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Advantages of operation flexibility and load sizing for PV-powered system design

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ABSTRACT

With their autonomous operation and low environmental impact, solar photovoltaics (PV) are an attractive power source for off-grid systems. However, the variable nature of solar energy is not well-suited to power conventional loads. Without careful consideration of the time-dependent power generation of PV, this discrepancy results in systems that are either over-designed and expensive, or compromise reliability. To accelerate the adoption of PV into new areas, it is essential to design PV-powered systems that are persistent, predictable, and affordable. In this paper, we analyze the cost reductions enabled by design optimization through time-flexible operation and improved load sizing. We consider two cases: (i) an idealized reference system, operating 8 h per day at 1 kW, generating an unspecified accumulable output, and (ii) a village-scale PV-powered electrodialysis desalination system, designed to generate 10 m^3 of drinking water per day. We found that time-flexible load operation reduced the power system cost of the idealized reference system by 39%, from $2662 to $1628, and designing its electrical load to operate for an optimal period of time enabled an additional cost reduction of 5% (to $1503). For the village-based desalination system, we found that flexible operation paired with expected large decreases in membrane cost (from $150 to $20 per unit) reduced the associated power system cost by 57.6% from $8935 to $3788.

1. Introduction

Solar photovoltaics (PV) represent an autonomous and environmentally benign power source for off-grid systems. PV module prices have declined by a factor of 10 during the last decade, enabling their use in new markets (Haegel et al., 2017; pvinsights.com, 2017). However, adapting existing systems to PV power is not always straightforward. While conventional energy sources and grid electricity are dispatchable and non-variable, PV is naturally variable (Gowrisankaran et al., 2016). An electrical load designed to operate on a continuous conventional energy source requires adaptation to operate with a variable PV power source. A storage medium can buffer the variability of the PV power source, rendering solar power predictable and persistent (Bermudez, 2017; Nikolaidis et al., 2016). In this paper, we investigate the cost reductions enabled by time-flexible load operation and optimal load sizing in the design of a PV-powered system with energy and product storage.

A key challenge in the field of PV-powered systems is to create systems that are not only sufficiently non-variable, but also simultaneously low-cost and reliable. Inadequate system design yields either excessive cost (over-design) or compromises reliability (under-design) Glavin and Hurley, 2012. PV-powered systems installed in remote locations typically require both low cost and high reliability. Co-design (as opposed to independent, disaggregated design) of the PV subsystem, storage media, and electrical load represents an opportunity for cost reduction and technological innovation (Sahraei et al., 2017). Cost reductions through system optimization are essential to accelerate PV-powered system adoption in low-income, remote environments (Chaurey and Kandpal, 2010; Karakaya and Sriwannawit, 2015).

In this work, we demonstrate how time-flexible system operation—as opposed to continuous, non-variable operation— and load sizing can be implemented in off-grid PV powered systems, and how these strategies reduce the overall system cost by accommodating for the natural time-variance of available PV power (Denholm and Margolis, 2007). Here, the term "flexible operation" refers to process insensitivity to operating schedule, while "optimal load sizing" is the ability to scale the load power to approach the cost-optimum average operating time of the system. We demonstrate that systems, such as

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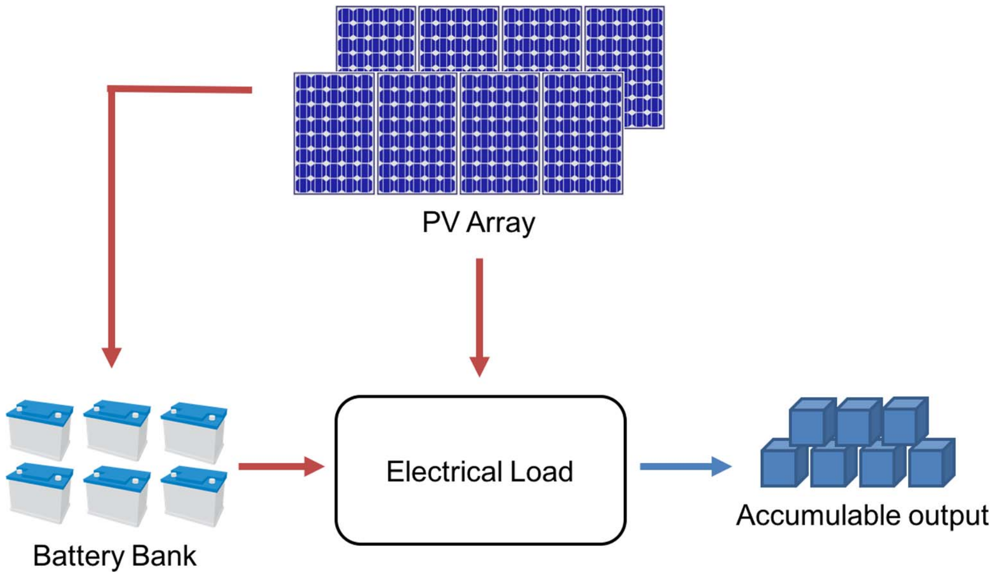

Fig. 1. The idealized reference system consisting of a 1 kW electrical load producing an accumulable output from 8 am to 4 pm daily; a PV array; and a battery bank. The PV array powers the load directly and charges the battery with excess power while the sun is shining. During times of low sunlight, the batteries power the load.

desalination or water pumping (EPRI, 2000), can accommodate some degree of time variance in operation without compromising critical performance by producing the correct amount of product averaged over a long amount of time, despite daily product variations. System cost is reduced by a decrease in the required storage capacity and PV array size. We also explore the cost reductions enabled by flexible load sizing—designing the load to operate at different power levels that complete the desired task over a corresponding duration, to accommodate for the diurnal and variable nature of solar energy.

We consider an idealized, reference system comprising a PV array, a battery bank, and a 1 kW electrical load producing an accumulable, storable output while operating 8 h per day from 8 am to 4 pm (Fig. 1). The PV array supplies power to the electrical load and the battery bank depending on the demands of each and the solar power available.

We then assess an actual prototype PV-powered electrodialysis reversal (PV-EDR) desalination system located near Hyderabad, India. We demonstrate how flexible operation and load sizing learnings can be incorporated into a system-design framework, to help accelerate the adoption of PV power across a wide range of applications. With a further adoption of PV, quality of life in remote areas can be improved, and the worst effects of climate change mitigated (Berney Needleman et al., 2016).

Previous work in the field of PV system optimization has focused on optimal power system sizing through simulation of electrical loads, power management, and PV power generation (Guo et al., 2015). Cost-optimized PV power systems for off-grid water pumping have been studied and tested, but have not analyzed the effects of flexible operation and load sizing (Olcan, 2015; Muhsen et al., 2016). Other work has focused on the optimization of off-grid reverse osmosis (RO) desalination systems powered by multiple energy sources (Bilton and Kelley, 2015; Habib et al., 2015). Sizing and scheduling multiple electrical loads in a microgrid setting to maximize solar energy utilization has also been studied (Habib et al., 2017; Jaramillo and Weidlich, 2016). The effect of temporal resolution on the sizing of an optimized PV-battery system has also been investigated previously (Beck et al., 2016).

2. Methods

2.1. Energy analysis

We used semi-empirical, satellite-based solar irradiance and temperature data from NSRDB (Renewable Energy Laboratory, 2016) for the region of Chelluru, India, from 2014, the most recent year in which this data was available. This location was chosen because the PV-EDR case study system was constructed there. The calculations presented here used historical meteorological data for one year. Specifically, the meteorological data was used to establish the threshold for which the output generation in the system is turned on and off. While we do not expect this threshold to change much, time series spanning several years would help establishing variations in threshold or product output, and improve the predictability of the process. Furthermore, longer time series could help establish how the system is affected by a changing climate (for example, longer droughts). Alternatively, results could be compared to those obtained using a typical meteorological year (Bian et al., in preparation), provided that data is available.

The temperature-corrected efficiency of the solar panels at each time interval, η_{PV}, was calculated using (Brihmat and Mekhtoub, 2014),

$$\eta_{\text{PV}}(t) = \eta_{\text{PV,nom}}\cdot(1+\alpha_{\text{p}}\cdot(T_{\text{amb}}(t)+k\cdot GHI(t)-T_{\text{std}})), \tag{1}$$

where $\eta_{\text{PV,nom}}$ is the nominal efficiency of the panels (15%), α_{p} is the temperature coefficient ($\alpha_p = -0.42\%$ Suniva Optimus Series Monocrystalline Solar Modules, 2016), $T_{\text{amb}}(t)$ is the ambient temperature, k is the Ross coefficient, which relates irradiance to module temperature ($k = 0.025$ Pearsall, 2017), GHI (t) is the global horizontal irradiance, and T_{std} is the standard testing temperature (25 Celsius). The power produced by one square meter of solar panels, $P_{\text{PV,1m}}$, was calculated by multiplying the instantaneous PV efficiency, η_{PV}, by the instantaneous global horizontal irradiance GHI (t). The PV array power output, P_{PV}, is simply the product of $P_{\text{PV,1m}}$ and the area of the PV array, A_{PV}.

The total energy stored in the battery bank E_{stored} was calculated via

$$E_{\text{stored}}(t) = E_{\text{stored}}(t-1) + t_{\text{int}}*\left(P_{\text{PV}}(t)-\frac{P_{\text{load}}(t)}{\eta_{\text{conv}}}\right)*\eta_{\text{batt}}, \tag{2}$$

during charging, and via

$$E_{\text{stored}}(t) = E_{\text{stored}}(t-1)-t_{\text{int}}*\left(\frac{P_{\text{load}}(t)}{\eta_{\text{conv}}}-P_{\text{PV}}(t)\right), \tag{3}$$

during discharging (Borowy and Salameh, 1996). Here, t_{int} is the interval length in seconds (300 s in this analysis), P_{PV} is the power being produced by the PV array, P_{load} is the power being consumed by the load, η_{conv} is the efficiency of the DC power converter (95%), and η_{batt} is the battery charge/discharge efficiency (85%) Linden and Reddy, 2002. Temperature effects were not considered in the battery operation because the battery banks for the reference and PV-EDR systems are