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Numerical investigation of the energy saving potential of a semi-transparent photovoltaic double-skin facade in a cool-summer Mediterranean climate

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HIGHLIGHTS

- A comprehensive simulation model has been developed to predict the overall energy performance of PV-DSF.
- Sensitivity analyses of air gap depths were conducted and the optimal air gap depth was identified.
- The overall energy performance and energy saving potential of the PV-DSF was evaluated.
- A comparative study was conducted between the PV-DSF and other commonly used window technologies.

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ABSTRACT

This paper presents the annual overall energy performance and energy-saving potential of a ventilated photovoltaic double-skin facade (PV-DSF) in a cool-summer Mediterranean climate zone. A numerical simulation model based on EnergyPlus was utilized to simulate the PV-DSF overall energy performance, simultaneously taking into account thermal power and daylight. Based on numerical model, sensitivity analyses about air gap width and ventilation modes have been lead in Berkeley (California) with the aim to optimize unit's structure design and operational strategy of PV-DSF. Via simulation, the overall energy performance including thermal, power and daylighting of the optimized PV-DSF was evaluated using the typical meteorological year (TMY) weather data. It was found that per unit area of the proposed PV-DSF was able to generate about 65 kW h electricity yearly. If high efficiency cadmium telluride (CdTe) semi-transparent PV modules are adopted, the annual energy output could be even doubled. The PV-DSF studied, also featured good thermal and daylighting performances. The PV-DSF can effectively block solar radiation while still providing considerable daylighting illuminance. Due simply to excellent overall energy performance, a PV-DSF at Berkeley can reduce net electricity use by about 50% compared with other commonly used glazing systems. Efficiency improvements of semi-transparent PV modules would further increase the energy saving potential of a PV-DSF and thus making this technology more promising.

1. Introduction

In the U.S. during 2010, approximately 41% of total energy consumption was spent in residential and commercial buildings. Heating, ventilating and air conditioning (HVAC) accounted for more than 50% of the total building energy use [1]. Thus, economically and in the interests of sustainability, energy saving in this area is of value. An effective way to reduce building energy consumption, but still ensuring the comfort and convenience of the building users, is by the reduction of heat transfer throughout the building envelope, and thereby reducing cooling/heating loads. Given that windows and glazing facades, for instance, usually have poor thermal insulation properties, the development of energy efficient curtain walls/facades could considerably reduce heat transfer from outside to the inside of buildings. In recent years, semi-transparent thin-film PV (STPV) windows/facades have been a focus of research interest due to their energy efficient performance levels [2–13]. STPV windows/facades not only generates electricity in situ through photovoltaic effect but also significantly reduces

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the air-conditioning cooling load by blocking solar heat gain [14–19]. Additionally, STPV windows with appropriate transmittance also enable full use of daylighting [15,20–23]. Much research related to the overall energy performance of STPV windows/facades has been conducted with the objective of determining their energy saving potential. Both experimental and simulation methods have been used and reported.

A comprehensive energy analysis has been conducted for semi-transparent building-integrated photovoltaic (BIPV) windows in Singapore [24]. To evaluate the overall energy performance in this instance, an index of net electrical benefits (NEB) including the generation of electricity, the reductions of cooling energy and artificial lighting energy was introduced. As a result, a better NEB was determined involving high PV efficiency and good thermal properties. In Singapore, when compared with other commonly used glazing systems, semi-transparent BIPV windows were found to be the best in terms of overall energy saving performance providing the window–wall-ratio was optimized in keeping with the various possible orientations. Li et al. [25] investigated the energy performance of a semi-transparent a-Si PV facade for a generic reference office building in Hong Kong. The simulation results showed that semi-transparent PV modules were able to reduce the annual building electricity use and peak cooling load by 1203 MW h and 450 kW, respectively, if combined with a dimmable lighting control system. Previous study reported that electricity generation of STPV window was relatively small, however, it worked as an efficient sun shading in summer and thus giving a potential for the reduction of investments for cooling equipment and savings on cooling energy use [26].

In Spain, the STPV facade energy saving potential based on different window-to-wall ratios and different transmittances was evaluated by Olivieri et al. [27]. The saving ranged from 18% to 59% compared to that of a normal glazing. Leite Didoné and Wagner [28] evaluated the energy saving potential of STPV windows in Brazil via simulation. The simulation results indicated that the STPV window has a considerable potential for reducing lighting and air-conditioning energy if used with appropriate control strategies. The impacts of optical characteristics on the overall energy performance of STPV windows have also been investigated by Chae et al. [29]. It was found that the optical response at each wavelength could significantly affect the thermal, power and daylighting performance or availability. To maximize the energy saving potential of STPV windows, it seems necessary for the optical characteristics to be customized when fabricating PV laminates. Kapsis and Athienitis [30] examined the impact of various building design parameters on the selection of ideal optical properties for STPV windows. It was reported that STPV windows with 10% visible transmittance had the best energy saving potential.

Previous studies have also reported the thermal insulation performance of single-skin STPV windows to be unsatisfactory because of high heat gain coefficients in summer and serious heat loss during winter nights [31]. A significant reduction of *U*-value could make PV window become one of the most energy efficient window alternatives [32]. To achieve this goal, ventilated double-skin STPV windows of various types were proposed and their thermal performances studied. Chow et al. [33] investigated the thermal performance of a naturally-ventilated STPV window together with the impact on air-conditioning cooling load reduction. The heat transfer and airflow in the ventilation cavity were simulated using the ESP-r simulation platform, separating the cavity into several thermal zones. The simulation results showed that the naturally-ventilated PV glazing, when compared to the common absorptive glazing window in Hong Kong, could reduce the annual air-conditioning energy use by 28%. Brandl et al. investigated the ventilation effect and thermal behavior of a BIPV façade with 3D CFD models [34]. Due to periphery openings, heat in the cavity was partly transferred to the exterior under the effects of natural ventilation. The thermal performances of single-skin and double-glazing STPV windows were compared using a hot-box designed for that purpose [35]. The experimental results indicated that, in East China, a double-glazing STPV window could reduce the indoor heat gain to 46.5% of that of a single-skin PV window. More importantly, the thermal comfort in the room was obviously better, as the inner surface temperature of the double-glazing STPV window was much lower than that of the single-glazing one. Elarga et al. [36] conducted a dynamic numerical analysis of the cooling energy performance of a ventilated BIPV façade with semitransparent PV cells inside the façade cavity. It was found that the integration of solar cells inside the façade cavity enabled the HVAC system to cool down the PV modules, which not only increased the energy conversion efficiency but also extend the life time of the system.

A novel ventilated photovoltaic double-skin facade (PV-DSF) was developed and has been presented in the authors' previous studies. Its thermal and power performances under different ventilation modes were demonstrated during long term outdoor testing [37,38]. The experimental results showed that the average solar heat gain coefficient (SHGC) of the ventilated PV-DSF was less than 0.15, a measurement which is far less than that of a single-skin STPV window. In addition, it was found that a ventilated PV-DSF could improve the daily energy output by a further 3%, a result based on its lower operating temperature.

From literature reviews, it is evident that although the energy saving potential of single-skin STPV windows has received much attention worldwide, the saving potential of double-glazing STPV windows has, in comparison, rarely been studied and reported. In the study reported in this paper, a comprehensive simulation model based on EnergyPlus is introduced to simulate the year round overall energy performance of a ventilated PV-DSF, situated in the cool-summer Mediterranean climate of Berkeley, California. Weather data, of a typical meteorological year (TMY) was used in the simulation. Based on the simulation model, sensitivity analyses of air gap depths and various ventilation modes were conducted to optimize the design of the PV-DSF structure and the operational strategy. For the optimized PV-DSF, the annual power generation, thermal and daylighting performances were comprehensively investigated. The monthly overall energy performance and net electricity use were also calculated. A study, comparing the PV-DSF and commonly used window glazing, was then conducted, with the aim of revealing the energy saving potential of the PV-DSF in cool-summer Mediterranean climate zones.

2. PV-DSF and simulation model

As shown in Fig. 1, the PV-DSF consists of an outside layer of semi-transparent a-Si PV panels, an inner layer of an openable window as well as an intermediate 400 mm air ventilation cavity. This PV-DSF possesses the following merits. Firstly, the inside openable window makes air exchange and solar passive heating possible, when needed. Secondly, as the PV panels are semi-transparent, with transmittance of about 7%, thus enabling some natural daylight to penetrate the PV panels and illuminate the room. The upper ventilation louvres can further significantly improve indoor daylighting because daylight can pass through the grille gaps and enter the room. Of final importance is the ventilation design. As shown in Fig. 1, cold air can enter the airflow cavity through the bottom inlet louvre, exchange heat with the PV panels as well as the inside windows and finally exhaust a considerable amount of waste heat via the upper outlet louvre. Previous experimental studies demonstrated that such ventilation not only reduces the cooling load by 15%, but also enhances the PV module's energy output by about 3% [37,38]. The key parameters of the PV-DSF are