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A feasibility study on a building's window system based on dye-sensitized solar cells

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ABSTRACT

This study assessed the applicability of semi-transparent photovoltaics (PVs) that can both produce electricity and transmit light in the window system of a building. The potential of window-integrated semi-transparent photovoltaics (WISPVs) in the current global climate was evaluated by varying the window performance and the conversion efficiency of dye-sensitized solar cells (DSSCs). The feasibility of WISPVs was examined quantitatively based on the standard building envelope properties from the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) and the reported DSSC conversion efficiency. The following seven cities, which are representative of what can typically be found in various climate zones, were selected for the building energy simulation: Miami (Zone 1), Sao Paulo (Zone 2), Sydney (Zone 3), New York (Zone 4), Seoul (Zone 4), Berlin (Zone 5), and Moscow (Zone 6). According to the simulation results from the ESP-r program, the WISPVs were more effective in Zone 4, but less effective in Zones 5 and 6.

1. Introduction

According to the life cycle cost (LCC) of a building's energy consumption, the maintenance phase comprises approximately 83% of the total energy consumption with construction (16%), planning and design (0.4%) and disposal (0.4%) comprising only small fraction [1,2]. A building's heating, cooling and lighting consumes approximately 80–90% of the maintenance phase, accounting for more than half of the energy consumption of a building [3,4]. To effectively reduce the maintenance costs of a building, it is important to consider the energy efficiency of a structure during the initial building design phase by conducting a simulation of the performance.

The overall energy consumption of a building can be reduced in two leading ways. In the first, the maintenance cost in building operations can be optimized because its energy requirements are affected mainly by the envelope properties, inter alia and window system. Therefore, varying the window performance properties and the position of window installation should be considered quantitatively. The second way involves the application of renewable energy to the building envelope, particularly PV technology. As the next generation solar cells, organic-based photovoltaics, which can be transparent to light, have been studied extensively as an alternative window system in recent years [5–9]. The application of semi-transparent photovoltaics to the building envelope can generate photovoltaic electric energy, and adjust the heating, cooling and lighting loads. A precise evaluation of window-integrated semi-transparent photovoltaics (WISPVs) using these factors is needed.

In current WISPV technology, a range of photovoltaic systems have been considered, such as amorphous silicon (a-Si) thin films, polycrystalline or monocrystalline Si, dye-sensitized solar cells (DSSCs) and polymer solar cells [10]. The development of WISPVs has become more feasible since the advent of organic-based photovoltaics (OPVs) including DSSCs, which are relatively cheap, flexible and can be made semi-transparent [11]. OPVs, however, typically show low energy conversion efficiency. Therefore, previous studies of OPV focused mainly on improving the efficiency [12]. Accordingly, research on WISPVs has focused on fully utilizing the maximum conversion efficiency using a window design strategy [13]. On the other hand, a range of window system properties need to be studied before WISPVs can be used practically, including the window wall ratio (WWR), solar heat gain coefficient (SHGC), solar transmittance (T_{sol}), visible transmittance (T_{vis}), light-to-solar-gain ratio (LSG), and the U-value under local or global climate conditions.

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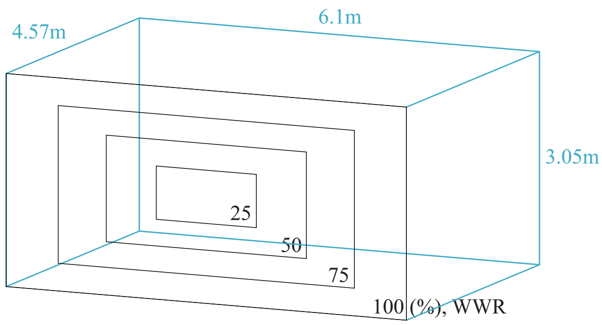

Fig. 1. Three-dimensional view of the prototypical building module.

Based on this research background, two main objectives were addressed: (1) an evaluation of the window performance properties, such as WWR, SHGC, T_{vis}, T_{sol}, LSG, and U-value, by varying the climate conditions in a DSSC-applied window system; and (2) a feasibility study of DSSCs in a building window system regarding the generation and consumption of energy by a building.

2. Methodology

Three main factors were chosen as the input data: the conversion efficiency of DSSCs, climate conditions and window properties. The building energy consumption consisting of four elements (heating, cooling, lighting, and photovoltaic energy generation) was used as the output data. The analysis was performed in the following five steps:

(1) set the building module and envelope properties for input data;
(2) classify the 6 types of the world climate;
(3) select 4 types of DSSCs and apply them to the window system;
(4) perform data analysis based on the overall energy consumption related to the variations in the conditions; and
(5) suggest guidelines for the DSSC window system in the given climates.

2.1. Simulation tool and input data

The ESP-r simulation program was used to evaluate the appropriate performance criteria for a window system in buildings [14,15]. This software package is recognized and used widely in more than 60 countries as an industry standard for the simulations. The authors employed the latest version of ESP-r 11.1 (updated in 2011), which considers the energy use of heating, cooling and lighting, peak energy load demand, and the occupant's thermal comfort in buildings.

The simulated building [16,17] was comprised of 4 perimeter zones containing 5 office modules each with each office module consisting of a zone, 4.57 m (15 ft) in depth by 6.1 m (20 ft) in width, with a floor-to-floor height of 3.05 m (10 ft). The office module is shown in Fig. 1. The window frame was made of 57.2 mm aluminum with a thermal break that has a U-factor of 5.68 W/m^2 K. The lighting and equipment loads were 10.76 W/m^2 and 8.07 W/m^2, respectively. The U-factor data of the other envelopes, such as the wall (0.26–0.39 W/m^2 K), floor and roof, was inserted based on level of climates addressed in the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard [18]. The glazing system was defined parametrically to better understand their effects on the energy performance. The glazing area is meant to be installed by WWRs corresponding to 25, 50, 75 and 100% of the wall area.

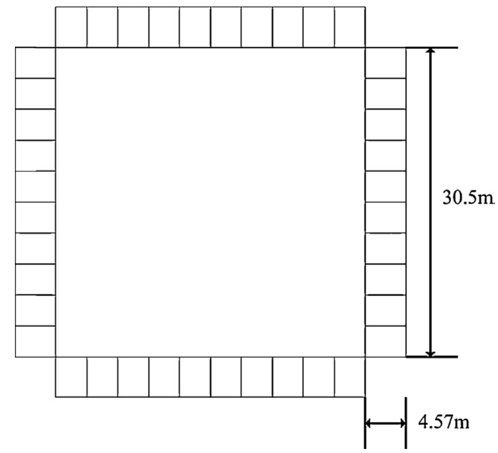

Fig. 2. Plan view of the prototypical building module.

Table 1
Combination performance properties regarding window system data.

Window	SHGC	T_{vis}	LSG	U-factor (W/m^2 K)	NFRC ID
A	0.20	0.39	1.95	0.81	8669
B	0.19	0.31	1.63	0.83	5208
C	0.17	0.24	1.41	0.79	5204
D	0.15	0.20	1.33	0.84	5772

2.2. Dye-sensitized solar cell data

In previous research, the properties of DSSCs used in the simulations were obtained from the laboratory-scale fabrication of four DSSCs and corresponding measurements [13]. By adopting the previous DSSC systems in this study, the transmittance of the four DSSCs were 45, 38, 30 and 25%, and the conversion efficiencies were 10.26, 11.50, 12.60 and 13.00%, respectively. The solar transmittance data was selected from Fig. 2 based on the individual visible transmittance. A search of all the available window systems in the National Fenestration Rating Council (NFRC) database was performed (Fig. 2) [19], and their visible transmittance and solar transmittance properties were plotted. In the simulation, the solar transmittance was chosen from the median value for the given visible transmittance. Fig. 2 shows four types of DSSC glazing according to the data marked 'A' to 'D'.

2.3. Optical properties for the type of window system

Using the four selected types of single DSSC glazing, the 'A' to 'D' window systems showed similar features in a center-of-glass U-factor of 1.49 to 1.53 W/m^2 K, a target that can be achieved with two layers of the glass system and an argon fill. The window system has a combination of selected DSSC glazing located on the outside, and low-e glasses located inside, as shown in the inset in Fig. 2. The properties of low-e glass installed in the window system have the following values: T_{sol} = 0.706, T_{vis} = 0.87 and filled with argon gas to a thickness of 12.7 mm. The combination performance properties regarding the window system data used for the simulation were selected from the NFRC database, and are listed in Table 1.

2.4. Climate data

The climate data was selected from ASHRAE and Energy Efficiency & Renewable Energy (EERE) [18,20]. Each categorized zone was also divided by the thermal criteria, where heating or cooling is used. According to the climate classification of the ASHRAE standard, which ranges from Zones 1 to 8, Zones 1 to 6 were selected