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An economic analysis of residential photovoltaic systems with lithium ion battery storage in the United States

Eric Tervo[a,*], Kenechi Agbim[b], Freddy DeAngelis[a], Jeffrey Hernandez[c], Hye Kyung Kim[c], Adewale Odukomaiya[a]

[a] George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA
[b] Department of Mechanical Engineering, Rice University, Houston, TX 77251, USA
[c] School of Chemistry and Biochemistry, Georgia Institute of Technology, Atlanta, GA 30332, USA

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ABSTRACT

Residential photovoltaic systems can reduce reliance on grid electricity, which may be desirable for numerous reasons. However, the economic viability of such systems is dependent on effective use of excess electricity generation, most often through net or bi-directional metering. With recent cost reductions in residential-scale lithium ion battery storage systems, these may be a practical alternative. In this work, we model the lifetime performance and economics of residential photovoltaics with lithium ion batteries across all 50 states in the U.S. We investigate in detail how photovoltaic size and battery capacity affect performance and cost metrics in California, Georgia, and Massachusetts. We find that with appropriate sizing, photovoltaic-battery systems can be more affordable than photovoltaics alone. We demonstrate that these systems may be competitive with grid prices when the federal investment tax credit and favorable financing terms are used, and we calculate the sell-back price required for bi-directional metering to reach cost parity with photovoltaic-battery systems in every state.

1. Introduction

Residential solar photovoltaic (PV) systems provide a means to reduce dependence on grid electricity, which may be desirable for economic, reliability, or environmental concerns. In the U.S., growth in residential PV installations has been driven by rapid price reductions due to technological advances and economies of scale. In 2016 alone, the median price for PV installations fell by 4% [1]. A significant limitation to residential PV effectiveness, however, is the mismatch between peak daytime solar irradiance and peak loads, which occur in the morning and evening [2]. For average-sized PV systems, this results in substantial excess electricity generation during the day [3]. A common solution is the use of net or bi-directional metering, in which excess generation is sold back to the grid at a rate less than or equal to the retail rate. Under some incentive programs, this rate may even exceed the retail rate [4]. However, in many states these programs only offer a low buyback rate, have limited availability, or often are not offered at all [5]. The issue is further complicated by a fragmented and changing regulatory landscape around net and bi-directional metering [6]. These factors motivate an alternative mechanism to utilize excess PV generation onsite, namely, battery storage. As with PV costs, lithium-ion battery costs are dropping rapidly; they have decreased by 65% since 2010 and are predicted to drop below \$100/kWh for electric vehicles within the next decade [7]. These cost decreases mean that residential lithium ion battery storage has the potential to be an economical alternative to bi-directional metering schemes. With a battery system installed along with the PV system, electricity generated during peak daytime hours is stored in the batteries and utilized later in the evening as the load increases and solar irradiance decreases. A simplified schematic of this mechanism is shown in Fig. 1, in which the PV-battery system supplements electricity from the grid but does not feed electricity back to the grid.

Pairing batteries with residential PV panels began to be seriously examined in the 1980's [8], and in more recent years there have been a number of research efforts to address the sizing of PV-battery systems for residential buildings [9]. Many of these case studies are focused on the German market [3,10–16], which is favorable to PV-battery systems for two reasons. First, the substantial German feed-in-tariff program greatly incentivizes investment in residential scale PV systems. Second, PV-connected battery systems are funded by a public support program which includes a reduced interest rate and an investment grant [14]. As a result, most of these studies focus on various optimization challenges

* Corresponding author.
E-mail address: eric.tervo@gatech.edu (E. Tervo).

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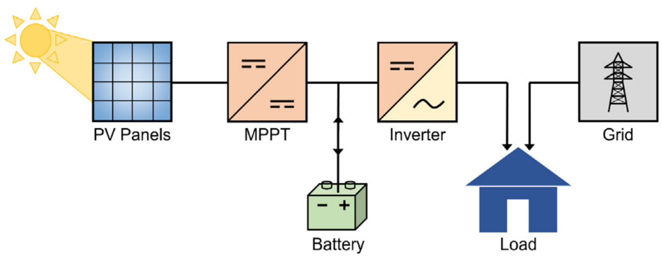

Fig. 1. Schematic of the residential photovoltaic and lithium ion battery system studied in this work. A maximum power point tracker (MPPT) regulates the load characteristics for maximum electricity production by the PV panels. The battery system is assumed to be direct current connected and share an inverter with the PV panels. Grid electricity supplements the residential load not met by the PV-battery system.

of grid-tied PV-battery systems. Other works focused on European and northern African markets have examined the use of lead-acid batteries with PV systems in the U.K. [17], various types of batteries to improve solar self-consumption in Portugal [18,19], PV and battery size optimization in Tunisia [20], and the development of standards for discharging PV-battery systems to the grid [21]. There is also a significant international body of work on the potential of load control, power flow management, demand response, and smart grids to improve the economics of PV-battery systems [22–30]. Many of these technologies are generally not yet widely available, though. A drawback of many existing studies on PV-battery systems is that their individual contributions to the system cost are not separated. A recent analysis [31] did separate the costs of PV and lithium ion batteries in a manner similar to our analysis, but their model was applied to megawatt-scale installations using national load data for Kenya and irradiance data for Johannesburg.

In comparison, there are relatively few recent studies examining the economics of PV-battery systems in the U.S. despite a clear need to understand their costs. As PV, wind, and other variable generation technologies increase in market penetration, significant levels of storage or other enabling technology such as demand response will be required [32–34], which has prompted some investigation of utility-scale PV-battery storage [35,36]. Some studies have examined aspects of residential PV-battery systems for limited locations in the U.S. [37–45], such as how they affect CO_2 emissions and reliance on the electricity grid [37]. However, the economic analysis often only includes net-metered rate structures [37,38], which are unavailable in many places as discussed earlier, do not provide an economic incentive to install a battery system, and do not allow separation of PV or battery costs from the rate structure for comparison to bi-directional metering or other enabling technologies. Other U.S. studies focus on tiered or time-of-use rate structures [39], smart home energy management/scheduling systems [39–42], and hybrid systems with combined heat and power [43,44] or wind energy [45] in addition to the PV and battery components.

With the recent introduction of more affordable options for residential-scale lithium ion battery storage, particularly Tesla's Powerwall system, there is an opportunity to re-examine the viability of these systems in the U.S. market. In the present work, we contribute to this re-examination by modelling the performance and economics of residential PV systems with lithium ion batteries under a simple immediate use energy control strategy, emphasizing their implementation as an alternative to net or bi-directional metering. We apply our model to the center of population of each of the 50 states in the U.S., and we provide a further detailed analysis of PV size, battery capacity, and their impact on performance and cost for California, Georgia, and Massachusetts. The levelized cost of the batteries is separated from the system cost to specifically evaluate its economic impact. We also calculate the required sell-back price in a bi-directional metering scheme to achieve cost parity with a given PV-battery system size. Finally, we provide a sensitivity analysis to better understand the relative importance of the model parameters. Our model is provided via Mendeley Data (http://dx.doi.org/10.17632/78kxg466rz.1) for use and modification in other scenarios and applications, such as other locations, load profiles, or component costs.

2. Methods

2.1. Photovoltaic and battery performance

PV panel electricity production and battery charge/discharge were calculated in hourly intervals for each of the 50 states in the U.S. The PV panels were assumed to be tilted South at an angle equal to their latitude, which approximately corresponds to the maximum year-long power output [46]. The nameplate efficiency of the panels was taken as η_{NP} = 15.34% according to an analysis of eight leading manufacturers by Flowers et al. [47] with a lifetime (period of economic analysis) of 30 years. This is longer than the 25 years used in many other PV economic studies [12,48,49] but consistent with reports that the actual lifetime of PV systems usually exceeds the standard 25 year assumption [50–53]. The area of panels installed A was determined according to $A = E_{PV,nom}/(\eta_{NP}*1\text{kW/m}^2)$ where $E_{PV,nom}$ is the desired nominal size in kW and a reference insolation of 1 kW/m^2 is used. Additional conversion losses are considered due to dust η_D = 98% [46], maximum power point tracker use η_{MPP} = 95% [46,54], DC losses η_{DC} = 98% [55,56], and temperature $\eta_T = \gamma_T(T_{PV} - T_{ref})$ where T_{ref} = 20 °C and T_{PV} are the reference temperature and PV cell temperature, respectively, and γ_T = 0.457% °C^{-1} is the temperature degradation coefficient. The PV cell temperature is modelled as [46,57]

$$T_{PV} = T + \frac{I_T}{800}(NOCT-20)\left(1-\frac{\eta_{NP}}{0.9}\right)\left(\frac{9.5}{5.7 + 3.8v}\right) \tag{1}$$

where T is the current ambient temperature, I_T is the solar irradiance on the tilted panel, $NOCT$ = 46.6 °C is the normal operating cell temperature, and v is the current local wind speed in m/s. The values for $NOCT$ and γ_T were obtained by averaging all values for mono- and polycrystalline silicon modules in the California Energy Commission's database of eligible systems for the California Solar Initiative as of June 1, 2017 [58]. Additionally, an annual performance degradation rate of γ_D = 0.8% is used [59]. The operating efficiency of the solar panels is then evaluated for each hour of the year at each location as

$$\eta = \eta_{NP}\eta_D\eta_{MPP}\eta_{DC}\eta_T[1-(n-1)\gamma_D] \tag{2}$$

where n is the year of operation.

The solar irradiance on the tilted panels I_T is found through a methodology similar to that of the National Renewable Energy Laboratory's System Advisory Model [57]. Representative hourly solar resources and environmental conditions for one year were obtained from typical meteorological year 3 (TMY3) data [60]. This dataset provides characteristic annual data that can be generalized to longer time periods with a smaller input dataset, making it well-suited to a comparative study of many locations as in this work. However, a drawback is that it does not include meteorological extremes, so an analysis using many years of irradiance data for one location would be recommended for practical system sizing. The global horizontal irradiance I, diffuse horizontal irradiance I_D, temperature T, wind speed v, and surface albedo ρ were extracted from the datasets for the TMY3 station closest to the center of population of each of the 50 states [61]. The well-known HDKR model [46,62] was selected to calculate I_T from these data as it accounts for factors such as circumsolar radiation and horizon brightening while still being computationally efficient. In this model, the irradiance on a tilted panel is written as [46]