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Optimal sizing of a nonutility-scale solar power system and its battery storage

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HIGHLIGHTS

- Optimal number of solar panels and battery units is determined.
- A stochastic mixed integer program is proposed for this purpose.
- Load, solar radiation, and grid price of electricity are treated as random variables.
- The approach is suitable for residential and industrial customers.
- Different models for net metering and no net metering situation are proposed.

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ABSTRACT

We propose a stochastic mixed integer optimization model to optimally size a solar power system and its battery storage for residential and nonresidential customers of electric power. The objective function of the model is to minimize the total cost associated with solar power system investments and the grid provided electric power over a planning horizon. We consider the uncertainty associated with solar radiation, load, and electricity price in the form of probabilistic scenarios. The model can be used with different grid pricing programs and under no net metering or net metering programs, respectively. A numerical example and its parametric analyses are used to demonstrate the efficacy of the model and develop some insights into optimal sizing of a battery storage enabled solar system. The analyses show the size of the solar system is influenced by the labor cost and the load size whereas the size of the battery storage is sensitive to the load size and the battery cost. Moreover, we find the optimal number of solar panels/batteries is larger under the net metering program than under no net metering program.

1. Introduction

Solar power harvesting is on the rise because it is abundant, has a low carbon footprint, and the cost of converting it to electrical power is declining. The Solar Energy Industries Association (SEIA) in its Q4 2017 Solar Market Insight report indicated that the United States (U.S.) installed 5223 MWdc of solar power in 2016 and this represented an increment of 59.8% in the installations with respect to 2015 [1]. The installations are done at two scales, utility and nonutility scales. The U.S. Energy Information Administration (EIA) [2] defines a utility-scale solar system as a system that supplies more than 1 MW of renewable energy directly into the electric grid whereas a nonutility-scale solar system supplies less than 1 MW. Furthermore, the nonutility-scale solar installations are categorized as residential (typically less than 25 kW) and nonresidential (i.e., commercial and industrial). The SEIA's report also indicates the nonutility-scale installations represented 49.14% of the installed capacity in the third quarter of 2017, resulting in 481 MWdc installed at nonresidential-scale and 517 MWdc at residential-scale.

The cost of installing a solar power system has declined by over 60% over the last decade, primarily due to the decline in the cost of solar panels [3]. The decline in solar panel cost has made the harvesting of solar power cost effective for nonutility installations. In addition, advances in battery technologies are accelerating the decline in the cost of storage batteries, and thus their residential installations. It is estimated that 20% of the U.S. energy storage deployments in 2016 (44.2 MW) were done by behind-the-meter customers, and this percentage is expected to grow to 53% by 2022 [4]. This trend makes the addition of storage to solar energy systems very appealing.

Photovoltaic cells, or solar cells, are responsible for harvesting and

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Nomenclature

Indices

t time index in hours
ω joint scenario index
(t,ω) time period t under the scenario ω index

Solar panel parameters

f_{PV} the discounted fixed cost of the balance of system for a solar subsystem installation in $
c_{PV} discounted cost of a solar panel in $/panel
c_{PV}^{L} discounted cost of labor for installing a solar panel in $/panel
$P_{PV,max}$ maximum power rating of a solar panel in kW
η_{PV} solar efficiency of a solar panel in %
A_{PV} area of a solar panel in m^2

Battery storage parameters

c_B discounted cost of a battery unit in $/unit
β_B storage capacity of the battery unit in kWh
P_{Br} nominal power rating of the battery unit in kW
DoD_B depth of discharge of the battery unit in %
α_B $=(1-(DoD_B/100))\beta_B$. Storage capacity of the battery unit at its depth of discharge in kWh

Model parameters

T planning horizon
$c(t,\omega_c)$ the average cost of electricity during time period t under scenario ω_c in $/kWh
$\pi(t,\omega_c)$ the probability of the scenario ω_c during time period t
$s(t,\omega_s)$ electricity retail price during time period t under scenario ω_s in $/kWh
$\pi(t,\omega_s)$ the probability of the scenario ω_s during time period t
$P_L(t,\omega_L)$ the load during time period t of the scenario ω_L in kW
$\pi(t,\omega_L)$ the probability of the scenario ω_L during time period t.
$\alpha(t,\omega_{PV})$ solar radiation during time period t of the scenario ω_{PV} in W/m^2
$\pi(t,\omega_{PV})$ the probability of the scenario ω_{PV} during time period t
$P_{PV}(t,\omega_{PV})=\eta_{PV}\cdot A_{PV}\cdot\alpha(t,\omega_{PV})/100$. Output of a solar panel during time period t under scenario ω_{PV} in kW
A available area for installing solar panels that has exposure to solar irradiation in m^2
$x_{PV,space}$ $=A/A_{PV}$. The maximum number of solar panels that could be installed on available space
UP_{max} maximum capacity of solar subsystem in kW
p^I initial state-of-charge of a battery in kW
M a large positive number

Model variables

$P_G(t,\omega)$ the amount of power purchased from the grid in kW
$P_{PV,G}(t,\omega)$ the power harvested by the solar subsystem that is sold to the grid in kW
$P_{PV,L}(t,\omega)$ the power harvested by the solar subsystem that is directly consumed by the load in kW
$P_{PV,B}(t,\omega)$ the power harvested by the solar subsystem that is stored by the battery system in kW
$P_B(t,\omega)$ the state-of-charge of the battery subsystem in kW
$P_{B,L}(t,\omega)$ the power stored in the battery subsystem that is consumed by the load in kW
$z(t,\omega)$ binary variable indicating if power is charged to $(z(t,\omega)=1)$ or discharged from $(z(t,\omega)=0)$ the battery subsystem
y_{PV} binary variable indicating if the solar system is installed $(y_{PV}=1)$ or not $(y_{PV}=0)$
x_{PV} integer variable indicating the number of solar panels to be installed
x_B integer variable indicating the number of battery units to be installed

converting solar energy to electrical power. A group of solar cells are connected together to form an array that is encapsulated into a panel. A solar power system consists of a number of solar panels and additional components that collectively are referred to as the *balance of system* (BoS) [5]. Components of the BoS depend on the specific installation and generally consist of power conditioning devices, inverters, wiring, installation hardware, and, possibly, electrical storage. Because of the intermittency of solar power, solar-generated electrical power is not dispatchable unless it is integrated with a storage system.

Installing residential-scale systems with battery storage has the potential of reducing consumers' cost of energy by making them impervious to the fluctuation of electricity prices and the intermittency of solar energy. In addition, installing batteries throughout a distribution network improves power stability by preventing large voltage and frequency swings at the distribution network substation [6].

Therefore, the economic motivation for a residential or a commercial/industrial customer to install a solar energy system with battery storage is to reduce the cost of grid-provided energy [7–9] and possibly to generate revenue by selling its surplus power to the grid [10–12] when net metering is offered. Net metering is a program that allows nonutility customers who generate their own electricity from a rooftop solar energy system to feed unused electricity back into the grid operated by a utility company [13]. The program compensates customers for their excess generation either at the full electricity retail rate or at some amount less than the full retail rate; the maximum level of compensation and the rate vary by location depending on the state and local policies [14].

The academic literature on optimal sizing of a nonutility solar energy installation is relatively scant. Most of the optimal sizing papers address large utility-scale and/or hybrid (wind- and diesel-generator-based) solar energy installations (e.g., [15–19]). Some of the published papers addressing non-industry-scale solar power system sizing are described below.

The heuristic algorithm proposed in [7] determines upper and lower boundaries of the size of a battery storage system while minimizing the consumer's energy and storage costs. The lower boundary is the capacity required to satisfy the load when there is insufficient harvested power and the load is forced to shave its consumption. The upper boundary is the necessary capacity for storing a surplus of harvested power and the load shaving requirements. The two-layer heuristic procedure in [10] is primarily concerned with the dynamic management of the battery charge and discharge cycles. In the first layer, the best state-of-the-charge management of the battery is determined; and in the second layer, the best battery size is identified.

The iterative procedure in [11] determines the optimum battery capacity of a grid-connected solar power system by considering three operation strategies that comply with the regulations of Sweden's electricity market. The goal of the strategies is to benefit a user economically by supplying its own consumption, selling the solar battery system's power surplus to the grid, and shaving the peak load of the system. The deterministic optimization model in [8] determines the size of a solar power system with battery storage while minimizing the energy cost over a planning horizon. The optimum size of the solar and