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Investigation on the daylight and overall energy performance of semi-transparent photovoltaic facades in cold climatic regions of China

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HIGHLIGHTS

- A novel daylight quality evaluation metric named "*N-Daylit* area" was developed.
- The daylighting simulation model in Daysim was experimentally validated.
- The daylight and energy performance of STPV facades was investigated.
- An optimal design of STPV facades was offered in view of daylight and energy saving.

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ABSTRACT

Building-integrated semi-transparent photovoltaics (STPV) technology has attracted more and more attentions for its obvious advantage in renewable energy utilization. However, the STPV facades have potential conflicts of interest between daylighting and energy efficient. Thus, this paper reported an investigation of the daylighting and overall energy performance of STPV facades in cold climatic regions of China, with the aim of resolving the conflicts. Firstly, the reliability of daylighting model in Daysim was experimentally verified. In addition, a novel dynamic daylighting evaluation metric named "*N-Daylit* area" was developed, considering the glare phenomenon and setting reasonable indoor illumination thresholds. On basis of this, the effect of several key design parameters, including transmittance、orientation and window-wall ratio (WWR), on the performance of STPV facades installed in a generic reference office was studied, by using a comprehensive simulation method. According to the simulation result, the transmittance and WWR of the STPV façade were recommended to be in the ranges of 50–60% and 40–50%, respectively, for the purpose to improve the energy efficiency of STPV facades with the premise of ensuring a satisfied daylight quality of the tested room. Furthermore, the results also revealed that south facing was the preferred orientation of STPV facades, to obtain the best daylighting quality and the lowest annual net electricity use of the space.

1. Introduction

It is worthy of our attention that the building sector is currently responsible for about one third of total global final energy use [1]. The energies are mainly used for heating, air-conditioning and lighting. Among these, the energy consumption through windows occupies a significant portion, accounting for 20–40% of the total energy used in a building [2], since the overall heat transfer coefficient of windows is normally five times greater than those of other building envelopes. Therefore, the energy efficiency of external windows is obviously crucial for building energy saving [3].

Semi-transparent photovoltaic (STPV) facade is a new attempt to combine the requirement for energy efficient window with the need for renewable energy generation [4]. The STPV facades are capable to generate solar power and satisfy the requirements of building aesthetics simultaneously [5,6]. In recent years, many studies have been conducted on the STPV façade for its advantages in building energy savings [7]. Peng et al. conducted a numerical study on the energy saving potential of a semi-transparent photovoltaic double-skin facade in Berkeley, California, and they found that a semi-transparent photovoltaic double-skin facade could reduce net building electricity use by about 50%, compared with other commonly used glazing systems [8]. Leite

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Nomenclature

COP	coefficient of performance
DA	daylight autonomy
EER	energy efficiency ratio
E_R	reflected illuminance, lx
E_{I-I}	incident illuminance, lx
E_I	illuminance at the inside, lx
E_O	illuminance at the outside, lx
E_{pv}	power generation of photovoltaic solar systems, kW
MBE	mean bias error
$Q_{cooling}$	annual energy used for cooling, kW
$Q_{heating}$	annual energy used for heating, kW
$Q_{lighting}$	annual energy used for lighting, kW
$Q_{overall}$	annual net energy demand of building, kW
RMSE	root mean square error
STPV	semi-transparent photovoltaic
SHGC	solar heat gain coefficient
T_{sol}	solar radiation transmittance
T_{vis}	visible light transmittance
UDI	useful daylight illuminance
U-value	thermal transmittance, $W/m^2{\cdot}K$
WWR	window-wall ratio
$x_{exp,i}$	experimentally measured illuminance
$x_{sim,i}$	simulated illuminance

[9] compared the applications of conventional and STPV facades in two Brazilian cities, and found that with use of STPV facades, building energy consumption was reduced by around 40%. The influence of STPV facades on building energy saving was also investigated by Miyazaki [10], and they concluded that for climates with hot summer and cold winter, such as in Tokyo, STPV facades with a transmittance of 40% and a Window-wall ratio (WWR) of 50% could provide optimal energy saving throughout the year. While for subtropical climates, such as in Hong Kong, STPV facades with a transmittance of 45% to 55% were preferable [11]. The energy saving performance of STPV facades adopted in central China with different architectural variables was also investigated by Xu [12], and they declared that building electricity savings of up to 30% was obtained with an optimized photovoltaic (PV) cell coverage ratio design.

Energy efficiency aside, as a building fenestration, special concerns are also needed to be paid on the daylight performance of STPV facades. The optical features of STPV facades, including the visible light transmittance and the color rendering property, are quite different from common windows with white glass. In order to ensure good indoor daylighting quality, an optimal configuration for double-skin STPV facades consisted of an outer layer of PV glass with a transmittance of 30%, and an inner layer of conventional low-e glass was suggested for an office building located at Toronto, Canada [13]. The optimal design could provide sufficient daylight within the perimeter zone, where the workplane illuminance levels were larger than 300 lx for 50% of the occupied hours throughout the year. Eero [14] claimed that from the view point of daylight quality, the optimal PV cell coverage ratios were 10% and 15% for southern (latitude 38°N) and northern (latitude 60°N) Europe, respectively. For the application of STPV facades in Tianjin, China, Li [15] recommended that the PV cells coverage ratio should be smaller than 60% to satisfy the indoor daylighting requirements. By comparison of the daylight performance between double-skin STPV facades and conventional double-glazing windows, Huang [16] found that using double-skin STPV facades could achieve better daylighting quality at the region from the external façade to a 4 m depth into the room.

The above-mentioned studies were quite useful for understanding the performance of STPV facades. However, most previous studies focused only on one performance metric, either the energy efficiency or daylighting quality, but ignored the inherent relationship between these two metrics: the daylighting quality directly influences the artificial lighting energy use, which eventually plays an important role in building energy consumption. Thus, it was not comprehensive to study only the energy efficiency of STPV facades without considering the daylighting variations. On the other hand, most previous research, relating to the daylight performance of STPV facades, assessed the

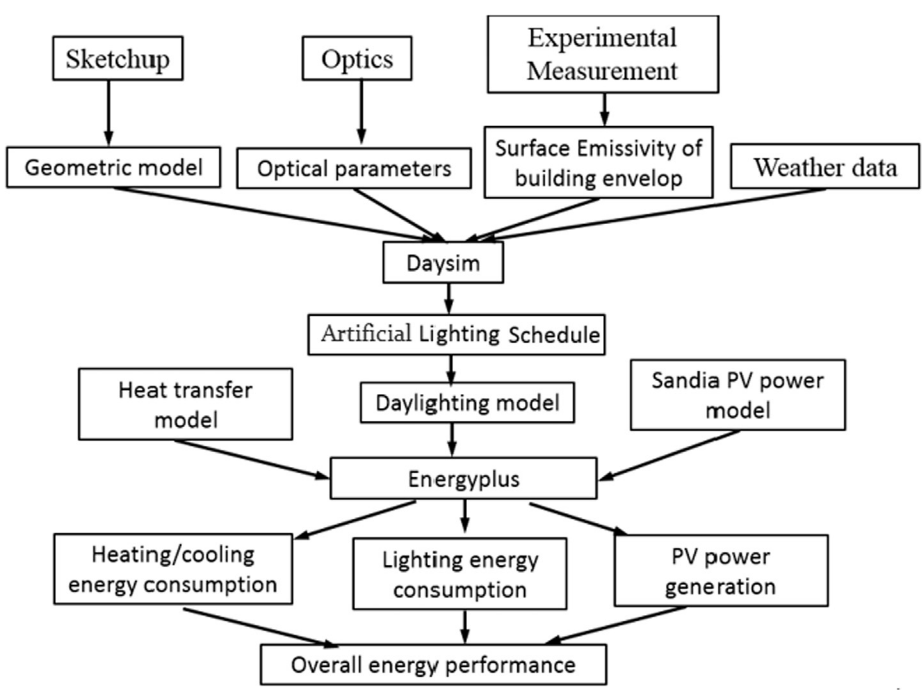

Fig. 1. The flowchart of the comprehensive simulation method.