Renewable and Sustainable Energy Reviews 76 (2017) 1153–1162

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

Environment-adjusted operational performance evaluation of solar photovoltaic power plants: A three stage efficiency analysis

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ARTICLE INFO

Keywords:
Solar PV power plants
Environmental factors
Data envelopment analysis
Slacks
Stochastic frontier analysis

ABSTRACT

There is widespread concern that environmental factor may not be playing a pivotal role in influencing the generation performance of solar photovoltaic (PV) plants. The aim of this paper is to provide a fair and impartial operational performance evaluation of solar PV power plants taking into account of the impacts of environmental factors from real field data. Stochastic frontier analysis (SFA) is used to attribute the impacts of environmental factors (temperature, cloud amount, elevation, wind speed and precipitation) on inputs (like insolation and daylight hours) of solar PV power plants; while data envelopment analysis (DEA) is used to compute the environment-adjusted operational efficiency of these plants. SFA is utilized in the adjustment process for its merit of separating statistical noise from the error term, and DEA is used for its advantage of capturing the interaction among multiple inputs and outputs in a scalar value. The empirical analysis shows that the average operational efficiency of 70 grid-connected solar PV power plants in the United States slightly declines after accounting the impacts of environmental factors and statistical noise. Finally, the results partially support the initial concern from the statistical perspective and temperature is found to be the most significant influencing environmental factor, while precipitation and wind speed show no significant influence on operational efficiency. Therefore, the necessity of accounting for the impacts of environmental factors in the performance evaluation of solar PV power plants should not be omitted.

1. Introduction

Facing with energy poverty, energy security and increasing concern over climate change, there is a growing consensus that low-carbon economy is our inevitable choice. Solar energy has been favored by a lot of countries because of its characteristics like inexhaustible, environmental friendly, no noise, and low maintenance cost. Since 2010, the world has added more solar photovoltaic (PV) capacity than in the previous four decades. As for the United States, the leading promoter of new energy, solar PV power has been growing at high rates over the past few years, owing to cost reductions in the production of PV modules and PV technology development which solved intermittency problem. In 2014, the U.S. solar industry reached the 20 gigawatt milestone, generating enough electrical capacity to power more than 4 million American homes.

The large-scale deployment of solar PV installations has inspired more research interest in efficiency improvement of solar PV systems. Many researchers have reviewed technology progress in solar PV system to enhance the quality and operational performance of solar PV system [1–5]. Also, there are several researches and reviews on discussing the possible approaches to improve solar PV system efficiency. For example, McColl et al. [6] compared how thermal management like sun-tracking or water cooling affect the performance of solar PV modules [6]. Effects of various cooling techniques like natural and forced air cooling, hydraulic cooling, heat pipe cooling, cooling with phase change materials and thermoelectric cooling of PV panels were compared and discussed [7]. Irwan et al. [8] showed the effect of water cooling on the efficiency of PV panel through experiment. The effects of nanofluids on the performance of solar collector and the efficiency of solar system have been examined in [9]. Different solar PV maximum power point tracking techniques have been comprehensively reviewed in [10].

Apart from continuous technology improvement, generation performance is usually improved through selecting benchmarks for better

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http://dx.doi.org/10.1016/j.rser.2017.03.119
Received 12 August 2016; Received in revised form 24 December 2016; Accepted 25 March 2017
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managerial cases. However, there are various uncontrollable environmental factors that affect the electricity generation of a PV power plant. Critical environmental factors that affect the generation and operation of the entire PV system have also been studied, including factors like temperature, solar irradiance, elevation, precipitation and soiling [11]. It is necessary to take the environmental factors into account so that people could have a realistic expectation of overall operational efficiency of solar PV power plant. Operational efficiency hereby means the relative generation performance of solar PV power plants, with the impacts of environmental factors controlled. The aim of this paper is to use a quantitative approach to facilitate benchmark selection and efficiency comparisons of solar PV power plants before and after controlling the impacts of environmental factors and statistical noise.

This paper is organized as follows: Section 2.1 provides a review on the environmental factors and ambient conditions affecting the generation performance of solar PV power plants. Section 2.2 reviews the traditional Data Envelopment Analysis (DEA) based performance evaluation on solar plants without considering the impacts of environmental factors. Section 2.3 reviews the evolution of performance evaluation methods accounting for the impacts of environmental factors. The research gap of environment-adjusted operational performance evaluation of solar PV power plants is identified. Section 3 presents the multi-stage efficiency analysis approach used in this paper for environmental-adjusted performance evaluation. An empirical analysis of operational performance evaluation of the U.S. solar PV power plants is provided in Section 4. Section 5 concludes the paper.

2. Literature review

2.1. Effects of environmental factors on the performance of solar PV system

This section reviews the eight major environmental factors that affect the performance of solar PV system in existing literatures.

2.1.1. Temperature

Apart from the impacts of total solar irradiance, incidence angle of the incident solar radiation and air mass, which affect the reception of solar insolation, PV temperature is the most important factor that affects PV efficiency [12]. Dinçer and Meral [13] examined that solar cells tend to produce higher voltage as the temperature drops, resulting in higher solar cell efficiency. With the temperature increases, the band gap of intrinsic semiconductor shrinks and the open circuit voltage decreases, resulting in more absorbed incident energy. Skoplaki et al. [14] briefly discussed the correlation between the operating temperature of PV modules and other variables including, e.g., solar radiation flux, back-side cell temperature, ambient temperature and wind speed. McColl et al. [6] compared how thermal management like sun-tracking or water cooling affected the performance of solar PV modules. García-Domingo et al. [15] found that increment of ambient temperature exerted a negative effect on the performance of concentrated PV module. As insolation and conversion efficiency is expressed as a function of module temperature, Nishioka et al. [16] found that the conversion efficiency decreases with a rise of the module temperature. They also concluded that PV system conversion efficiency decreases faster when the module temperature exceeds 25 °C. Experiment found that water cooling can decrease the operating temperature by 5 °C to 23 °C and increase the generation by 9–22% [8].

2.1.2. Solar irradiance

The research of García-Domingo et al. [15] showed that direct normal irradiance has a major role in affecting the performance of concentrated PV module. Through an indoor lab experiment, Jiang et al. [17] found that the relationship between solar density and generation efficiency is inverse U-shaped when keeping dust density fixed, with generation efficiency reached its highest value at medium level of solar intensity. Similarly, an inverse U-shaped curve is identified between generation efficiency and total solar irradiance in outdoor conditions [12].

2.1.3. Elevation

Raja [18] asserted that insolation becomes tenser with elevation increases, because of lower air pressure, shorter path through the atmosphere, and the decreasing concentration of unmixed gases and aerosols. Gökmen et al. [19] noted that places, like hills and mountains, with high elevation should pay special attention to the cooling effect of wind. However, the experiment data of Elkhatib et al. [20] on rooftops between 200 and 800 feet showed no significant improvement of generation efficiency with increased elevation.

2.1.4. Wind speed

Wind has a cooling effect and can help the ventilation of PV system [15,19,21,22]. Results from Gökmen et al. [19] mathematical model and experimental case study showed that wind speed can greatly affect the operating performance of a PV system, especially in windy locations [15,19]. Conversion efficiency in windy location increased up to 18% compared with windless location in the study of Obara et al. [22]. However, Gaglia et al. [12] claimed that the positive cooling effect of wind speed is relatively small comparing to the negative effect of temperature and solar insolation on PV efficiency.

2.1.5. Soiling

Dust accumulation, which is always depicted by soiling ratio, is a vital factor influencing the performance of PV system as it blocks the insolation transmitted through the PV module and thus the solar energy converted by the modules [17,23]. Indoor experiment of Jiang et al. [17] showed that dust accumulation has a negative linear relationship with generation efficiency. Outdoor experiment of Paudyal et al. [24] found that the high dust concentration at bottom could result in hot spot and ultimately permanent module damage. Adinoyi et al. [25] studied the performances of PV modules exposed to outdoor conditions and concluded that the decrease in electricity generation is the result of dust frequency and intensity. Trackers and more frequent cleaning schedules can help to improve generation efficiency in dusty conditions. Cleaning is recommended immediately after dust period, with running water and use of a sponge [26]. Micheli et al. [27] analyzed the data from six soiling station and found good correlation between the soiling ratio and particular matter. Linear correlation was also found between reduction of PV module efficiency and dust density [28]. Researches have also investigated how different physical properties of soiling affect the performance of PV modules [29–32].

2.1.6. Precipitation

Adinoyi et al. [25] testified that precipitation improves the generation of solar PV modules in dusty areas, but cannot be relied upon for cleaning. On the contrary, Kalogirou et al. [26] concluded that the occasion rain during winter is enough to keep panels clean. Micheli et al. [27] observed that precipitation raise the soiling ratio after a long dry season or a dusty period. In particular, soiling ratio is more correlated with frequency of rain than the amount of precipitation.

2.1.7. Latitude

Latitude controls the duration of daylight and the path oblique rays travelled from the sun. High-latitude regions usually have lower levels of sunshine and low-latitude regions have higher levels [18].

2.1.8. Clouds

Kankiewicz et al. [33] observed the impact of passage of clouds on the performance of a utility-scale solar PV power plant (25 MW DeSoto Next Generation Solar Energy), and found that the fluctuations in generation were dampened as PV modules were grouped together.

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