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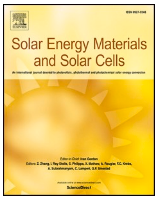

Performance level criteria for semi-transparent photovoltaic windows based on dye-sensitized solar cells

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ABSTRACT

Since the discovery of the photovoltaic (PV) effect in the 19th century, various PV windows have been developed to improve the energy performance of a building and expand the supply of renewable energy. Dye-sensitized solar cells (DSSCs) have attracted attention as promising alternatives to conventional silicon solar cells because of their transparency and aesthetic value. This study aims to analyze the effect of DSSC windows on the building environment and energy performance and build a database to help architects select appropriate DSSC windows for future zero-energy buildings (ZEBs). We use DesignBuilder, a building energy analysis program, to evaluate indoor illuminance, indoor temperature, cooling and heating energy, lighting energy, and power generation. Our prototype DSSC windows exhibit an improved heat transmission rate (i.e., U-value) but lower visible-light transmission (VLT) than low-emissivity glazing windows; thus, they decrease the heating energy and increase the cooling and lighting energy. We predict that DSSC windows meeting the criteria of 13% power conversion efficiency (PCE) and 30% VLT will achieve energy savings of 4861.44 kWh/yr. PV windows with over 50% VLT with any PCE can be beneficial to net zero-energy and net energy-plus buildings.

1. Introduction

The sustainability of human society relies on finding renewable energy sources, together with energy efficiency. Commercial and residential buildings spend a considerable amount of energy for heating, ventilation, air-conditioning (HVAC), domestic hot water (DHW), and lighting with an expected energy consumption growth greater than that of the transportation and industrial sectors [1]. Recently, zero-energy buildings (ZEBs), where the delivered energy is less than or equal to the on-site exported energy, have been conceptualized, and the implementation of this concept has become compulsory for new residential and commercial construction in some parts of the world [2]. In this viewpoint, buildings should harvest energy from their surroundings by themselves. Because solar energy alone can fulfill a significant portion of the global primary energy demand, building-integrated photovoltaics (BIPVs) have been considered promising solutions to achieve net-zero energy. Photovoltaic (PV) modules can directly convert solar irradiation to electricity, and they can be integrated into the building envelope; i.e., walls, roofs, facades, and solar shades. As part of the building envelope, windows have a significant influence on energy demand and heating/cooling load, especially in high-rise buildings with a sizeable window-to-wall ratio (WWR) [3,4]. They are also crucial for the indoor comfort of residents [5,6]. Accordingly, innovative PV windows are highly anticipated for the further development of ZEBs.

To date, various PV windows have been fabricated from crystalline silicon solar cells, thin-film solar cells (e.g., a-Si:H, $CuInGaSe_2$, CdTe), and molecular absorber solar cells, such as dye-sensitized solar cells (DSSCs), and organic PV cells [7–11]. Although numerous efforts have been invested to promote the application of PV windows in buildings, many barriers have still remained. In particular, Because architects are BIPV gatekeepers, the satisfaction obtained from meeting aesthetic requirements encourages the widespread adoption of PV glazing systems in buildings. Unfortunately, the Silicon solar cells are typically opaque and regularly spaced to allow natural light to enter the building (i.e.,

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"see-through" solar windows). The increase in the area covered by the PV cells allows for more electrical power to be generated and reduces the solar heat gain. However, this can result in dappled shadows and a limited view for the occupants. In the meantime, "light-through" solar cells, such as DSSCs, have attracted considerable attention because of the flexibility offered by optical transparency and colors. Their inherent features, such as superior performance in dim light and low angle dependence of incident light, make them favorable for BIPV applications [12]. DSSCs exhibit better performance on hot sunny days and cloudy days than crystalline Si solar cells. Asghar et al. [13] reported that the DSSCs produced more energy throughout the day and exhibited 20–30% higher energy yield in summer months in Abu Dhabi, United Arab Emirates. Yuan et al. [14] conducted outdoor tests in Shanghai, China for over four years and produced 15–20% more electricity from May to August under high-temperature and low-irradiance conditions. The total energy production of DSSCs throughout the years was slightly higher than that of polycrystalline Si solar cells in hot and humid climates. Lee and Yoon [15] monitored the power performance of multi-layered DSSC windows, which consisted of a "DSSC module (9 mm)" + "air space (12 mm)" + "clear glass (5 mm)", in Korea for two years. The average daily power yield of the vertical DSSC window ranged from 1.75 to 3.93 kWh/kWp·d, and that of the 30° sloped window ranged from 2.16 to 5.34 kWh/kWp·d.

Windows play a pivotal role in determining the energy performance of buildings in terms of heating/cooling loads and artificial lighting. Furthermore, PV windows possess an undesired compromise between the power conversion efficiency (PCE) and visible-light transmission (VLT). Thermal insulation of semi-transparent PV windows is still under investigation. Therefore, the efficacy of adopting PV windows should be evaluated by three aspects: optical and thermal performance along with energy generation. In this study, we investigated the applicability of prototype DSSC windows by analyzing the indoor illuminance and temperature; cooling, heating, and lighting energy levels; and the energy performance of DSSCs. We also analyzed the overall energy performance of a building as a function of the VLT and PCE of DSSC windows.

2. Simulation model

To examine the efficacy of DSSC windows, we analyzed the light, heat, and energy performance, and proposed technical development guidelines for using DSSCs. Our methodology can be summarized as follows: 1) interior illuminance (using VLT as the lighting environment); 2) indoor temperature (based on the window performance, as the thermal environment); 3) cooling/heating, lighting, energy consumption, and peak daytime energy (as the energy performance); and 4) power production related to the DSSC efficiency are analyzed. Subsequently, based on the results of this analysis, 5) a database for determining a proper performance level of an ideal DSSC window is developed by changing the VLT and PCE conditions.

Factors 1) to 4) are vital for considering the application of solar cells in windows. First, VLT indicates the proportion of visible light in solar radiation energy passing through the glazing. VLT is an essential factor that determines the visual comfort in an indoor environment. As such, it affects the indoor work environment, visibility, and glare reduction. Moreover, indoor lighting is determined by the VLT, thereby causing different lighting loads. The cooling/heating load varies with the lighting load, which affects the lighting and cooling/heating energy consumption. Accordingly, VLT was selected as a primary analysis factor for energy-saving building plans. In particular, photosensitizers and their amount in DSSCs are directly related to absorbing visible light, and thus, generating electricity.

Second, indoor temperature according to the window combination is a factor that directly influences the operation of the cooling and heating system. The U-value, solar heat gain coefficient (SHGC), and solar coefficient (SC) of the window considerably affect its operation.

Third, regarding the building energy performance, cooling, heating, and lighting energy levels were analyzed. Peak daytime energy was also analyzed for the stable operation of the building energy consumption.

Fourth, power production according to the PCE of the DSSC and the total energy of the building were calculated.

Finally, we analyzed the current performance of the DSSC window using factors 1) to 4), and built a performance database to help determine the proper selection level when the continuous development of DSSC windows is achieved and devices are applied in future building windows. To this end, we calculated the total energy consumption of a building by setting various VLT and PCE levels, as well as the main features of DSSC windows, and proposed a feasible performance range.

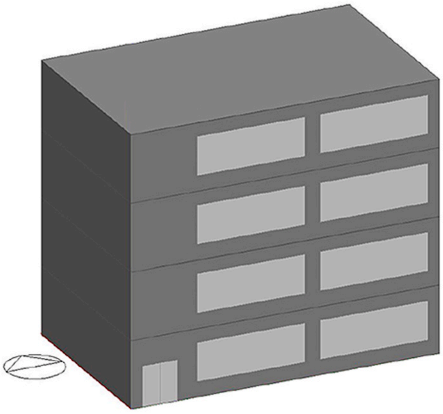
DesignBuilder Version 5.0.1.024 was used for the performance analysis in this study. DesignBuilder is an integrated building energy analysis simulation software, based on EnergyPlus, and includes the standard conditions of LEED and ASHRAE 90.1 [16]. Hourly, monthly, and yearly energy consumption; elemental and peak loads; thermal performance; and daylighting, were considered by inputting information regarding the local climate, building model, thermal insulation of the structures, building operation schedules, air conditioning and lighting, and heat generation.

The simulation target was an office building with a standard size and shape, located in Seoul, South Korea [17,18]. Table 1 lists the input variables and operational settings. The heat transmission rate was calculated based on the recently revised building energy conservation design standard [19]. The surface reflectance values of the ceiling, wall, and floor were assumed to be 70, 50, and 25%, respectively, according to the general guidelines for lighting design [20]. For the heating and cooling system, we selected a fan coil unit, which is generally applied in office buildings designed using DesignBuilder. For the weather data, the annual Seoul standard weather data were used. Energy consumption was calculated as site energy.

Table 2 lists the three types of windows investigated in this study. The widely used low-emissivity (low-e) window was set as the base model. A low-e window is a multilayer glazing structure and is composed of clear glazing, an air layer, and low-e (three-sided coating) glazing. Prototype DSSC windows are constructed in a form similar to the multilayer glazing structure, which is commonly used in actual windows. They are composed of five layers, in the following order; clear glazing (3 mm), air layer (12.55 mm), DSSC (4.4 mm), air layer (12.55 mm), and clear glazing (3 mm). To calculate the thermal and optical properties of glazing, glazing data from DesignBuilder, based on the data from the International Glazing Database (IGDB), were used. Table 3 lists the thermal and optical properties of the DSSC. We used the DSSC test report values from Korea Conformity Laboratories, a certified testing agency in South Korea. The U-value, SHGC, VLT, inside/outside visible reflectance, solar transmission, inside/outside solar reflectance, infrared transmittance, inside/outside transmittance, and emissivity were determined using the test method reported in KS L 2514 [21]. In addition, the SC was determined using the test method developed by the National Fenestration Rating Council (NFRC) 300:2017 [22]. The PCE, provided by a DSSC manufacturer (Orion Co. Ltd.), was used. Fig. 1 shows an image of the 10 cm × 10 cm specimen used during the test.

For window modeling with a combination of glazing layers, the U-Value, SHGC, and VLT were established using the ASHRAE calculation method, based on the WINDOW6 [23] program data. The international glazing database (IGDB) is a comprehensive database compiled by the NFRC and provided through the specialist WINDOW and OPTICS [24] fenestration analysis software provided by Lawrence Berkeley National Laboratory (LBNL). The IGDB contains detailed spectral data from approximately 2500 manufacturers of glazing pane products worldwide. DSSC windows are limited to two types, DSSC-R (red) and DSSC-G (green), according to the DSSC color.

Table 1
Simulation model parameters.

Modeling		
Location	Seoul, Republic of Korea	
Area and other data	Total building footprint	640 m^2 (160 m^2 for each floor)
	Number of floors	4F
	Zoning pattern	Perimeter/core
	Building orientation	South
	Floor heights (Flr-to-Flr)	3.5 m
Building envelope constructions	Roof surface (U-value)	0.15 W/m^2K
	Above grade wall (U-value)	0.24 W/m^2K
	Ground floor (U-value)	0.2 W/m^2K
	Infiltration	0.7ACH
Schedule	Heating period	January 01 - February 28 November 01 - December 31
	Cooling period	June 01 - September 31
Exterior window	Size	5.6 m × 2 m (16AE)
	WWR	40%
System	Heating/Cooling system type	Fan coil unit (4-Pipe)
	Heating/Cooling seasonal COP	0.85/5.96
	Heating/Cooling setpoint temperature	20 °C/26 °C
	Heating/Cooling setback temperature	15.5 °C/29.4 °C
Occupied load	Lighting	Office-10.2 W/m^2 Core-2 W/m^2
	People	0.161 person/m^2
	Office equipment	11.8 W/m^2
	Dimming control	Office-400 Lux Core-200 Lux

3. Results and discussion

3.1. Low-e glazing versus DSSC performance

Fig. 2 details the simulation space settings for the irradiance analysis. The middle (third) floor of the building was used. To analyze indoor illuminance, based on the VLT of the south DSSC window, the center office, which has minimal peripheral disturbances, was selected as the target space. The dimming control sensor was placed at the center of the room at a working height of 0.75 m. Clear sky conditions were selected. The measurement moment was set as 12:00 on December 21, which is noon on the winter solstice. At that time, the average illuminance in the south window peaked, based on a previous study analyzing the indoor illuminance according to the amount of lighting [25]. Besides, dimming control sensors were used to analyze the lighting energy consumption. Table 4 outlines the indoor illuminance simulation results.

Low-e glazing showed the highest indoor illuminance, followed by DSSC-R and DSSC-G, in accordance with the descending VLT. The VLT performance of the DSSC windows was lower than that of the low-e glazing, by approximately 91–95%, depending on the color. Accordingly, the average indoor illuminance was 83.98 lux for DSSC-R and 46.73 lux for DSSC-G, which represent only 6.19% and 3.44% those of low-e glazing, respectively. The standard indoor illuminance of an office building is 300–500 lux [26]. The standard indoor illuminance cannot be satisfied using only natural lighting with the current VLT level for DSSC windows. To identify the feasible irradiance level for an office building using DSSC windows, the performance needs to be evaluated at various VLT levels of the DSSC.

To examine the thermal environment performance, the indoor temperature was analyzed using different window combinations. The target space was limited to the center office on the third floor. The same space was selected for indoor illuminance, excluding the core, to which low-e glazing is commonly applied. The indoor temperature was analyzed by considering the solar gain of each window. The SHGC represents the fraction of incident solar radiation arriving in the room through a window. A higher SHGC implies greater solar heat gain. Solar gain must

Table 3
Physical properties of DSSC.

Type	DSSC-R	DSSC-G
TiO_2 thickness [um]	8	8
Dye material	Z907	SQ2
Electrolyte material	Ionic liquid (OJH-1)	Ionic liquid (OJH-1)
U-Value [W/m^2K]	5.77	5.77
SHGC	0.41	0.40
SC	0.47	0.45
VLT [%]	6.0	3.5
Inside/Outside visible reflectance [%]	9.1/9.4	8.1/5.1
Solar transmittance [%]	19.2	16.1
Inside/Outside solar reflectance [%]	11.2/11.3	10.4/9.1
Infrared transmittance [%]	20.3	21.1
Inside/Outside transmittance [%]	16.3/16.0	15.7/15.9
Emissivity	0.89	0.89
Efficiency value [%]	2.99	2.12

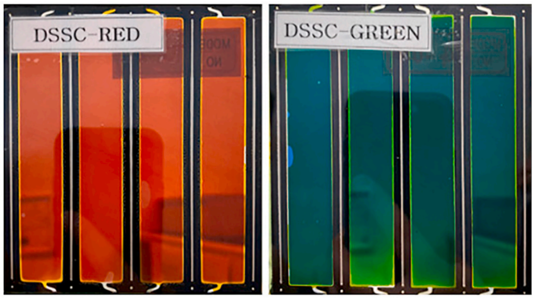
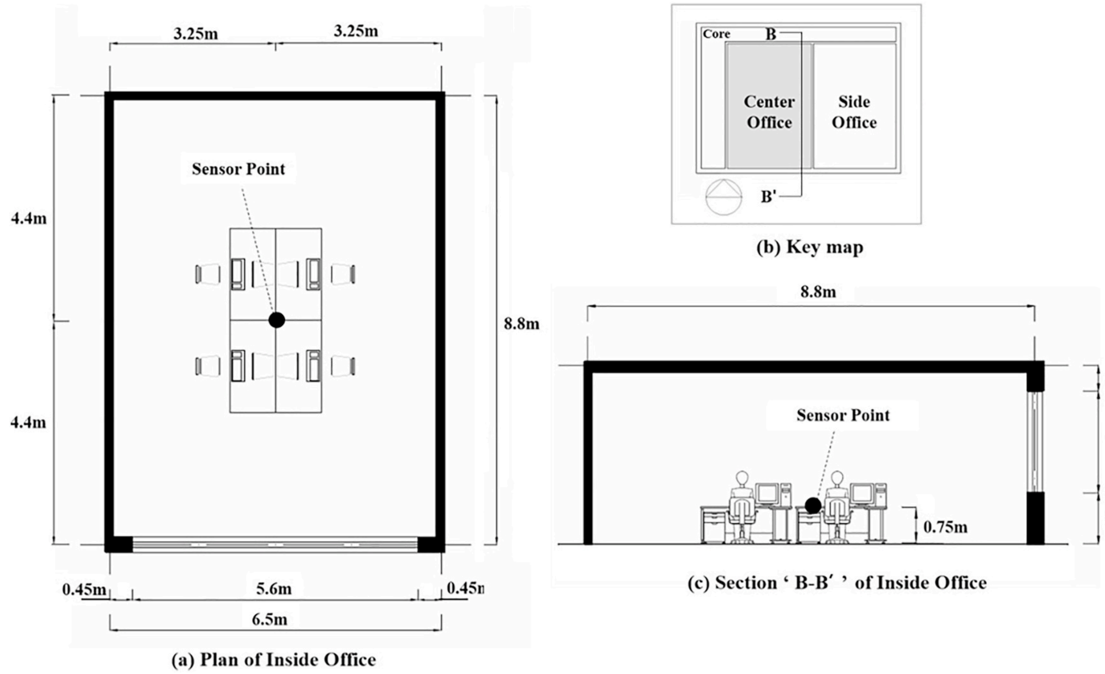


Fig. 1. Specimen of DSSC with different dyes.

Table 2
Physical properties of exterior window.

Window type	Glazing layer [No. Thickness]	U-Value [W/m^2K]	SHGC	SC	VLT [%]	Note
Low-E	Clr 6 + Air12 + Clr6	1.540	0.490	0.560	59	Base case
DSSC-R	Clr3+Air12.55+DSSC4.4 (Red) +Air12.55 + Clr3	1.082	0.426	0.490	4.9	
DSSC-G	Clr3+Air12.55+DSSC4.4 (Green) +Air12.55 + Clr3	1.077	0.417	0.479	2.8	



(a) Plan of Inside Office

(b) Key map

(c) Section ‘ B-B′ ’ of Inside Office

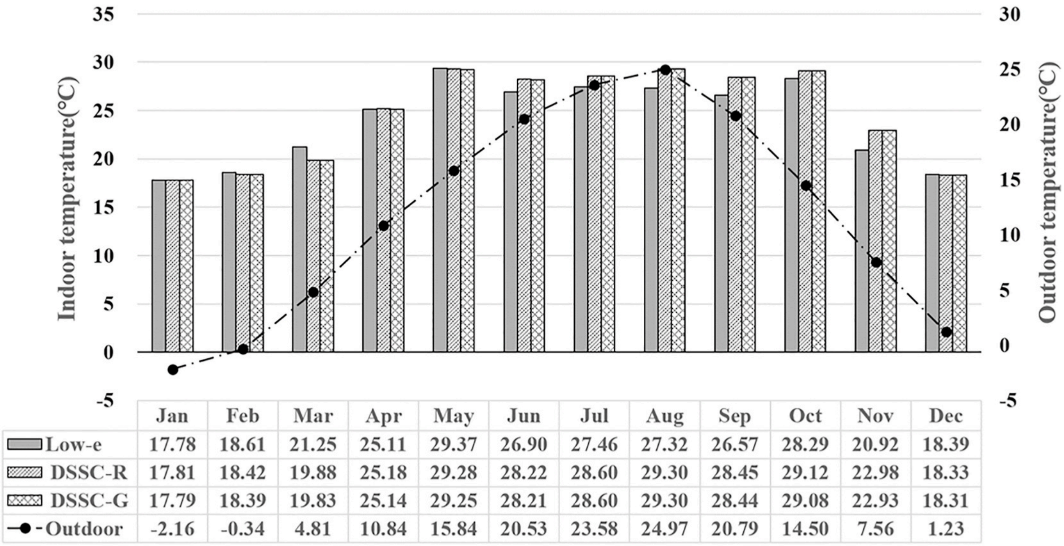
Fig. 2. Simulation space layout and measurement sensor location; (a) Plan of inside office, (b) Key map,(c) Section ‘B–B’ of inside office.

Table 4
Indoor illuminance using VLT, 3F, center office.

Window type	VLT [%]	Average illuminance [Lux]	Min illuminance [Lux]	Max illuminance [Lux]
Low-E	59	1356.55	118.97	2594.13
DSSC-R	4.90	83.98	6.22	161.73
DSSC-G	2.80	46.73	3.10	90.36

be considered because a low SHGC can reduce the cooling energy in summer and increase the heating energy in winter. The simulation was conducted with the cooling/heating systems turned off.

Fig. 3 shows the variations in the indoor temperature according to the solar gain of each window type. In summer, low-e glazing showed the lowest average indoor temperature of 28.47 °C. DSSC-R and DSSC-G both showed a slightly higher average indoor temperature of 28.64 °C, which is 0.18 °C higher than that of the reference low-e glazing model. During winter, low-e glazing showed the lowest average indoor temperature of 19.24 °C, whereas that of DSSC-R was 19.39 °C, which is 0.15 °C higher than that of the reference model. In addition, during the intermediate season, the average indoor temperature of DSSC-R increased by 0.67 °C, compared to the reference model. Low-e glazing exhibited the highest solar gains, but DSSC-R exhibited the highest indoor temperature regardless of the season, followed by DSSC-G. Low-e glazing exhibited the lowest indoor temperature, contrary to the solar gains. The low indoor temperature of low-e windows can be attributed to the different values of SHGC and U-value. The SHGC values for low-e, DSSC-R, and DSSC-G were 0.490, 0.426, and 0.417, respectively. Since the SHGC of low-e glazing is higher than that of the two types of DSSC, the solar gain of low-e glazing is higher than that of the others. The U-values of low-e, DSSC-R, DSSC-G were 1.540 W/m^{2}K, 1.082 W/m^{2}K, and 1.077 W/m^{2}K, respectively. A higher U-value implies more heat loss



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
▮ Low-e	17.78	18.61	21.25	25.11	29.37	26.90	27.46	27.32	26.57	28.29	20.92	18.39
▨ DSSC-R	17.81	18.42	19.88	25.18	29.28	28.22	28.60	29.30	28.45	29.12	22.98	18.33
▩ DSSC-G	17.79	18.39	19.83	25.14	29.25	28.21	28.60	29.30	28.44	29.08	22.93	18.31
-●- Outdoor	-2.16	-0.34	4.81	10.84	15.84	20.53	23.58	24.97	20.79	14.50	7.56	1.23

Fig. 3. Indoor temperature from solar gains, 3F, center office.

through glazing when the outdoor temperature is higher than the indoor temperature. In particular, significant heat loss occurs during winter and a certain period in summer. Due to the comprehensive thermal effect of SHGC and U-value of glazing, the amount of heat stored in the room is less when the low-e glazing is applied. Consequently, the indoor temperature with the low-e glazing is lower than that with the other two types of DSSC windows.

To examine the building energy consumption according to the window model, the cooling, heating, and lighting energy consumption values were analyzed, followed by the respective peak energies. Table 5 and Fig. 4 show the cooling, heating, and lighting energy consumptions. The reference low-e glazing model exhibited the lowest total energy consumption of 28,879 kWh. The heating energy consumption ratio was higher than that of the cooling. This was followed by DSSC-R and DSSC-G. Thus, DSSC-G exhibited the highest total energy consumption of 53,647 kWh, which is 24,768 kWh (85.7%) higher than that of the reference model.

The two DSSC-type windows showed lower heating energy levels than that of the reference model. The heating energies of DSSC-R and DSSC-G were 5693 kWh and 5356 kWh, which are 35.9% and 39.7% lower than that of the reference model, respectively. In contrast, the reference model showed the lowest cooling energy at 5939 kWh. The cooling energy of DSSC-R increased by 1475 kWh (24.8%), whereas that of DSSC-G increased by 1619 kWh (27.2%). The decrease in heating energy is caused by the heat transmission rate of the DSSC, which reduces the indoor heating loss during winter. For the cooling energy, it was difficult to resolve the indoor heat generation during summer because the heat generation of the interior lighting, owing to VLT, increased, leading to overcooling. This confirms that DSSCs decrease the heating energy in office buildings in cold weather, when the building is vulnerable to indoor heat loss.

The lighting energy showed significant differences between the reference model and the DSSC windows. Lighting energy is directly correlated with VLT. Therefore, the effects of VLT on the lighting energy of each window type were analyzed by applying a dimming control sensor. The control sensor is the same as that mentioned in the indoor illuminance analysis in Fig. 2. The VLT was 4.9% for DSSC-R and 2.8% for DSSC-G, which was approximately 8% that of the low-e glazing value. Thus, the lighting energy consumption of the DSSC windows increased significantly in comparison with the reference model. The lighting energy consumption of DSSC-G was 40,731 kWh, which signifies an increase of 26,683 kWh (189.93%), in comparison with the reference model. Thus, DSSC-G exhibited the highest lighting energy consumption among the three models, followed by DSSC-R at 37,827 kWh, which increased by 23,778 kWh (169.26%). This is because the VLT of the DSSC windows is significantly lower than that of the reference model, thereby increasing the use of artificial indoor lighting. Thus, although DSSC windows decrease the heating energy, their total energy consumption (combined cooling, heating, and lighting energy) was higher than that of the reference model.

The total building energy consumption was analyzed by considering the power generation by the DSSC windows shown in Table 6. High power generation by the DSSC windows employed in this study cannot be expected owing to the extremely low PCE of the DSSCs. The annual power generations of DSSC-R and DSSC-G were 1881 kWh and 1375 kWh, respectively. These values represent only 6.97% and 9.39% of the annual energy consumption. When this was taken into account, the total energy consumptions of DSSC-R and DSSC-G were 49,054 kWh and 52,272 kWh, respectively. Analysis of the annual cooling, heating, and lighting energy consumption and power generation data suggests that DSSC windows can be employed as efficient exterior construction materials when the lighting energy is significantly reduced through VLT improvement. Furthermore, it is necessary to achieve an appropriate PCE as a PV material, rather than as a typical window.

Table 5
Annual energy consumption.

Window type	Amount of energy [kWh/yr]			
	Heating	Cooling	Lighting	Total
Low-E	8891	5939	14,048	28,879
DSSC-R	5693	7414	37,827	50,935
DSSC-G	5356	7559	40,731	53,647

For investigating the peak energy requirement of the tested window types, the amounts of cooling, heating, and lighting energy consumptions were compared on the peak days during the year as shown in Table 7 and Fig. 5. The peak energy consumption occurred during 12 days in August for cooling and 21 days in January for heating. Low-e glazing showed the lowest energy consumption level on the peak heating day at 297.26 kWh, and DSSC-G showed the highest level at 341.62 kWh. For both, the DSSC-R and DSSC-G windows, the heating energy decreased by 53.15 kWh (22.44%) and 54.82 kWh (22.88%) compared to the reference model, and the cooling energy increased by 35.47 kWh (29.13%) and 38.78 kWh (31.84%), respectively. The lighting energy of the DSSC also increased compared to the reference model. The lighting energy consumptions of DSSC-R and DSSC-G increased by 146.28% and 163.24% on the heating peak day and by 286.04% and 315.07% on the cooling peak day, respectively. Further variations in lighting energy on the cooling peak day are caused by the lower lighting energy consumption by the base model than in the heating season. DSSC models use a similar amount of lighting energy regardless of the external conditions due to the low VLT.

The power production levels of DSSC-R during peak days were 3.97 kWh and 4.23 kWh on January 21 and August 12, respectively, which are higher than those of DSSC-G. However, as with the annual power generation, power production based on the PCE of the DSSC was extremely small, contributing very little to the reduction in peak cooling, heating, and lighting energy consumption. When DSSC windows are used in the building, the peak heating energy reduction during winter can improve indoor comfort by contributing to the stable operation of the building energy consumption. However, during summer, energy costs may increase, and indoor discomfort may occur owing to the increase in peak cooling energy.

3.2. DSSC window performance database

The VLT and PV generation efficiencies of DSSC windows, as an exterior building material, were analyzed. VLT is an important factor for determining the visual comfort of an indoor environment by controlling the window transparency. Thus, because VLT has a direct effect on the use of artificial indoor lighting, it is a basic factor that should be considered for energy savings in buildings. The PCE of the PV has the most important role in terms of producing power and contributing to the reduction in the building's energy consumption.

To this end, in this study, the total energy consumptions of the cooling, heating, and lighting energy were analyzed by changing the VLT in 10% increments from 5 to 60%, and the PCE in 1% increments from 2 to 20%. The VLT value was set based on DSSC-R as shown in Table 2, which is the earliest developed and most widely used DSSC. A DSSC window layer was composed by adjusting the VLT of the DSSC cell as shown in Table 8.

To compare the energy consumption according to the VLT, a VLT of 5% was established as the reference model, which is similar to the VLT of the DSSC window in this study. A VLT of 7% was also analyzed, which is similar to the VLT of the DSSC. The results are outlined in Table 9 and Fig. 6. The higher the VLT, the higher the heating energy and the lower the cooling and lighting energy levels. Compared to the reference model (5% VLT), the heating energy increased by 6646 kWh/yr (16.74%) to 8932 kWh/yr (56.90%) as the VLT increased in 10% units from 10 to 60%. The rate of increase gradually decreased from 906 kwh/yr (15.92%) to 195 kWh/yr (3.44%). The cooling energy decreased by less than the increase rate of the heating energy and the decrease rate of the

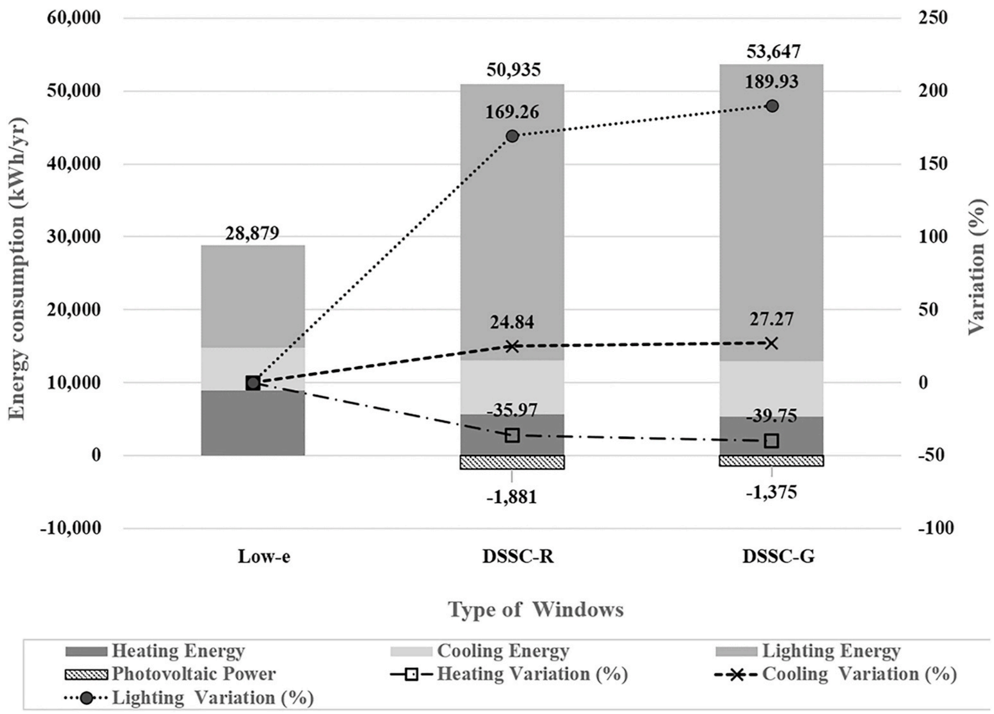


Fig. 4. Annual energy consumption and PV Power (variation: percentage change compared to base model (low-e glazing)).

Table 6
Net energy accounting for DSSC power generation.

Window type	Generated energy [kWh/yr]	Net energy [kWh/yr]
Low-E	–	28,879
DSSC-R	1881	49,054
DSSC-G	1375	52,272

lighting energy. The cooling energy decreased from 7032 kWh/yr (5.15%) to 5267 kWh/yr (28.96%) as the VLT changed from 10 to 60%. As with heating, the reduction rate gradually decreased from 8.94% to 0.96%. The lighting energy consumption, which is the affected the most by the changes in the VLT, decreased further as the VLT increased. It decreased to 11,370 kWh/yr (69.94%) when the maximum VLT was 60%, compared to 37,827 kWh/yr of the reference model. The reduction rate decreased from 22.42% to 3.14% owing to the VLT. As these results indicate, an increase in the VLT decreases the lighting energy, resulting from the decreased use of indoor artificial lighting owing to the natural light; thus, the cooling energy decreases and heating energy increases because of the decrease in internal heat.

Table 10 shows the PV power production according to the PCE of the DSSC. The minimum PCE was set to 2%, which is close to the PCE of the DSSC utilized in this study. When the PCE increased by 1%, the power production increased by the same amount: 648 kWh/yr. Thus, the power generation was 12,972 kWh/yr when the PCE was 20%, the maximum level applied in this study, and 1297 kWh/yr, when it was 2%, which was the minimum.

The change in the energy consumption of DSSC windows, according to the changes in VLT and PCE, compared to the total energy consumption of low-e glazing windows presented in Fig. 4, is shown in Fig. 7. Studies on DSSC glazing are more common in other countries than in Korea. Based on the existing literature, for single windows, the VLT of a DSSC is 53% [27,28] and PCE is 11% [29,30]. The cell efficiency of DSSCs, suggested by the National Renewable Energy Laboratory, is 13% as of 2020. However, double or triple windows must be employed to satisfy the window insulation standards of South Korea, causing a difference in VLT compared to the studies conducted in other countries. The simulation results show that the minimum VLT is 30% and the amount of energy savings is 4861.44 kWh/yr to satisfy the PCE of 13%. From a VLT of 50%, energy savings are possible in combination with all power generation efficiencies.

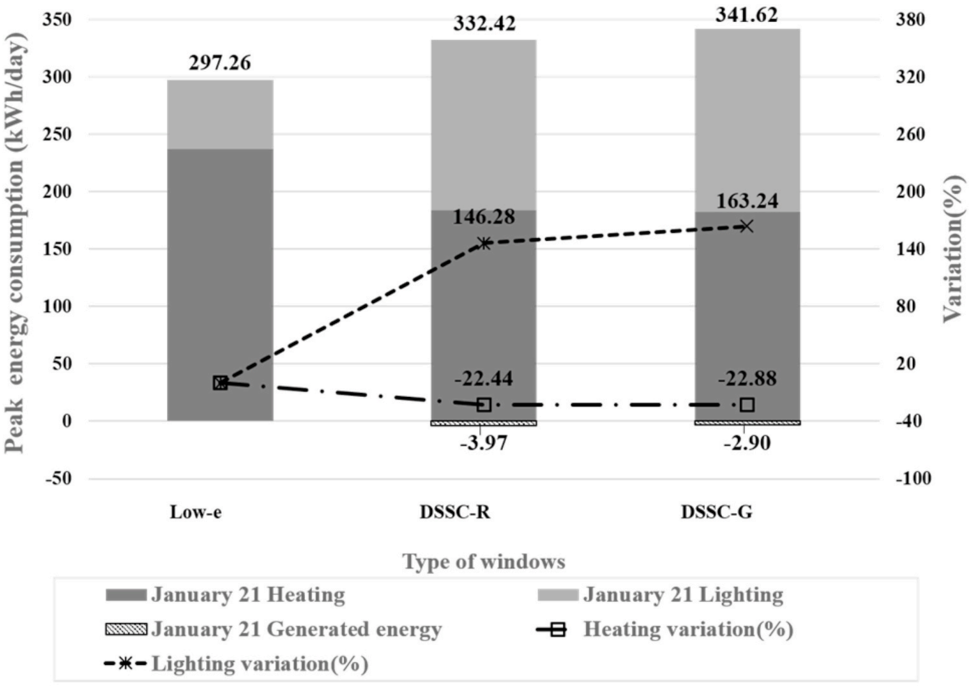
4. Conclusions

The correlations between the environmental performance and energy consumption of a building with DSSC windows were analyzed using DesignBuilder, a computer simulation program, to facilitate the selection of DSSC windows with accurate performance levels. The results can be summarized as follows.

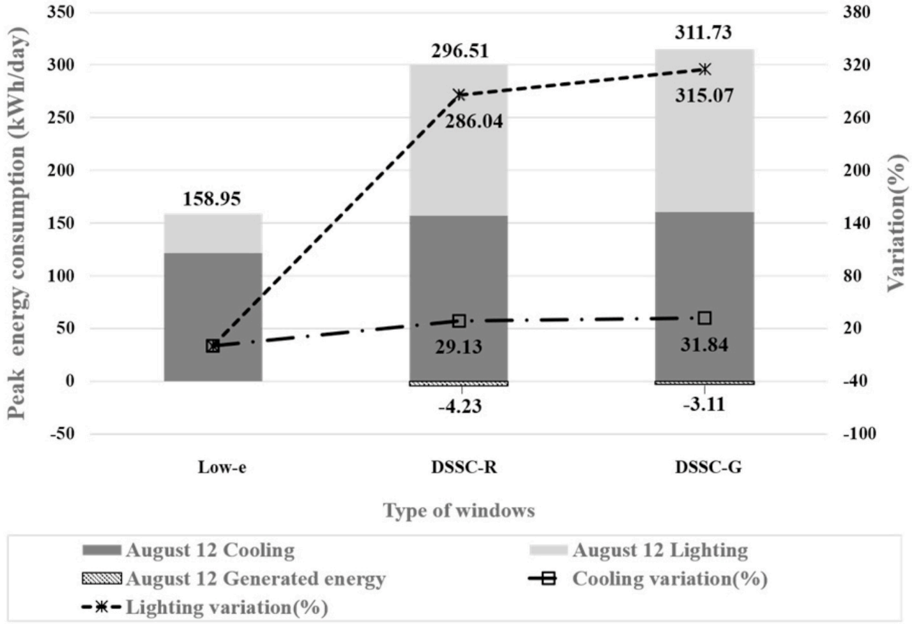
1. The average indoor illuminance decreased in the following order, based on the window type and the VLT: low-e glazing (1356.55 lux) > DSSC-R (83.98 lux) > DSSC-G (46.73 lux). The office indoor illuminance standard of 300–500 lux could not be satisfied by natural light only when the colored BIPV windows were utilized. To achieve

Table 7
Peak energy consumption.

Window type	Heating peak day (January 21) [kWh/day]			Cooling peak day (August 12) [kWh/day]		
	Heating	Lighting	Generated energy	Cooling	Lighting	Generated energy
Low-E	236.89	60.37	–	121.78	37.17	–
DSSC-R	183.74	148.68	3.97	157.25	143.49	4.23
DSSC-G	182.70	158.92	2.90	160.56	154.28	3.11



(a) Heating peak day (January 21)



(b) Cooling peak day (August 12)

Fig. 5. Peak energy consumption and PV power (variation: percentage change compared to base model (low-e glazing)); (a) heating peak day (January 21), (b) cooling peak day (August 12).

a proper level of indoor illuminance, the current VLT performance of the DSSCs should be improved.

2. Low-e glazing showed the highest annual solar gain, followed by the DSSC windows (R and G), while the annual average indoor temperature was higher with DSSC windows than with low-e glazing owing to the combined effect of the SHGC and the U-value. Low-e glazing gains more solar energy with a higher SHGC but loses more heat with a higher U-value. As a result of the comprehensive thermal effect due to the higher SHGC and U-value, the amount of stored heat in the room through the window using low-e glazing is less than that of the DSSC, resulting in a lower temperature.
3. The total annual energy consumption decreased in the following order: DSSC-G (53,647 kWh) > DSSC-R (50,935 kWh) > low-e glazing (28,879 kWh); DSSC-G exhibited the largest increase of 24,768 kWh (85.77%) due to its excessively high lighting and cooling energy requirements and low VLT. For improving the energy

Table 8
The VLT of DSSC windows based on the VLT of DSSC.

DSSC cell VLT [%]	DSSC windows VLT [%]
6.2	5
8.5	7
12	10
24	20
36	30
48	40
60	50
72	60

Table 9
The building energy consumption with DSSC windows based on VLT.

VLT [%]	Amount of energy [kWh/yr]				Note
	Heating	Cooling	Lighting	Total	
5	5693	7414	37,827	50,935	Base case
7	6113	7251	34,945	48,309	
10	6646	7032	31,203	44,882	
20	7552	6369	22,722	36,644	
30	8105	5848	17,581	31,535	
40	8491	5521	14,456	28,468	
50	8736	5338	12,559	26,634	
60	8932	5267	11,370	25,571	

performance of colored BIPV windows, a significant improvement in the VLT is required.

4. The power production levels of the DSSC-R and DSSC-G windows were only 6.97% and 9.39%, respectively, of the annual total building energy consumption, indicating a very low contribution to energy consumption. To realize the role of DSSC windows as PVs, a higher PCE is urgently needed.
5. While evaluating the energy performance of the colored BIPV windows when their VLT and PV PCE values were parametrically changed, practically reasonable levels of the VLT and PV PCE were suggested. The minimum level of energy savings, compared to that using low-e glazing, was realized when a BIPV window with 20% VLT for a 14% PCE was utilized. In addition, at > 50% VLT, energy savings were possible at every level of the PV PCE. However, in practice, it is expected that there will be technical and economic limitations to achieving the maximum possible VLT and PCE values. Therefore, further research and development should be conducted when considering the actual performance level that can be implemented.

In this study, we compared the solar gain, indoor temperature, cooling and heating energy, lighting energy, power generation, and the lighting and energy environment characteristics of DSSC windows. Furthermore, we constructed a database for VLT and PCE to facilitate the selection of the actual performance level for the application of DSSC windows. The results confirmed that the current characteristics of DSSC windows have weaknesses in terms of a building's indoor illuminance and energy consumption compared to the widely applied low-e glazing. The effective performance level of DSSC windows, which can reduce energy consumption compared to low-e glazing, was found to be a

Table 10
PV power generation based on DSSC efficiency.

DSSC cell efficiency [%]	Power generation [kWh/yr]
2	1297
3	1945
4	2594
5	3243
6	3891
7	4540
8	5189
9	5837
10	6486
11	7134
12	7783
13	8432
14	9080
15	9729
16	10,378
17	11,026
18	11,675
19	12,324
20	12,972

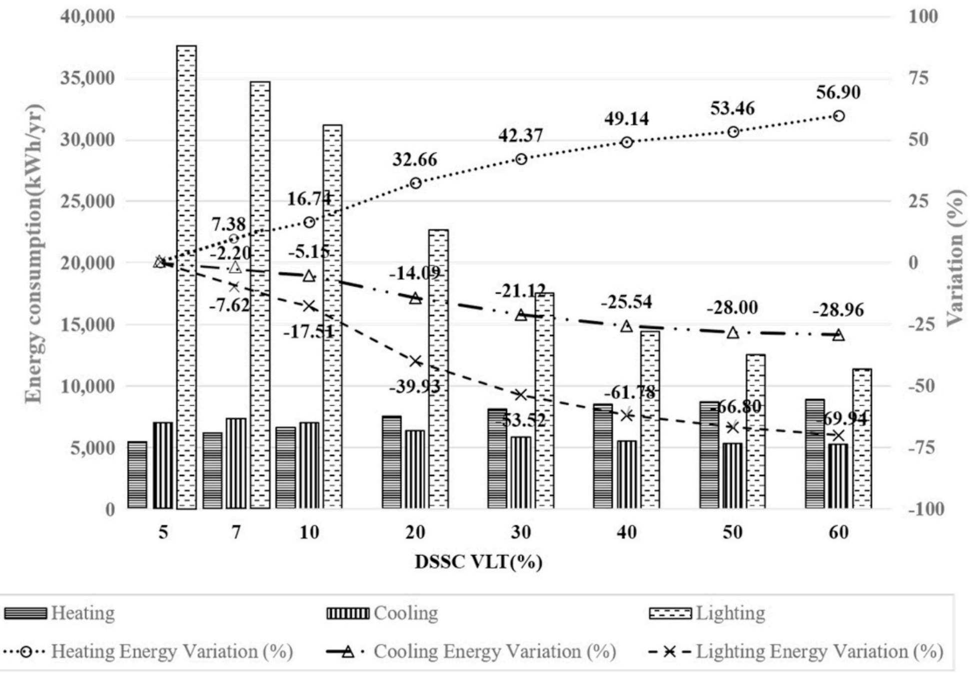
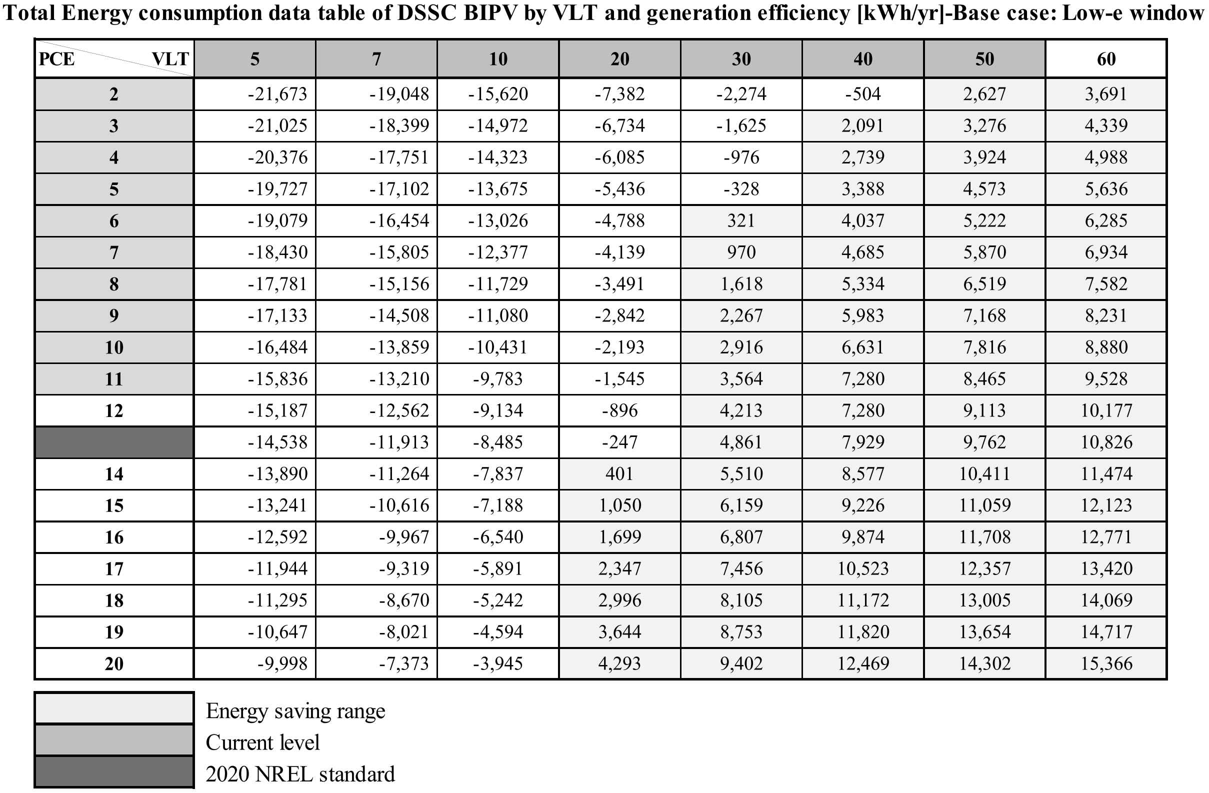


Fig. 6. The building energy consumption with DSSC windows by VLT (Variation: A percentage change compared to VLT 5%).



Total Energy consumption data table of DSSC BIPV by VLT and generation efficiency [kWh/yr]-Base case: Low-e window

PCE \ VLT	5	7	10	20	30	40	50	60
2	-21,673	-19,048	-15,620	-7,382	-2,274	-504	2,627	3,691
3	-21,025	-18,399	-14,972	-6,734	-1,625	2,091	3,276	4,339
4	-20,376	-17,751	-14,323	-6,085	-976	2,739	3,924	4,988
5	-19,727	-17,102	-13,675	-5,436	-328	3,388	4,573	5,636
6	-19,079	-16,454	-13,026	-4,788	321	4,037	5,222	6,285
7	-18,430	-15,805	-12,377	-4,139	970	4,685	5,870	6,934
8	-17,781	-15,156	-11,729	-3,491	1,618	5,334	6,519	7,582
9	-17,133	-14,508	-11,080	-2,842	2,267	5,983	7,168	8,231
10	-16,484	-13,859	-10,431	-2,193	2,916	6,631	7,816	8,880
11	-15,836	-13,210	-9,783	-1,545	3,564	7,280	8,465	9,528
12	-15,187	-12,562	-9,134	-896	4,213	7,280	9,113	10,177
	-14,538	-11,913	-8,485	-247	4,861	7,929	9,762	10,826
14	-13,890	-11,264	-7,837	401	5,510	8,577	10,411	11,474
15	-13,241	-10,616	-7,188	1,050	6,159	9,226	11,059	12,123
16	-12,592	-9,967	-6,540	1,699	6,807	9,874	11,708	12,771
17	-11,944	-9,319	-5,891	2,347	7,456	10,523	12,357	13,420
18	-11,295	-8,670	-5,242	2,996	8,105	11,172	13,005	14,069
19	-10,647	-8,021	-4,594	3,644	8,753	11,820	13,654	14,717
20	-9,998	-7,373	-3,945	4,293	9,402	12,469	14,302	15,366

□ Energy saving range
▨ Current level
■ 2020 NREL standard

Fig. 7. Total energy consumption using VLT for DSSC windows and the level of PCE (current level: standard of existing research).

minimum of 20% VLT based on the power generation at each PCE. Since the results of this study are based on a database obtained through simulations, the actual performance range for feasible VLT and PV generation efficiencies of DSSC windows should be selected using the results as a basis data, for continued research into the application of DSSC windows.

CRediT authorship contribution statement

Min Hee Chung: Conceptualization, Methodology, Software. **Bo Rang Park:** Validation, Writing - original draft. **Eun Ji Choi:** Investigation. **Young Jae Choi:** Resources. **Choonyeob Lee:** Data curation. **Jongin Hong:** Formal analysis. **Hye Un Cho:** Visualization. **Ji Hyeon Cho:** Visualization. **Jin Woo Moon:** Supervision, Project administration.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.solmat.2020.110683.

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