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Light Shelf Development Using Folding Technology and Photovoltaic Modules to Increase Energy Efficiency in Building

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Abstract: Some recent research in the area of light shelves has been focused on applying photovoltaic modules to light shelves to save building energy. However, due to the modules installed on the light shelf reflectors, most such light shelves have failed to improve both daylighting and generation efficiency. This study proposes a folding technology to improve light shelves' daylighting and generation efficiency that uses photovoltaic modules and validates their performance using a testbed. The major obtained findings are as follows: (1) The proposed folding technology has a structure in which reflectors and photovoltaic modules fold alternately by modularizing the light shelf. The reflector and photovoltaic modules are controlled by adjusting the degree of folding. (2) Because light shelf angles for improving daylighting and generation differed depending on the application of the photovoltaic module, the optimal light shelf specifications differed. (3) Compared to previous light shelf technologies, the light shelf with folding technology and a photovoltaic module reduced energy use by 31.3% to 38.2%. This demonstrates the efficacy of the proposed system. (4) Applying a photovoltaic module can lower the indoor uniformity ratio, which means that the daylighting performance of the light shelf is degraded due to the reduction of the area occupied by the reflector.

Keywords: light shelf; photovoltaic module; folding technology; performance evaluation; energy efficiency

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1. Introduction

Recently, research on daylighting and shading systems such as light shelves, light pipes, blinds, louvers, and awnings has been increasing to reduce the consumption of lighting energy in indoor spaces and create a comfortable indoor light environment [1–5]. Among these systems, a light shelf is a type of reflector that contributes to lighting energy savings by reflecting and introducing natural light deep into a room [6–9]. It can also increase daylighting efficiency by responding to external environmental factors like solar altitude [10] by controlling the angle of the reflector. Several studies on light shelves have been conducted, indicating that their efficiency is widely recognized. Recent studies on light shelves [11,12] have discovered that applying photovoltaic modules that convert sunlight into electricity to the light shelf can increase building energy savings. However, most of the approaches studied [12] have involved the application of photovoltaic modules to part of the light shelf reflector. When photovoltaic modules are attached to the light shelf reflector, the two components end up having the same angle, which is not suitable for maximizing daylighting and generation performance at the same time. This is because light shelves and photovoltaic modules require different angles to maximize daylighting and generation performance.

As a result, this study proposes and validates a method for simultaneously improving the daylighting and generation efficiency of light shelves that use photovoltaic modules using a full-scale testbed.

1.1. The Light Shelves Concept and Operation Technologies

As shown in Figure 1, a light shelf is one of the most prevailing daylighting systems installed on windows (inside or outside) that saves lighting energy by introducing natural light inside a building (room) by reflecting sunlight through the light shelf reflector [8–10]. Light shelves can also help to solve indoor illuminance imbalances caused by differences in illuminance between areas near and far from windows by preventing entry of some of the excessive natural light from the window. On the other hand, it can introduce natural light deeper into an indoor space by reflecting natural light from the ceiling, and reflector, so reflections from the reflector and ceiling surface are typically considered. The variables such as angle, height, reflectance, and width of light shelves determine its performance. Similarly, the light shelf angle is a primary variable to respond to external environmental factors such as the solar altitude, as shown in Figure 1 [10,12].

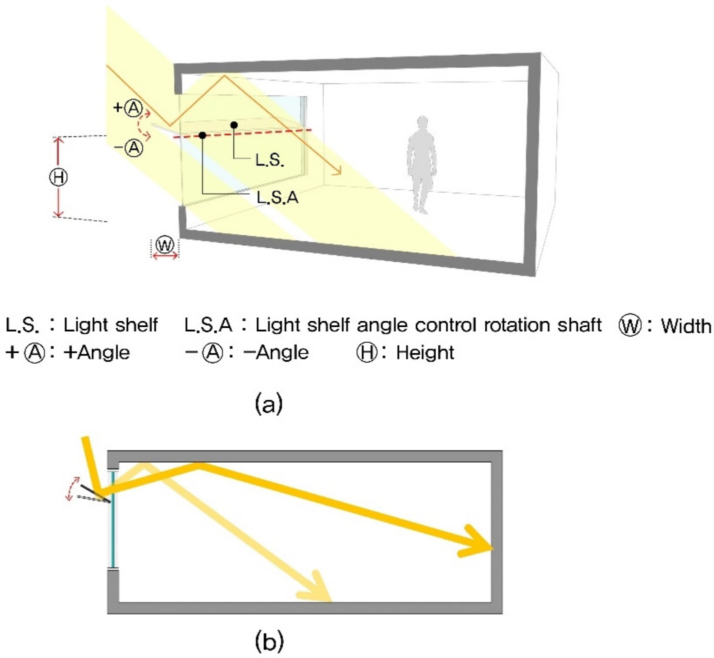


Figure 1. Light shelf concept and operation: (**a**) Concept and variables, (**b**) Inflow of the natural light by manipulating angle of the light shelf.

Several studies have been conducted on light shelves to improve their daylighting performance, and some of these are listed in Table 1. Researchers have attempted to enhance the light shelf reflectors' shape and also used multiple building envelope component technologies such as blinds and awnings to improve light shelf daylighting performance [8,9,11–21]. Some recent studies, in particular, have concentrated on movable light shelves using information technologies such as user recognition and location awareness [10,22]. However, these studies controlled the light shelf angle using a rotating shaft (see Figure 1). Previous studies on light shelves with photovoltaic modules [11,12] have attached photovoltaic modules to the front or part of the light shelf reflector. Installing photovoltaic modules on the part of the light shelf reflector was more advantageous in saving building energy than applying them to the front due to enabling daylighting and concentrating light at the same time [12]. Previous studies that used photovoltaic modules on light shelves [12] encountered difficulties in maximizing daylighting and generation at the same time because the reflector that reflects natural light and the photovoltaic module that concentrates light maintain the same angle.

Table 1. Previous studies on light shelves.

Author	Purpose	Photovoltaic Module Application	Consideration of Operation Technologies
Lim and Heng [8]	Proposal and performance evaluation of dynamic internal light shelf in high-rise office buildings	No	Not considered (Fixed light shelf)
Claros and Soler [13]	Performance evaluation according to light shelf reflectance		
Warrier and Raphael [14]	Indoor visual comfort analysis according to the presence of light shelves		
Lee [9]	Performance evaluation of perforated light shelves in response to external wind pressure		Light shelf angle control by a single rotating shaft
Lee et al. [15]	Performance evaluation of light shelves with diffusion sheets		
Lee and Seo [16]	Proposal of a prism sheet application method for improving light shelf performance		
Mangkuto et al. [17]	Parametric design study of light shelves for application to hospital buildings		
Lee et al. [18]	Performance evaluation of light shelves by applying curvature		
Meresi [19]	Evaluation of the light shelf performance based on the application of the external blinds		
Lee [20]	Development and performance evaluation of a light shelf that can change the reflectivity		
AmirEbrahimi-Moghadam et al. [21]	Performance evaluation of interior light shelves		
Kim et al. [10]	Development and performance evaluation of light shelves based on user-awareness technology		
Lee et al. [22]	Performance evaluation of light shelves with location-awareness technology		Light shelf and light shelf angle control by multiple rotating shafts
Hwang et al. [11]	Performance evaluation of photovoltaic-integrated light shelf systems	Yes	Not considered (Fixed light shelf)
Lee [12]	Performance evaluation of light shelves according to photovoltaic module attachment ratio		Light shelf angle control by a single rotating shaft

1.2. Concept and Power Generation Principle of Photovoltaic Modules

As shown in Figure 2, a photovoltaic module is a structure of photovoltaic cells connected by a ribbon to generate the required energy [23,24]. A photovoltaic cell is the smallest unit that converts solar energy into electrical energy and has p-n semiconductor junction structures. When photovoltaic cells absorb photons from the outside, electrons and holes are generated inside the photovoltaic cells, as shown in Figure 2. These electrons and holes migrate to n-type and p-type semiconductors. This movement drives the load of the photovoltaic cells, generating electrical energy. The generation process allows the photovoltaic cell to transform the solar energy into electrical energy. Temperature is a factor that has a significant impact on the power generation efficiency of photovoltaic cells. This efficiency decreases as the temperature rises [25–30]. In addition, the photovoltaic cells should be perpendicular to the sun to increase power generation efficiency, and the efficiency decreases as the sunlight deviates from a vertical angle [31–33].

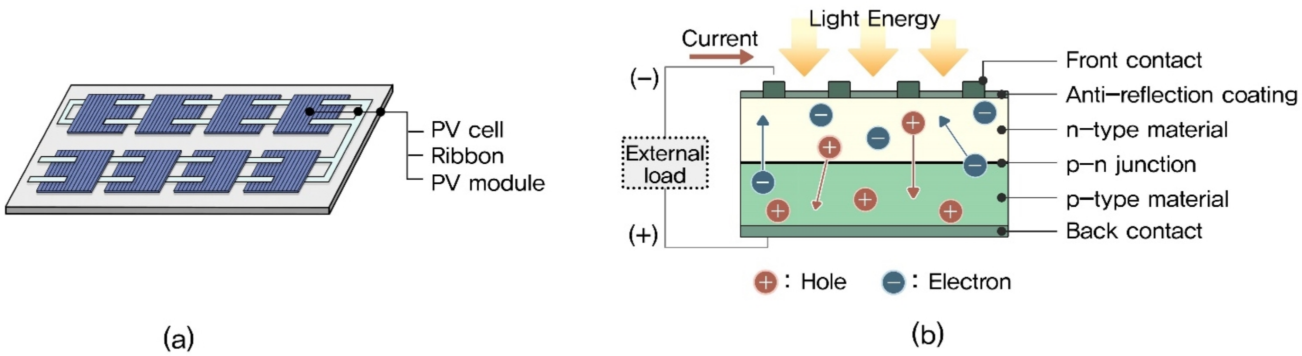


Figure 2. Photovoltaic module concept and power generation principle of photovoltaic cells: (**a**) Photovoltaic module concept, (**b**) Principle of the power generation.

1.3. Indoor Illuminance Standards for Lighting Control

Maintaining optimal indoor illuminance can increase the efficiency of visual work by creating a comfortable light environment for occupants and saving building energy by preventing unnecessary lighting control [34]. The optimal range of indoor illuminance is determined by the type of workplace or the level of visual work. This study considered the optimal illuminance standards in the United States [35], Japan [36], and Korea [37] based on the grade of visual work, as shown in Table 2. The illuminance standards in these countries, however, differ. As a result, this study established the optimal indoor illuminance standard at 500 lx based on the intersection for general visual work in the United States, Japan, and Korea and used this standard to assess the performance of light shelves.

Table 2. Indoor illuminance standards for visual work in the US, Korea, and Japan.

Country	Optimal Indoor Illuminance Standards	Task Grade	Illuminance Range (lx) Minimum-Standard-Maximum
USA	IES [35]	General	500-750-1000
		Simple	200-300-500
Japan	JIS Z 9110 [36]	General	300-500-600
		Simple	150-200-300
Republic of Korea	KS A 3011 [37]	General	300-400-600
		Simple	150-200-300

2. Methods

2.1. Proposal of Light Shelf That Applies Folding Technology and Photovoltaic Modules

This study adopted folding technology to propose a way to simultaneously improve the daylighting and generation performance of light shelves that apply photovoltaic modules, and the details are as follows.

First, the light shelf was designed with a folding structure to improve daylighting and generation performance, as shown in Figure 3. The light shelf was divided and modularized in a horizontal direction with the daylighting window to implement such a folding structure, and a hinge structure connected the divided light shelf modules. Second, reflectors and photovoltaic modules were installed alternately from the window side of the light shelf, which applies a folding technology and photovoltaic modules. As a result, folding the light shelf made the reflector angle symmetrical with the photovoltaic module angle (see Figure 3). This principle enables the proposed system to outperform conventional flat light shelves in terms of daylighting and generation. Third, the proposed system folds and unfolds the light shelf by moving along a rail, unlike previous methods in which the light shelf rotates around a rotating shaft.

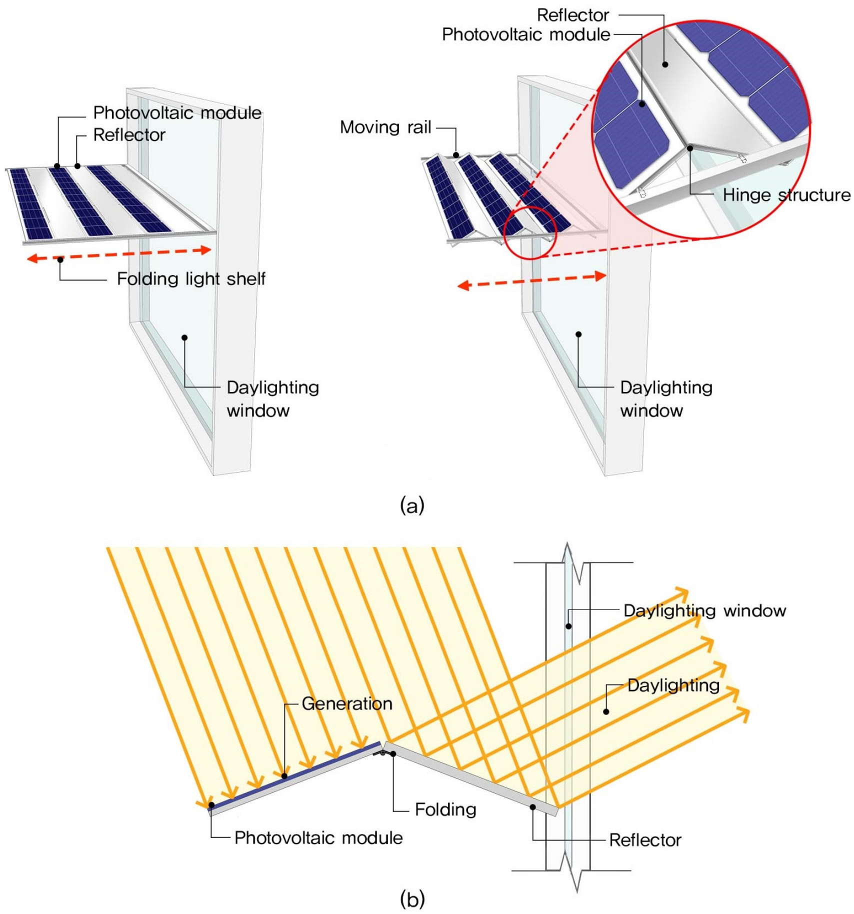
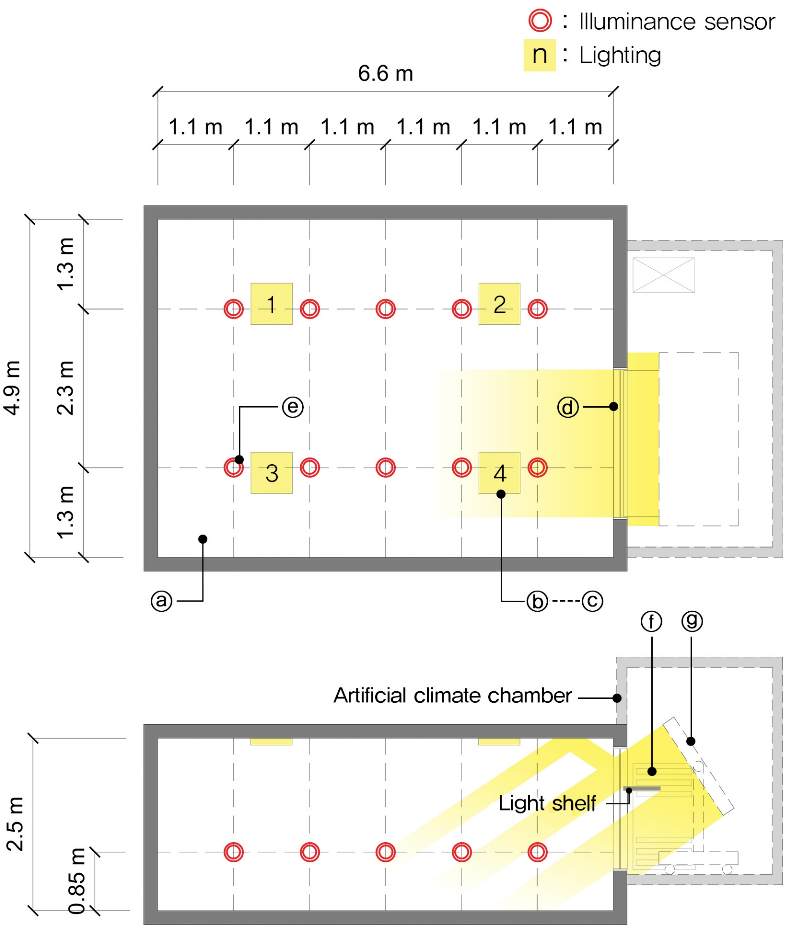


Figure 3. The concept and principle of the light shelf that applies folding technology and photovoltaic modules: (**a**) Structure of proposed system, (**b**) Daylighting and generation by the proposed system.

2.2. Environment for Performance Evaluation

A full-scale testbed including an artificial climate chamber was built to evaluate the performance of the proposed light shelf that applies folding technology and photovoltaic modules, and the details are as follows.

First, as shown in Figures 4 and 5, the dimensions of the internal space of the testbed were 4.9 m × 6.6 m × 2.5 m (W × D × H). The reflectance of the floor, wall, and ceiling was set to 25%, 46%, and 86%, respectively. The window used to install the light shelf measured 1.9 m × 1.7 m (W × H) and was made of 24 mm thick pair glass with an 80 percent transmittance. Second, eight illuminance sensors were installed to measure the change in illuminance of the indoor space caused by the light shelf. Because of the height of the work surface, they were placed 0.85 m from the floor. Third, four lights were installed in the testbed using the IES 4-point method [35]. These LED lights were capable of 8-level dimming control (excluding lights off). Fourth, the testbed had an artificial climate chamber installed adjacent to the outside of the window. An artificial solar irradiation apparatus was installed in the chamber that would stimulate the brightness and altitude of the sun by regulating the intensity and angle of the natural light. The performance evaluation was carried out in an artificial environment due to its advantages in implementing a consistent external environment. The Grade-A artificial solar irradiation apparatus also ensured measurement uniformity following ASTM E927-85, resulting in valid results across performance evaluations. Due to mechanical limitations, this apparatus could not simulate the sun's azimuth. The temperature range of the artificial climate chamber was also adjustable in light of the findings of related works [25–27] that the generation efficiency of photovoltaic modules was significantly affected by temperature. Fifth, the current study develops an energy monitoring system to more precisely estimate lighting energy consumption (see Figure 4 for more detail).



ⓐ Testbed
Size: 4.9 m (W) x 6.6 m (D) x 2.5 m (H)
Reflexibility: Ceiling (86 %), Wall (46 %), Floor (25%)

ⓑ Lighting
8 Level dimming (LED type) 4ea
Dimension (mm): 600 x 600
Dimming Range: 10 – 100 %

ⓒ Energy monitoring
Model: SPM – 141
Measurement capacity: Single phase (220 V, 1 – 50 A)
Error rate: Within 2.0 %
Measurement items: power, voltage, current (real – time, and accumulated amount)

ⓓ Daylight window
Size: 1.9 m (W) x 1.7 m (H)
Type: pair glass 24 mm (6 mm + 12 mm + 6 mm)
Transmissivity: 80 %

ⓔ Illuminance sensor
Sensing element: Silicon photo sensor, with filter
Detection range: 0 – 20,000 lx
Precision: ± 0.3

ⓕ Chamber thermostat

ⓖ Artificial solar irradiation apparatus
Light source with adjustable intensity
Light source with adjustable height / angle

Figure 4. The layout, cross-section, and equipment in the testbed for performance evaluation.

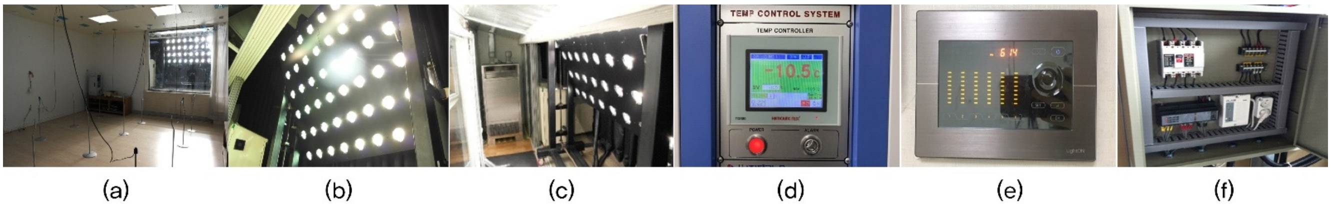


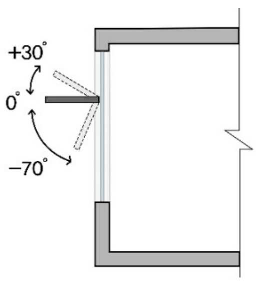
Figure 5. Environment for performance evaluation: (**a**) Testbed, (**b**) Artificial Solar Light Radiation Apparatus, (**c**) Chamber thermostat, (**d**) Chamber temperature controller, (**e**) Light dimming controller, (**f**) Energy monitoring system.

2.3. Methods of Performance Appraisal

The performance appraisal was conducted to prove the effectiveness of the daylighting and generation performance of the light shelf that applies folding technology and photovoltaic modules.

First, as shown in Table 3, this study set up three scenarios based on whether or not photovoltaic modules were used and how they worked. Case 1 was a standard light shelf that did not include a photovoltaic module. Case 2 was a light shelf with a photovoltaic module attached to the reflector, resulting in the photovoltaic module and reflector having the same angle. However, the area where the photovoltaic module was attached in Case 2 had the same size as the reflector where reflection occurs, considering the previous study findings [12], in which installing photovoltaic modules on the part of the light shelf reflector was found to provide advantages in terms of saving building energy by enabling daylighting and generation at the same time. As shown in Figure 1, a single rotating shaft was used to change the angles of the light shelves in Cases 1 and 2. In Case 2, the light shelf angle increased from −70° to 30° in 10° increments while considering the photovoltaic module's generation function. Case 3 was designed around a light shelf that employs folding technology as well as photovoltaic modules. As shown in Table 4, the light shelf is folded in stages. Each stage of folding changed the light shelf width, reflector angle, and photovoltaic module angle. The photovoltaic cells used in the photovoltaic module are specified in Table 5. Finally, as shown in Figure 6, this study used a profile to make the light shelf for a performance evaluation.

Table 3. Case settings for performance evaluation.

Case	**Light Shelf**		**Photovoltaic Module Application (# of Photovoltaic Cells Applied)**	**Folding Technology Application**	**Operation Method**	**Light Shelf Angle**
	Width	**Angle**				
1	0.6 m	−10°, 0°, 10°, 20°, 30°	Not applied (0)	Not applied	Rotation by a rotating shaft	
2		−70°, −60°, −50°, −40°, −30°, −20°, −10°, 0°, 10°, 20°, 30°	Applied (33 *)			
3		0° (fixed)	Applied (33 *)	Applied (divided into 6 modules)	Operates along a rail axis	

* The efficiency decreases at rate of 6.1% when the Photovoltaic module was applied using 33 photovoltaic cells.

Table 4. Folding shape, light shelf angle, and photovoltaic module angle according to the width of Case 3.

Folding Stage	Light Shelf Width (W)	Reflector Module Angle (α)	Photovoltaic Module Angle (β)
1 (Straight, no folding)	0.60 m	0°	180°
2	0.58 m	14.8°	165.2°
3	0.56 m	21.0°	159°
4	0.54 m	25.8°	154.2°
5	0.52 m	29.9°	150.1°
6	0.50 m	33.6°	146.4°

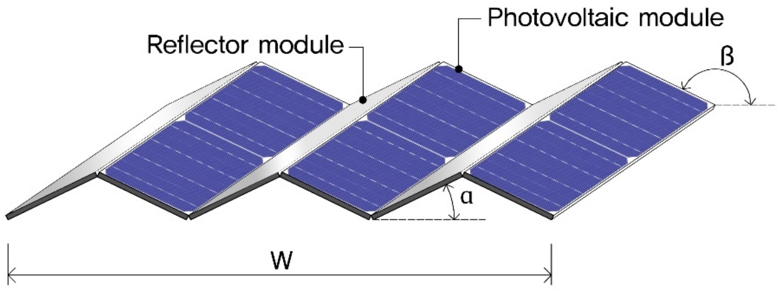


Table 5. Photovoltaic cell specifications.

Item	Specifications	Item	Specifications
Max. Power	2 W	Max. Current (Impp)	670 mA
Max. Voltage (Vmpp)	3 V	Size	165 mm × 100 mm
Efficiency	16.3%	Reflectance	1–6%

Figure 6. Light shelf fabrication for performance evaluation.

Secondly, monitored the distribution of indoor illuminance according to the cases set for performance evaluation to derive the minimum illuminance, average illuminance, and uniformity ratio. The uniformity ratio was the ratio of the minimum illuminance to the average.

Thirdly, the study determined the dimming level and lighting energy consumption for each case to achieve optimal indoor illuminance, and the details are as follows. As shown in Figure 7, dimming control was only used when the minimum value measured by the eight illuminance sensors was less than 500 lx. If the minimum value measured by the illuminance sensors was greater than 500 lx, all lights were turned off without dimming control. The system monitored the values measured by the illuminance sensors while increasing the dimming levels sequentially from the light closest to the illuminance sensor with the minimum value. During this process, dimming control ended when all measurements by the illuminance sensors reached 500 lx. Finally, the performance of each case was compared by calculating the lighting energy consumption based on the level of dimming control.

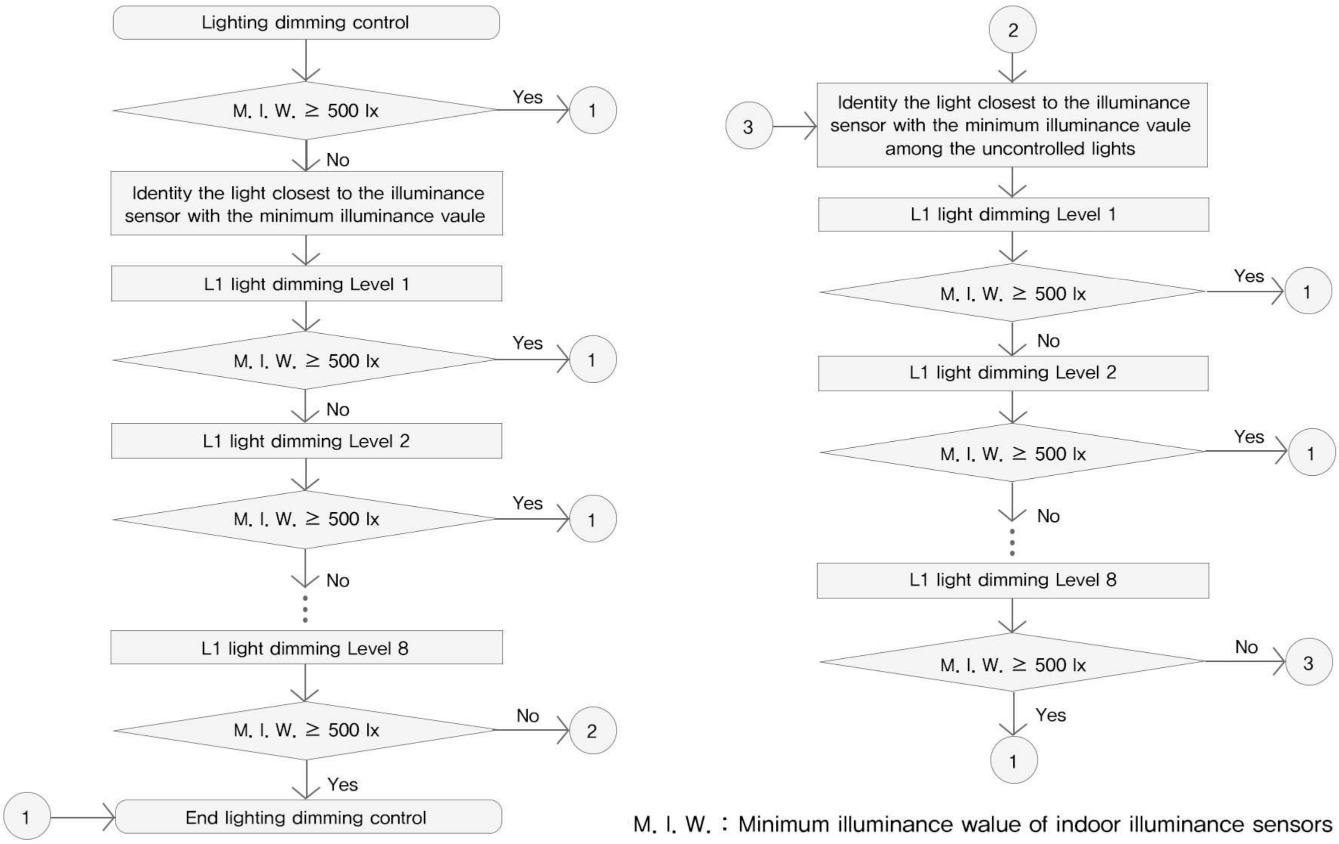


Figure 7. Lighting dimming control flow chart for performance evaluation.

Fourth, the energy produced by the photovoltaic module's generation performance was measured in this study. The photovoltaic module's energy was calculated by multiplying the module's maximum voltage (Vmp) and maximum current (Imp) while producing power. Table 6 shows the specifications of the photovoltaic module used for performance evaluation and the equipment used to measure the voltage and current.

Table 6. Specifications of the voltage and current measuring device (Equipment name: MULLER 3201).

Item	Specifications	Image
Measurement item (measurement capacity)	DC Voltage (0~600 V), DC Current (0~60 A)	
Error rate	±(0.5% + 3)	

Fifth, the artificial climate chamber of the testbed created the external environment of the outdoor space, where the performance evaluation was conducted for summer, mid-season, and winter, as shown in Table 7. The experiment was performed under three external conditions based on seasonal variation (i.e., summer, middle season, and winter). More specifically, each condition was controlled hour by hour to reflect potential change in external illuminance and solar radiation during a 5 h session between 10 am and 3 pm. The external environment's characteristics were specifically based on Seoul, Korea, which has four distinct seasons. The outdoor temperature for each season was determined by considering the Korea Meteorological Administration's average climate data for the past thirty years [38]. However, the solar irradiation for each season was determined by varying the intensity of the artificial solar irradiation apparatus rather than by observing actual climate data. This limitation was due to the performance evaluation being conducted in an artificial environment.

Table 7. Climatic settings for performance evaluation based on geographical specification.

Season	Meridian Altitude	External Illuminance (lx)/Solar Radiation (W/m^2)					Outdoor Temperature
		10:00–11:00	11:00–12:00	12:00–13:00	13:00–14:00	14:00–15:00	
Summer	76.5	70,000/530	80,000/638	80,000/638	80,000/638	70,000/530	27.1 °C
Middle season	52.5	50,000/414	50,000/414	60,000/476	60,000/476	50,000/414	17.2 °C
Winter	29.5	20,000/289	30,000/332	30,000/332	30,000/332	20,000/289	−3.2 °C

Sixth, the optimal specifications (optimal angle and folding stage) were derived for each case. These were derived by considering lighting energy saving as a priority. When multiple specifications saved the same amount of energy, the one with the highest uniformity was deemed to be optimal. Conditions that would result in the glare as a result of introducing natural light directly into the room via the light shelf without bouncing it off the ceiling, on the other hand, were excluded from the optimal specifications.

3. Results and Discussion

3.1. Performance Evaluation Results

This study conducted a performance evaluation to validate the effectiveness of the light shelf that applies folding technology and photovoltaic modules. The results are as follows.

Firstly, Figure 8 illustrates the performance evaluation results of Case 1 (light shelf with no photovoltaic module), which shows that light shelf angle affects the daylighting performance. Increasing the light shelf angle during the summer was beneficial in saving lighting energy and improving the indoor uniformity ratio. Increasing the light shelf angle was also helpful during the middle season, but the uniformity ratio deteriorated when the light shelf angle was 30°. As shown in Figure 9, setting the angle at 30° allows high illuminance light to reach a specific area only by reflecting off the light shelf, resulting in an illuminance imbalance in the indoor space. In winter, the increment in the light shelf angle was suitable for saving lighting energy by increasing the amount of natural light entering the room through light shelf reflection, but adjusting the light shelf angle to 30° was inappropriate for saving lighting energy and improving the indoor uniformity ratio. This is because the solar altitude is lower in the summer compared to the winter and middle seasons, allowing natural light to enter deep into the indoor space through the daylighting window. Furthermore, during the winter, the solar altitude is 27.5°, so when the light shelf angle is 30°, the light shelf only acts as a shade, as shown in Figure 9. A light shelf angle of 20° was also excluded from the optimal specifications during the winter because, like using a 30° angle during the middle season, it could reduce the uniformity ratio and cause glare. As a result, the optimal light shelf angles for Case 1 during the summer, mid-season, and winter were 30°, 20°, and 10°, respectively, with lighting energy consumption of 0.471 kWh, 0.309 kWh, and 0.134 kWh.

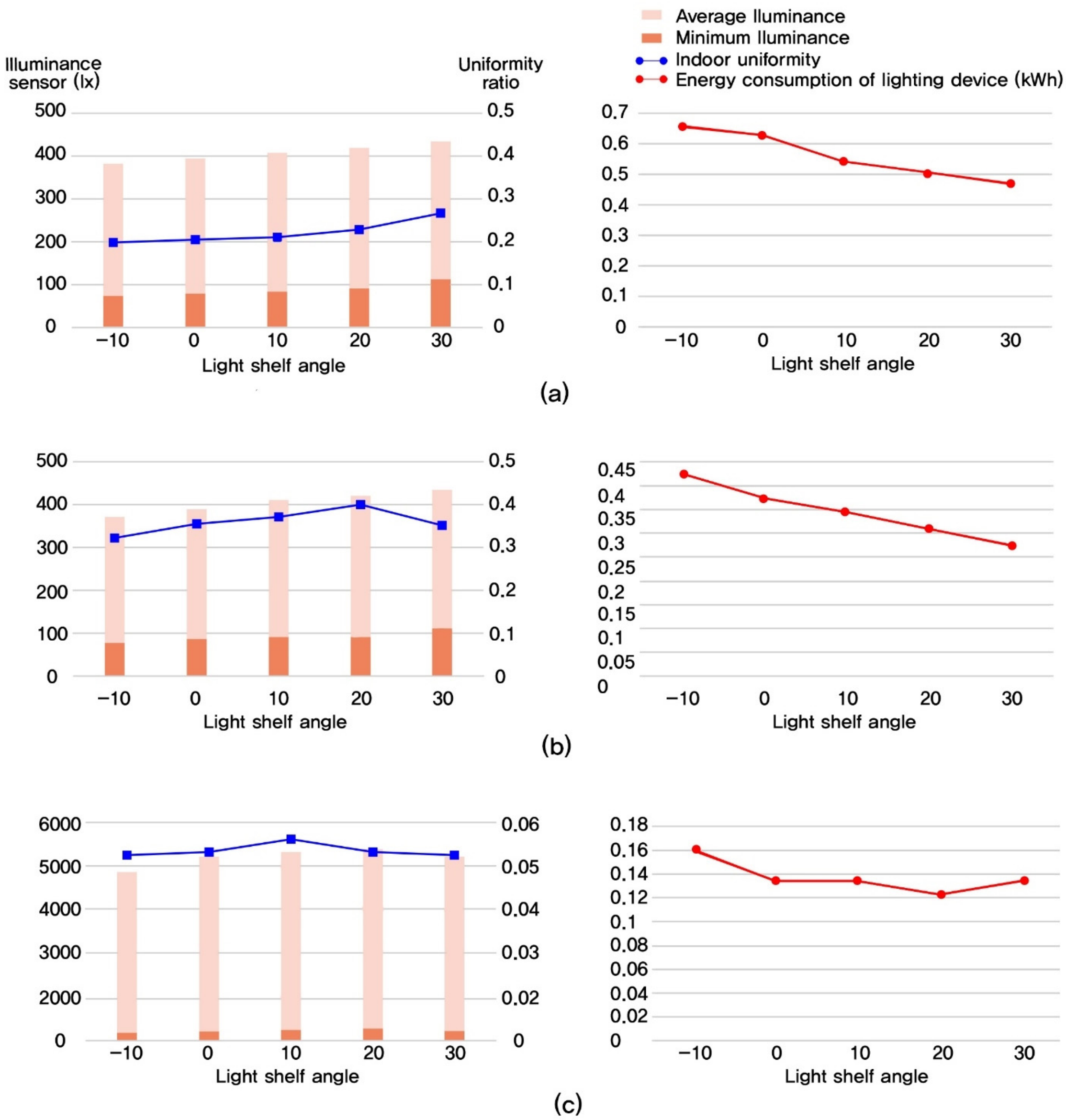


Figure 8. Indoor uniformity and lighting energy consumption according to the light shelf angle in Case 1: (**a**) Summer, (**b**) Middle season, (**c**) Winter.

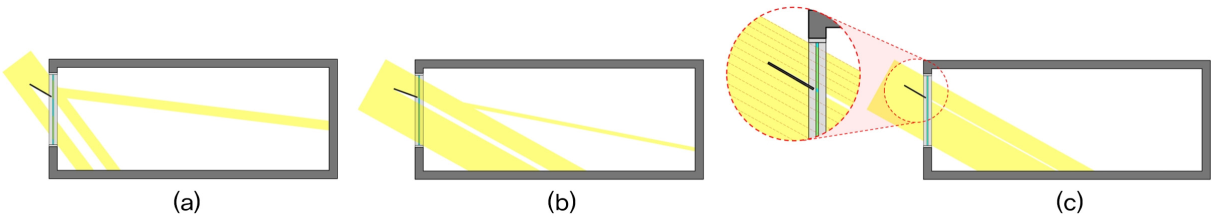


Figure 9. The inflow of natural light according to the light shelf angle in Case 1: (**a**) Middle season, Angle 30°, (**b**) Winter, Angle 20°, (**c**) Winter, Angle 30°.

Secondly, Figure 10 shows the output of a performance evaluation of Case 2 (light shelf applying photovoltaic module). In terms of saving lighting energy, the optimal specifications during summer, mid-season, and winter were 30°, 20°, and 10°, respectively, the same as Case 1. However, in Case 2, the area of the reflector used for daylighting was reduced by 50% compared to Case 1, reducing the amount of natural light entering the room through light shelf reflection and deteriorating uniformity, as shown in Figure 11. Case 2 also has a higher lighting energy consumption than Case 1. Meanwhile, the photovoltaic module in Case 2 generated the most power at light shelf angles of −10°, −40°, and −60°, which proves that the closer the incident angle of natural light is to vertical, the higher the power generation efficiency. However, it is difficult to maximize both the daylighting and generation performance at the same time in Case 2 because it controls the reflector for daylighting and the photovoltaic module for concentrating light at the same angle. Therefore, the optimal specifications for Case 2 during summer, mid-season, and winter were 10°, −10°, and 20°, respectively, and the lighting energy consumption was 0.406 kWh, 0.314 kWh, and 0.100 kWh, respectively.

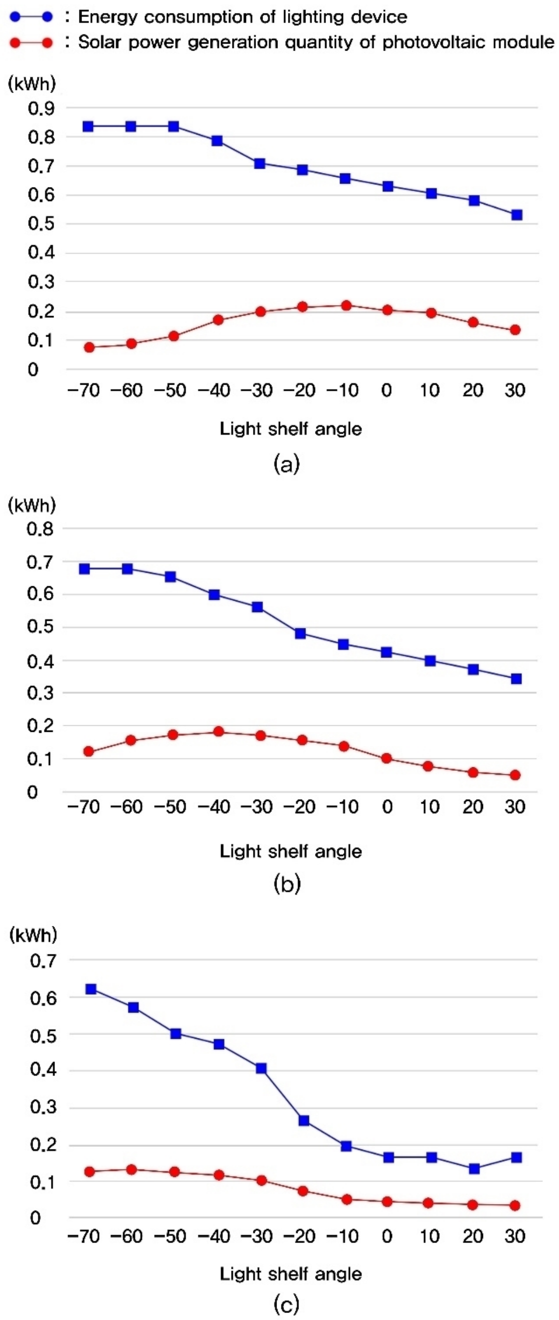


Figure 10. Lighting energy consumption and the power generated by the photovoltaic module according to the light shelf angle in Case 2: (**a**) Summer, (**b**) Mid-season, (**c**) Winter.

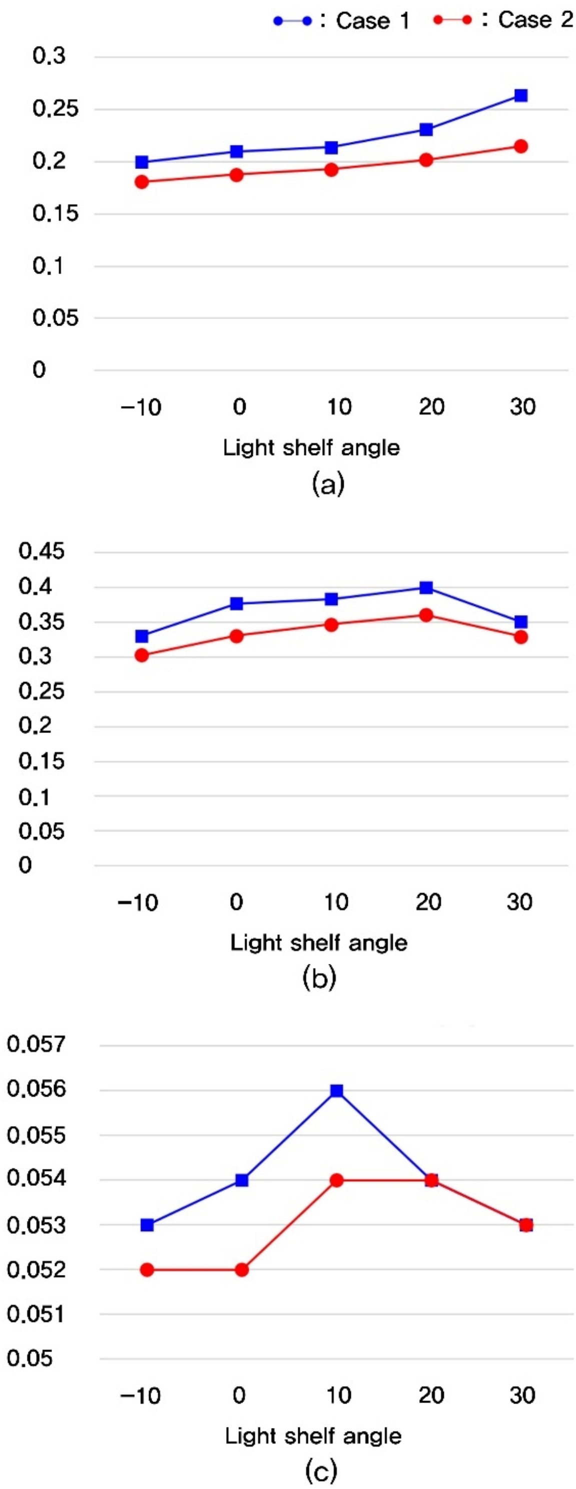


Figure 11. Case 1 and Case 2 indoor uniformity analysis: (**a**) Summer, (**b**) Mid-season, (**c**) Winter.

Thirdly, Figure 12 shows the results of a performance appraisal of Case 3 (light shelf applying folding technology and photovoltaic module). The optimal specifications for Case 3, considering only lighting energy savings and improving indoor light uniformity during summer, mid-season, and winter were folding stages 6, 4, and 3(4), respectively. During the winter, however, as shown in Table 4, folding stages 3 and 4 reduce the light shelf angle to 21° and 25.8°, respectively. These angles, like a light shelf angle of 20° in the winter, cause glare by allowing the direct flow of natural light into the interior space by reflecting off the light shelf, so they were excluded from the optimal specifications. Taking these factors into account, the best specifications for saving lighting energy and improving indoor uniformity in Case 3 were folding stages 6, 4, and 2 for summer, mid-season, and winter, respectively. The optimal specifications for generating power by the photovoltaic module in Case 3 were folding stages 3, 6, and 6 for summer, mid-season, and winter, respectively. Therefore, the optimal specifications for Case 3 during summer, mid-season, and winter were folding stages 6, 4, and 4, respectively, and the lighting energy consumption was 0.307 kWh, 0.224 kWh, and 0.034 kWh, respectively.

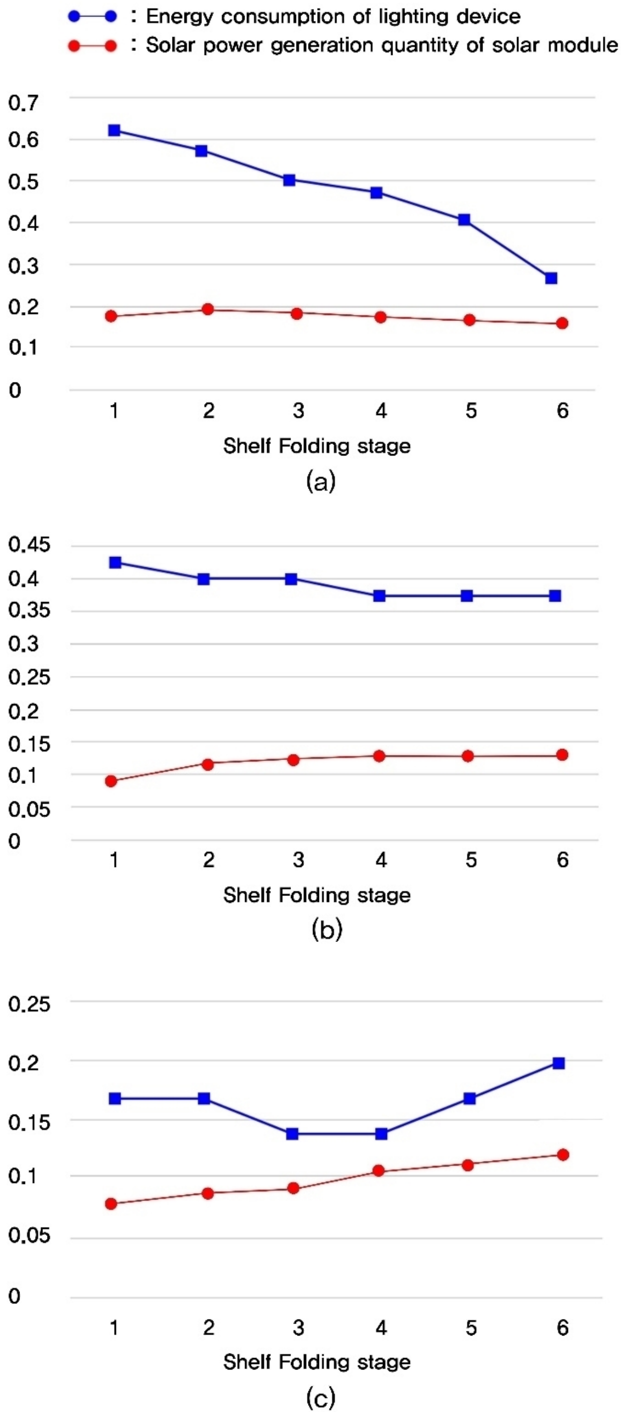


Figure 12. Lighting energy consumption and the power generated by the photovoltaic module according to the folding stage in Case 3: (**a**) Summer, (**b**) Mid-season, (**c**) Winter.

3.2. Performance Evaluation Discussion

This study proposed a folding technology to improve light shelves' daylighting and generation efficiency that incorporates photovoltaic modules and validated its effectiveness through a performance evaluation. A discussion of the results follows.

First, the optimal specifications for Cases 1, 2, and 3 were derived through evaluating their performance. Figure 13 shows the energy consumption based on these results. Case 2 reduced energy consumption by 10.3% compared to Case 1, demonstrating the effectiveness of the photovoltaic module used on light shelves. Case 3 reduced energy consumption by 31.3% compared to Case 2, due to improved daylighting and generation efficiency achieved by adjusting the reflector and photovoltaic module angles through folding. In particular, although the proposed light shelf that applies folding technology and photovoltaic modules (Case 3) had an operating range of only 0.1 m, it reduced building energy by a significant amount compared to the conventional light shelf. These results prove the effectiveness of the proposed system (Case 3).

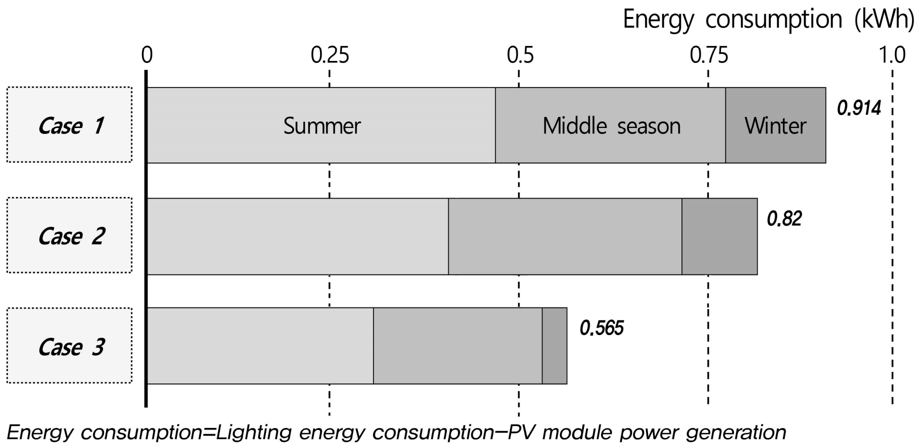


Figure 13. Energy consumption analysis (by Case).

Second, Case 3 uses folding technology to cope with external wind pressure and snow load by completely folding the light shelf. For example, if you are concerned about the damage caused by wind pressure exceeding a certain level, you can fold the light shelf to avoid any damage caused by protruding outside. Case 3, in particular, connects each module with a hinge structure, resulting in gaps between each module. Compared to conventional movable light shelves, this structural feature responds quickly to external environmental factors such as wind pressure.

Third, installing photovoltaic modules on light shelves reduces the area occupied by reflectors to perform daylighting, which reduces the amount of natural light flowing indoors through light shelf reflection. In this context, the light shelf with a photovoltaic module may cause issues, such as increasing the amount of lighting energy required to maintain optimal indoor illuminance and reducing indoor uniformity. Therefore, further research should be conducted on adjusting the width of the light shelf according to the area occupied by the photovoltaic module in the light shelf.

4. Conclusions

A folding technology was proposed to improve the daylighting and generation performance of light shelves that apply photovoltaic modules, and its performance was evaluated through a full-scale testbed. The main findings are as follows.

First, the proposed light shelf that employs folding technology and photovoltaic modules has a structure in which reflectors and photovoltaic modules are installed alternately by modularizing the light shelf. A hinge structure connects each module, allowing the system to be folded. This structure enables the reflector module and photovoltaic module to be symmetrical and operate at different angles depending on the degree of folding. Due to such structural features, the proposed light shelf that applies folding technology and photovoltaic modules can improve both daylighting and generation efficiency. This system also employs a novel operation method based on rails instead of conventional light shelves, which control the light shelf angle via a rotating shaft.

Second, the optimal light shelf angle for each case was derived. The optimal light shelf angles were based on the lighting energy consumption and uniformity ratio to maintain the optimal indoor illuminance. Angles that may cause glare were excluded, even if they were excellent in terms of saving energy. The optimal angles for a light shelf without a photovoltaic module during the summer, mid-season, and winter were 30°, 20°, and 10°, respectively, indicating that the angles must be controlled by operating or moving the light shelf to improve performance. In contrast, the optimal angles for a light shelf with a photovoltaic module during the summer, mid-season, and winter were 10°, −10°, and 20°, respectively, compared to a light shelf without a photovoltaic module. The photovoltaic module and light reflector module require different angles to increase power generation efficiency and daylighting efficiency.

Third, the light shelf that applies folding technology and photovoltaic modules can reduce energy consumption by 38.2% and 31.3%, respectively, compared to light shelves with no photovoltaic modules and light shelves with photovoltaic modules but no folding technology. These results validate the effectiveness of the application of photovoltaic modules to light shelves and prove that the folding technology can improve both daylighting and generation efficiency.

Fourth, the light shelf that applies a photovoltaic module was unsuitable in terms of improving the indoor uniformity compared to the light shelf with no photovoltaic module because the area occupied by the reflector decreases due to installing the photovoltaic module, which leads to reducing the amount of natural light flowing into the room through the light shelf. This aspect should be considered when designing light shelves that apply photovoltaic modules.

This study is significant because it proposes and validates a new technology related to light shelves to save building energy, a primary current concern. However, due to the use of a testbed, the performance evaluation was carried out in a restricted external environment. Other limitations include the fact that various other light shelf variables, such as width and height, were not considered. As a result, additional in-depth studies should be conducted in further research in this sector.

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