Department of City and Regional Planning, UC Berkeley, USA
[c] Lawrence Berkeley National Laboratory, USA

## HIGHLIGHTS

- We calculate the profitability of residential battery systems.
- Available batteries can significantly increase consumer self-sufficiency.
- Batteries are uneconomic with current tariffs for most consumers.
- We calculate the conditions required for widespread residential battery adoption.
- Electricity prices above \$0.40/kW h and PV subsidies below \$0.05/kW h are required.

## ARTICLE INFO

*Keywords:*
Energy storage
Residential batteries
Rooftop PV
Battery economics
Prosumer self-sufficiency

## ABSTRACT

Solar photovoltaic (PV) has the potential to make an important contribution to global sustainability, however, the misalignment between solar production and residential demand presents challenges for widespread PV adoption. Combining PV and storage is one way that this challenge can be overcome. In this work, we use one year of smart meter data from 369 consumers in three different US regions and calculate their economic benefits from both PV and coupled PV-battery systems. We consider a range of different electricity pricing schemes from the consumer regions, including both Feed-In-Tariff (FIT) and Net-Energy-Metering (NEM) policies. Significantly, our work uses real demand data, real PV generation data and optimizes each individual consumer's battery operation to minimize their electricity bill. Furthermore, we study the effect of batteries on consumer self-sufficiency, which is important because increasing self-sufficiency is a primary motivating factor behind battery adoption. We find that PV is profitable for the majority of consumers with most current pricing scenarios but PV-battery systems are always less profitable. However, batteries can provide very significant increases in self-sufficiency and we find that a majority of consumers can exceed 70% self-sufficiency with a 20 kW h battery and a PV system that produces the equivalent of their consumption. This is compared to an average self-sufficiency of 35% with PV only. Finally, recognizing that a number of factors could lead to profitable batteries in future, we study the sensitivity of battery profitability to future electricity prices in a FIT scenario, also accounting for future decreases in PV and battery costs. We find that if PV-battery systems are to become better investments than PV-only for the majority of consumers, retail electricity prices above \$0.40/kW h and FIT rates below \$0.05/kW h are a likely requirement.

## 1. Introduction

The electricity industry is the single biggest contributor to global greenhouse gas emissions worldwide [1]—in the US it accounts for 30% of total GHG emissions [2]. Of this, the US residential sector represents 36% of the nation's total electricity consumption [3] and is therefore an important area where emissions reduction can occur. Solar Photovoltaic (PV) panels are a popular way of reducing emissions via low-carbon solar-generated electricity, the uptake of which has been driven by many factors, including favorable policies, huge declines in the costs of PV panels and heightened public awareness of environmental issues. As a result, many different regions worldwide have experienced, or are currently experiencing, a boom in the levels of installed PV in the local distribution grid. For example, at the end of 2015 California had over 10 GW of installed solar, of which 3 GW was installed in 2015 [4], while in Germany the installed PV capacity has recently surpassed 40 GW (having been only 2 GW in 2005) [5].

When electricity consumers install PV, they become "prosumers",

* Corresponding author at: Department of City and Regional Planning, UC Berkeley, USA.
*E-mail address:* martag@berkeley.edu (M.C. González).

https://doi.org/10.1016/j.apenergy.2018.01.056
Received 8 August 2017; Received in revised form 19 January 2018; Accepted 22 January 2018
Available online 20 February 2018

**Nomenclature**

*Acronyms*

| | |
|---|---|
| FIT | Feed In Tariff |
| MILP | Mixed Integer Linear Program |
| NEM | Net Energy Metering |
| NPV | Net present Value |
| TOU | Time Of Use |

*Subscripts*

| | |
|---|---|
| $i$ | for the *ith* consumer |

*Parameters and variables*

| | |
|---|---|
| $\eta^{chg}/\eta^{dis}$ | battery charging/discharging efficiency (%) |
| $\pi(t)$ | electricity price for grid import at $t$ (\$/kW h) |
| $\pi^{EX}$ | reward for exported solar (\$/kW h) |
| $\pi^{b}(t)$ | electricity buy price for the battery at $t$ (\$/kW h) |
| $\chi_i^{PV}/\chi_i^{PVB}$ | consumer $i$ total yearly electricity bill with PV/ PV + battery (\$) |
| $B^{PV}/B^{B}$ | electricity bill saving due to PV/Battery (\$) |
| $Cap^{PV}/Cap^{B}$ | capital costs of PV/battery installation (\$) |
| $CF(y)$ | net cash flow in year $y$ (\$) (\$) |
| $D_i$ | consumer $i$'s yearly consumption (kW h) |
| $E_i^{GR}$ | consumer $i$'s total grid imported electricity |
| $ES_i(t)$ | action of consumer $i$'s battery at $t$ (kW h) |
| $Li$ | battery lifetime (years) |
| $N$ | number of time periods |
| OM | operation & maintenance cost (\$) |
| $P(t)$ | battery power during $t$ (kW) |
| $P^{R,chg}$,$P^{R,dis}$ | battery rated charge/discharge (kW) |
| $S_i$ | consumer $i$'s total yearly generation (kW h) |
| $SOC(t)$ | battery state of charge at $t$ (kW h) |
| $SOC^{min}/SOC^{max}$ | min/max battery state of charge (kW h) |
| $\Delta SOC(t)$ | change in battery state of charge at $t$ (kW h) |
| $SS_i$ | consumer $i$'s self-sufficiency (%) |
| $c_i(t)$ | consumer $i$'s cost at $t$ (\$) |
| $d_i(t)$ | demand of consumer $i$ at $t$ (kW h) |
| $r^d$ | discount rate (%) |
| $r^{inf}$ | inflation rate (%) |
| $s_i(t)$ | PV generation of consumer $i$ (kW h) |
| $t$ | time period (15-min timestep) |
| $\Delta t$ | duration of time period $t$ |
| $y$ | year |

producing electricity as well as consuming it. One primary challenge with PV "prosumption" is that the time of peak PV generation is mismatched with the typical peaks in residential electricity consumption. This misalignment has the potential to cause a number of operational problems for the electricity system if PV adoption becomes widespread [6]. These include increasing the required ramping rates for the grid [7], altering utilization factors for existing power plants [8], causing voltage and frequency reliability concerns [9,10], and increasing wholesale electricity price fluctuations [11]. In areas with very high local rates of solar PV adoption, the local daytime electricity demand may be reduced to such an extent that over-generation occurs, due to the minimum running requirements of local thermal power plants in the system [12]. This situation is exemplified by the CAISO (California Independent System Operator) solar "duck" curve.

These issues cause divergent opinions between pro-solar groups and incumbent electric utilities, with pro-solar groups focusing on the positive environmental aspects of PV and incumbent electric utilities on the operational challenges posed. In the US, a controversial issue is whether or not to preserve Net Energy Metering (NEM) [13]—which is currently the favored policy approach for residential PV in several US states. Under a NEM policy, consumers with PV installed are billed based on their *net* electrical usage, and surplus solar-generated electricity is rewarded at the same price per kW h as electricity from the grid would have cost at that time period. Alternatively, Feed In Tariffs (FITs) are the preferred approach in much of Europe. FIT policies usually oblige the local utility to buy all of a consumers surplus solar generation at a fixed export rate, which is specified by the relevant regulatory body. Both of these policies have been designed to promote investment in PV, however FIT rates are designed to be progressively reduced as target levels of capacity are achieved and surpassed. FIT agreements can also include provisions of payment for self-consumed electricity or limitations of the amount of electricity that is exported [14] and NEM is generally equivalent to a FIT for exported electricity which is equal to the retail electric rate at all times. It is also hugely important that as target levels of PV and target installation costs are achieved, regulatory support for PV is slowly fading [15].

Energy storage represents one solution to the challenges associated with intermittent solar generation [16,6]. Storage can absorb surplus solar generation at times with low demand, releasing it at times with high demand. At a centralized scale for utilities, compressed air energy storage and pumped hydroelectric energy storage technologies are currently best placed to add value to wind or solar generation [17], however at the residential scale lithium-ion batteries are the most promising option [18]. Other promising storage technology options are under development, which include super-capacitors [19] and fuel cells, which are particularly interesting due to the potential to also provide heat [20], however at present batteries remain the only widely available option for residential-scale energy storage. Batteries also benefit from favorable public opinion—a recent survey found that 78% of consumers approved of the idea of residential batteries [21]—and several companies are already marketing batteries to residential PV consumers. However, while customers favored the use of batteries to increase their self-sufficiency, saving money on electricity bills was the most important reason for battery adoption for the majority of residential consumers [21,22].

Several recent studies have examined economics of residential batteries using a variety of methodologies. [23] examines the economics of battery storage using a single yearly electricity demand profile and a real PV electricity generation profile in the UK, optimizing the battery schedule using Mixed Integer Linear Programming (MILP) and finding that no battery is profitable with current UK flat electricity rates and "economy 7" tariffs. However the study suggests batteries may be profitable once costs fall below £ 138/kW h and consumers are billed with wholesale prices. [24] uses hourly data from 36 real consumers to simulate 894 demand profiles and also simulates hourly PV generation for each consumer. The batteries are always scheduled for self-consumption and the study finds that batteries are profitable once the costs fall below €214/kW h in a German context with current electricity prices. [25] considers a single Australian household with five different sizes of solar PV installation and a fixed battery size for each PV installation. The batteries are scheduled for self-consumption and different tariffs considered. For the demand profile studied, it was found that the payback periods were shorter for smaller PV systems. The study also calculated a reduction in $CO_2$ emissions, however this did not include any potential emissions reduction for exported electricity, which was the primary reason that [26] found batteries lead to an increase in global emissions. Again with a focus on Australia, [27] considered the savings due to batteries under a range of real and