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Performance of a building-integrated photovoltaic/thermal system under frame shadows

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ABSTRACT

Air layer exists between glass covers and cells in most building-integrated photovoltaic/thermal (BIPV/T) systems. This layer significantly reduces heat loss and improves the thermal efficiency of BIPV/T systems. However, the frame border that supports the glass cover casts a shadow over cells near the frame according to the air layer thickness, system orientation and location of the sun, thereby affecting photovoltaic performance. This study aims to find out the effect of such air layer on thermal and photovoltaic performance of BIPV/T systems. The distribution of frame shadows and photovoltaic loss caused by such shadows is analyzed. Then thermal and photovoltaic performance of BIPV/T system with different air layer thicknesses is evaluated. The influences caused by the air layer thickness, orientation of the BIPV/T system, solar altitude, and solar azimuth are analyzed. An approach is presented to evaluate the annual performance of the BIPV/T system. The results show that the frame shadow reduces system photovoltaic efficiency to 2.6% (normal efficiency, 13.0%) in the worst case scenario in Hefei (E117°17′, N31°52′). The maximum annual electrical loss caused by the frame shadow is 70.15 kWh/m^2 at an azimuthal angle of −45°. The quantity of total outputs increases with increasing air thickness. But the maximum comprehensive outputs are 359.95 kWh at 20 mm air thickness.

1. Introduction

Renewable energy sources are increasingly being utilized to meet existing demands, security, and reliability. Solar energy is an advantageous radiation source because of its extensive availability, pollution-free operation, and safety [1–3]. On the other hand, the buildings generally consume a significant amount of energy; therefore studies have focused on building-integrated photovoltaic/thermal (BIPV/T) technology [4–7].

The BIPV/T technology is an application of photovoltaic/thermal (PV/T) technology in building energy saving. The PV/T technology can integrate a PV module and a solar thermal collector in a single system. The PV module coverts solar energy into electrical energy while the thermal collector converts the remaining solar energy into thermal energy and draws out excess heat from the PV module. PV/T system can effectively use solar radiation by simultaneously generating thermal and electrical energy[8]. It produces more energy per unit area at lower cost compared to a PV module and a thermal collector adjacent to each other [9]. The BIPV/T technology combines PV/T system with the outside surface of building. It provide electric and thermal energy for buildings, as well as reduce thermal and cold loads. [10–12]. Tse's economic analysis reflects a desirable potential of BIPV/T technologies under subtropical climate region [13]. Furthermore, an expected lower initial cost because of mass production and competition will lead to an economic viability of the system in areas with less favorable climatic conditions [14]. Although the market is still small compared to PV and photo-thermal markets, but a number of commercial products are now available, and the number of producers and installed systems are growing.

The structure shown in Fig. 1 is a normal structure of BIPV/T system. The structure of BIPV/T systems differs from those of PV and BIPV systems. An air layer exists between the glass cover and cells to reduce the heat loss of the thermal collector and enhance the thermal efficiency. While this same structure is commonly used in BIPV/T systems [15–17], the air layer is detrimental to the PV module because of the frame shadow. When sunlight strikes the

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frame at slanted incidence, the frame casts a shadow over a portion of the cells and reduces their photovoltaic efficiency. Shadow is a significant issue during the application of the BIPV/T technology. A lot of studies have focused on shadows which are normally caused by tree, building, stain spot and so on [18–20]. However, the frame shadow, which is caused by the frame of BIPV/T system, has not been studied before.

Unlike other kinds of shadows, the frame shadow has a regularly form and is hardly to avoid because it is caused by structural characteristics and applied fields of BIPV/T system. Frame shadows occur in both BIPV/T system and common PV/T system. In our previous study, the effect of frame shadows in PV/T system was studied, with results showing that even a small frame shadow can cause a significant decrease in photovoltaic efficiency (39.3% decrease in photoelectric efficiency in the worst case scenario) [21]. Compared with PV/T system, the size and distribution of frame shadow are more significant to BIPV/T system for the following reasons. On one hand, the BIPV/T system is often combined with the building enclosure. So it is difficult to keep the system towards the south like the common PV/T system for the limitation of building enclosure. Thus, larger shadows may be observed at the side edge of the BIPV/T system. Furthermore, most BIPV/T systems are perpendicular to the horizontal plane. Therefore, shadows will appear at top edge of BIPV/T systems, especially at midday during summer, when irradiation levels are highest. This situation does not occur in the common PV/T system. It is convenient for PV/T system to select an optimal inclination angle to avoid top shadow. On the other hand, the frame shadow in BIPV/T system appears during the entire day, and the system is affected by both side and top frame shadows. But the frame shadow in PV/T system, by contrast, mainly appears in the morning and evening, when irradiation is weak and cumulative effects are relatively low. Thus, the effects of frame shadow are more significant on the BIPV/T system than on the PV/T system. Frame shadows and their effects on the annual photovoltaic performance of BIPV/T systems should be analyzed because of their wide distribution, hardly to avoid and continuous influence.

In addition, the air layer thickness, which is equal to the frame height, is the dominant factor to affect the distribution of frame shadow. A thicker air layer means a higher frame height, and the effect of frame shadow on the photovoltaic performance will be more obvious. The air layer thickness also affects thermal performance of the system. There is a trade-off between photovoltaic yields and thermal collections. Therefore, the photovoltaic and thermal performances of BIPV/T system with different air thicknesses also need to be analyzed.

In this paper, the principal objective is to evaluate the performance of the BIPV/T system under frame shadows and discuss the trade-off between photovoltaic and thermal performances. We analyze the distribution of frame shadows in different seasons, which is related to BIPV/T system orientation, solar altitude, and solar azimuth. The effects of frame shadows on the photovoltaic performance of the BIPV/T system are investigated by using a mathematical model. Then the annual thermal yields with different air layer thickness are estimated. This paper proposes an approach to evaluate the average annual performance of BIPV/T systems. The results obtained can be applied to optimize the design and installation of BIPV/T systems.

2. Mathematical model

2.1. Frame shadow

The size and distribution of the frame shadow is associated with the BIPV/T structure, building orientation, solar altitude, and solar azimuth. The size of the frame shadow is described by W_{side} and W_{up}, which are given as follows:

$$W_{side} = |h\tan\left(\theta_{side}\right) - l_{side}|, \theta_{side} = \gamma_s - \gamma \quad (1)$$

$$W_{up} = h\tan\left(\theta_{up}\right) - l_{up}, \theta_{up} = \alpha_s - \alpha \quad (2)$$

where

$$\sin\alpha_s = \sin\varphi\sin\delta + \cos\varphi\cos\delta\cos\omega \quad (3)$$

$$\sin\gamma_s = \cos\delta\sin\omega/\cos\alpha_s \quad (4)$$

where γ_s is the solar azimuth, α_s is the solar elevation, φ is the latitude, δ is the solar declination, ω is the hour angle, and γ is the azimuthal angle of the BIPV/T plate formed between the normal direction of the plate and the southern direction. This parameter is positive and negative in the clockwise and counter-clockwise directions, respectively. α is the inclination angle of the BIPV/T plate formed between the normal vector direction of the plate and the horizontal plane. The symbols are shown in Fig. 2.

2.2. Photovoltaic model

2.2.1. Equations for voltage in the PV cell

The current in a PV cell is expressed in Eq. (3) as follows:

$$I = I_{ph} - I_o\left\{exp\left[q\left(V + IR_s\right)/\left(nkT\right)\right] - 1\right\} - \left(V + IR_s\right)/R_{sh} \quad (5)$$

where I and V are the current and voltage, respectively. Here, I_{ph} is the photocurrent, R_{s} represents the series resistance of the cell, and R_{sh} is the shunt resistance of the cell. These parameters vary with irradiation intensity S and are given as follows:

$$I_{ph} = I_{ph,ref}S/S_{ref} \quad (6)$$

$$R_s = R_{s,ref}\left[1 - \beta\ln\left(S/S_{ref}\right)\right], \quad (7)$$

where β is approximately 0.217

$$R_{sh} = R_{sh,ref}S_{ref}/S, \quad (8)$$

where subscript "*ref*" indicates that parameters are tested under reference conditions. I_o is the saturation current of the equivalent diode, n is the ideality factor, T is the temperature, q is the electron charge (1.6×10^{-19}C), and k is the Boltzmann constant (1.38×10^{-23} J/K).

To facilitate subsequent calculations, Eq. (1) is rewritten into a voltage equation through the Lambert W function [22]. Hence, the equation does not contain a voltage item:

$$V = R_{sh}\left(I_{ph} + I_o - I\right) - IR_s - nkTW\left(Y\right)/q \quad (9)$$

where

$$Y = exp\left\{qR_{sh}\left(I_{ph} + I_o - I\right)/\left(nkT\right)\right\} qI_oR_{sh}/\left(nkT\right) \quad (10)$$

2.2.2. I–V equation of the PV module

A 36-cell PV module is used as an example to determine the effects of frame shadows on the photovoltaic performance of the BIPV/T system (Fig. 3). Given the small size of the frame shadow, the shaded cells in the PV module are partly shaded for the majority of the time.

The conduction and blocking of bypass diodes must be considered under shadow conditions. The I–V equation of the PV module is described by a piecewise function given by Eq. (11)

$$V = \begin{cases} \sum_{A} V_i - \sum_{B} V_{bypass}, & I_{phB} < I < I_{phA} \\ \sum_{ALL} V_i, & 0 < I < I_{phB} \end{cases} \quad (11)$$