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Study on Lighting Energy Savings by Applying a Daylight-Concentrating Indoor Louver System with LED Dimming Control

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Abstract: This study analyzed the effect of indoor lighting energy reduction using a daylight-concentrating indoor louver system, which is a renewable energy equipment item. Daylight-concentrating indoor louver systems enhance indoor lighting by directing natural light, entering through windows, into the room via louvers. This study demonstrates significant lighting energy savings through the use of LED-linked dimming control, particularly during the transitional season, achieving an 85.65% reduction in power consumption. In contrast, the winter season showed higher cumulative power consumption due to reduced natural light availability, with a three-day average consumption of 1128.22 W compared to 836.60 W in the transitional season, representing a 25.85% increase. The illuminance distribution analysis revealed that, while winter had higher illuminance at 1 m from the window, the transitional season recorded higher values at 3 m and 5 m, indicating more effective natural light penetration. The solar altitude during the transitional season facilitated even light distribution through daylighting louvers. These findings confirm the substantial energy savings and improved illuminance distribution achieved with daylighting louvers and LED dimming control, with notable efficiency during the transitional season. Consequently, daylight-concentrating indoor louvers are confirmed to be effective in reducing indoor electric lighting energy consumption.

Keywords: daylight-concentrating indoor louvers; daylighting; LED dimming control; lighting energy

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1. Introduction

1.1. Purpose of Study

A daylight-concentrating indoor louver optimizes the use of natural light from outside and reduces dependence on indoor lighting, thereby improving the energy efficiency of the building. This device works on the principle that sunlight or natural daylight entering through transparent materials like window glass is concentrated or reflected by louver slats located indoors. This allows the light to penetrate deep into the interior and illuminate the space. This type of daylight-concentrating equipment was designated as a renewable energy facility eligible for support in South Korea in 2018, following the revision of guidelines regarding the support of renewable energy facilities [1]. In South Korea, the minimum certification grade for some building groups will be raised starting in 2025 [2]. Consequently, to achieve minimum certification for zero-energy buildings, the installation rate of various renewable energy facilities, including daylight-concentrating equipment and solar power systems, is expected to increase. Therefore, it is necessary to review the quantitative targets for lighting energy savings in buildings through the application of this equipment.

1.2. Precedent for Study

Numerous studies have been conducted on the reduction in building lighting energy consumption through the application of louver-type shading devices. The results of lighting energy saving vary depending on the type and configuration of louvers, as well as the integration of control systems. Optimal energy-saving studies considering these variables have been implemented through simulations [3,4]. Experimental monitoring studies using shading devices developed with optimized variable combinations have validated the lighting energy-saving effects. Jung et al. implemented a solar tracking movable louver (STML) system on existing louvers, which showed a reduction in lighting and heating/cooling energy by 35.7~48.7% [5].

Research has been conducted on the impact of reflective surfaces of indoor louver slats, such as those in the daylight-concentrating indoor louver system examined in this study, on indoor illuminance and lighting energy savings. Oh found that incorporating daylight-concentrating louvers implementing control based on solar altitude can reduce lighting energy consumption by 34.5% through monitoring [6]. Eltaweel et al. investigated daylight distribution within buildings by combining prismatic panels with automated louver systems in indoor louvers [7]. When controlling daylight-concentrating indoor louvers along with LED dimming control, significant energy savings have been observed. Implementing an automatic control system that optimizes the use of natural light can save up to 45~47% of energy [8]. Seo and Choi found that a daylight-concentrating indoor louver system equipped with light sensors can achieve an average lighting energy saving of 29.77%, even on partially cloudy days [9]. Another study demonstrated that the application of a daylight-concentrating system resulted in hourly lighting energy savings of 67~68% and daily lighting energy savings of 52~61%, depending on external illumination at the time [10].

In this study, an on-site experiment was conducted to review the performance index for lighting energy savings in buildings using a daylight-concentrating indoor louver developed as a renewable energy item. To evaluate lighting energy savings, the effect of applying both a daylight-concentrating device and LED dimming control was analyzed and compared. Additionally, the amount of lighting energy savings was compared and analyzed based on the degree of sunlight penetration during transitional and winter seasons.

2. Methods

2.1. Experimental Subject

The experimental subject, a daylight-concentrating indoor louver system, features high-reflectivity material coating on the slat surfaces to concentrate and reflect light indoors, as shown in Figure 1. In this study, louvers with a slat depth of 60 mm and a specular reflectance of over 90% at an angle of 60° were tested. The daylighting indoor louver system is divided into a light-concentrating section and a shading section, allowing for different angle controls for the upper and lower parts, as illustrated in Figure 1a,b. For this experiment, the upper slats of the louvers were set at an angle of 0° (horizontal) to concentrate light indoors, while the lower slats were adjusted to block daylight.

(**a**) (**b**) (**c**)

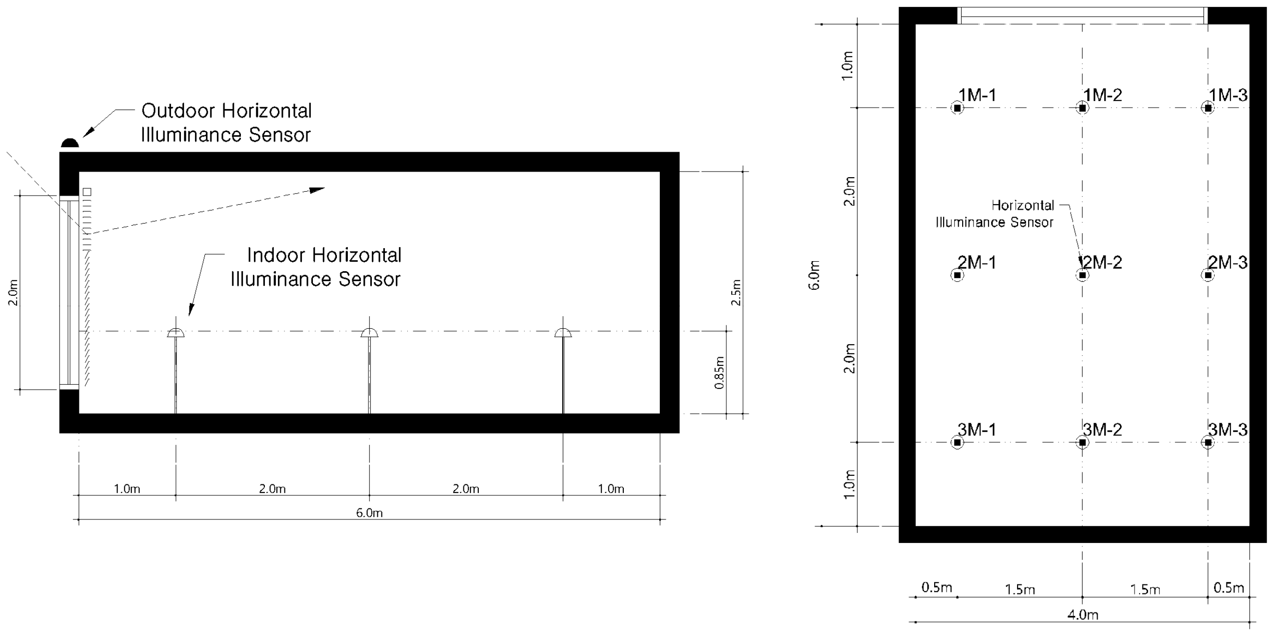
Figure 1. Daylight-concentrating indoor louver. (**a**) Product applied for real office building; (**b**) prototype product; (**c**) reflective slat.

2.2. On-Site Chamber Conditions

The analysis of indoor illuminance and lighting energy savings was conducted in Jincheon-gun, Chungcheongbuk-do, Republic of Korea. As illustrated in Figure 2, the chamber has a south-facing opening, with dimensions of 2 m in height and 3 m in width, fitted with 5 mm single-pane glass windows. A daylight-concentrating indoor louver system, sized to cover the window areas, was installed. The experiment chamber was constructed and set up according to the average I/O illuminance ratio experimental conditions presented in the daylight-concentrating equipment construction standards in an open space [11]. The dimensions of the experimental chamber are shown in Figure 3. Nine indoor illuminance sensors and three lighting control sensors were placed at a height of 0.85 m, as depicted in Figure 3a,b. Three lighting control sensors were positioned 1 m, 3 m, and 5 m from the center of the windows. The chamber's interior lighting consists of LED lights installed on the ceiling, as shown in Figure 3c. The specifications of the equipment used in this experiment are detailed in Table 1.

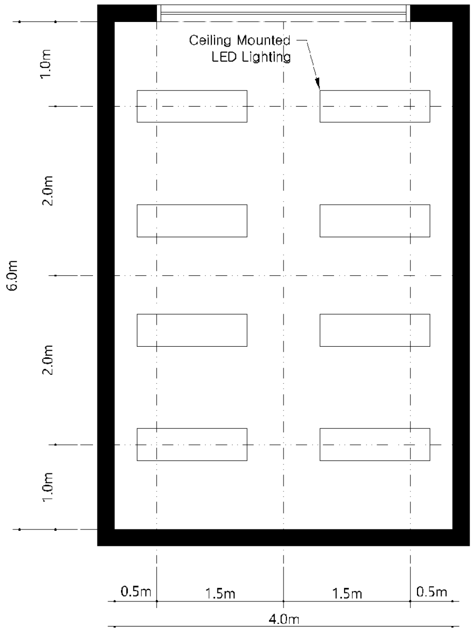
(**a**) (**b**) (**c**)

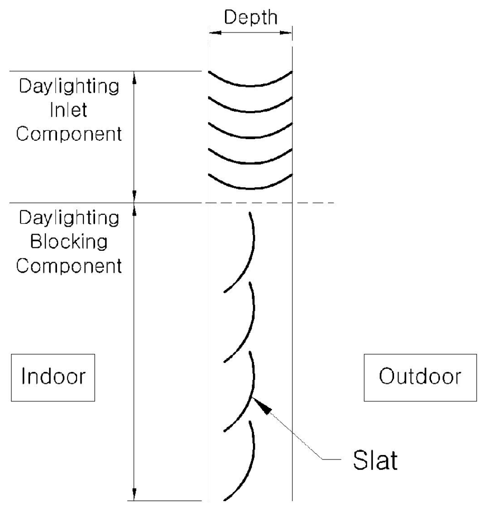
Figure 2. On-site experimental chamber. (**a**) Exterior of chamber facing south direction; (**b**) inside of chamber with experiment subject applied; (**c**) illuminance sensor with lighting control sensor.



(**a**) (**b**)

Figure 3. *Cont.*





(c) (d)

Figure 3. Experimental chamber diagram with dimension: (**a**) section; (**b**) floor plan with illuminance sensor location; (**c**) ceiling plan with LED lighting location; (**d**) blind angle condition.

Table 1. Specification of instrument.

Contents	Type	Specification
Indoor Lighting System	Source Power Density Power Consumption per Unit	LED lamp 12 W/m^2 38 W
Illuminance Measurement	Sensor	LI-210R
Lighting Control Instrument	Sensor Dimming Driver	DALI MSensor 02 Driver LCA 45 W 500–1400 mA

2.3. Evaluation and Anaylsis Methods

The lighting energy-saving effect was analyzed by comparing the lighting energy consumption when dimming control was applied to LED lighting to maintain at least 300 lx in a chamber, against using the LED lighting continuously without dimming control. The experiments were conducted over three days during the transitional season (dimming control: 18–21 November; regular lighting: 23–25 November) and three consecutive days in winter (dimming control: 27–29 January) under clear weather conditions with external illuminance levels exceeding 50,000 lx during the 11 a.m. to 1 p.m. When the indoor illuminance level exceeded 300 lx at any of three lighting control sensors, the eight ceiling-mounted lights were dimmed accordingly. The target indoor minimum illuminance for the study was set at 300 lx, based on the illuminance classification for offices (category G: 300–400–600 lx) in the Korean Standard requirement of illumination [12].

Indoor illuminance and power consumption data were collected at one-minute intervals throughout the experiment. For analysis, the one-minute interval measurements were averaged into 30 min intervals. The analysis of lighting energy savings and changes in indoor illuminance focused on the hours between 9 a.m. to 6 p.m., corresponding to typical working hours. The maximum, minimum, mean, and median illuminance values were derived and compared. Lighting energy was analyzed based on the cumulative consumption over the experimental period.

3. Results

3.1. Lighting Energy According to Regular Lighting and Dimming Control

The effectiveness of lighting energy savings achieved by the daylight-concentrating indoor louver system during the transitional season is illustrated in Figures 4 and 5. Figure 4 shows the scenario where indoor lighting remained constant without any control throughout the experimental period, while Figure 5 depicts the scenario where indoor lighting was subject to dimming control. For each condition, indoor illuminance and instantaneous power consumption were measured over three days and plotted over time. During the period without lighting control, the real-time lighting power consumption remained stable, ranging from a minimum of 305.77 W to a maximum of 308.28 W, with minimal fluctuations. In contrast, during the dimming control period, real-time lighting power consumption varied significantly. It ranged from a minimum of 14.60 W to a maximum of 133.02 W. These variations reflect the dimming adjustments based on indoor illuminance changes.

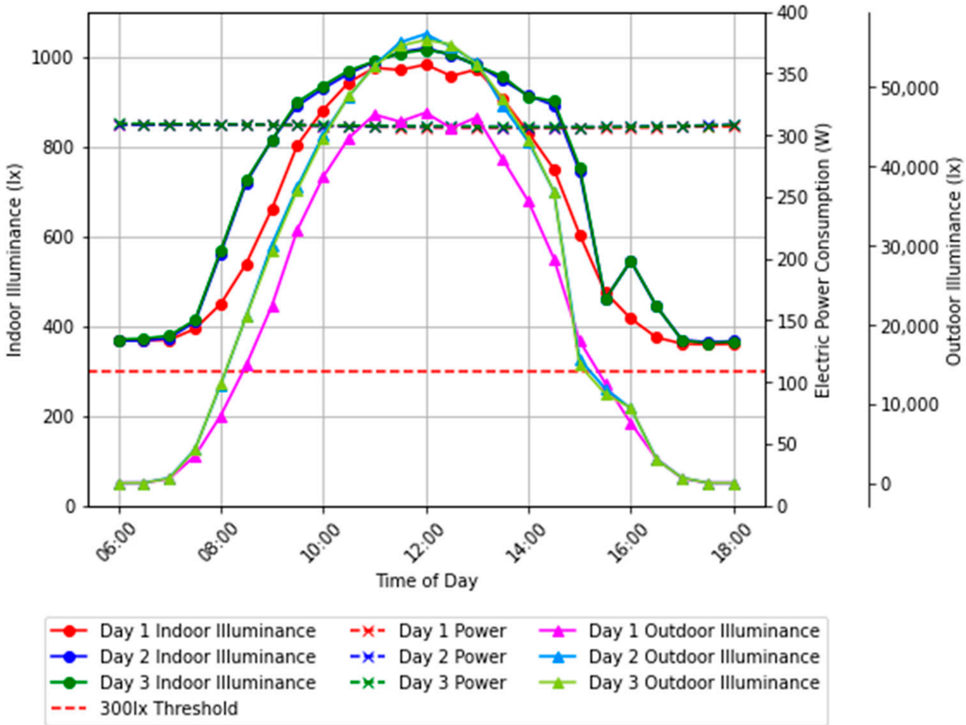


Figure 4. Illuminance and power consumption by regular lighting (transitional season).

The average illuminance values measured from nine sensors in the chamber were analyzed and presented in Figures 4 and 5. Over the three days with constant lighting, the minimum and maximum illuminance values were 358.34 lx and 1019.05 lx, respectively, with a median of 890.32 lx. During the dimming control period, the illuminance values ranged from a minimum of 147.08 lx to a maximum of 717.49 lx, with a median of 515.82 lx. Notably, the lighting power remained below 15 W between 10 a.m. and 2 p.m. This indicates that no lighting power was used for approximately four hours. The average indoor illuminance during the times when lighting power fluctuated was approximately 559.13 lx.

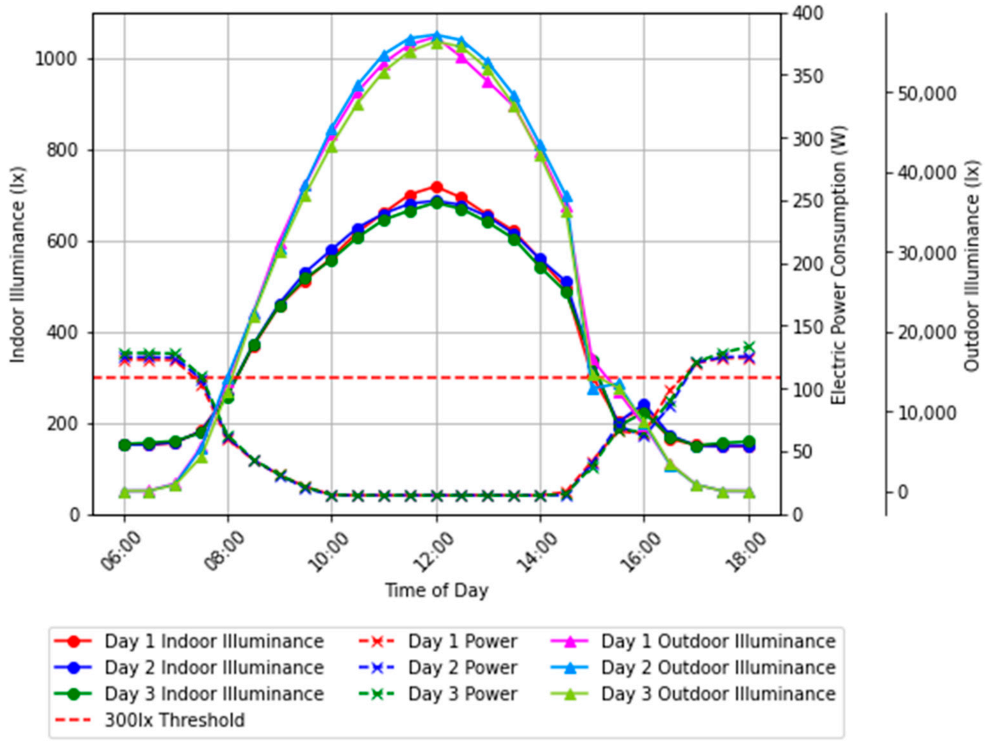


Figure 5. Illuminance and power consumption by dimming control (transitional season).

The implementation of the daylight-concentrating indoor louver with dimming control led to substantial energy savings, reducing lighting power consumption by approximately 85.65%. As shown in Table 2, the average lighting power consumption under the uncontrolled general lighting condition was 5830.72 W, with a three-day cumulative consumption of 17,492.16 W. Under the dimming control condition, the average daily cumulative lighting power consumption between 9 a.m. and 6 p.m. was 836.60 W, resulting in a three-day cumulative consumption of 2509.81 W.

Table 2. Average illuminance and power usage during office hours (9:00 to 18:00).

Lighting Condition	Season	Average Illuminance [lx]			Instantaneous Power [W]		Cumulative Power Consumption [W]	
		Min	Max	Median	Min	Max	Daily Average	Three Days
Standard Electricity Lighting	Transitional	358.34	1019.05	890.32	305.77	308.28	5830.72	17,492.16
Dimming Controlled Lighting	Transitional	147.08	717.49	515.82	14.6	133.02	836.6	2509.81
	Winter	169.04	741.11	494.45	14.62	160.48	1128.22	3384.67

3.2. Lighting Energy Savings with Dimming Control According to Season

The analysis of the winter experiment, conducted similarly to the transitional season experiment with dimming control for indoor lighting, is shown in Figure 6. During the winter dimming control period, real-time lighting power consumption ranged from a minimum of 14.62 W to a maximum of 160.48 W, indicating that the lighting was dimmed in response to changes in indoor illuminance. Both the minimum and maximum indoor illuminance values during the winter were higher compared to the transitional season. As shown in Table 2, the maximum illuminance in winter was 741.11 lx, which is 23.62 lx higher than the transitional season's maximum of 717.49 lx. The minimum illuminance in winter was 169.04 lx, 21.96 lx higher than the transitional season's minimum of 147.08 lx.

However, the median illuminance value was higher in the transitional season, at 515.82 lx, compared to 494.45 lx in winter.

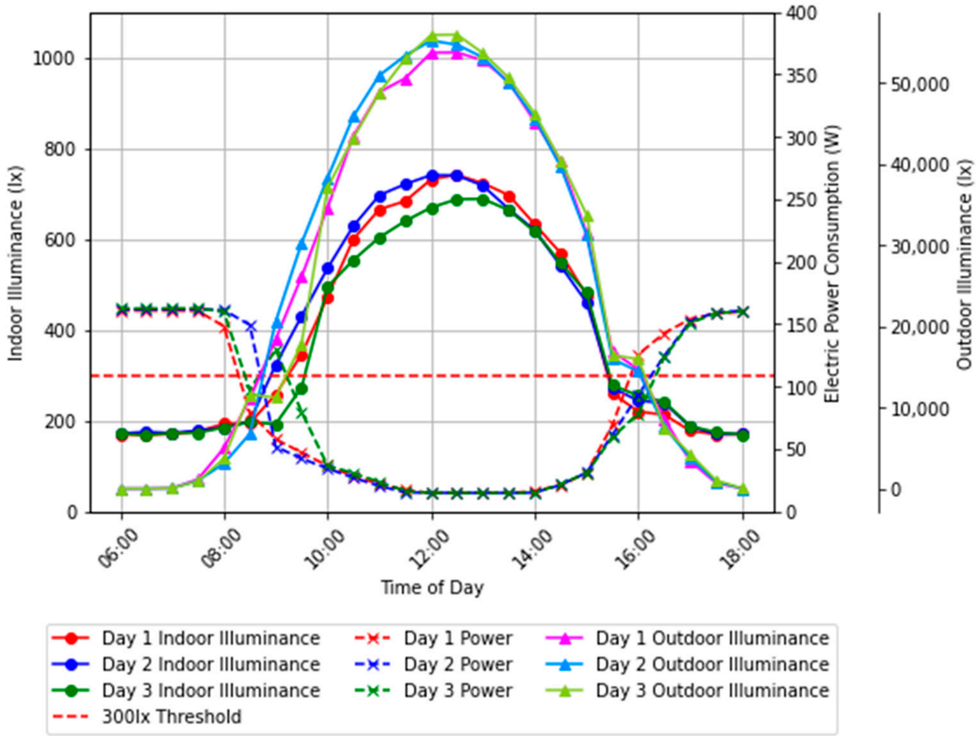


Figure 6. Illuminance and power consumption by dimming control (winter season).

Lighting power consumption was found to be higher in winter than in the transitional season. As shown in Table 2, the average daily power consumption in winter was 1128.22 W. In comparison, the transitional season had an average daily power consumption of 836.60 W. This represents a 25.85% increase in power consumption during winter. A comparative analysis of Figures 5 and 6 reveals differences in the duration of low-lighting power periods between seasons. During the transitional season, the period when lighting power fell below 15 W began at 10 a.m. and ended between 2 p.m. and 2:30 p.m., resulting in approximately 4 to 4.5 h of inactive lighting. In winter, this period started later, between 11:30 a.m. and 12 p.m., and ended between 1:30 p.m. and 2 p.m., resulting in only about 1.5 to 2 h of inactive lighting.

3.3. Variations in Indoor Illuminance and Lighting Energy by Season

In the previous section, it was observed that the maximum and minimum average illuminance values at nine indoor locations were higher during the winter than in the transitional season. However, the actual lighting power consumption was greater in winter. This section further analyzes the distribution of illuminance at specific measurement points during both seasons. Figures 7–9 illustrate the average illuminance values measured at distances of 1 m, 3 m, and 5 m from the window on selected days from both seasons.

Due to the lower solar altitude and the curvature of the daylighting shading device in winter, natural light penetrated effectively up to 1 m from the window but did not reach as deeply into the interior as it did during the transitional season. At a 1 m distance from the window, the illuminance values were higher in winter compared to the transitional season, as shown in Figure 7. According to Table 3, the average illuminance values measured 1 m from the window over three days were 557.36 lx, 719.27 lx, and 549.99 lx during the transitional season, compared to higher values of 709.40 lx, 878.26 lx, and 680.10 lx in winter. However, at distances of 3 m and 5 m from the window, the illuminance values were higher during the transitional season, as depicted in Figures 8 and 9. Table 3 confirms that the illuminance values at these distances were lower in winter compared to the transitional season. Consequently, the average daily cumulative lighting power consumption during working hours was 25.85% higher in winter than in the transitional season. The median real-time power consumption was 15.97 W in the transitional season and 30.76 W in winter.

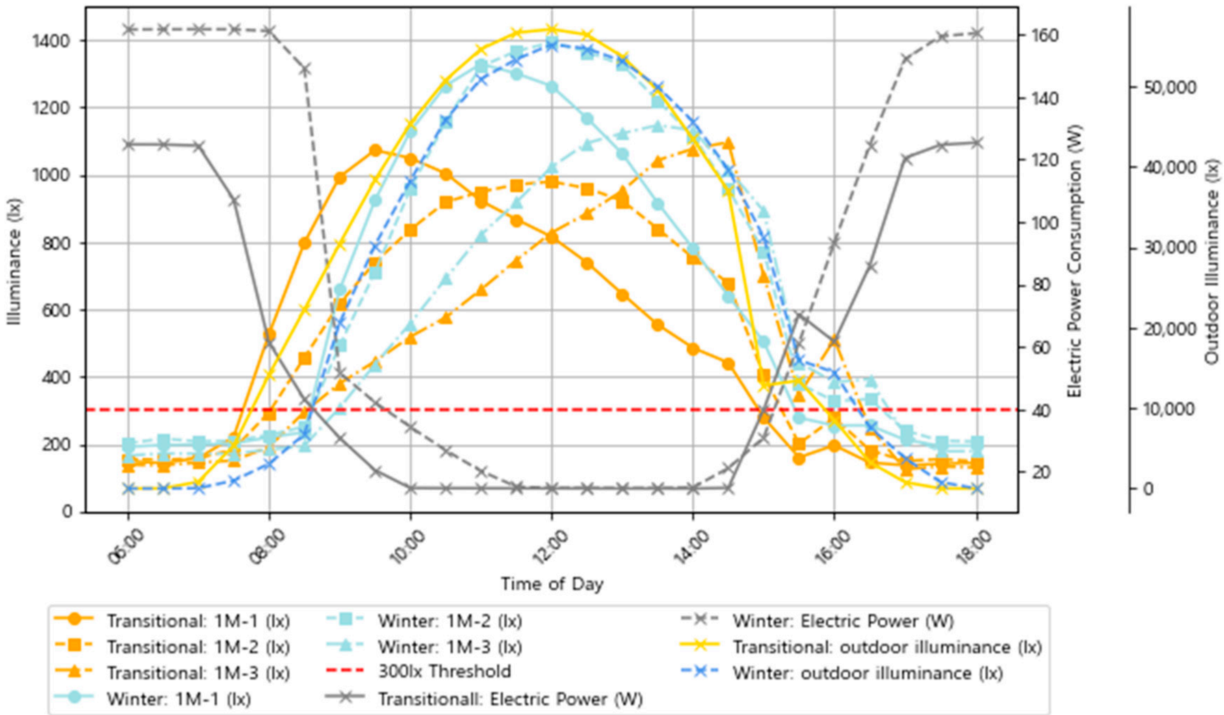


Figure 7. Illuminance values at 1 m from window during transitional and winter season.

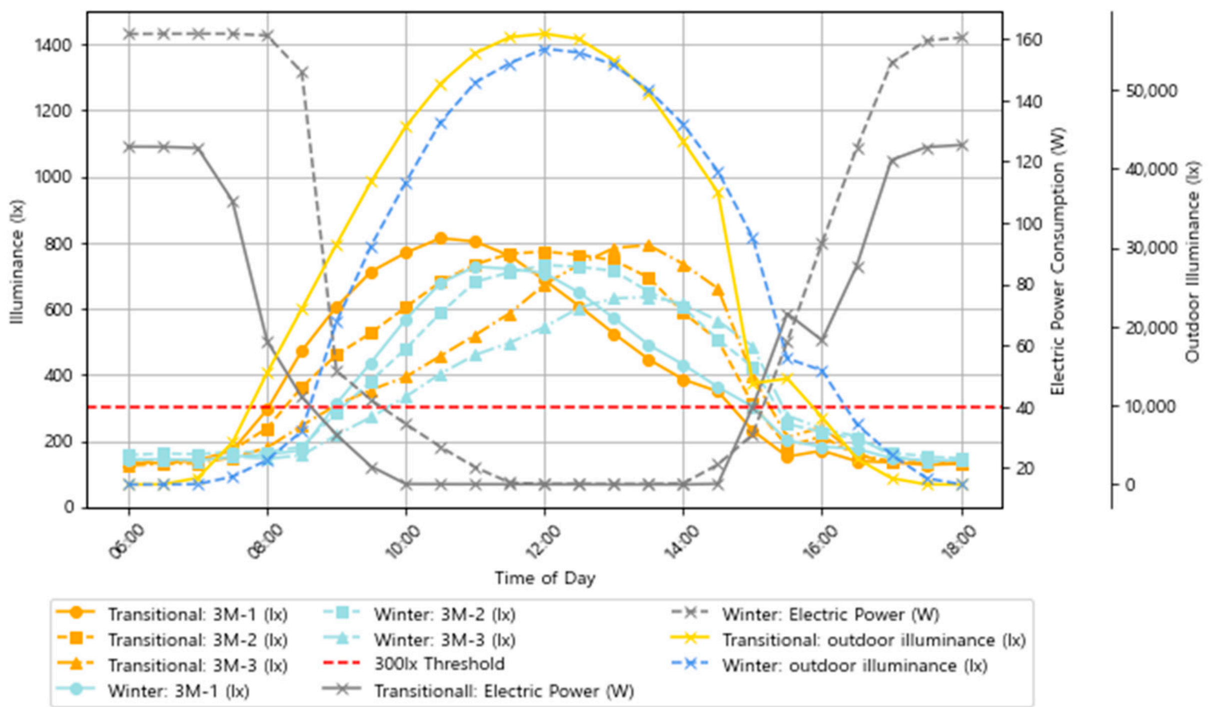


Figure 8. Illuminance values at 3 m from window during transitional and winter season.

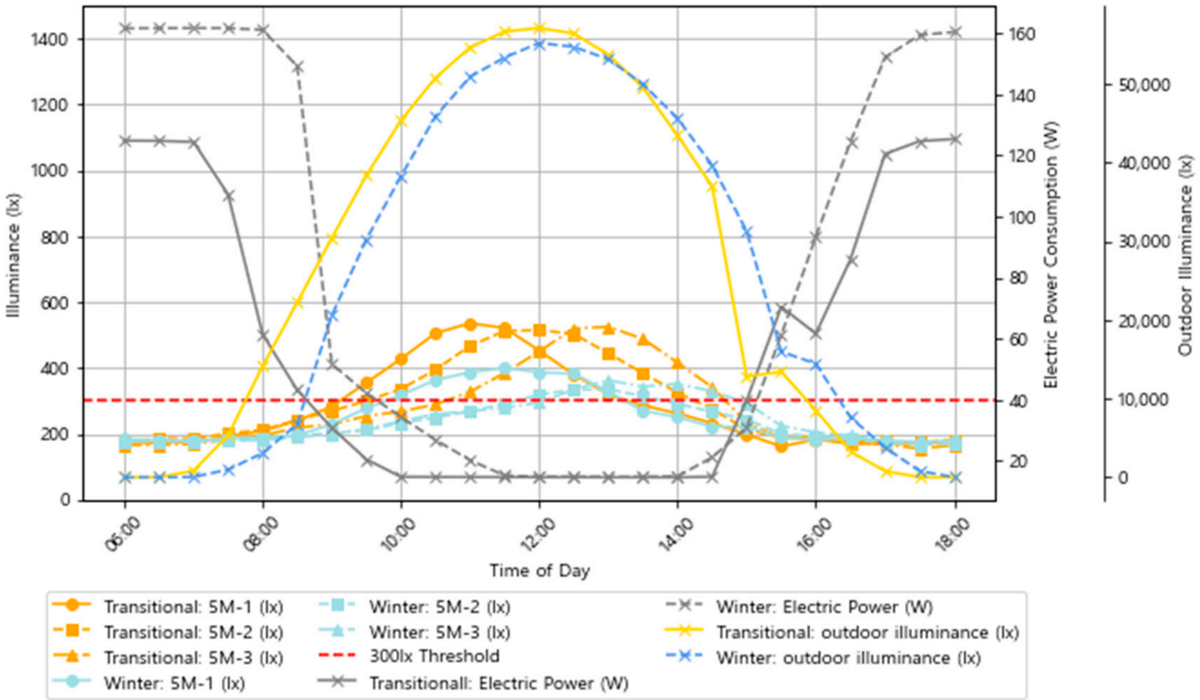


Figure 9. Illuminance values at 5 m from window during transitional and winter season.

Table 3. Average illuminance by sensor location and power usage during office hours (9:00 to 18:00).

Season	Distance from Window	Average Illuminance [lx]			Power Consumption [W]			
		1	2	3	Average	Min	Max	Median
Transitional	1 m	557.36	719.27	549.99	836.6	14.61	127.55	15.97
	3 m	451.38	523.78	403.56				
	5 m	280.79	295.29	263.53				
Winter	1 m	709.4	878.26	680.1	1127.22	14.67	160.13	30.76
	3 m	388.15	455.34	384.93				
	5 m	240.2	248.53	250.72				

4. Discussion

Indoor lighting energy consumption during working hours poses a significant challenge to achieving zero-energy buildings (ZEBs). However, this study demonstrates that integrating LED dimming control with a daylight-concentrating indoor louver, a renewable energy technology, can significantly reduce lighting energy consumption. Specifically, this integration can achieve an 85.65% reduction compared to conventional lighting. To effectively assess the impact of a daylight-concentrating indoor louver, it is essential to consider illuminance values at different locations within a space, rather than relying solely on average indoor illuminance or one representative illuminance at the zone. For instance, experiments conducted during transitional and winter seasons revealed that while average illuminance values were higher in winter, the required illuminance did not distribute evenly throughout the interior. Consequently, localized lighting control was necessary.

These findings highlight that to achieve ZEB goals, lighting control must not be based on average illuminance values alone. Instead, dimming control should be adjusted according to specific illuminance needs at various locations within a room. By actively utilizing natural daylight, this approach ensures that the desired illuminance is maintained, ultimately reducing lighting energy consumption. In conclusion, for effective energy savings in ZEBs, integrating location-specific dimming control with daylighting technologies is crucial. This strategy maximizes the use of natural daylight, maintains desired indoor illuminance, and significantly reduces building lighting energy consumption.

5. Conclusions

This study conducted a quantitative performance analysis of energy savings in buildings applying various renewable energy technologies, particularly focusing on a daylight-concentrating indoor louver system integrated with LED dimming control. The need for such analysis arises from the increasing certification standards for zero-energy buildings (ZEBs) to achieve carbon neutrality. The daylight-concentration indoor louver system was included as a renewable energy facility in 2018, necessitating thorough quantitative analysis.

The experiments measured the lighting energy savings under conditions specified in the construction standards for daylight-concentrating equipment. The analysis was conducted in an experimental chamber where dimming control was activated when indoor illuminance exceeded 300 lx, focusing on measurements taken between 9 a.m. and 6 p.m.

The results indicate significant lighting energy savings, particularly during the transitional season, with an 85.65% reduction in power consumption achieved through LED-linked dimming control compared to the regular lighting. In contrast, during the winter season, although the minimum and maximum average indoor illuminance values were higher, the cumulative power consumption was also greater. Specifically, the three-day average cumulative power consumption was 1128.22 W in winter. In the transitional season, it was 836.60 W. This represents a 25.85% increase in power consumption during winter. The increase is due to the shorter duration of sufficient natural light availability in winter.

Illuminance distribution analysis showed that, at a distance of 1 m from the window, the winter season recorded higher illuminance values. However, at distances of 3 m and 5 m, the transitional season recorded higher values, indicating a more effective penetration of natural light during this period. The solar altitude during the transitional season facilitated more even distribution of light indoors through the daylight-concentrating indoor louvers.

In conclusion, this study confirms the substantial lighting energy savings achieved through the integration of daylighting indoor louvers and LED dimming control. It also highlights the seasonal variations in illuminance distribution and energy savings, with a particular emphasis on the increased efficiency observed during the transitional season. Future research should focus on verifying the effects of illuminance distribution and energy savings during the summer, as well as exploring the impact of seasonal adjustments in slat angles on indoor illuminance and energy savings. This research contributes to the broader understanding of optimizing renewable energy technologies in building design to achieve energy efficiency and carbon neutrality.

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Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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