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Thermoeconomic analysis of residential rooftop photovoltaic systems with integrated energy storage and resulting impacts on electrical distribution networks

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ABSTRACT

This paper investigates residential rooftop photovoltaic (PV) systems for long-term thermoeconomic benefits from PV homeowners' perspectives and for impacts on the electrical distribution network from grid operators' perspectives. The costs of generating electricity from grid-connected PV systems are studied with and without energy storage at the PV homeowners' sites. Three selling scenarios for excess PV energy conversion are considered: net metering, wholesale pricing, and no payback. PV systems in Utah are utilized as case studies in this analysis. The presence of PV systems gives homeowners economic benefits such as reduced annual electricity bills. However, the levelized costs of electricity are considerably higher than the weighted electricity price in Utah. Currently, the addition of energy storage only benefits customers in Utah under the no payback policy. The impacts of PV systems toward electrical distribution networks are then studied on a distribution test system. Excess PV generation from residential PV systems causes voltage rise in the electrical distribution network. The results from this paper can educate consumers about the lifetime benefit of integrating solar energy into their homes. For grid operators, residential PV systems with energy storage can reduce the negative impacts on the grid compared with high PV penetration alone.

1. Introduction

Distributed generation has become a popular choice for power generation in recent decades [1]. Distributed energy systems, especially those incorporating renewable energy generation, are emerging as more widespread choices for power generation, while presenting unique challenges for integration into the existing electric utility system [2]. Among different renewable energy technologies, solar PV is one of the most popular options. These systems enter the market in a range of different sizes: utility-scale (1–10 MW), medium-scale (10–1000 kW), and small-scale (< 10 kW) [3,4]. In the United States, the number of small-scale residential PV systems have increased significantly (1 million homes in 2016) and have become an important part of distributed generation resources [5]. Depending on the application and the facility served by the electrical generation, PV power systems can be sized to meet the electricity demand. However, the timing of PV generation and a building's electrical needs rarely coincide.

There are two popular options to configure residential PV systems: grid-connected and off-grid systems [6,7]. Even though the option for grid defection using residential solar PV systems can be achieved, generation costs are highly expensive at present [8]. As a result, the majority of residential PV systems in the U.S. are grid-connected. Furthermore, these systems are often configured either with or without energy storage. For the grid-connected residential PV option without energy storage, there are two essential elements to interacting with the electric utility: sending electricity to the grid and receiving electricity from the grid. During the day when energy demand is less than the energy conversion from rooftop solar PV, PV homeowners can sell the excess electricity to the grid. Contrarily, homeowners with PV systems draw energy from the grid at night since there is no energy conversion from the rooftop solar PV. The method for selling excess electricity depends on local policies. Some of the programs that have been used are net metering, wholesale pricing, or no payback [9–13]. Under the net metering policy, PV homeowners receive utility credits for sending excess PV generation to the grid, whereas PV homeowners under the wholesale pricing policy sell the excess PV generation to the grid at wholesale prices. Furthermore, the no payback policy means that PV homeowners will not receive credits for excess PV generation. The second option for homeowners with PV is to purchase energy storage to store the unconsumed energy [14]. However, the addition of energy

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Abbreviations

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CAISO	California Independent System Operator
EIA	Energy Information Administration
EPRI	Electric Power Research Institute
ES	Energy Storage
IECC	International Energy Conservation Code
NREL	National Renewable Energy Laboratory
PBP	Payback period
OpenDSS	Open Distribution System Simulator
O&M	Operations and maintenance

Nomenclature

η	solar PV efficiency (%)
A	solar PV panel area (m^2)
C	cost ($)
E	energy (kWh)
I	solar irradiation (kWh/m^2)
$LCOE$	levelized cost of electricity ($/kWh)
n	annual electricity bill payment (Year)
PR	performance ratio (%)
$R_{utility}$	utility electricity price ($/kWh)
$R_{wholesale}$	wholesale electricity price ($/kWh)

Subscripts

$_{bill,annual}$	annual electricity bill
$_{capital}$	capital cost
$_{ES}$	energy storage (battery) system
$_{invt}$	inverter
$_{misc}$	miscellaneous
$_{PVonly}$	PV system without energy storage
$_{PV+ES}$	PV system with energy storage
$_{net}$	net energy
$_{load}$	electrical load

storage introduces extra costs to the PV system as a whole. In this configuration, electricity can still be drawn from the grid if the energy demand is more than the PV generation or the stored energy available.

The addition of PV systems can create potential problems to the existing distribution networks. A large amount of PV penetration (i.e. excess PV generation being sent the grid) can cause voltage rise and reverse power flow, which reduces the stability of the networks [15–17]. Energy storage in PV systems has been cited as a solution to reduce the impacts of those issues [18–20]. As a result, grid operators can benefit from the presence of energy storage in PV systems. However, the option for installing energy storage in residential PV systems is usually determined by the homeowners. From the consumer's viewpoints, this option will largely be influenced by the cost benefits. Therefore, the decision made by PV homeowners can potentially affect the electrical network stability. The inclusion of energy storage in PV systems can increase the total cost of the systems while reducing the likelihood of network instability. On the other hand, the electrical network will be more likely to experience network instability in the event of high PV penetration from PV systems without energy storage. Ultimately, the actual benefit of energy storage involves interrelated parties and needs to be studied based on specific locations with local electricity price and energy policy.

The effects of PV generation will be examined from both the consumers' and the grid operators' perspectives in this paper. A case study with 12 different locations in Utah will be considered. This study incorporates the effective levelized cost of electricity (LCOE) as a metric to quantify the long-term benefit for PV homeowners with and without energy storage. Knowledge of costs and financial benefits to install rooftop PV systems and energy storage can assist the consumers with the decision making. Three different selling scenarios (net metering, wholesale pricing, and no payback) for the excess PV energy produced are used. Comparing different policy options is useful for analyzing the pros and cons of each policy, as demonstrated in Table 1.

The results from PV and energy storage investments introduce different effective prices for electricity, which will be compared to the price of electricity from the local utility. Additionally, grid operators can identify potential problems with the electrical networks due to the high penetration of PV generation. Analysis on the effects of PV systems toward the distribution networks will be performed to ensure the stability of the electrical networks. Moreover, the integration of customer-side energy storage into the PV systems will be explored to evaluate its effectiveness of minimizing voltage rises to the grid.

2. Methodology

2.1. Costs of electricity generation from PV systems

A thermoeconomic analysis needs to be established to evaluate the economic benefits of electricity generation from PV systems. Generating electricity with rooftop solar PV systems requires several components. Solar PV panels and inverter (DC to AC) are the two main components, whereas energy storage is an optional add-on to the system. The capital costs of installing a solar PV system consist of the cost of solar PV panels, inverter, energy storage (optional), and miscellaneous costs. The miscellaneous costs include site permitting, labor cost, site preparation, wiring, and start up cost.

The residential PV systems can be scaled to meet the location-based electricity demand of residential units. The methodology for sizing the PV systems in this study is based on guidelines for sizing residential rooftop PV systems [21,22]. The calculation for sizing PV systems takes into consideration system latitude, average daily sunlight hours, module type, and array type. The residential daily average electricity usage in kWh is obtained from the residential hourly load database, which is maintained by the U.S. Department of Energy [23]. The

Table 1
Selling scenarios considered for excess PV electricity production.

Selling scenario	Homeowner impacts	Grid operator impacts
Net metering	Credit received for electricity produced that can be used for electricity purchased at another time at the retail rate.	Grid system acts as storage on behalf of the homeowner.
Wholesale pricing	Compensation received for electricity produced at the current wholesale rate.	Grid purchases additional non-dispatchable generation at times of excess PV production.
No payback	Homeowner receives no credit, compensation, or penalty for exporting electricity to the grid.	Grid receives additional non-dispatchable generation at times of excess PV production.