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A Prototype Design and Development of the Smart Photovoltaic System Blind Considering the Photovoltaic Panel, Tracking System, and Monitoring System

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Abstract: This study aims to design and develop the prototype models of the smart photovoltaic system blind (SPSB). To achieve this objective, the study defined the properties in three ways: (i) the photovoltaic (PV) panel; (ii) the tracking system; and (iii) the monitoring system. First, the amorphous silicon PV panel was determined as a PV panel, and the width and length of the PV panel were determined to be 50 mm and 250 mm, respectively. Second, the four tracker types (i.e., fixed type, vertical single-axis tracker, horizontal single-axis tracker, and azimuth-altitude dual-axis tracker) was applied, as well as the direct tracking method based on the amount of electricity generated as a tracking system. Third, the electricity generation and environmental conditions were chosen as factors to be monitored in order to evaluate and manage the technical performance of SPSB as a monitoring system. The prototype model of the SPSB is designed and developed for providing the electricity generated from its PV panel, as well as for reducing the indoor cooling demands through the blind's function, itself (i.e., blocking out sunlight).

Keywords: smart photovoltaic system blind; prototype model; photovoltaic panel; tracking system; monitoring system

1. Introduction

To solve the global warming potential and depletion of fossil fuels, the Paris agreement was adopted through the 21st Conference of the Parties held in Paris, France in December 2015. In response to this, the South Korea government established the '*Nationally Determined Contributions*' to reduce GHG emissions by 37% below the business-as-usual emission level by 2030 [1–4]. Accordingly, energy reduction is required in the building sector, which accounts for about 40% of the total fossil fuel consumption [5,6]. The South Korea government established the policy '*Obligation to Zero Energy Building by 2025*'. In a related move, the '*4th Renewable Energy Penetration Plan*' was established, and among the new and renewable energy sources, the ratio of photovoltaic (PV) system was increased from 2.7% (2015) to 4.1% (2030) [7–9]. However, there are certain limitations in looking to achieve the aforementioned goals using the rooftop PV system [10]. Thus, several previous studies were conducted to find the ways to install the PV system on the building façade, as well as rooftop. Menoufi et al. [11] conducted the life cycle assessment of a building integrated concentrated PV scheme. Compared with the environmental impact of building integrated PV, that of a building integrated concentrated PV scheme, was analyzed to be lower. Tak et al. [12] designed a changeable organic semi-transparent solar cell window and analyzed its effect in terms of building energy efficiency and user comfort. In this context, the '*Act on the promotion of green buildings*' became effective in May 2015, which makes it compulsory to install shading devices in public buildings (office buildings and education facilities) whose total floor area exceeds 3000 m^2 with exterior walls that have windows or are made of glass [13]. The PV system blind can be considered one of the best solutions to provide the electricity generated from its PV panel and to reduce the indoor cooling demands through the blind's main function (i.e., blocking out sunlight) [14,15].

As shown in Table 1, previous studies concentrated on the design of the PV system and experiments on the building façades (vertical) as well as the building roofs (horizontal). In particular, these previous studies considered the properties of the PV system with regard three aspects (i.e., PV panel, tracking system, and monitoring system). The literature review can be summarized in three ways, as follows.

First, in terms of the PV panel, some of the previous studies have analyzed the technical performance of the PV system. Koo et al. [10], Mandalaki et al. [15], and Mandalaki et al. [16] analyzed the performance of the electricity generation with respect to the rooftop PV system and the shading devices with the integrated PV using the crystalline PV panel, respectively. Bahr [17] analyzed the PV blinds' optimal design parameters in terms of type of PV panel (i.e., crystalline silicon (c-Si) and a-Si) and installation options (i.e., ratio between the blinds installation distance to the module depth and tilt angle). Hwang et al. [18] conducted the optimization of the building integrated PV system considering four installation factors (i.e., module type, inclination, installation distance to module length ratio, and direction).

Second, in terms of the tracking system (i.e., tracker type and tracking method), some of the previous studies have analyzed the technical performance of the PV system. Lazaroiu et al. [19], Cruz-Peragón et al. [20], and Virtuani and Fanni [21], Heslop and Macgill [22], Mousazadeh et al. [23], and Dolara and Mussetta [24] performed comparative analyses on the electricity generation of the PV system according to the tracker type. In these previous studies, the performance of the electricity generation on the PV panel was found to be carried out in the order of the dual tracker, single tracker, and fixed type. Abdallah and Nijmeh [25] and Abdallah and Badran [26] developed a tracking system based on the direct tracking method and indirect tracking method, respectively. Through this, the performance of electricity generation due to the application of the tracking system was evaluated.

Third, in terms of the monitoring system, some of the previous studies have analyzed the technical performance of the PV system. Kang et al. [27] analyzed the relationship between the two variables by monitoring the electricity generation and temperature on the blinds integrated PV panels. Zahran et al. [28] developed a monitoring system for electricity generation and the temperature of PV surface by using Labview software developed by National Instruments (Austin, TX, USA). Kim et al. [29] and Kim et al. [30] performed the monitoring of the electricity generation and illuminance to analyze the electricity generation and incoming daylight from the PV blind.

Table 1. Literature review on the PV system.

Authors	Type of Application		Properties of the PV System									Type of Research		Country
			PV panel			Tracking System		Monitoring System						
									Environmental Condition					
	Rooftop (Horizontal)	Façade (Vertical)	c-Si	a-Si	CIGS	Tracker Type	Tracking Method	Electricity	Temperature	Solar Radiation	Illuminance	Design	Experiment	
Mandalaki et al. [16]	-	●	●	-	-	Fixed type	-	●	-	-	-	●	-	Greece
Koo et al. [10]	●	-	●	-	-	Fixed type	-	●	-	-	-	●	-	South Korea
Mandalaki et al. [15]	-	●	●	-	-	Fixed type	-	●	-	-	-	●	●	Greece
Bahr [17]	-	●	●	●	-	Fixed type	-	●	-	-	-	●	-	UAE
Hwang et al. [18]	-	●	●	●	-	Fixed type	-	●	-	-	-	●	-	South Korea
Lazaroiu et al. [19]	●	-	-	-	-	Fixed type, Single-axis tracker	-	●	-	-	-	-	●	-
Cruz-Peragón et al. [20]	●	-	-	●	-	Fixed type, Dual-axis tracker	-	●	-	-	-	●	-	Spain
Virtuani and Fanni [21]	●	-	●	●	-	Fixed type, Dual-axis tracker	-	●	-	-	-	-	●	Switzerland
Heslop and Macgill [22]	●	-	●	●	-	Fixed, Single-axis tracker, Dual-axis tracker	-	●	-	-	-	●	-	Australia
Mousazadeh et al. [23]	-	-	-	-	-	Fixed, Single-axis tracker, Dual-axis tracker	Direct tracking method	●	-	-	-	-	●	-
Dolara et al. [24]	●	-	●	-	-	Fixed type, Single-axis tracker	-	●	-	●	-	-	●	Italy
Abdallah and Nijmeh [25]	●	-	-	-	-	Fixed type, Dual-axis tracker	Direct tracking method	●	-	-	-	-	●	Jordan
Abdallah and Badran [26]	●	-	-	-	-	Fixed, Single-axis tracker	Indirect tracking method	●	●	●	-	-	●	Jordan
Kang et al. [27]	-	●	●	-	-	Single-axis tracker	-	●	●	-	-	●	-	South Korea
Zahran et al. [28]	●	-	-	-	-	-	-	●	●	-	-	-	●	-
Kim et al. [29]	-	●	●	-	-	Single-axis tracker	-	●	-	-	●	-	●	South Korea
Kim et al. [30]	-	●	●	-	-	Single-axis tracker	-	●	-	-	●	-	●	South Korea

Note: c-Si stands for the crystalline silicon PV panel; a-Si stands for the amorphous silicon PV panel; and CIGS stands for the copper-indium-gallium-selenide PV panel (CIGS: copper-indium-gallium-selenide).

As with the literature review, there are several limitations in the previous studies. First, the electricity generation of the c-Si PV panel and the a-Si PV panel were analyzed for the PV blind and rooftop PV system, whereas that of the copper-indium-gallium-selenide (CIGS) PV panel was not taken into account for the analysis. Second, as for the rooftop PV system, various tracker types (i.e., fixed, single-axis, and dual-axis tracker types) and tracking methods (i.e., direct and indirect tracking methods) were analyzed. On the other hand, as for the PV blind, only the fixed type and single-axis tracker type was analyzed and, accordingly, there is a lack of research that comprehensively considers the dual-axis tracker type and tracking method. Third, few studies are conducted to evaluate the feasibility of the PV blind that takes into consideration the three properties (i.e., PV panel, tracking system, and monitoring system) and performs the experimental research. To address these challenges, this study aimed to design and develop the prototype models of the smart photovoltaic system blind (SPSB) with consideration of the three properties (i.e., PV panel, tracking system, and monitoring system). The three properties (i.e., PV panel, tracking system, and monitoring system) of the SPSB were defined in Section 2. Additionally, detailed techniques applicable to the SPSB by property (i.e., PV panel: PV techniques and PV panel's design variables; tracking system: tracker type and tracking method; and monitoring system: monitoring factor) were explained. In Section 3, the developed three prototype models of the SPSB were described in terms of three properties (i.e., PV panel, tracking system, and monitoring system). Finally, the conclusion of this study was presented in Section 4.

2. A Prototype Design of the Smart Photovoltaic System Blind

To reduce the building energy, it is essential to develop a PV system that can be applied not only to the rooftop areas of buildings, but also to building façades. The proposed SPSB is a product that can be applied to building façades, especially to the external window areas of buildings. The major properties of the SPSB are composed of three characteristics: (i) the PV panel; (ii) the tracking system, and (iii) the monitoring system (refer to Figure 1). The PV panel generates the electricity through photoelectric effects using solar radiation. The tracking system helps maximize the electricity generation of the SPSB by controlling the angle of incidence between the PV panel and the incoming solar radiation using the printed circuit board and controller. The monitoring system establishes the current, voltage and power produced though the PV panel as a database and evaluates the optimal tilted and azimuth angle of the SPSB that maximizes the electricity generation. Based on the evaluation results, the tilted and azimuth angle of the PV panel is controlled to maintain the maximum electricity generation of the SPSB.

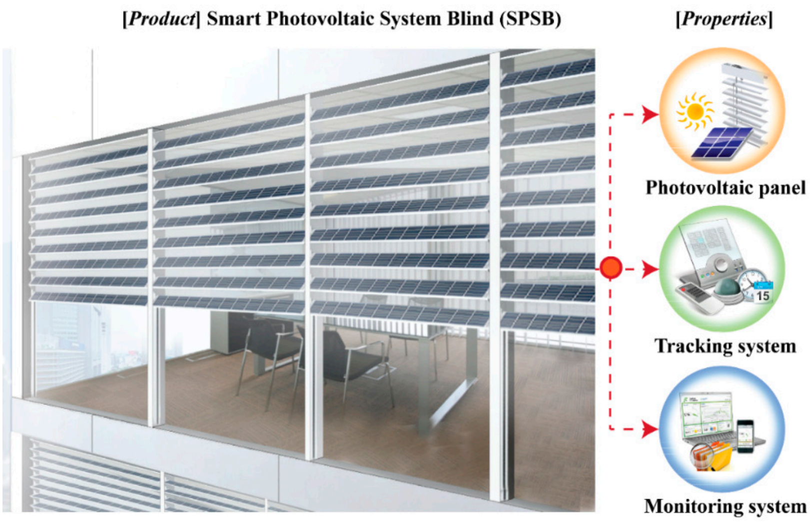

Figure 1. Concept of the smart photovoltaic system blind.

The SPSB is capable of making a variety of combinations of these three properties (i.e., PV panel, tracking system, and monitoring system) according to the particular circumstances and the user's decision. As a result, the technical performance of the SPSB (i.e., the amount of electricity generation) is determined. Therefore, the terminology "smart" used in this study signifies that the SPSB can generate maximum electricity output by combining the three properties [13].

2.1. Properties 1: PV panel

In terms of the PV panel properties, two factors were considered for the development of the SPSB in this study: (i) PV techniques applicable to the SPSB and (ii) PV panel designs applicable to the SPSB.

2.1.1. PV Techniques Applicable to the SPSB

The PV techniques applicable to the SPSB are largely divided into two generations: (i) the first-generation PV techniques (i.e., mono-crystalline silicon (mono-Si) and poly-crystalline silicon (poly-Si)); and (ii) the second-generation PV techniques (a-Si, CIGS, and cadmium telluride (CdTe) thin-film). The third-generation PV techniques (i.e., dye-sensitized PV panel (DSSP), organic PV (OPV) panel, and nano PV panel) were excluded from this study since the technology is still in an experimental stage [13,31–36]. To determine the PV techniques applicable to the SPSB, this study considered two main issues: (i) usability issues (i.e., efficiency, shading effect, and certification) and (ii) constructability issues (i.e., width, length, thickness, and weight) (refer to Table 2) [37–41].

Table 2. Usability and constructability issues of the first- and second-generation PV panels.

Classification			**First-Generation PV Panels**		**Second-Generation PV Panels**		
			Mono-Si	**Poly-Si**	**a-Si**	**CIGS**	**CdTe**
Usability issue	Efficiency (module level)		14.5%	14.0%	5.8%	10.5%	9.9%
	Shading effect		High	High	Low	Low	Low
	Harmful effect		No	No	No	No	Yes
Constructability issue	Size	Width	Customized	Customized	Customized	Customized	Customized
		Length	Customized	Customized	Customized	Customized	Customized
		Thickness	35 mm	48 mm	2.6 mm	2.5 mm	27.9 mm
	Weight		11.7 kg/m^2	11.6 kg/m^2	2.5 kg/m^2	2.4 kg/m^2	16.7 kg/m^2

Note: Mono-Si stands for the mono-crystalline silicon PV panel; Poly-Si stands for the poly-crystalline silicon PV panel; a-Si stands for the amorphous silicon PV panel; CIGS stands for the copper-indium-gallium-selenide PV panel; and CdTe stands for the cadmium telluride PV panel.

(i) Usability issues of the PV panel: The usability issues of the SPSB took into account three factors (i.e., shading effect, efficiency, and certification). First, the efficiency of the PV panel is a factor determined by the photoelectric effect—the conversion of solar radiation into electricity. Additionally, as the photoelectric effect of PV cell is greater, the efficiency of the PV panel increases. As shown in Table 2, the efficiency of the PV panel was determined to be the average efficiency of PV panel in module level (i.e., mono-Si: 14.5%, poly-Si: 14.0%, a-Si: 5.8%, CIGS: 10.5%, and CdTe: 9.9%) [42]. The efficiency of the second-generation PV panel (a-Si: 5.8%, CIGS: 10.5%, and CdTe: 9.9%) was determined to be 1.33–2.50 times inferior to that of the first-generation PV panel (i.e., mono-si: 14.5% and poly-si: 14.0%). However, unlike the first-generation PV panel, the second-generation PV panel exhibits excellent applicability due to the application of the thin film PV technique [35,42]. Second, the shading effect of the PV panel is a factor that has a significant influence on the electricity generation performance of the PV panel, and there is a noticeable difference in the sensitivity depending on the type of PV panel. As shown in Table 2, the second-generation PV panels (a-Si, CIGS, and CdTe: low) are superior to the first-generation PV panels (mono-Si and poly-Si: high) in terms of the shading effect [17,43,44]. Thus, with regard the shading effect of the PV panel, the second-generation PV panels were determined as a PV technique applicable to the SPSB. Third, the possible harmful effects of the PV panel were a factor determined depending on whether or not the toxic material may be used. According to the *Enforcement Rule of the 'Act on the promotion of the development, use and diffusion of new and renewable energy'* in South Korea, CdTd PV panels which are manufactured using toxic materials (i.e., cadmium and tellurium) were excluded from these considerations [45,46].

(ii) Constructability issues of the PV panel: The constructability issues of the SPSB took into account two factors (i.e., size and weight). Towards this end, this study considered the PV technique applicable to the SPSB based on the size and weight of the wood venetian blind as it is superior when compared to other types of blinds in terms of both size and weight [47]. First, in terms of size, the first and second-generation PV panels met the standards (i.e., width: below 63.5 mm, length: below 2438 mm, and thickness: below 3 mm) of the venetian blind. For example, in terms of width, the maximum width at which the wood venetian blind can be manufactured is 63.5 mm, and both the first and second-generation PV techniques (mono-Si, poly-Si, a-Si, and CIGS: customized) satisfy this criteria. Second, in terms of weight, the first-generation PV panel (mono-Si: 11.7 kg/m^2 and poly-Si: 11.6 kg/m^2) does not meet the standard (i.e., weight: 3 kg/m^2) of the venetian blind, whereas the second-generation PV panel (a-Si: 2.5 kg/m^2 and CIGS: 2.4 kg/m^2) does. Thus, in terms of the constructability issues of the PV panel, the second-generation PV panels were chosen as the PV technique applicable to the SPSB [48].

2.1.2. PV Panel's Design Variables Applicable to the SPSB

To determine the PV panel design applicable to the SPSB, the optimal size capable of maximizing the electricity generation of PV panels should be considered. Towards this end, three factors were considered in this study: (i) the length of the PV panel; (ii) the width of the PV panel; and (iii) the distance between the centerline of the SPSB and the exterior window. This is because the influence of the shading effect caused by the slat of the SPSB should be minimized to maximize the electricity generation of the SPSB.

(i) Length of the PV panel: According to previous studies, the length of the PV panel has little effect on the electricity generation per unit area. However, the length of the PV should be considered as a factor affecting the range of tracking [27].

(ii) Width of the PV panel: According to previous studies, the width of the PV panel is a factor that has a great effect on the electricity generation per unit area. This is because as the width of the PV panel increases, the shading effect caused by the upper slat increases. Thus, there is a need to determine the optimal width of the PV panel in order to maximize electricity generation [27].

(iii) Distance between the centerline of the SPSB and the exterior window: According to previous studies, the distance between the centerline of the SPSB and the exterior window is a factor that has an effect on the electricity generation per unit area [47]. This is because a farther distance between the SPSB and exterior window leads to reduced solar radiation, resulting in the reduction of electricity generation [27].

2.2. Properties 2: Tracking System

In terms of the tracking system properties, the two factors were considered for the development of the SPSB in this study: (i) the tracker type and (ii) the tracking method. First, the tracker type can take account of the fixed type, single-axis, and dual-axis tracker. Second, the tracking method can take account of the direct tracking method and the indirect tracking method [23,49].

2.2.1. Tracker Types Applicable to the SPSB

The tracker types should be considered to maximize electricity generation by increasing the solar radiation that reaches the PV panel. These tracker types can be categorized into the single-axis tracker and dual-axis tracker (refer to Figure 2).

(i) Single-axis tracker type: The single-axis tracker type is a technology that has one axis of rotation and can be divided into four tracker types: (1) the horizontal single-axis tracker (HSAT); the vertical single-axis tracker (VSAT); (2) the tilted single-axis tracker (TSAT); and (3) the polar aligned single-axis tracker (PASAT). The HSAT can track the daily north-south motion of the sun through the axis of rotation horizontal to the ground (refer to tracker type (A) in Figure 2). The VSAT can track the daily east-west motion of the sun through the axis of rotation vertical to the ground (Refer to tracker type (B) in Figure 2). The TSAT sets the axes of rotation between the horizontal and the vertical. Thus, the daily east-west motion of the sun is tracked by setting the axis of rotation to be parallel to the axis of the earth's rotation (refer to tracker type (C) in Figure 2). The PASAT is aligned to the polar star. Through this, the tilt angle becomes equal to the latitude of installation and allows it to align with the Earth's axis (refer to tracker type (D) in Figure 2) [23,49,50].

(ii) Dual-axis tracker type: The dual-axis tracker type is a technology that has two axes of rotation and can be divided into two tracker types: (1) the tip-tilt dual-axis tracker (TTDAT); and (2) the azimuth-altitude dual-axis tracker (AADAT). In general, the TTDAT tracks the daily east-west motion of the sun and north-south motion of the sun by rotating the PV panel fixed to the top of the pole (refer to tracker type (E) in Figure 2). The AADAT can track the daily east-west motion of the sun and the daily north-south motion of the sun using a large ring mounted on the ground with a series of rollers (refer to tracker type (F) in Figure 2) [23,49,50].

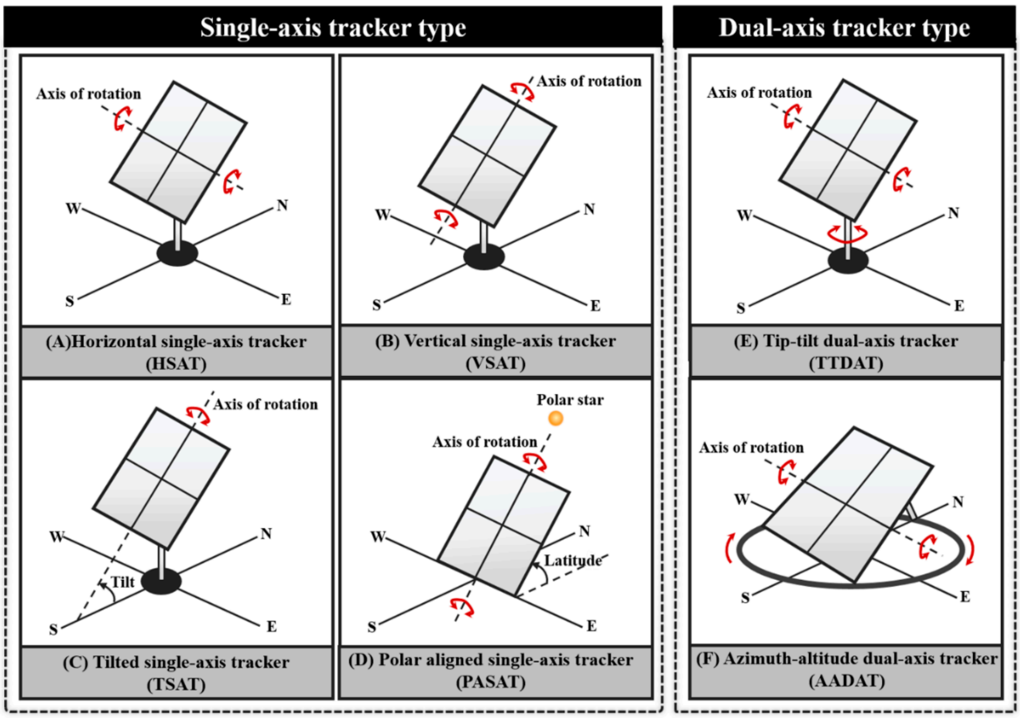

Figure 2. Single- and dual-axis tracker types.

2.2.2. Tracking Methods Applicable to the SPSB

According to control strategies, the tracking methods can be categorized into two types: (i) the direct tracking method; and (ii) the indirect tracking method.

(i) Direct tracking method: The direct tracking method is a method for controlling the tracking system based on the results of the direct measurement from the PV system, and the measurement data can be divided into two types (i.e., solar radiation and electricity generation). The solar radiation-based direct tracking method determines the tracking direction by using a photo-sensor and evaluating the maximum solar radiation data. The electricity generation-based direct tracking method determines the tracking direction based on the evaluation of the current data produced from the PV system. However, the direct tracking method has a disadvantage in that malfunction in tracking can occur as a result of temporary errors [51,52].

(ii) Indirect tracking method: The indirect tracking method is for controlling the tracking system by calculating the position of the sun according to both the date and time. However, this method has disadvantages in that it is difficult to reflect the difference of the electricity generation depending on the location and direction where the PV system is installed.

2.3. Properties 3: Monitoring System

The purpose of the monitoring system is to evaluate the technical performance of the SPSB (i.e., the amount of electricity generation) and to establish the maintenance strategy on the SPSB. Toward this end, the following two factors should be monitored and established as a database: (i) electricity generation; and (ii) environmental conditions.

(i) Electricity generation: In order to evaluate the technical performance of the SPSB, information regarding the amount of electricity generated (i.e., current, voltage, and power) is monitored and established as a database. With the use of this monitoring information, especially on the electricity generation, the electricity generation-based direct tracking method can be applied [27–30,51,52].

(ii) Environmental conditions: The SPSB is a technology based on a variety of electronic components, and it is affected by various external elements. In particular, the environmental conditions (i.e., temperature, humidity, and solar radiation) are a factor that has a very large influence on the performance of the SPSB. Accordingly, information regarding the environmental conditions (i.e., temperature, humidity, and solar radiation) should be monitored and then established as a database in order to perform effective maintenance management on the SPSB [26–28].

3. Development of Prototype Models of the Smart Photovoltaic System Blind

As shown in Figure 3, this study has developed three prototype models of the SPSB to improve the technical performance of the SPSB. The first prototype model was developed to evaluate the possibility of technical realization of the three properties (i.e., PV panel, tracking system, and monitoring system) in a form of blind. The frame and control system of the first prototype model were developed by using the 'Lego Product (e.g., Lego brick, Lego Mindstorms, etc.)' and Labview software, respectively. The second prototype model was developed to achieve a technology level for a real product through integrating these three properties. The third prototype model was developed to improve the technology level of the SPSB for applying it to the real building façade. The frame and control system of the second and third prototype model were developed by using materials actually used to make the real window frames and Labview software, respectively.

Meanwhile, this study considered the three properties to develop the three prototype model. As shown in Table 3, different technologies were applied by properties according to the purpose of the prototype model. The detailed explanations of the prototype model with regard the three properties (i.e., PV panel, tracking system, and monitoring system) are presented in Section 3.

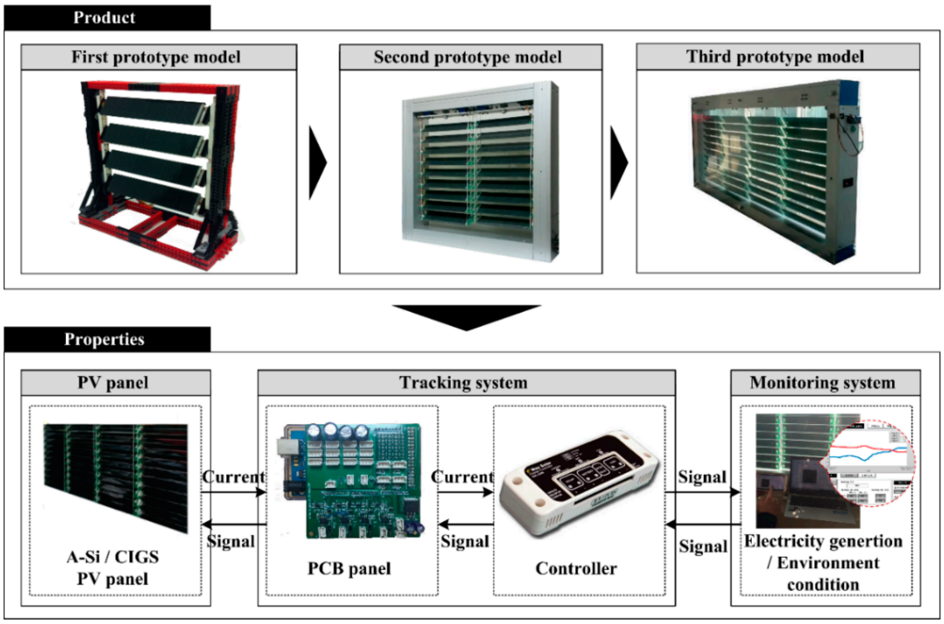

Figure 3. The prototype models of the SPSB and the associated properties.

Table 3. Characteristic by the prototype model of the SPSB.

Properties	Classification		First Prototype Model	Second Prototype Model	Third Prototype Model
PV panel		a-Si CIGS	- ●	● -	● -
Tracking system	Tracker type	Single Dual	VSAT -	HSAT, VSAT AADAT	HSAT, VSAT AADAT
	Tracking method	Direct Indirect	● -	● -	● -
Monitoring system	Electricity generation	Current Voltage Power	● - -	● ● ●	● ● ●
	Environmental condition	Temperature Humidity	- -	- -	● ●

Note. a-Si stands for the for the amorphous silicon PV panel; CIGS stands for the copper-indium-gallium-selenide PV panel; VSAT stands for the vertical single-axis tracker; HSAT stands for the horizontal single-axis tracker; and AADAT stands for the azimuth-altitude dual-axis tracker.

3.1. Properties 1: PV panel

3.1.1. PV Techniques Installed in Prototype Models of the SPSB

In consideration of the PV techniques applicable to the SPSB (i.e., usability and constructability issues), the a-Si and CIGS PV panels which are the second-generation PV panels were used to develop the prototype models of the SPSB (refer to Table 3). As shown in Table 2, the efficiency of the CIGS PV panel is superior to that of the a-Si PV panel. The CIGS PV panel was used in the first prototype model, whereas the a-Si PV panel was used in the second and third prototype models. The reason for changing from the CIGS PV panel to a-Si PV panel is as follows. The a-Si mini PV panel which can be applied to the SPSB prototype model can be produced as a product, while the CIGS mini PV panel cannot. This is because, unlike the a-Si PV panel, the CIGS PV panel, which applies a roll-to-roll manufacturing process, cannot be produced in the form of mini CIGS PV panel which can be applied to the SPSB prototype model. Thus, a-Si PV panel was used in the second and third prototype models to guarantee the stability and reliability of electricity generation measurement results and the supply of components for developing the prototype model of the SPSB. Specific details for each prototype model are as follows.

The first prototype model consisted of a total of four blind slats, and the 'SP1-75' CIGS PV panels manufactured (maximum power: 75 W) by Solopower were attached to each blind slat (refer to Table 4) [53,54]. The 'SP1-75' CIGS PV panels were selected as products that can be purchased in South Korea. Since the 'SP1-75' CIGS PV panel is too large to be applied to the first prototype model, 'SP1-75' CIGS PV panels were cut to be applicable size for the blind slat of the first prototype model. In addition, CIGS PV panel attached to all blind slats were linked in parallel. The second and third prototype models of the SPSB used the '502500-16V' a-Si PV panel manufactured by Solar Center (refer to Table 4). Furthermore, a-Si PV panels attached to all of the blind slats were linked in parallel. The second prototype model of the SPSB was composed of nine blind slats per column and had a total of two columns and 18 blind slats. The third prototype model of the SPSB was composed of ten blind slats per column and had a total of two columns and 40 blind slats.

Table 4. Specifications of the PV panel by prototype model.

Classifications	First Prototype Model	Second Prototype Model	Third Prototype Model
PV panel	SP1-75	502500-16V	502500-16V
Manufacturer	Solopower	Solar Center	Solar Center
Size of PV panel	398 mm × 2197 mm × 2 mm	250 mm × 50 mm × 2 mm	250 mm × 50 mm × 2 mm
Maximum power (P_{max})	75 W	1.5 W	1.5 W
Maximum power voltage (V_{mp})	21.8 V	16 V	16 V
Optimum operating current (I_{mp})	3.4 A	95 mA	95 mA
Short-circuit current (I_{sc})	4.3 A	99 mA	99 mA
Open-circuit voltage (V_{oc})	30.6 V	19.4 V	19.4 V

3.1.2. PV Panel's Design Variables Installed in Prototype Models of the SPSB

As mentioned in Section 2.1.2, the three factors (i.e., length of the PV panel, width of the PV panel, and distance between the centerline of the SPSB and the exterior window) were considered for the development of the prototype models of the SPSB.

The length of the SPSB can be adjusted according to the circumstance and user's decision. However, the length of the prototype models was determined based on the size of the PV panel to guarantee the stability and reliability of the electricity generation measurement results and the supply of components for developing the prototype model of the SPSB. Accordingly, as shown in Table 4, the lengths of the PV panel of the first, second, and third prototype models were determined to be 398 mm, 250 mm, and 250 mm, respectively, based on the length of the 'SP1-75' CIGS PV panel and the '502500-16V' a-Si PV panel [53,54]. Second, the width of the PV panel applied to the SPSB can be determined according to the blind type (e.g., venetian blind, pleated blind, etc.). In this study, the width of the PV panel was determined to be 50 mm based on the size of a standard venetian blind [47]. As mentioned in Section 2.1.2, the greater distance between the SPSB and exterior window leads to the degradation of the electricity generation performance of the SPSB. In this regard, the distance between the centerline of the SPSB and the exterior window was determined to be 25 mm [27].

3.2. Properties 2: Tracking System

3.2.1. Tracker Types Installed in Prototype Models of the SPSB

According to previous studies, the performance of the electricity generation of the PV system was enhanced in the order of the dual-axis tracker type, single-axis tracker type, and fixed type [19–22]. To improve the performance of the electricity generation of the SPSB, the application of the tracker is required. Therefore, among the total five tracker types, four tracker types (i.e., fixed type, VSAT, HSAT, and AADAT) that can track the daily east-west motion and north-south motion of the sun were applied to the prototype model of the SPSB.

The first prototype model applied the VSAT to track the north-south motion of the sun. In the second and third prototype models, the four tracker types (i.e., fixed type, VSAT, HSAT, and AADAT) that can track the daily east-west motion and north-south motion of the sun were all applied. Figure 4 shows the concept diagram of the third prototype model of the SPSB. All the PV panels on the blind slat are connected each other with lifting and rotating ropes. The prototype model of the SPSB moves along the north-south motion of the sun using the motor 'A', motor 'B', rotating rope, and wire-puller, whereas the prototype model of the SPSB moves along the east-west motion of the sun using motor 'C' and gears. Aforementioned in Section 2.2.1, the VSAT and HSAT can track the daily east-west motion (*X*-axis) and north-south motion (*Y*-axis) of the sun, respectively. In addition, the AADAT can track the daily east-west motion (*X*-axis) and north-south motion (*Y*-axis) of the sun. In particular, since the third prototype model is composed of four columns, a comparative analysis on the performance of the electricity generation of the SPSB can be conducted by applying the four tracker types (i.e., fixed type, VSAT, HSAT, and AADAT) at the same time.

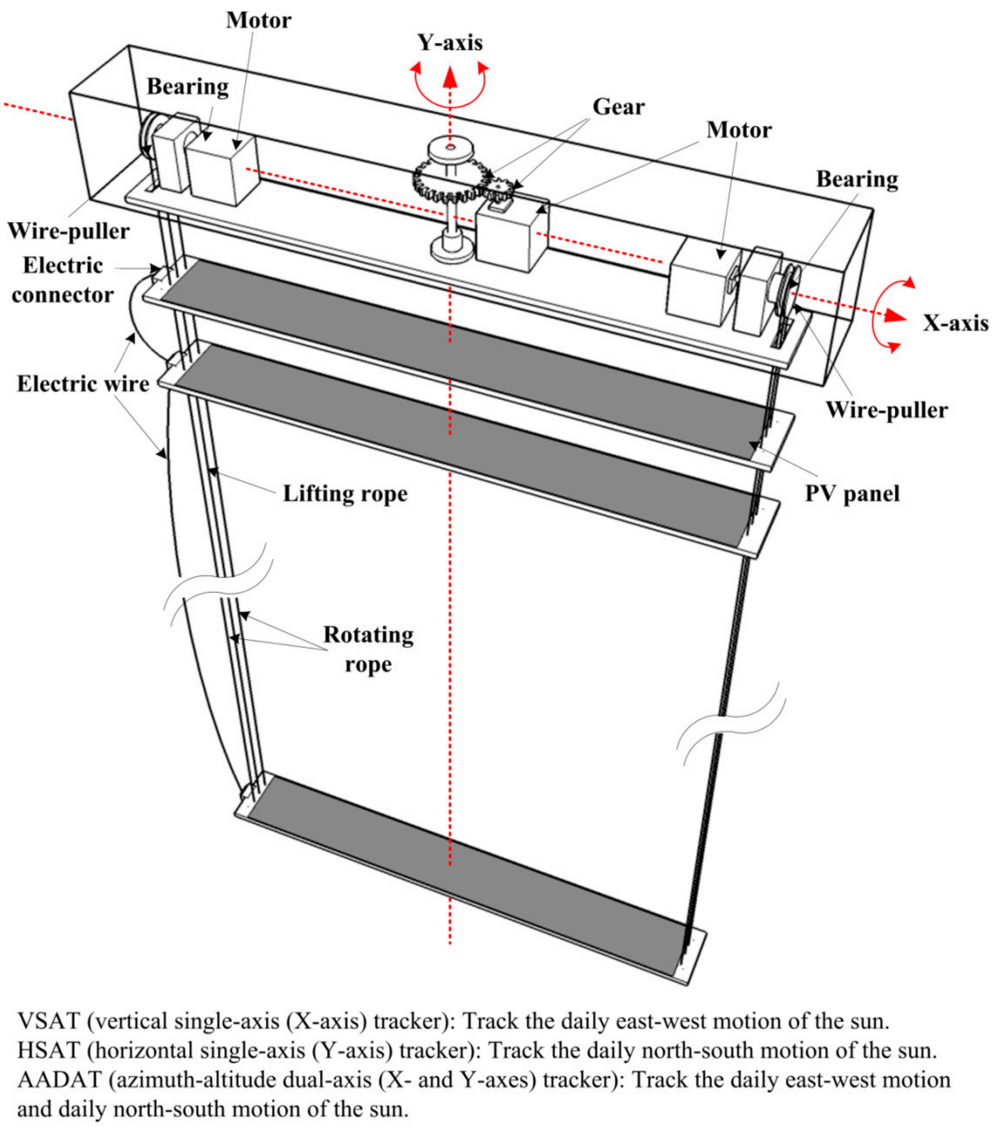

Figure 4. Concept diagram of the third prototype model of the SPSB.

3.2.2. Tracking Methods Installed in Prototype Models of the SPSB

Among the two tracking methods, the direct tracking method was used to develop the prototype model. Particularly with consideration of the costs, the direct tracking method based on the produced electricity generation was applied to the three prototype models of the SPSB.

Figure 5 shows the schematic circuit for measuring the electricity generation of the SPSB. Two factors were considered to measure the current of the prototype model: (i) amplification; and (ii) the low-pass filter.

First, the three prototype models produce small levels of electricity as a miniature representation of the SPSB. For example, the third-generation prototype model of the SPSB can produce a current of up to 950 mA (e.g., third prototype model: 95 mA × 10 module) per column. However, due to the performance of the PV panel and weather conditions (e.g., solar radiation, temperature, sky coverage, etc.), the electricity generation of this prototype model decreases. Accordingly, the amplification should be performed to measure the low current of the prototype model of the SPSB.

Second, the filtering on the amplified low current of the SPSB should be conducted using the low pass filter. The low-pass filter removes the noise amplified in the process of the amplification of the low current of the prototype model by blocking frequencies higher than the cutoff frequency and passing frequencies lower than the cutoff frequency [51].

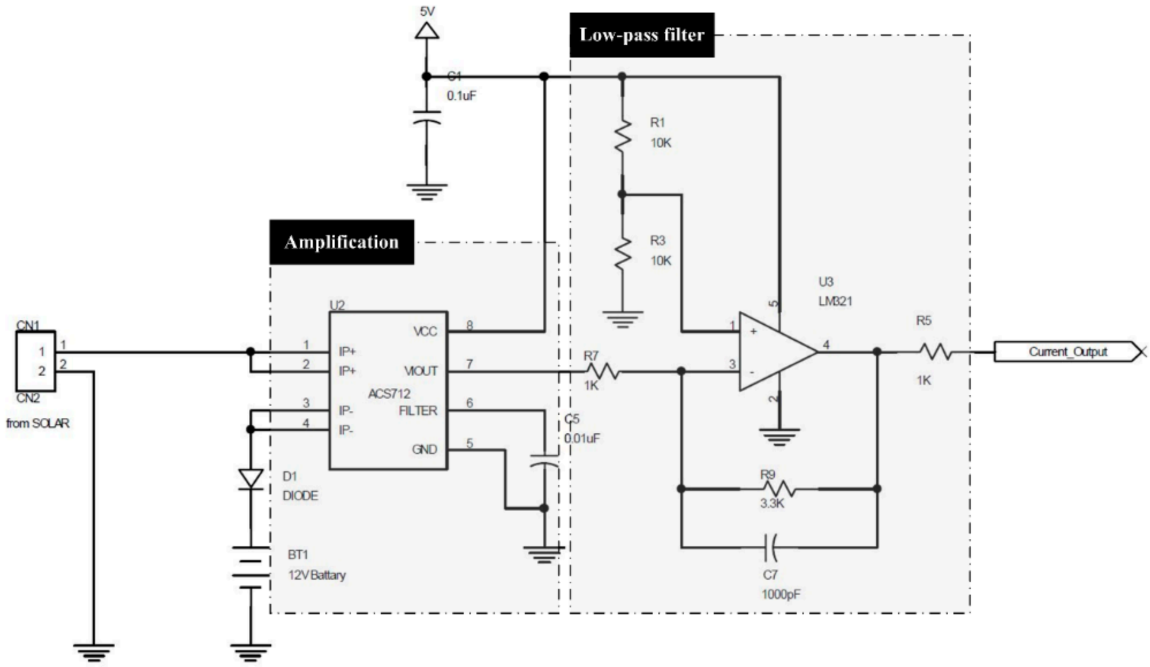

Figure 5. Schematic circuit for measuring the amount of electricity generated from the SPSB.

3.3. Properties 3 (Monitoring System)

The monitoring system of the first and second prototype model of the SPSB displays the time-series data only on the electricity generation (i.e., current, voltage, and power). However, the monitoring system of the third prototype model of the SPSB not only can establish a time-series database on the electricity generation but also the environmental conditions (i.e., temperature and humidity) and optimal tiled and azimuth angles (refer to Figure 6). Through this, the electricity generation depending on the tracker type and environmental conditions can be analyzed in areas where the SPSB is installed. As a result, the optimal tiled and azimuth angle according to the environmental condition can be determined.

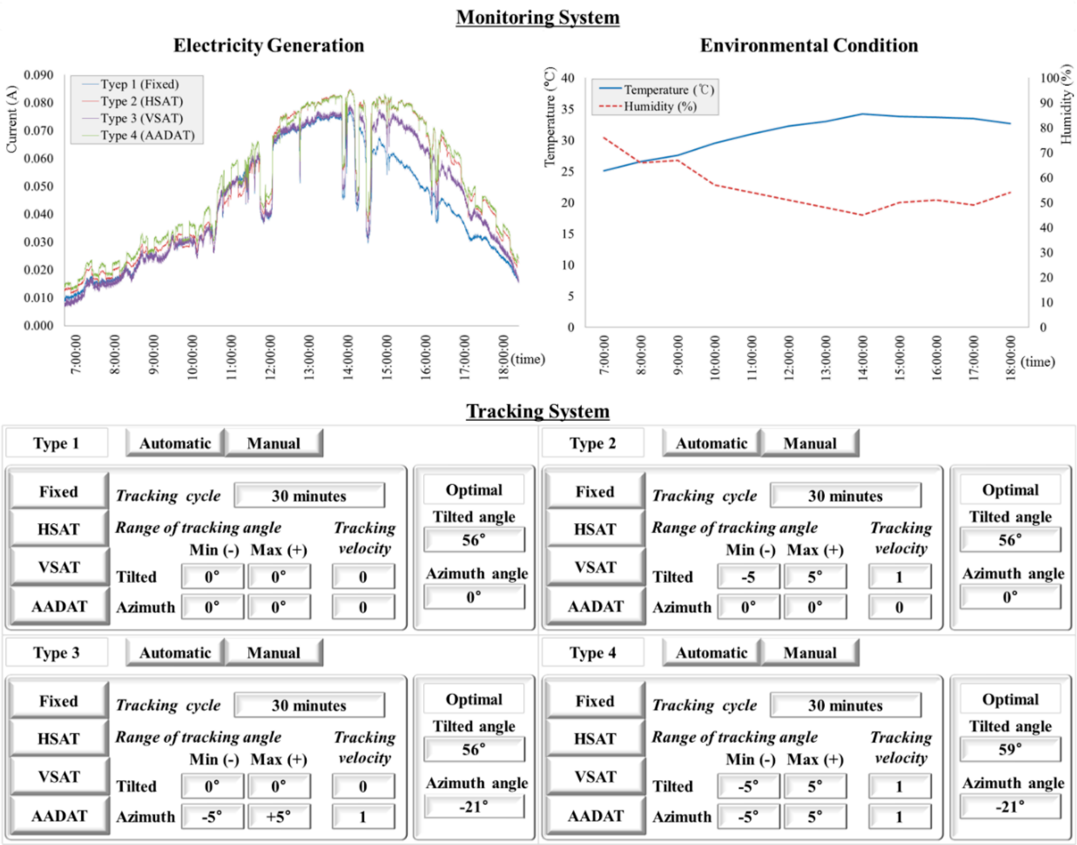

Figure 6. Graphical user interface of the monitoring system in the third prototype model.

3.4. Discussion

This study developed three prototype models of the SPSB to be installed on the building façade. It sought to improve the technical performance of the SPSB (i.e., the amount of electricity generation) in the development process of the three prototype models, starting from the first prototype model. In the most recently developed prototype model of the SPSB, the third prototype model, the following technologies were applied according to the three properties (i.e., PV panel, tracking system, and monitoring system): (i) a-Si PV panel; (ii) four tracker type (i.e., fixed type, VSAT, HSAT, and AADAT) and a tracking method (i.e., direct tracking method); and (iii) monitoring system (i.e., electricity generation and environment conditions).

The experimental studies were conducted using the third prototype model of the SPSB. Figure 7 shows the electricity generation of the third prototype model by tracker type (i.e., fixed type, VSAT, HSAT, and AADAT) (6 August 2015). First, the electricity generation of the third prototype model shows the inverted U-shape (with the highest value at 14:00 (0.80~1.02 W) and a lower value at 7:00 (0.01–0.03 W) and at 18:00 (0.04–0.09 W)). Additionally, the temperature and humidity show the inverted U-shape (highest value at 14:00 (34.2 °C) and the lowest value at 7:00 (25.1 °C)) and the U-shape (lowest value at 14:00 (45%) and the highest value at 7:00 (76%)), respectively. This is because the solar radiation in South Korea is highest at 14:00 (2.89 MJ/m^2) [55]. Second, the dual-axis tracker (i.e., AADAT) can improve the electricity generation of the third prototype model than other methods (single-axis tracker (i.e., HSAT and VSAT) and fixed type). Additionally, compared with the electricity generation of the third prototype model using VSAT, the electricity generation of the third prototype model using HSAT is improved. The VSAT applied to SPSB has a limitation for tracking the east-west motion of the sun. This is because SPSB installed in the window has a limitation on the depth.

Meanwhile, with the use of the third prototype model of the SPSB, the following experimental studies can be carried out. First, an evaluation on the electricity generation by tracking system (i.e., the tracker type and tracking method) according to the location of the SPSB installation can be performed. Second, in the maintenance phase, the optimal electricity generation strategy for maximum electricity output can be established using monitoring data such as electricity generation (i.e., current, voltage, and power) and environmental conditions (temperature, humidity, and solar radiation).

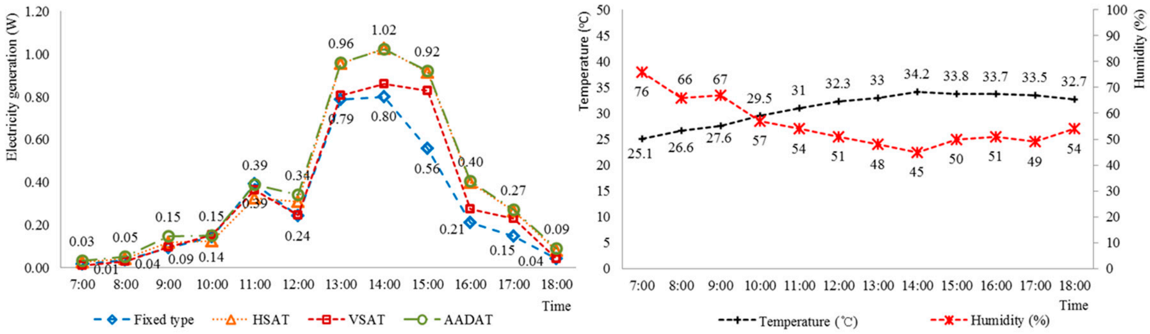

Figure 7. Electricity generation and the environmental condition of the third prototype model.

4. Conclusions

To cope with POST-2020, the South Korea government established the '*Nationally Determined Contributions*' to reduce GHG emissions by 37% below the business-as-usual emission level by 2030. The PV system blind can be considered one of the best solutions to provide electricity generated from its PV panel and to reduce the indoor cooling demands through the blind's main function. Thus, this study aimed to design and develop the prototype model of the SPSB. Toward this end, the study defined the properties in three ways (i.e., PV panel, tracking system, and monitoring system). It also developed three prototype models in order to improve the technical performance of the SPSB. In the third prototype model, the following technologies were applied by properties. First, in terms of the PV techniques applicable to the SPSB, the a-Si PV panel was chosen. Second, in terms of the tracking system, the four tracker types (i.e., fixed type, VSAT, HSAT, and AADAT) and the direct tracking method based on electricity generation were applied. Third, in terms of the monitoring system, the electricity generation and environmental conditions were monitored to evaluate and manage the technical performance of the SPSB. The result of experimental study was conducted using the third prototype model of the SPSB. First, the electricity generation of the third prototype model shows the inverted U-shaped. Second, the electricity generation of the third prototype model is superior in order of the AADAT, HSAT, VSAT, and the fixed type applied to SPSB.

The prototype model of the SPSB is designed and developed for providing electricity generated from its PV panel, as well as for reducing the indoor cooling demands through the blind's main function (i.e., blocking out sunlight). Furthermore, it is expected that it will establish an optimal operation strategy to maximize the amount of electricity generated from the SPSB by considering the three properties. To improve the SPSB, future research can be employed to the computational intelligence techniques (e.g., artificial neural network, harmony search meta-heuristic algorithm, genetic algorithm, etc.) as follows: First, the electricity generation from the SPSB considering environmental conditions (e.g., orientation, number of story, weather, etc.) of the building will be forecasted for optimizing the optimal size of the SPSB applicable to the building. For that, the use of the time-series historical data of the electricity and environment conditions makes it possible to forecast the electricity generation from the SPSB [56–58]. Second, the efficiency of the electricity generation can be improved through the hybrid tracking method. For that, the hybrid tracking method can be developed through a combination of various direct and indirect tracking methods using the computational intelligence techniques [59–61]. Third, in terms of the building energy supply and demand, the monitoring system of the SPSB will be developed using the computational intelligence techniques. The optimal operation strategy of the SPSB can be determined considering the electricity generation from the SPSB and electricity consumption from the electronics [62].

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Nomenclature

AADAT	Azimuth-altitude dual-axis tracker
a-Si	Amorphous silicon
CdTe	Cadmium tell
CIGS	Copper-indium-gallium-selenide
C-Si	Crystalline silicon
DSSP	Dye-sensitized photovoltaic panel
HSAT	Horizontal single-axis tracker
Mono-Si	Mono-crystalline silicon
OPV	Organic photovoltaic panel
PASAT	Polar aligned single-axis tracker
Poly-Si	Poly- crystalline silicon
PV	Photovoltaic
SPSB	Smart photovoltaic system blind
TTDAT	Tip-tilt dual-axis tracker
TSAT	Tilted single-axis tracker
VSAT	Vertical single-axis tracker

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