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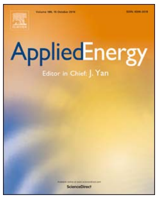

Vertical bifacial solar farms: Physics, design, and global optimization

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HIGHLIGHTS

- Efficient insolation model combining meteorological data and clear-sky model.
- Non-uniform illumination on panels from direct, diffused, and albedo light.
- Non-uniform illumination combined with circuit model to find hourly energy-output.
- Global, location specific optimization and output of vertical bifacial solar farm.
- Vertical bifacial outperforms monofacial farm by 10–20% globally (2 m row spacing).

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ABSTRACT

There have been sustained interest in bifacial solar cell technology since 1980s, with prospects of 30–50% increase in the output power from a stand-alone panel. Moreover, a vertical bifacial panel reduces dust accumulation and provides two output peaks during the day, with the second peak aligned to the peak electricity demand. Recent commercialization and anticipated growth of bifacial panel market have encouraged a closer scrutiny of the integrated power-output and economic viability of bifacial solar farms, where mutual shading will erode some of the anticipated energy gain associated with an isolated, single panel. Towards that goal, in this paper we focus on geography-specific optimization of *ground-mounted vertical bifacial solar farms for the entire world.* For local irradiance, we combine the measured meteorological data with the clear-sky model. In addition, we consider the effects of direct, diffuse, and albedo light. We assume the panel is configured into sub-strings with bypass-diodes. Based on calculated light collection and panel output, we analyze the optimum farm design for maximum yearly output at any given location in the world. Our results predict that, regardless of the geographical location, a vertical bifacial farm will yield 10–20% more energy than a traditional monofacial farm for a practical row-spacing of 2 m (corresponding to 1.2 m high panels). With the prospect of additional 5–20% energy gain from reduced soiling and tilt optimization, bifacial solar farm do offer a viable technology option for large-scale solar energy generation.

1. Introduction

A conventional monofacial panel collects light only from the front side; the opaque back-sheet prevents collection of light scattered from ground (or surroundings) onto the back face of these panels. This extra energy from albedo can be partially recovered using a bifacial panel, where both faces of the panel and the cells are optically transparent. The concept of bifacial panels have been analyzed and experimentally demonstrated since 1980s [1,2]. Indeed, an isolated bifacial panel has been shown to have up to 50% extra output [2] compared to a monofacial panel. Moreover, recent improvements in the design and fabrication of bifacial cell technology suggest several additional advantages [3]. For example, bifacial cells have a lower operating temperature (due to the absence of infrared absorption at the back metal) and better temperature coefficient (e.g., as in the passivated-contact HIT cells [4]). These characteristic features improve lifetime and integrated power output.

Several studies in the literature have reported energy output of isolated, *standalone* bifacial panels both numerically [5–8] and experimentally [9–11]. These studies include optimization of the tilt angle and elevation from ground for a single bifacial panel at various locations in the world. The recent work by Guo et al. [12] provides a global

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analysis of vertical bifacial panel. Given an albedo threshold, they have shown that an isolated vertical panel will always produce more power compared to an optimally tilted monofacial panel, irrespective of the geographic location.

The energy gain of an isolated panel defines the upper limit of the performance potential of a solar cell technology. Eventually, the panels will have to be installed in a farm, where one must account for the mutual shading of the panels. Clearly, the area-averaged power output will now be reduced. Under these circumstances, it is not clear if the advantages found for isolated panels can still sustain. Recently, Appelbaum [13] has provided a partial answer by analyzing a solar farm at Tel-Aviv (latitude 32°N). His work focused on vertically vs. optimally tilted bifacial panel arrays. The optimally tilted farm yields 32% more energy than the vertical farm (in latitude 32°N)—however, it is not clear how the outputs compare to the monofacial panel array. It is also difficult to know if the conclusions apply to other regions of the world. An analysis that broadens the previous work to all the locations of the world (a global optimization) will be helpful. This analysis is particularly important because ITRPV roadmap projects that the bifacial market share will increase from 5% in 2016 to 30% in 2026 [14]. Many PV manufacturers (e.g., Panasonic, Prism Solar, LG, SolarWorld, Centrotherm, etc.) are now producing bifacial panels. A few recent solar farms (e.g., Asahikawa Hokuto Solar Power Plant in Japan, and La Silla PV plant in Chile) are utilizing bifacial panels. Given this rapid progress, it is important to clearly understand the complex physics, design, and optimization of bifacial solar farms.

Among various farm configurations, vertically aligned bifacial panels have been of particular interest because of reduced soiling (dirt or snow) which increases overall energy output. In addition, the higher output in the afternoon due to the ‘double-humped’ daily output profile [12] coincide with the peak electricity demand. Since optimally tilted bifacial panels will always produce slightly more energy compared to the vertical farms, the analysis of vertically aligned panels may be viewed as a lower limit of energy produced by an optimized bifacial farm.

In this paper, we offer detailed model, physics, and a worldwide perspective regarding ground-mounted vertical bifacial solar farms. We combine the global meteorological data from NASA with the clear-sky model from Sandia to estimate hourly insolation. This new algorithm bypasses the loading of extremely large hourly database, and allows efficient computation towards global analysis of new technologies while maintaining realistic and daily averaged meteorological information.

Next, we model the direct and diffused light collection [15–17], as well as the non-trivial physics of albedo light collection [18,8] while accounting for relevant shadings on the panels and the ground. Our generalized formulation models the non-uniform illumination along the panel height. Only a fraction of the light incident on the panels will produce electricity [19] because of the spatially non-uniform illumination and the nature of the electrical connection for the panels. The second aspect is often not accounted for in literature. We use the spatially non-uniform light collection data along with the appropriate circuit model of the panels to accurately find the hourly *energy-output* from the panels and the farm.

Mutual shading between adjacent panels penalizes energy-output, thereby restricting panels from being closely packed in the farm. We explain how this results in an optimum period between the panels. At high latitudes, the sun-path is more tilted, resulting in larger optimum panel-period. In addition, at the same latitude, locations with more diffuse insolation tend to have a larger panel-period.

Finally, we present a global perspective on the annual yield of vertical bifacial solar farms. The key conclusion of the paper is this: With inter-row separation of 2 m (typically required for maintenance) for 1.2 m wide panels, a ground-mounted vertical bifacial farm outperforms a traditional monofacial farm by 10–20%, regardless of the geographical location. The gain may persist even for smaller inter-row separation, once the energy loss due to soiling [20–23] is accounted for. The maximum performance gain requires a denser packing of vertical bifacial panels, the implication of which must be accounted for in the levelized cost of electricity (LCOE) calculation [24,25].

In Sections 2.1 and 2.2, we present the details of the irradiance model, and the physical model to calculate the light collection and power generation of the panels and the farm. In Sections 3.1–3.3, we discuss the physics and design-optimization of the farm. Finally, in Section 3.4, we present the global perspective and prospects of the optimally designed vertical bifacial solar farm. Our conclusions are summarized in Section 4.

2. Method

2.1. Irradiance model

2.1.1. Simulation of hourly GHI

Temporal solar irradiance data consist of the position of the sun and its intensity. This information is crucial to simulate and optimize the energy yield of solar farms. To simulate such data, we first start by calculating the position of the sun (solar Zenith θ_Z and Azimuth γ_S angles) at arbitrary time and geographic locations by using the NREL's solar position algorithm [26] implemented in Sandia model library [27]. Here, θ_Z is the refraction-corrected Zenith angle, which depends on altitude and ambient temperature. Second, we input the sun position data into the Haurwitz clear sky model to generate the Global Horizontal Irradiance (GHI or I_{GHI}) [28,29] on a minute-to-minute basis. Note that the clear sky model often overestimates insolation, especially when the atmosphere is cloudy or overcast. Hence, in the third and final step, we integrate the simulated GHI over time, which is then scaled to match the satellite-derived monthly average GHI data (for 22 years) from the NASA Surface meteorology and Solar Energy database [30], whereby local variation of GHI caused by cloudiness and altitude is incorporated into the calculation. Therefore, our modeling framework fully incorporates the impacts of geographic and climatic factors to model the location-specific solar irradiance.

2.1.2. Decomposition of GHI into DHI and DNI

Calculating the irradiance on a tilted surface requires decomposing GHI into two components: Direct Normal Irradiance (DNI or I_b) and Diffuse Horizontal Irradiance (DHI or I_{diff}). The relationship between the two components can be written as

$$I_{GHI} = I_b \cos\theta_Z + I_{diff}. \tag{1}$$

Based on (1), however, it is impossible to separate I_b and I_{diff} from I_{GHI}. Therefore, we estimate the diffuse fraction of I_{GHI} using the Orgill and Hollands model which empirically calculates the diffuse fraction using the clearness index of the sky (k_T) [31]. The clearness index is defined as the ratio between I_{GHI} and extraterrestrial irradiance (I_0) on a horizontal surface, i.e.,

$$k_T = \frac{I_{GHI}}{I_0 \times \cos\theta_Z}. \tag{2}$$

For a specific time and location, I_{GHI} is already known while the extraterrestrial irradiance can be evaluated analytically [32]; therefore, we can obtain the clearness index k_T on a minute-to-minute basis using (2). Knowing I_{GHI} and k_T, we use the Orgill and Hollands model to determine I_{diff}, which allows us to deduce I_b from (1). An illustrative calculation of irradiance at Washington DC on September 22 is shown in Fig. 2.

There are several empirical models for decomposing GHI found in literature [33–35]. Generally, good agreement have been found among these models [36]. Also, we assume isotropic sky model [37] for diffuse irradiance I_{diff}. The Perez model [38] provides a more elaborate and somewhat more complex representation of the diffuse light. However, we expect that our numerical results will not be overly sensitive to the