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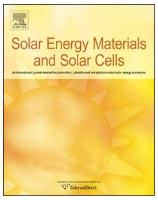

Influence of photovoltaic angle-dependence on overall power output for fixed building integrated configurations

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ABSTRACT

Building integrated photovoltaic (BIPV) systems are an emerging approach to reduce installation costs while supplementing building energy needs. However, the physical constraints of the building architecture often prevent photovoltaic systems from being installed at their optimal orientation. Recently, it was shown that thin film photovoltaics can be designed for improved angle-dependent responsivity at specific angles. In this study, the complex impact of angular dependency on overall power output is explored based on detailed hourly solar position, location, and flux data. These results demonstrate that reducing the angular roll-off dependence can enhance overall power outputs by 30% or more in fixed orientation configurations depending on the geographical location, orientation, and angle-dependent roll-off characteristics.

1. Introduction

Building integrated photovoltaics (BIPVs) have received considerable attention due to their sustainable attributes and functional value [1–3]. A typical BIPV application, for example, is the use of silicon-based or copper indium gallium selenide photovoltaics (PVs) on rooftops and shingles. A significant number of studies have been conducted to identify the optimal tilt angle and orientation to obtain longer periods of near-normal incident illuminated sunlight [4,5]. However, considering the trajectory of the sun, these deployed solar cells are rarely illuminated at normal incidence. In addition, the high cost of rotational mounting systems and environmental considerations (wind, snow, etc.) have primarily limited practical designs to fixed configurations, and many synergistic BIPV approaches (such as solar shingles) are already necessarily in fixed configurations. Hence, it is critical to design PVs that give stable performance over a range of incident angles.

In comparison to traditional silicon-based PV applications, thin film and organic photovoltaic technologies have increased their market share due to their potential for light weight, flexible, and transparent applications [6]. Importantly, thin film PVs can be designed to have specific angle dependence properties [7–9] with the improvement of external and internal quantum efficiencies [10,11]. Moreover, window integrated solar cells are gaining attention due to the development of transparent photovoltaics (TPVs) which have exceptional low-cost potential and are enabled by new excitonic materials [12,13]. In this case, TPVs can be considered for siding, windows, and skylights, which normally have fixed structures [14]. Recently, TPV designs with enhanced angle-dependence were demonstrated, leading to the improvements in responsivity by as much as 50% at particular oblique angles with nearly identical performance at normal incidence [15–17]; the improvements were achieved by considering and optimizing layer structures for non-normal incidence.

For all of these PV technologies, fixed configuration deployment situations naturally leads to the question: what impact can the designs with minimized angle-dependence have? Here, the overall power output for the TPV designs with different responsivities over varying incidence angle and solar radiation was evaluated to assess the impact of angle-dependent PV efficiency in a range of configurations and locations.

2. Theory and modeling

The global tilted irradiance (I_{GT}), which is needed to estimate the power output from a solar panel, is calculated using the

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Nomenclature

FF	fill factor
I_{DFH}	METSTAT-modeled diffuse horizontal irradiance (kW/m^2)
I_{DFT}	Global tilt irradiance (kW/m^2)
I_{DRN}	METSTAT-modeled direct normal irradiance (kW/m^2)
I_{DRT}	direct tilt irradiance (kW/m^2)
I_{EH}	extraterrestrial horizontal irradiance (kW/m^2)
I_{GH}	METSTAT-modeled global horizontal irradiance (kW/m^2)
I_{GR}	ground reflected irradiance (kW/m^2)
I_{GT}	global tilted irradiance (kW/m^2)
I	input intensity (kW/m^2)
J_{SC}	photocurrent density (A)
METSTAT	meteorological–statistical solar model
Q	yearly power output
R	responsivity (A/W)
V_{OC}	open-circuit voltage (V)
A	Azimuth angle of the PV module (degrees)
B	tilt angle of the PV module (degree)
δ	improvement of yearly power output
η	efficiency of a solar cell
Θ	incidence angle of solar ray to PV modules (degrees)
φ	hourly mean zenith angle of the sun (degrees)
ω	hourly mean azimuth angle of the sun (degrees)

average values of the hourly data of sun position and solar irradiance published in the National Solar Radiation Database over a ten-year period [18,19]. The calculation follows the separation method described in the Hay model [20]:

$$I_{GT} = I_{DRN}\cos\theta + I_{DFT} + I_{GR} \tag{1}$$

and

$$I_{DFT} = I_{DFH}\left[\frac{(I_{GH}-I_{DFH})\cos\theta\cos\varphi}{I_{EH}} + \frac{(1-(I_{GH}-I_{DFH}))(1+\cos\beta)}{2}\right] \tag{2}$$

where I_{DRN} is the direct normal irradiance; I_{DFT} is the diffuse tilted irradiance; I_{GR} is the ground reflected irradiance; I_{GH} is the global horizontal irradiance; I_{GR} is the ground reflected irradiance; I_{DFH} is the diffuse horizontal irradiance; I_{EH} is the extraterrestrial horizontal irradiance; θ is the incident angle of direct solar irradiance with respect to the PV module; φ is the zenith angle of the sun with respect to the horizon; ω is the azimuth angle of the sun with respect to north; β is the tilt angle of the PV module with respect to the horizon; and α is the azimuth angle of the PV module (Fig. 1). The solar irradiance is modeled by the meteorological–statistical solar method (METSTAT) [19]. Here, I_{GR} can be neglected due to the insignificant impact on I_{GT} comparing to the I_{DT} and I_{DFT} [21]. Then, θ is calculated by the following equation:

$$\theta = \cos^{-1}\left(\vec{S}\cdot\vec{M}\right) \tag{3}$$

where $\vec{S} = (\omega, \varphi-90°, 1)$ is the unit vector of incoming radiation, and $\vec{M}$ is the normal vector of the PV module defined in the left-handed spherical coordinate system $(\alpha, \beta, 1)$, which is calculated from a unit vector within the ground plane, $\vec{G} = (\alpha-90°, 0°, 1)$, and a second unit vector perpendicular to $\vec{G}$ within the tilted plane, $\vec{T} = (\alpha+180°, \beta, 1)$, of the PV module as $\vec{M} = \vec{T}\times\vec{G}$.

Hourly instantaneous power output (Q_i) is calculated from the power conversion efficiency of the PV module (η) and the illumination flux (I) by the following equation:

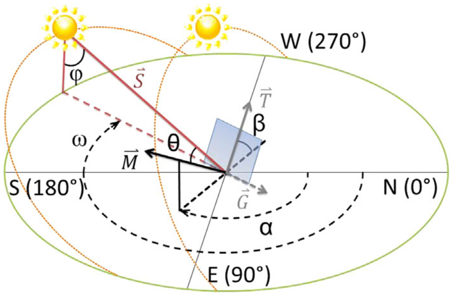

Fig. 1. Schematic showing all angles related to the position of the sun in the northern hemisphere and orientation of the PV module. Note that the dotted lines are in the horizontal plane and the solid lines are out-of-plane for clarification.

$$Q_i(\theta, I) = \eta(\theta, I)I = \left[\mathrm{FF}\,(\theta, I)V_{oc}\,(\theta, I)R(\theta, I)\right]I \tag{4}$$

where R is the responsivity calculated from $R(\theta, I) = J_{sc}(\theta, I)/I$; J_{SC} is the short-circuit photocurrent density; V_{OC} is the open-circuit voltage; and FF is the fill factor.

To determine the effect of θ and I, angular dependency and intensity are assumed to be essentially independent so that

$$\eta(\theta, I) = \eta(\theta, I_{ref})\eta(\theta_{ref}, I) \tag{5}$$

where the reference intensity is 1 mW/mm^2 (1-sun), and the reference incident angle is 0°. While the impact of angular dependency on FF and V_{OC} is typically negligible [13], the intensity dependencies of FF, V_{OC}, and R are nonetheless captured in the intensity dependent component of experimentally determined efficiencies. Therefore, the angle dependent component of η is proportional to the angle dependent R at a fixed I [15].

In the simulation of yearly power output, the average value of responsivity ($\bar{R}$) over 0–90° incident angle is used for the diffuse irradiance components. Then, the yearly power output (Q) is evaluated for a conventional thin film PV (device A), a thin film PV architecture designed with improved angle dependence (device B) [15], and devices with idealized angle-dependent cut-offs shown in Fig. 2 as follows:

$$Q(\theta, I) = \sum_{i=1}^{\tau}\left[(R(\theta, 1)I_{DRN,i} + \bar{R}I_{DFT,i})1\ \mathrm{h}\right] \tag{6}$$

where τ is the number of hours in one year. The yearly power output for A and B were normalized to the power output of device A at $\beta = 0°$, and the yearly power output for the cutoff devices were normalized to the ideal device response at each tilt. The ideal

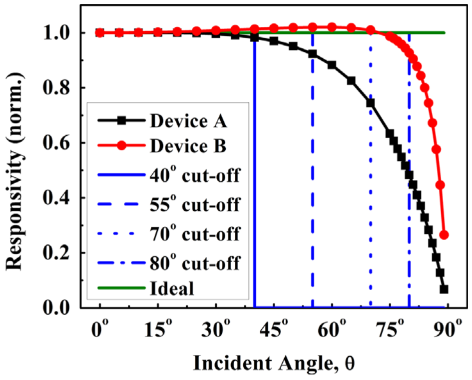

Fig. 2. Normalized angle-dependent responsivity for a conventional thin film PV (device A), thin film PV designed for improved angle-dependence (device B), and selected cutoff angle of angle-dependence designed thin film PVs.