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Research Article

Performance Evaluation of DSC Windows for Buildings

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Interest in BIPV systems with dye-sensitized solar cells (DSCs) that can replace building windows has increased for zero energy buildings. Although DSCs have lower efficiency in terms of electricity generation than silicon solar cells, they allow light transmission and application of various colors; they also have low production costs, which make them especially suitable for BIPV systems. DSC research is interdisciplinary, involving electrical, chemical, material, and metal engineering. A considerable amount of research has been conducted on increasing the electrical efficiency of DSC and their modules. However, there has not been sufficient research on building applications of DSC systems. The aim of this study is to evaluate the optical performance and thermal performance of DSC windows in buildings. For this study, DSC experimental models with different thicknesses and dye colors were manufactured, and their optical properties, such as transmittance and reflectivity, were measured by a spectrometer. The thermal and optical characteristics of double-glazed windows with DSC were analyzed with a window performance analysis program, WINDOW 6.0.

1. Introduction

With increasing use of energy in buildings to make the indoor environment more comfortable, there is growing interest in renewable energy technology for buildings. Building-integrated photovoltaics (BIPV) is a zero-energy building technology that has been paid considerable attention. In this field, solar panels are installed around the exterior of a building so that they not only protect the building but also generate energy.

Although dye-sensitized solar cells (DSCs) provide lower efficiency in electricity generation than silicon solar cells, DSCs allow light transmission and application of various colors; they also have low production costs, which make them especially suitable for BIPV. In addition to performing their original function of generating electricity, DSCs also affect energy generation by substituting for exterior finishing materials of buildings such as those used in doors, windows, and shadings; they also can help to create a pleasant indoor environment.

The optical performance of windows is an important factor in indoor visual comfort and also in the cooling and heating load of buildings in relation to solar heat gain. The appropriate use of daylight with windows is an important way of creating a visually pleasant environment for occupants both physically and psychologically, while saving on electricity for lighting.

On the other hand, if there is an excessive amount of daylight indoors, visual discomfort will arise due to factors such as glare. In the case of a large office building, excessive amounts of daylight will greatly increase the energy use for cooling, which will lead to an increase in the total energy consumption of the building.

A DSC module is a chemical solar cell formed with conductive glass, TiO_2, a dye, and an electrolyte. The efficiency and optical performance of this cell differ depending on the elements used in it. In particular, the color and visible transmittance, which are included in elements important in the application of DSC to building windows, are affected directly by dye type and thickness of TiO_2. Also, DSC-applied windows, in comparison to normal transparent windows, have lower light transmittance, which results in different optical performance. Therefore, in order to use DSC as conventional windows in building, the characteristics of their

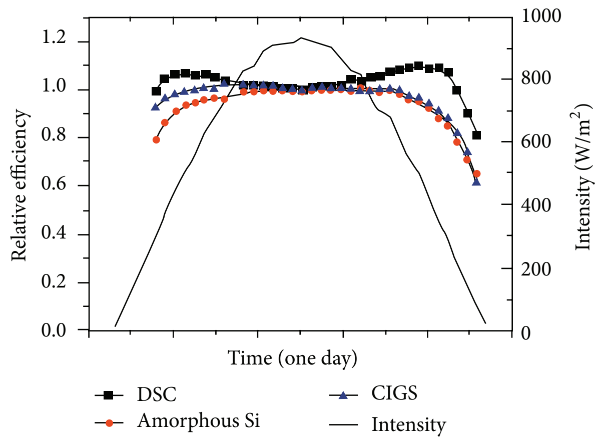

FIGURE 1: Data from comparative *I-V* measurements of DSC, amorphous Si and CIGS modules, on the roof top [5].

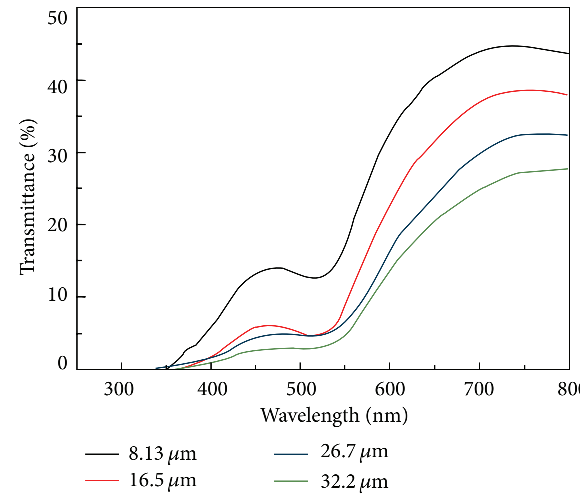

FIGURE 2: Transmittance of DSC with different TiO_2 thicknesses [6].

optical performance and thermal performance should be defined. Many studies are underway in various disciplinary fields, including chemical, material science, and manufacturing engineering for improving DSC's electrical efficiency and durability. For example, studies have been conducted on types of TiO_2 (titanium dioxide), porosity and conductivity [1], thin film materials of counter electrodes [2], development of dyes to facilitate electron emissions, development of solid electrolytes for improving stability [3], grid studies for allowing large-size manufacturing [4], and so forth.

It was reported that dye solar modules can achieve higher yields than silicon modules on a relative basis, that is, per Watt of installed power under outdoor illumination over a period of several months [5]. Fraunhofer ISE compared the relative efficiency of different PV modules under a clear sunny day, as Figure 1 shows.

There are also studies underway on the material characteristics of DSC, including research on the transmittance of transparent electrodes of FTO (fluorine-doped tin oxide) glass (see the data shown in Figure 2) and research into the optical characteristics of light with varying thickness of TiO_2.

Research on semi-transparent photovoltaics, which can be utilized as building envelope materials, has been conducted. Semi-transparent photovoltaics can impact the building load by heat gain and transmitted light. Miyazaki et al. [7] analyzed the energy savings of an office building with the use of semi-transparent BIPV modules in relation to the optimum solar cell transmittance and window to wall ratio (WWR). The results showed that solar cell transmittance of 40% and a WWR of 50% led to the minimum electricity consumption in the building when artificial lighting was controlled. The overall energy performance was analyzed in terms of heating and cooling loads, daylight availability, and electricity generation by using the EnergyPlus program. Lu and Law studied the thermal performance of semi-transparent BIPV modules. They evaluated several important design parameters for the design of solar technology: orientation, solar cell area ratio, efficiency of solar cells, and module thickness.

TABLE 1: Property of DSCs.

Sample type	Dye color	TiO_2 thickness
N719 1T	Red	7 μm
N719 2T	Red	9 μm
N719 3T	Red	11 μm
N749 1T	Green	7 μm
N749 2T	Green	9 μm
N749 3T	Green	11 μm

Lynn et al. [8] evaluated the impact on the internal environment by the color of thin film solar cells. A color rendering index that indicates the closeness to natural light depending on the color of an amorphous solar cell was analyzed.

In the present paper, we made a relative comparison between optical performance results according to the dye type and the thickness of the TiO_2 for the purpose of applying the DSC module to windows. The scope of this study, nonpenetration on the silver finger section, was not included, while the other constitutional elements excluding this part were all considered equally. In addition the performance of DSC windows was analyzed according to their thermal and optical properties using WINDOW 6.0, a window performance analysis program.

2. Optical Performance of DSCs

2.1. Experimental Method. Table 1 and Figure 3 show samples of the DSC used to measure the optical performance. Six samples that consist of different dye types and thicknesses of TiO_2 were prepared. Typically used red-type dyes and green-type dyes were used for the samples. The thicknesses of the TiO_2 were 7 μm, 9 μm, and 11 μm. Thicker specimens were produced by increasing the thickness of the dye deposited on the surface of the TiO_2 differently by increasing the dye absorption time.

The dimensions of the samples were 10 mm × 10 mm × 4.5 mm; TiO_2 and an electrolytic solution MPN were used.

Table 2: Electrical performance of DSCs.

Dye	TiO_2 thickness	J_{sc} [mA/cm^2]	V_{oc} [V]	FF [%]	Effiency [%]
N719 RED	7 μm	11.25	0.800	75.08	6.75
	9 μm	13.43	0.764	74.39	7.63
	11 μm	14.74	0.744	72.61	7.97
N749 GREEN	7 μm	7.21	0.702	70.64	3.57
	9 μm	9.92	0.683	72.73	4.92
	11 μm	11.85	0.669	71.54	5.67

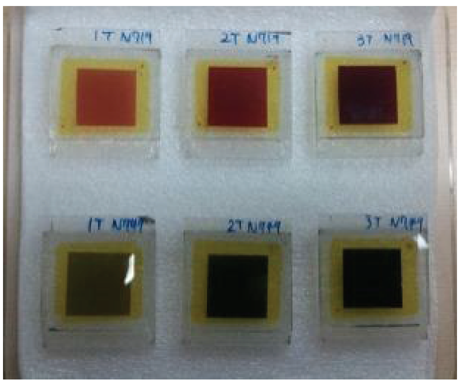

Figure 3: DSCs with different dye and thickness.

Figure 4: Optical spectrum analyzer.

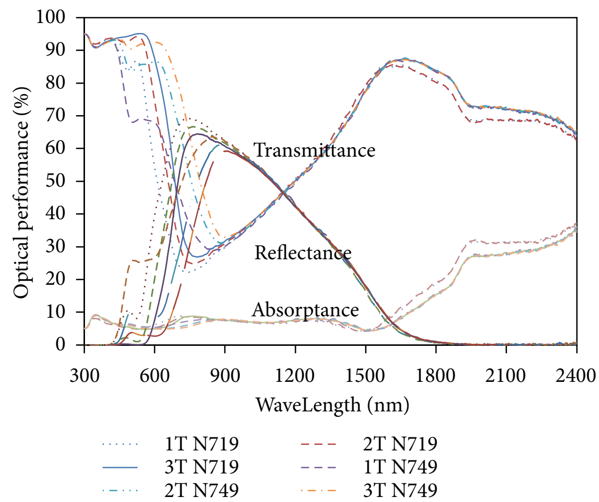

Figure 5: Optical performance of DSC according to the wavelength.

Table 2 lists the electrical efficiency of the samples. It can be seen that the samples with greater dye thickness have higher electrical efficiency. It was obvious that the DSC's electrical efficiency is related to the type of dye; DSC with red type has maximum efficiency of 7.97%, while the DSC with green type has efficiency of 5.67%.

The optical performance of the DSC samples was measured using an optical spectrum analyzer (Figure 4), which provides highly precise transmittance and reflectance measurement. The spectrum analyzer has a wide wavelength range of 185 to 3,300 nm, which represents the ultraviolet, visible, and near-infrared regions. Use of a high-performance double monochromator makes it possible to attain an ultra-low stray-light level (0.00005% max. at 340 nm) with a high resolution (maximum resolution: 0.1 nm). Transmittance and reflectance were measured at a step of 1 nm in a wavelength range between 300 nm and 2400 nm. Absorption is found by the correlation between transmittance and reflectance.

2.2. Optical Performance of DSC. Figure 5 shows the optical performance for the different DSC samples in terms of transmittance, reflectance, and absorption according to the wavelength range. In the visible light spectrum the transmittance varies according to the dye thickness. Transmittance in the visible light spectrum was the highest for the red-type 1T, at 33.3%, while it was the lowest for the green-type 3T, at 8.2%.

Also, as the absorption thickness for the dye increases, the transmittance is reduced, by a maximum of 43% for red type. For green type, it is reduced by a maximum of 71%. In the ultraviolet range, where wavelengths are short, most of the light did not permeate but was absorbed instead. In the visible light range (T_{vis}, 380–780 nm), which directly affects the generation performance of the DSC module, the transmittance of the red type and green type is 33% and 28%, respectively.

Also, in the red wavelength range of 640–780 nm, N719 had higher transmittance than that of N749, whereas in the green wavelength range of 480–560 nm, N749 had higher transmittance. This is attributed to the fact that transmittance varies in the visible wavelength range according to the different transmittance and absorption for different colors.

In the near infrared range (NIR, 789 nm–2500 nm), in which there are greater thermal effects compared to those for the visible light spectrum or for ultraviolet rays, transmittance gradually decreases and, at the range of 1800 nm and over, transmittance is nearly zero, and light is either absorbed or reflected.

About 10% reflectance was maintained for the DSC samples in the wavelength range of 300 nm–1500 nm, and there was a maximum of 37.3% reflectance in the wavelength range beyond 1500 nm. The reflectance of the DSC varies according to the dye type: the reflectance of the red type and green type is 24% and 21%, respectively.

As for the absorption, it showed a pattern opposite to that of transmittance in the visible light wavelength range and opposite to that of reflectance in the infrared wavelength range.

Table 3: Composition of window units.

Window type	Layers*
Clear unit	Cl-Air-Cl
N719 1TW	Cl-DSC [N719 1T]-Air-Cl
N719 2TW	Cl-DSC [N719 2T]-Air-Cl
N719 3TW	Cl-DSC [N719 3T]-Air-Cl
N749 1TW	Cl-DSC [N749 1T]-Air-Cl
N749 2TW	Cl-DSC [N749 2T]-Air-Cl
N749 3TW	Cl-DSC [N749 3T]-Air-Cl

*Cl: 6 mm clear glass; air: 12 mm air gap; DSC: 4.5 mm.

3. Performance Analysis of DSC Windows

3.1. Modeling of DSC Windows. Generally, window units with DSC modules have to be multilayered by attaching reinforced glass to the entire surface for safety and protection. In this study, two window units (Figures 6 and 7) were designed for modeling in order to analyze their performance. For the simulation performance, the optical properties, such as transmittance and reflectivity, measured earlier for the DSC samples were used in the WINDOW 6.0 program.

In order to analyze the performance of DSC-applied glazing, two different types of glazing units were designed: a typical double glazing and a double glazing with DSC modules.

Figure 6 shows the 24 mm glazing type with clear glass, while Figure 7 shows the 26.5 mm multilayered type with DSC and an air layer, which helps to meet the standard for overall heat transmission coefficient. Also, the optical properties of the DSC samples measured earlier were applied to make six different types of DSC window models, which are shown in Table 3.

The WINDOW 6.0 simulation program used for the analysis was developed by Lawrence Berkeley National Laboratory (LBNL) in the USA [9]. It can calculate steady-state thermal performance indices of windows under user-specified environment settings. The thermal performance for expressing solar transmittance performance of windows can currently be expressed by the solar heat gain coefficient (SHGC) and the shading coefficient (SC), along with the coefficient of overall heat transmission.

The SHGC is an index that determines the total quantity of solar radiation that passes through a window, while the SC shows the degree to which solar radiation is blocked. The SHGC and SC are very important factors in the assessment of the energy balance of a building, as they are related to the solar heat gain of the building. The SHGC for multilayered windows can be defined by (1) later [10]. The SHGC is determined by the difference between the heat fluxes into an indoor environment with and without incident solar radiation:

$$\mathrm{SHGC} = T_{\mathrm{sol}} + \frac{q_{\mathrm{in}(l_s=0)} - q_{\mathrm{in}}}{l_s}, \quad (1)$$

where T_{sol} is total solar transmittance of the glazing system, $q_{\mathrm{in}(l_s=0)}$ is heat flux into the indoor environment without incident solar radiation (W/m^2), q_{in} is heat flux into the indoor environment with incident solar radiation (W/m^2), and l_s is incident solar radiation (W/m^2).

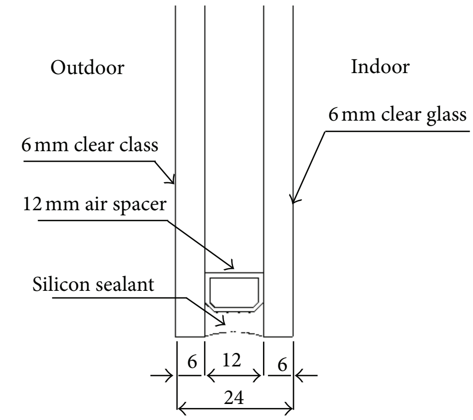

Figure 6: Composition of a typical glazing unit.

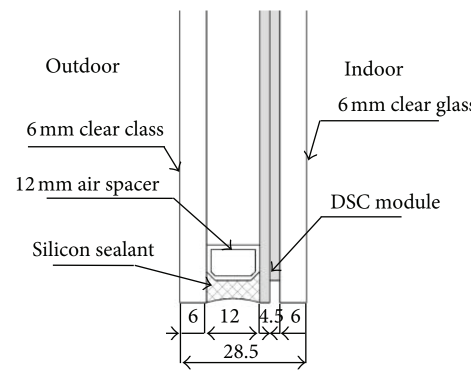

Figure 7: Composition of DSC glazing.

Table 4: Thermal performance and optical performance of the window units.

Type	SHGC	SC	T_{sol}	T_{vis}
Clear unit	0.719	0.826	0.6296	0.789
N719 1TW	0.292	0.336	0.1619	0.268
N719 2TW	0.277	0.319	0.1423	0.199
N719 3TW	0.270	0.311	0.1306	0.153
N749 1TW	0.287	0.329	0.1522	0.229
N749 2TW	0.263	0.302	0.1203	0.118
N749 3TW	0.250	0.287	0.1040	0.066

3.2. Analysis of Thermal Performance and Optical Performance of DSC Windows. In order to define the thermal performance and optical performance of the DSC window units, it is necessary to calculate the SHGC, SC, solar transmittance (T_{sol}), and visible light transmittance (T_{vis}) of those units. First, the optical data obtained in the spectroscopic analysis were fed into the program. Table 4 shows the simulation results of the thermal performance and optical performance of different types of window units.

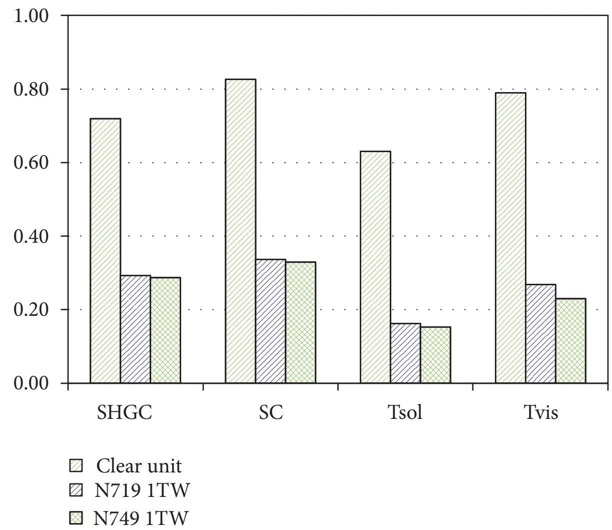

Figure 8: Performance of typical windows and DSC windows.

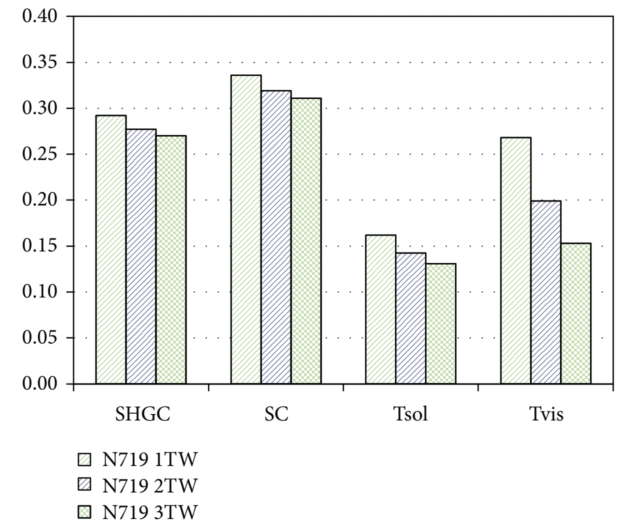

Figure 9: Thermal performance and optical performance for N719 types of DSC windows.

In order to compare the thermal performance and optical performance of the DSC window units according to dye type, the simulation results for the DSC windows units of red 1T and green 1T were analyzed along with the results of a typical window unit. Figure 8 compares the simulation results of the SHGC, SC, T_{sol}, and T_{vis} of the window units. The SHGC for red-type and green-type DSC windows is almost the same at 0.29, while that of the typical window unit with clear glass is 0.72. The SC was 0.83 for the typical unit, while the red-type and green-type DSC windows have values of 0.33, showing a tendency similar to that of SHGC. T_{sol} was 0.63 for the typical window, while for the red-type and green-type DSC windows it was 0.15 and 0.16, respectively, which is almost 4 times lower than that of the typical window and is attributed to the semi-transparent characteristics of the dye. The SHGC, SC, and T_{sol} values for the DSC window units are almost the same regardless of the dye type, that is, red type or green type.

The visible transmittance of the typical window unit, T_{vis}, which represents its optical characteristics, was 0.79. For the red-type and green-type DSC windows, the T_{vis} values were 0.27 and 0.23, respectively, which are much lower than that of the typical window. This difference is also attributed to the dye, and the T_{vis} values for the DSC window units are slightly different due to the dye type.

Figures 9 and 10 show the performance of the windows with different types of DSC. For the performance of windows with the red-type (N719) DSC, the SHGC depends on the thickness of the dye: 0.29 for the 1T (2 μm) case, 0.28 for the 2T (4 μm), and 0.27 for the 3T (6 μm). SC similarly decreased as the dye thickness increased, decreasing from 0.34 to 0.32 and then to 0.31. The same trend was observed for T_{sol} as well, which decreased from 0.16 to 0.14 and then to 0.13. However, the variation of T_{vis} was greater than the previous indices as the dye thickness increased: 0.27 for 1T, 0.20 for 2T, and 0.15 for 3T.

For the green-type dye, green type, SHGC of the window units decreased slightly as the dye thickness increased, decreasing from 0.29 to 0.26 and then to 0.25. The value of SC varied from 0.33 to 0.30 and then to 0.29. The same trend was observed for T_{sol} as well, which decreased from 0.15 to 0.12 and then to 0.10. While the value of T_{vis} varied from 0.23 to 0.12 and then to 0.07, indicating extremely low transmittance. For the optical performance of the DSC window units according to the type of dye, the window with the red-type dye, red type, outperformed that with the green-type dye, green type, by a maximum of 28% depending on the dye thickness.

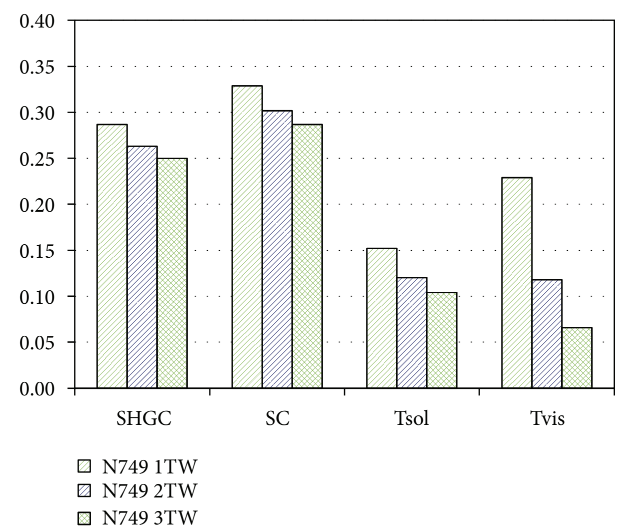

Figure 10: Thermal performance and optical performance for N749 types of DSC windows.

4. Conclusions

This paper dealt with the performance of window units with DSC having different dyes and thickness, which affect the optical and thermal properties of the DSC. The properties of the DSC, such as solar transmittance and reflectivity, were measured using a spectrometer for different spectrum ranges. The WINDOW 6.0 program was used to analyze the thermal performance and optical performance of the DSC windows with the measured DSC properties.

It was found that as the thickness of TiO_2 increases, transmittance decreases and absorption increases, where the difference was shown clearly in the visible light spectrum. As for the absorption, it showed a pattern opposite to that of transmittance in the visible light wavelength range. On the other hand, the reflectance of the DSC was almost unaffected by the dye thickness.

As for the thermal performance and optical performance of the DSC windows, SHGC was reduced by about 60% and SC was reduced by about 69%, on average, compared to the typical window unit with double-layered clear glass. The SHGC reduction of the DSC windows can reduce a building's cooling load. Therefore, it is expected that DSC windows will be very advantageous for use in office buildings, which require more energy for cooling in many regions. Also, the thermal performance and optical performance of the DSC windows varied depending on the thickness of the particular dye used for the DSC. For both dye colors, T_{vis} was more sensitive to the dye thickness than any other factors, such as SHGC, SC, and T_{sol}. In particular, the T_{vis} of green type color is more dependent on the dye thickness than that of red type. Therefore, when applying DSC to windows in buildings, the red-type 1T will be more suitable in terms of taking in more light, while the green-type 3T, with the lowest solar gain, will be more suitable for reducing the cooling load of buildings.

The scope of this study did not include the electrical performance of DSC modules in window units. Further research on the electrical performance of DSC windows, the characteristics of the total energy performance of buildings with DSC windows, and their economic performance should be conducted.

Conflict of Interests

The authors declare no conflict of interests.

Acknowledgments

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