

Article

Daylighting Performance of Light Shelf Photovoltaics (LSPV) for Office Buildings in Hot Desert-Like Regions

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Abstract: Visual comfort and energy consumption for lighting in large office buildings is an area of ongoing research, specifically focusing on the development of a daylight control technique (light shelf) combined with solar energy. This study aims to investigate the optimum performance of light shelf photovoltaics (LSPV) to improve daylight distribution and maximize energy savings for the hot desert-like climate of Saudi Arabia. A radiance simulation analysis was conducted in four phases to evaluate: appropriate height, reflector, internal curved light shelf (LS) angle, and the integrated photovoltaic (PV) with various coverages (25%, 50%, 75%, and entirely external LS). The results revealed that the optimum is achieved at a height of 1.3 m, the addition of a 30 cm reflector on the top of a window with an internal LS curved angle of 10° with 100% coverage (LSPV1, LSPV2). Such an arrangement reduces the energy consumption by more than 85%, eliminates uncomfortable glare, and provides uniform daylight except for during the winter season. Hence, the optimization of the LSPV system is considered to be an effective solution for sustainable buildings.

Keywords: LSPV; visual comfort; energy consumption; angle

1. Introduction

Presently, the Kingdom of Saudi Arabia is witnessing unprecedented development as part of the implementation of its ambitious 2030 vision. Launched in 2016, the vision intends to build a thriving, diversified, and sustainable economic model which has a lesser dependence on the income from oil and savings from fossil fuel subsidies [1]. Solar energy has been recognized as a relatively significant source of renewable energy compared to the other sustainable energy sources in the Kingdom of Saudi Arabia. Considering the ample solar radiance and the prevailing desert-like climatic conditions [2], photovoltaic (PV) technology could play a vital role in overcoming energy issues in this hot and arid region [3]. The Saudi Electricity Company revealed that lighting accounts for over 30% of the total energy consumed in office buildings to provide the required amount of light [4]. Therefore, the rationalization of energy use and the improvement of daylighting design techniques such as light shelves [5–7], semi-transparent photovoltaics (STPV) [8], louvers [9], and light transportation [10] need to be considered.

One of the essential daylighting techniques is light shelves. A light shelf is a horizontal surface that reflects daylight deep inside a building. Light shelves are placed above eye-level and have highly reflective upper surfaces that reflect daylight onto the ceiling and deeper into a space. It is a flexible system that offers a variety of design solutions. It can be installed easily on an external or internal surface [6], and can be designed in various geometries like fixed flat models and curved reflective surfaces [11], dynamic shading device design [5,12], and integrated as a solar module [13]. Thus,

precise operation of the various design solutions associated with light shelves, such as solar modules, is required to enhance lighting and electricity generation efficiency in response to external conditions, as depicted in Figure 1.

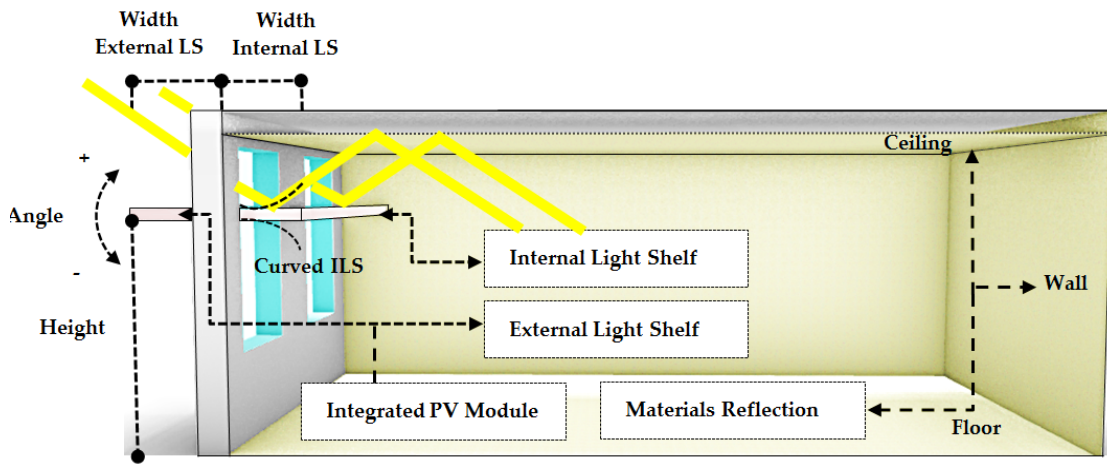


Figure 1. Design solutions and variables associated with a light shelf that influence the daylight distribution.

Much research has been conducted concerning the daylight performance of light shelves using several configurations (dimensions, geometry, angles, and material) using experiments in the field under varying sky conditions or through simulations. As specified in Table 1, previous research has primarily evaluated the optimization of the aspects concerning light shelves to enhance the distribution of daylight in vast spaces to facilitate enhanced visual comfort. Nevertheless, there was specific research concerning a light shelf whose width and length was modified by isolating the light shelf reflector along with the bottom and top reflectors [14].

Several other studies analyzed an integration of building envelope technologies like louvres [15], in-built photovoltaics (PV) [13], and awning systems [16] to facilitate a decrease in the energy requirements of the building. A review of the existing literature indicates that there are only a few pieces of research that assess the performance of solar panels integrated with light shelves. Hwang et al. [17] examined the characteristics of the light shelf system using in-built PVs by lining the outer light shelf with solar panels in a southern orientation, placed at varying angles. Heangwoo Lee [13] recently suggested a solar-integrated light shelf having only a fraction of it covered with solar panels at varying angles; however, the internal shelf would not be used. Hence, the current study aims to assess the optimum performance of the combination of external and internal light shelves using integrated solar panels in several places to facilitate the appropriate distribution of daylight in the office structure and optimize energy savings, especially under the hot desert-like climatic conditions of Ha'il city.

Table 1. Studies conducted on light shelf performance on daylighting.

Title of Study and Year	Light Shelf Parameters	Experimental Measurement	Daylighting Simulation	Integrated PV with Light Shelf
Maximizing the light shelf performance by interaction between light shelf geometries and a curved ceiling, Jordan, 2010 [11]	Geometries, curved ceiling	no	yes	no
Power performance of photovoltaic-integrated lightshelf systems, South Korea, 2014, [17]	Full solar panel (one size)	yes	yes	yes
Analysis of the Impacts of Light Shelves on the Useful Daylight Illuminance in Office Buildings in Toronto , 2015, [18]	Width, depth, and height	no	yes	no
Dynamic internal light shelf for tropical daylighting in high-rise office buildings, Malaysia, 2016, [5]	Height of ILS, number of ILS	yes	yes	no
Evaluating daylight performance of light shelves combined with external blinds in south-facing classrooms in Athens , 2016, [15]	Material, angle, combination with louvers	no	yes	no
Investigating the Influence of Light Shelf Geometry Parameters on Daylight Performance and Visual Comfort, a Case Study of Educational Space in Tehran, Iran , 2016, [19]	Dimension, angle, orientation	no	yes	no
Energy-saving performance of light shelves under the application of user-awareness technology and light-dimming control, South Korea, 2018, [20].	Angle	yes	yes	no
A preliminary study on the performance of an awning system with a built-in light shelf, South Korea, 2018, [16].	Angle, awning system	yes	yes	no
Development and Performance Evaluation of Light Shelves Using Width-Adjustable Reflectors, South Korea, 2018, [21].	Width adjustability	yes	no	no
Performance evaluation of a light shelf with a solar module based on the solar module attachment area, South Korea, 2019, [13].	Angle, PV coverage	yes	yes	yes
Experimental Analysis of the Performance of Light Shelves in Different Geometrical Configurations Through the Scale Model Approach, South Korea, 2020, [6].	Angle, curved LS, ILS reflector	yes	no	no
Optimization of Daylight Performance Based on Controllable Light-shelf Parameters using Genetic Algorithms in the Tropical Climate of Malaysia , 2020, [22]	Angle, width/depth ratio, height, and reflectivity	yes	yes	no
Performance Evaluation of External Light Shelves by Applying a Prism Sheet, South Korea, 2020, [23].	Applying prism sheets with angles	yes	no	no

1.1. The Sun Path of Ha'il City

Sun path diagrams are appropriate for depicting the annual changes happening about the Sun's path. As shown in Figure 2, the midday sun in Ha'il city is at a 39° inclination during the winter solstice. The inclination is 84° during the summer solstice. These numbers indicate a 45° deviation

between the solstices as a result of the Earth's declination, varying between -23° and $+23^\circ$ over the year. In contrast, during spring and autumn, the Sun has a similar path and an inclination of 63° , which is present between the two solstices.

The solar energy incident on the southern and northern parts of the building is not the same since the southern side has better incident sunlight compared to the northern side. In contrast, considering the eastern and western directions, the incident solar energy exhibits symmetry. As a result, there should be a difference in the light intensity once the light shelves are attached.

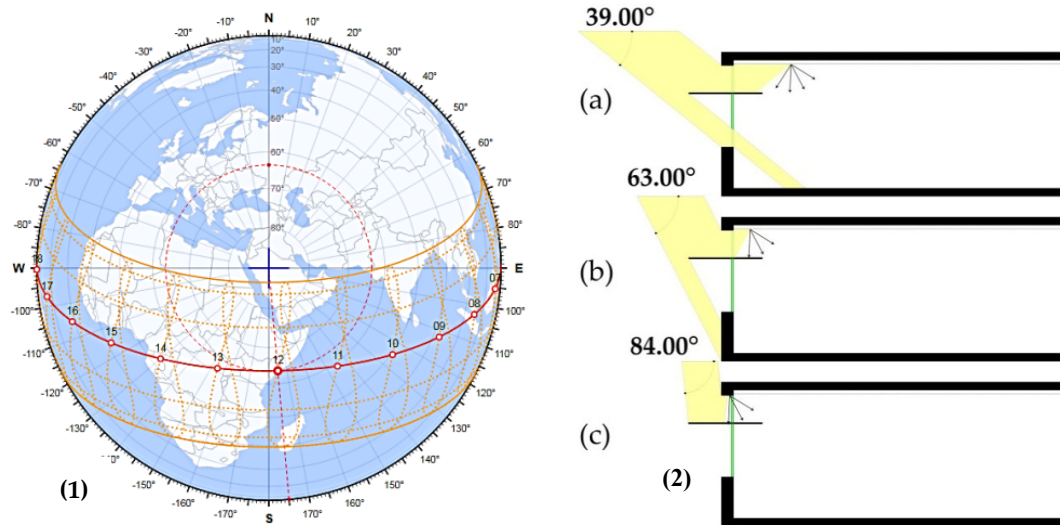


Figure 2: (1) Sun path at the city of Ha'il using Andrew–Marsh 2D modeling, (2) the inflow of daylight corresponding to the incident angle of design rays at midday. (a) Winter solstice; (b) spring/autumn equinox; (c) summer solstice.

1.2. Recommended Indoor Illuminance

According to the International Organization for Standardization (ISO) standard 8995-1:2002 [24], typically, the illumination at the workplace (especially in areas comprising continuous work) should not fall below 300 lux; however, the delta between the suggested illuminances is not substantial because they are usually associated with the Commission International d'Eclairage (CIE) regulations. Recommended illumination in the United States [25], Japan [26], and European countries [27] range between 300 lux to 1000 lux. For most countries whose data were reviewed, 500 lux illumination is maintained at the desk level for routine office work, as presented in Appendix A. Most countries recommend 750 lux for drawing since it is a task that requires high accuracy. In contrast, the lower limit of horizontal illumination in an office setting concerning a computer lies in the 300–750 lux range. In this study, the indoor illumination standard for light shelf performance evaluation was set to between 300–750 lux based on the review of the aforementioned optimum indoor illumination standards.

2. Materials and Methods

This research considers both qualitative and quantitative analyses of the simulation of numerical parameters (reflector, height, and Internal light shelf (ILS) curve) as a mechanism for three-phased data collection. Subsequently, the PV modules are integrated at varying coverage values.

The following sections present the simulation technique, the light shelf configurations used for the case study, and the assessment criteria implemented in this study. Figure 3 provides a summary of the chosen case.

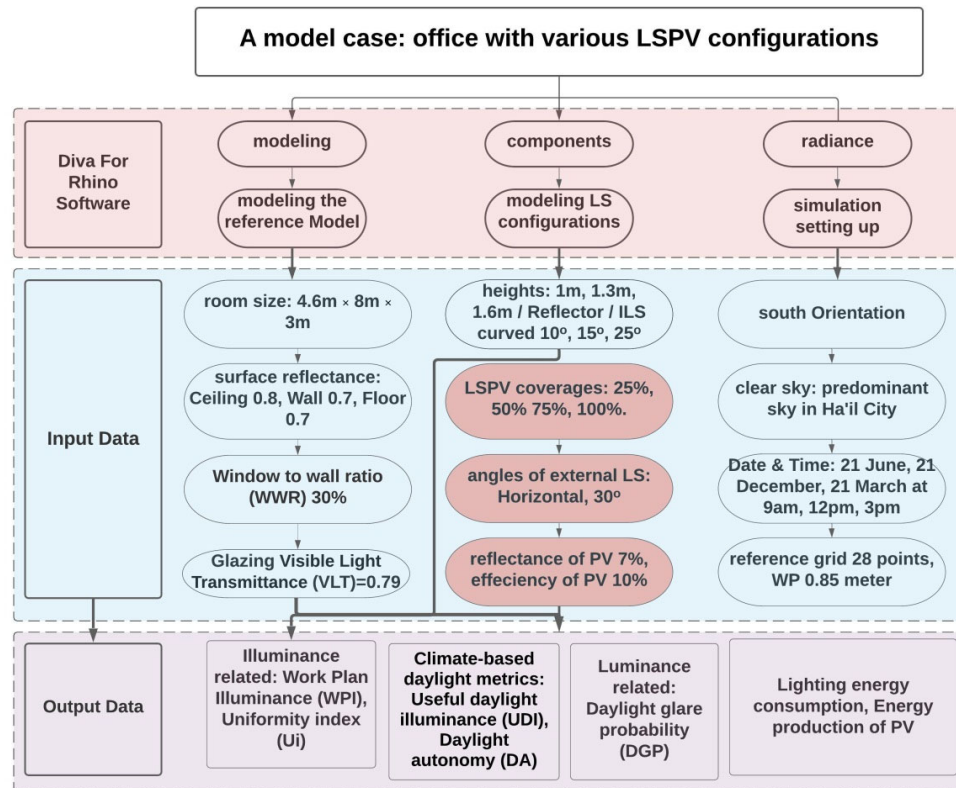


Figure 3. Schematic diagram for the simulation method.

2.1. Computer Simulation (Diva for Rhino)

This research used Diva for Rhino as the tool to simulate daylight performance for different light shelf configurations. Diva employs a Radiance backwards ray-tracer calculation method and the DAYSIM daylighting analysis engine to run daylight simulation [28]. The software considers the distribution of emitted rays and supports the analysis of reflection, transmission and refraction from surfaces. The Meteoronorm metrological database (TMY) is used by Diva, where the hourly data of weather aspects like radiance, illuminance, temperature and humidity are validated by the rating authority [29].

2.2. Light Shelf Configurations

In this study, 11 internal–external light shelf configurations were tested using daylight simulation, as shown in Table 2. The combined internal and external light shelf (LS) configurations have been assessed using four main phases:

- First phase: three horizontal light shelves of different dimensions, placed at varying heights as defined by previous studies [30–32]. The Internal LS depth is equal to the height of the clerestory window above it while the external LS depth is 1.5 times the height of the clerestory window.

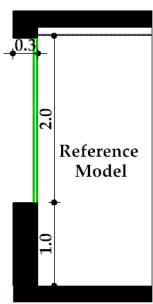
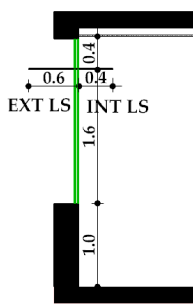
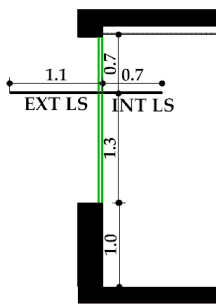
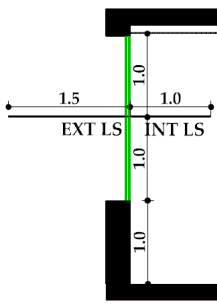
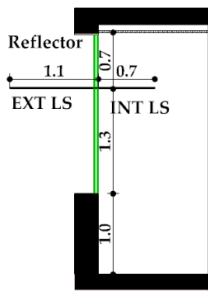
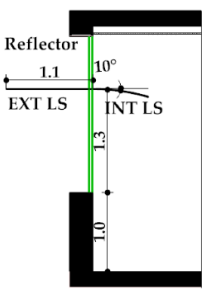
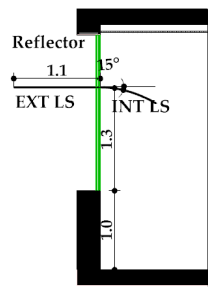
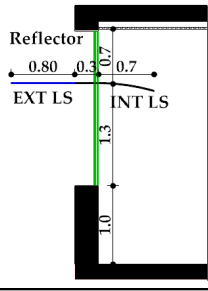
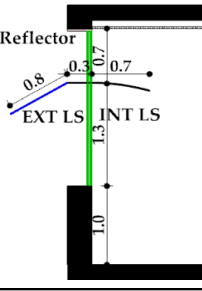
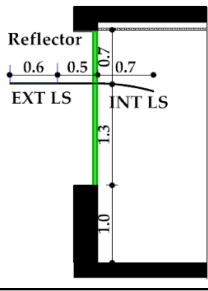
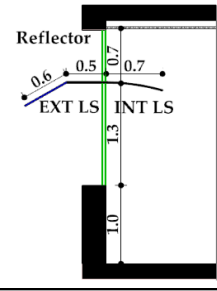
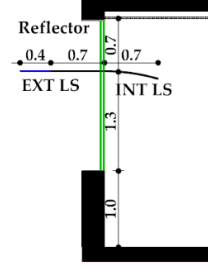
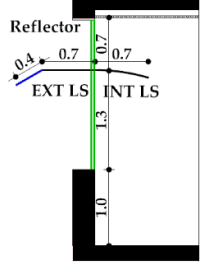
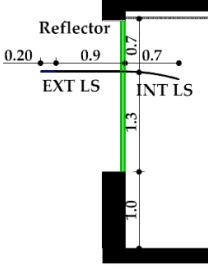
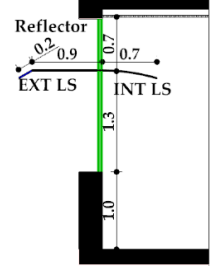
$$d_{\text{int light shelf}} = h_{\text{clerestory}}$$

$$d_{\text{ext light shelf, max}} \leq 1.5 \times h_{\text{clerestory}}$$

The three configurations in the first phase are LS1H1, LS2H2, and LS3H3, and they have fixed heights of 1.6 m, 1.3 m, and 1.0 m, respectively.

- Second Phase: once the appropriate height of the LS is chosen, a reflector material is added on the top of the window to enhance the illumination of the daylit area at the back and then compared with the reference model.
- Third phase: three downward-curved internal LS (having angles of 10°, 15° and 25°) were examined and compared with horizontal internal LSs with the reflector material specified in the second phase.
- Fourth Phase: four different PV coverage and tilt angles are integrated with the external LS. LSPV1, LSPV3, LSPV5, and LSPV7 are designed to have external horizontal light shelves with 100%, 75%, 50%, and 25% coverage, respectively. The remaining configurations of LSPVs have the same coverage but are tilted at 30° to reflect maximum energy and prevent the occurrence of glare.

Table 2. Light shelf configurations used in simulation for each phase.

Phase 1 (Height)	Reference Model	LS1H1	LS2H2	LS3H3
				
Phase 2 (Reflector)	LS2H2 + R	Phase 3 (Curved ILS)	LS C1	LS C2
				
Phase 4 (Integrated with PV)	LSPV1	LSPV2	LSPV3	LSPV4
				
	LSPV5	LSPV6	LSPV7	LSPV8
				

2.3. Description of the Case Study and Climatic Conditions

The model chosen for reference in this case study considers a typical vast office structure built in ‘Diva for Rhino’ with a depth of 8.0 m and a width of 4.6 m. As depicted in Figure 4, the office was aligned with the southern façade using a lateral typology. In the context of the reference model, the window-to-wall ratio (WWR) is 0.3. At the same time, the opening is double glazed using low-E material, and has a visible light transmittance (VLT) value of 0.79. Table 3 lists the radiance parameters used for daylighting simulation.

Table 3. Radiance parameters used in the daylighting simulation.

Radiance Parameter	Ambient Bounces	Ambient Divisions	Ambient Sampling	Ambient Accuracy	Ambient Resolution
Value	7	1500	100	0.1	300



Figure 4. Exterior and interior 3D reference model and furniture arrangement.

This study used data pertaining to the Ha'il area as representative of the hot desert-like climate of Saudi Arabia, which is summarized in Table 4. This area is located around the center of the Arabian Peninsula, and its coordinates are 27°31' N, 41°41' E. The average temperature is 31.1 °C and the coldest month is January, which has a mean temperature of 10.6 °C. The area receives intense solar radiation—the average monthly incident solar energy experiences significant seasonal variation over the course of the year. The monthly maximum global horizontal radiation values range from 243 kWh/m² in summer and 118 kWh/m² in winter. At the same time, the global diffuse radiance is approximately 29%. There is shallow cloud cover in this area. The area experiences clear skies on more than 70% of the days in an average year, while 29% of the days are overcast or mostly overcast; hence, this area has clear sky conditions according to the CIE standard [33]. Furthermore, the daylight range is between 10.4–13.6 h, which indicates plenty of daylight through the year.

Table 4. Monthly climatic conditions of Ha'il city.

	January	February	March	April	May	June	July	August	September	October	November	December
Average air temperature (°C)	10.2	13.5	17.8	23.3	28.1	31.9	33.2	33.8	30.6	25.1	17	12.2
Global horizontal irradiance (kWh/m ²)	125	132	183	204	228	243	238	225	195	168	125	118
Global diffuse irradiance (kWh/m ²)	38	40	53	62	64	56	61	60	51	45	40	29
Sun hours	10.6	11.2	12	12.8	13.5	13.8	13.7	13.1	12.3	11.5	10.8	10.4
Cloud cover (%)	26	22	23	24	17	3	10	9	6	17	26	29

2.4. Modelling Approach and Analysis Criteria

The simulated work plane illuminance (WPI) values were transcribed into a tabular form which contains the average illumination of four grid points in each row (lines as shown in Figure 5a). Furthermore, the quality of daylight distribution employed the uniformity index (U_i) of interior daylight, which is the ratio of the average illumination to the maximum illumination. This ratio should not be less than 0.6 above the work plane, as per the NBN L13-001 code and international guidelines [34]. The simulations were performed within the design days at the summer and winter solstices and during the mid-season (21 June, 21 December, 21 March) at 9.00 a.m., 12.00 p.m., and 3.00 p.m. to evaluate the annual variation and the critical period. The choice of the simulated points (grids) inside the office followed the grids plotted as per the arrangement of work planes. The minimum number of points in the deep-office prototype was 28. The distance between the simulated grid points was kept at 1 m for accurate results, as depicted in Figure 5. The reflection by the surfaces used in this experimental set is presented in Table 5.

Table 5. Material reflection coefficient percentages.

Material	Reflection Coefficient
Ceiling	80%
Floor	20%
Wall	70%
Furniture	50%
Light shelf	90%
Solar panel	07%
Reflector	99%
Double glazing low-E	VLT 79%

For more details, the analysis of LSPV in last phase used climate-based daylight metrics that include the useful daylight illuminance (UDI), daylight autonomy (DA) and daylight glare probability (DGP), supported by a 3D illuminance contour map for glare assessments. The criteria of assessments of each metric are summarized in Table 6. The simulation of lighting energy consumption is through daylight control strategy (photosensor controlled dimming: 300 lux), where eight light-emitting diode (LED) indoor artificial lights (17.5 W luminaire power, luminaire luminous flux: 1552 lm and luminaire efficacy: 89 lm/W) were placed in the middle of line 1, 3, 5 and 7 and linked with illumination sensors (S1, S2, S3, S4, S5, S6, S7 and S8). The light distribution of the lighting in this study is shown in Figure 5b. The illumination sensors were placed 0.85 m above the floor surface, based on the height of the work plane. Their operating profiles follow their real use from 8.00 a.m. to 5.00 p.m.

The amount of energy produced by the multi-crystalline photovoltaic module was derived using the Simple model. This model was simulated by multiplying the fraction of surface area that had active solar cells by the total solar radiation incident on the PV array; module conversion efficiency was set to $\eta = 10\%$. While the area of the solar module used varies according to the case set used in this study, the amount of energy produced depends primarily on photovoltaic array efficiency and inverter modelling efficiencies at the operating conditions. Nevertheless, the difference between lighting energy consumption and the energy produced is either positive or negative. Hence, for every configuration, the net energy production is the most significant performance indicator required to determine the optimum LSPV configuration.

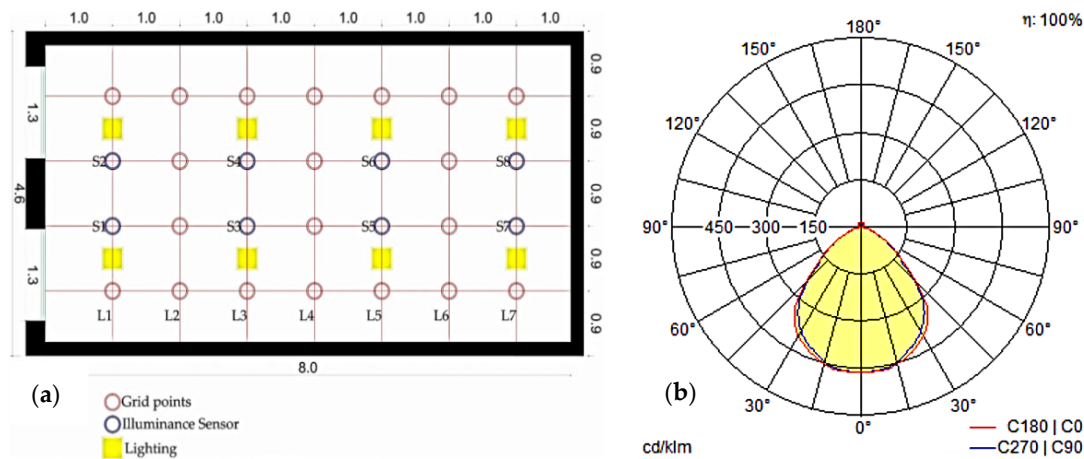


Figure 5. (a) Plan view representation of the grid points, illuminance sensors and lighting positions, (b) light distribution of conical illuminance.

Table 6. The performance indicators of visual comfort used in this study.

Criteria	Performance Indicator of Delighting Quantity and Quality
WPI	WPI recommended 300–750 lux
UI	Uniformity index must be greater than 0.5
UDI	100 lux < dark area (need artificial light) 100 lux–2000 lux (comfortable), at least 50% of the time >2000 lux too bright with thermal discomfort
DA	Set up 300 lx
DGP	0.35 < imperceptible glare 0.35–0.40 perceptible glare 0.4–0.45 disturbing glare >0.45 intolerable glare
Net energy	Energy production of solar panels—energy consumption of artificial lighting

3. Results and Discussion

3.1. Analysis of Phase One

Figure 6 depicts how light shelf height affects the daylighting performance of light shelves regarding the uniformity and distribution of WPI levels at distances of 1 m and 7 m from the window of the office where testing was performed. Remarkably, WPI levels in front of the window exceed 750 lux for all height levels used in this study and all design days. Additionally, the WPI levels of LS2H2 and LS3H3 are less compared to LS1H1, especially at midday. The illuminance level at the back daylight area was less than half of the illuminance level of the front area. However, the WPI levels were almost within the recommended range. Consequently, the uniformity index of LS1H1 is less than 0.5 at the winter solstice and during the mid-season due to the low angle of incidence of the Sun's path, as depicted in Figure 2. This leads to a higher contrast between daylight distribution near the window and the back surface. The LS2H2 and LS3H3 configurations achieved the uniformity index value at all times except during the winter solstice. It is worth mentioning that the width of the external light shelves influenced the integrated solar panel in terms of power generation during the last phase. However, its drawback is that there may be infringement concerns regarding the prospect right and damage due to wind pressure [6]. Therefore, the LS2H2 configuration was chosen for the width of the light shelf and 2/3rd of the window height, which is in line with previous studies [31].

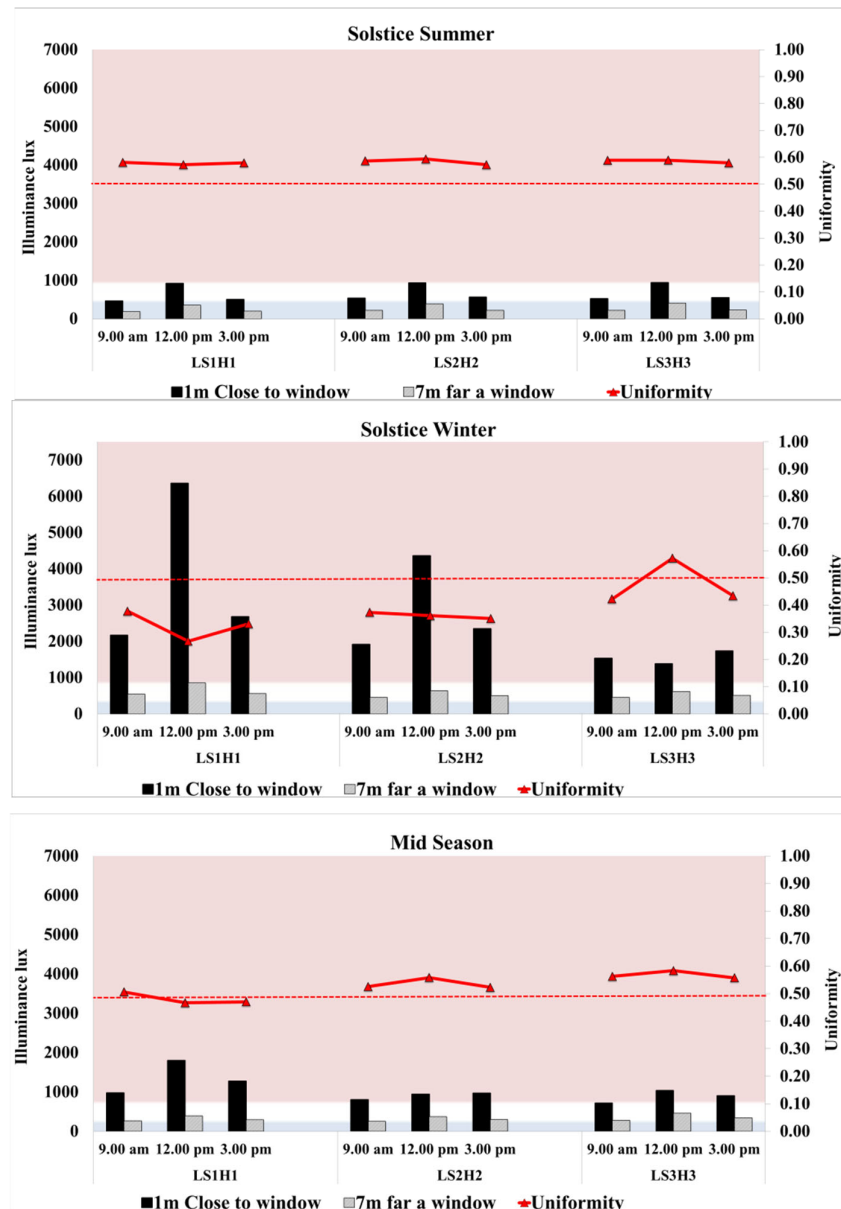


Figure 6. The effect of the position of internal and external light shelves at a distance of 1 m and 7 m from the window.

3.2. Analysis of Phase Two

Figure 7 depicts the introduction of the reflector material added at the top of the window compared to LS2H2. There is a remarkable increase of about 10% in WPI level distribution in the back daylight area. However, the WPI value pertaining to the front and back daylight area during the winter solstice is much higher than the recommended value, especially at midday. The uniformity index also witnessed improvement for all design days compared to the LS2H2 configuration (without a reflector), except for during the winter solstice. Thus, the use of a reflector at the top of the window, along with external and internal light shelves, is a useful daylight configuration for improving the WPI in the back space of the model. This result aligned with Zazzini et al.'s research [6]. Furthermore, uniformity is also enhanced in the said configuration; however, remarkable reflection is a concern when the Sun's path is low during the winter season.

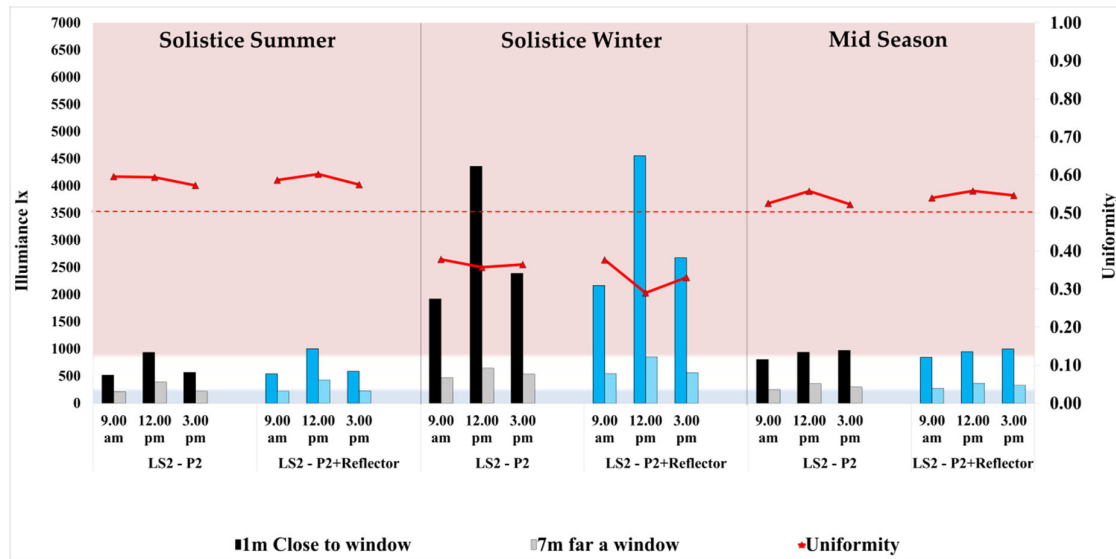


Figure 7. The performance of a reflector on the top of window combined with external and internal light shelves.

3.3. Analysis of Phase Three

Figure 8 depicts the distribution of indoor illuminance using three different internal curved LS angles (10%, 15%, and 25%) compared to horizontal LS on all design days. The results revealed that the use of an internal curved LS with 10° tilt angle recorded the highest value of WPI and uniformity index at a distance of 7 m from the window. The back daylight area saw an increase of up to 5–11% on these parameters during the summer and winter solstices; however, the increase was less than 4% at the spring equinox. The uniformity index also saw an improvement for all the seasons. The WPI value at about a 4 m distance from the window (middle area) and the front area is within the recommended range, except at midday, where it is consistently higher than 750 lux. The LSC3 configuration with 25° tilt angle presents the least optimal case since the WPI increased for the front area but decreased for the back area, which results in less uniformity in daylight distribution. Thus, the optimal tilt angle of LS is 10° (LSC1) for all seasons. In contrast, Heangwoo et al. [35] found that the optimal specifications for external curved light shelves are different depending on the season, but are effective at improving the indoor uniformity ratio compared to a flat light shelf during summer.

Overall, the observations from the optimized light shelf configurations after the three phases (height, reflector, curved internal light shelf) were compared with the reference model (without the light shelf). The proposed model illustrated a significant improvement considering the uniformity index on all design days, especially during midday. Furthermore, there was an increase of about 13–20% in the absolute WPI value concerning the back daylight area during the summer season for the entire day. At the same time, the absolute WPI value reduced for the middle (63°) and low (39°) sun path altitudes, as specified in Appendix B.

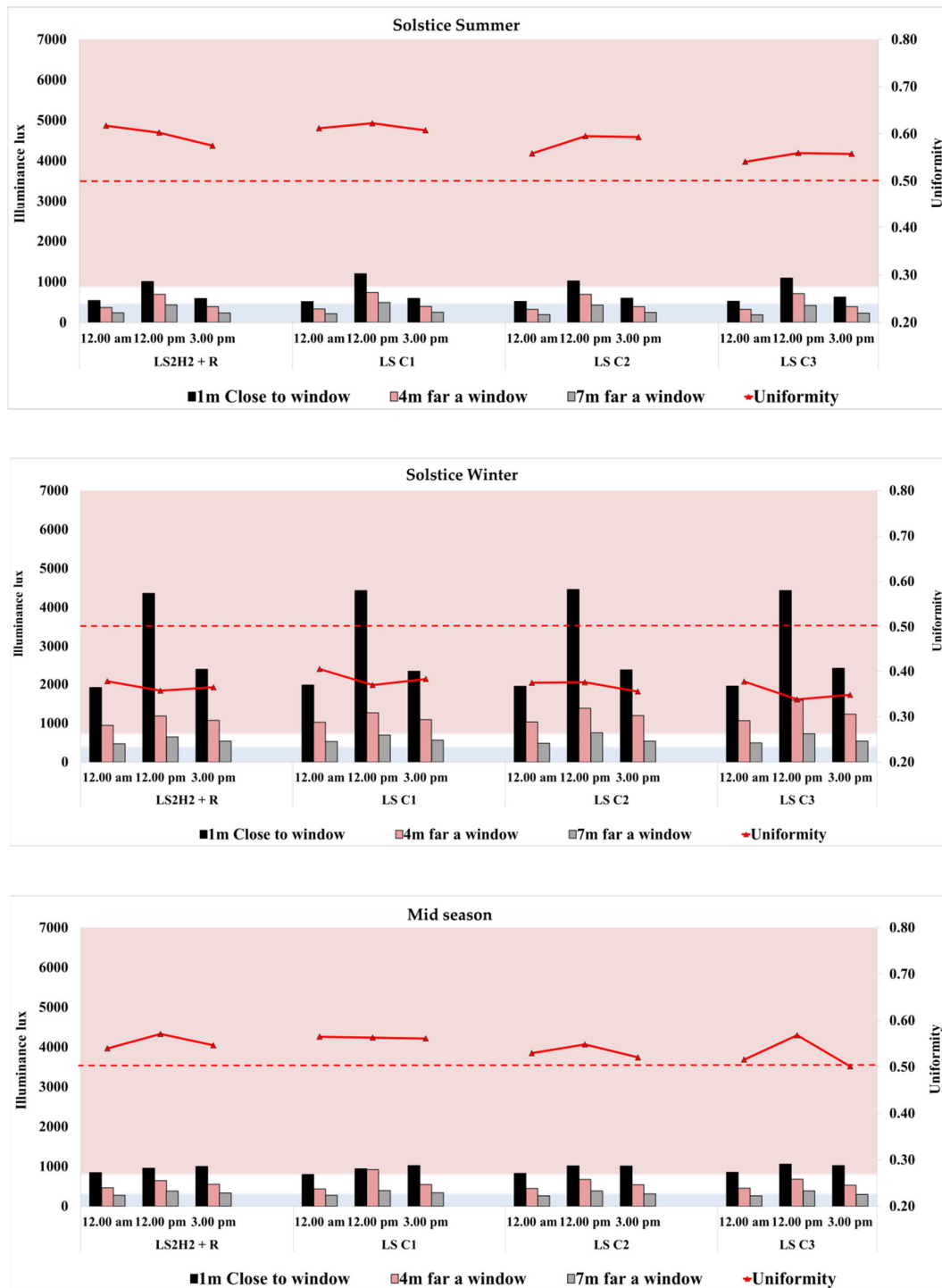


Figure 8. The performance of various curved light shelves in distance of 1 m, 4 m and 7 m from the window and Uniformity.

3.4. Performance Evaluation of Light Shelf Photovoltaic Configurations (LSPV) (Phase Four)

Tables 7–9 present the WPI distribution and uniformity index for the reference model and the many LSPV configurations corresponding to CIE clear sky within the design days. During the summer season, the WPI values and their averages concerning the reference model are higher than all LSPV configurations, especially during midday, as measured in the front area. It is also observed that in all cases, the uniformity index is higher than 0.5. Notably, the usage of LSPV leads to a

noteworthy improvement in the WPI and uniformity index as compared to the reference model. The improvement in these parameters is better during midday, especially for configurations LSPV1 and LSPV2. In the case of the winter season, all WPI values are higher than 500 lux for all the configurations, except for the middle and back daylight area specific to the LSPV2 configuration. At the same time, the uniformity index improved for all the cases, but it was still less than 0.5. As for the mid-season results, the LSPV with a 30° tilted angle witnessed an increase in WPI at midday, while the LSPV with a horizontal angle witnessed an increase during the evening as a result of the low sun position. The only configuration that had uniformity was LSPV2, unlike the reference model.

Figure 9 presents the mean values of the DA and UDI metrics for the deep office considering all SPV configurations. The analysis revealed that the reference model achieved 78.9% of the 300 lux mean value of DA, which is the highest percentage compared to the LSPV configurations, where LSPV with 100% and 75% coverage is less than 50%. The annual distribution of DA for every grid point is depicted in Appendix C. In contrast, the UDI of LSPV (100–2000 lux) is higher at 90% compared to 83% for the reference model due to the high rate of visual discomfort compared to the LSPV configurations. The LSPV2 configuration almost eliminated visual discomfort (UDI > 2000).

Table 10 shows the magnitude of discomfort caused by glare for the reference model; optimal cases were determined using daylight glare probability (DGP) and a 3D contour map. The results revealed that a perceptible glare occurred only during the winter season when measured close to the window as per the reference model. This happened when the Sun was at its lowest and in direct view, specifically at noon. All LSPV configurations reduce the amount of DGP to an imperceptible glare condition. Eventually, configurations LSPV1 and LSPV2 with 100% coverage were considerably improved regarding visual comfort by reducing the mean values of DGP by at least nine degrees compared to the reference model.

Table 7. The point in time illuminance of PV integration with light shelves and uniformity at solstice summer.

Configurations	Solstice Summer	L1	L2	L3	L4	L5	L6	L7	Average	Uniformity
Reference Model	9.00 a.m.	441	432	363	292	236	196	177	305	0.58
	12.00 p.m.	1016	972	795	628	501	415	376	672	0.56
	3.00 p.m.	480	467	392	316	257	216	194	332	0.59
LSPV1	9.00 a.m.	352	333	278	229	190	162	148	242	0.61
	12.00 p.m.	658	644	543	449	376	323	300	470	0.64
	3.00 p.m.	427	408	351	299	259	230	215	313	0.69
LSPV2	9.00 a.m.	350	333	287	245	210	183	169	254	0.67
	12.00 p.m.	577	558	478	401	336	289	267	415	0.64
	3.00 p.m.	376	354	304	259	219	191	175	268	0.65
LSPV3	9.00 a.m.	380	362	303	248	205	175	159	262	0.61
	12.00 p.m.	764	755	645	530	441	372	341	550	0.62
	3.00 p.m.	426	404	399	278	230	197	180	302	0.60
LSPV4	9.00 a.m.	308	339	284	277	190	160	145	243	0.60
	12.00 p.m.	700	686	587	485	401	340	308	501	0.61
	3.00 p.m.	420	402	342	284	236	202	184	296	0.62
LSPV5	9.00 a.m.	472	454	385	320	265	226	205	332	0.62
	12.00 p.m.	849	838	711	583	480	404	368	605	0.61
	3.00 p.m.	562	537	460	385	323	279	254	400	0.64
LSPV6	9.00 a.m.	431	410	342	277	225	189	170	292	0.58
	12.00 p.m.	898	889	748	604	489	406	365	628	0.58
	3.00 p.m.	532	512	439	369	314	272	248	384	0.65
LSPV7	9.00 a.m.	502	481	405	337	268	225	203	346	0.59
	12.00 p.m.	932	918	771	627	513	428	390	654	0.60
	3.00 p.m.	565	546	466	385	321	276	260	403	0.65
LSPV8	9.00 a.m.	517	496	419	442	280	235	211	371	0.57
	12.00 p.m.	898	889	748	604	448	406	365	623	0.59
	3.00 p.m.	507	488	406	323	260	216	191	342	0.56

Table 8. The point in time illuminance of PV integration with light shelves and uniformity at solstice winter.

Configurations	Solstice Winter	L1	L2	L3	L4	L5	L6	L7	Average	Uniformity
Reference Model	9.00 a.m.	2434	3111	2501	1478	979	741	635	1697	0.37
	12.00 p.m.	7242	11280	8307	2669	1880	1420	1185	4855	0.24
	3.00 p.m.	2932	3881	3089	1816	1112	827	702	2051	0.34
LSPV1	9.00 a.m.	1804	2393	1571	914	638	515	450	1184	0.38
	12.00 p.m.	4166	2970	1520	1093	850	691	606	1699	0.36
	3.00 p.m.	2196	2197	1743	1002	670	543	474	1261	0.38
LSPV2	9.00 a.m.	1420	1927	1215	722	524	421	370	943	0.39
	12.00 p.m.	1703	1239	939	740	557	475	322	854	0.38
	3.00 p.m.	1635	2080	1250	763	546	435	380	1013	0.38
LSPV3	9.00 a.m.	1860	2235	1630	970	683	546	472	1199	0.39
	12.00 p.m.	4225	2990	1560	1117	880	712	621	1729	0.36
	3.00 p.m.	2228	2961	1498	1031	711	566	490	1355	0.36
LSPV4	9.00 a.m.	1550	2113	1336	784	551	445	391	1024	0.38
	12.00 p.m.	2497	1705	1139	882	688	562	499	1139	0.44
	3.00 p.m.	1854	2434	1458	870	620	485	420	1163	0.36
LSPV5	9.00 a.m.	1860	2446	1571	973	654	519	452	1211	0.37
	12.00 p.m.	4274	3080	1636	1190	922	750	654	1787	0.37
	3.00 p.m.	2308	3020	1817	1080	751	590	515	1440	0.36
LSPV6	9.00 a.m.	1728	2273	1518	881	630	500	432	1137	0.38
	12.00 p.m.	3234	2170	1340	1006	793	641	563	1392	0.40
	3.00 p.m.	2096	2695	1640	977	522	542	472	1278	0.37
LSPV7	9.00 a.m.	1943	2515	1686	994	707	560	484	1270	0.38
	12.00 p.m.	4332	3110	1662	1170	908	737	644	1795	0.36
	3.00 p.m.	2372	3085	1860	1127	800	633	551	1490	0.37
LSPV8	9.00 a.m.	1874	2464	1622	956	675	538	462	1227	0.38
	12.00 p.m.	3738	2585	1832	1067	825	670	586	1615	0.36
	3.00 p.m.	1773	2910	1096	1052	713	567	492	1229	0.40

Table 9. The point in time illuminance of PV integration with light shelves and uniformity at mid-season.

Configurations	Equinox Spring	L1	L2	L3	L4	L5	L6	L7	Average	Uniformity
Reference Model	9.00 a.m.	1208	856	645	502	394	324	284	602	0.47
	12.00 p.m.	6507	2525	1366	993	769	626	540	1904	0.28
	3.00 p.m.	2154	1173	814	615	481	394	348	854	0.41
LSPV1	9.00 a.m.	677	543	452	366	299	251	226	402	0.56
	12.00 p.m.	684	678	574	467	382	319	287	484	0.59
	3.00 p.m.	2196	2502	1743	1002	505	543	474	1281	0.37
LSPV2	9.00 a.m.	546	435	360	293	240	199	177	321	0.55
	12.00 p.m.	1703	1240	939	577	483	475	422	834	0.51
	3.00 p.m.	687	550	461	378	313	257	240	412	0.58
LSPV3	9.00 a.m.	704	580	478	386	312	259	231	421	0.55
	12.00 p.m.	799	789	676	551	447	374	336	567	0.59
	3.00 p.m.	2228	2960	1747	1031	711	566	490	1390	0.35
LSPV4	9.00 a.m.	652	534	441	361	295	252	228	395	0.58
	12.00 p.m.	2494	1700	1140	882	688	562	498	1138	0.44
	3.00 p.m.	825	653	554	454	373	315	282	494	0.57
LSPV5	9.00 a.m.	816	674	557	448	359	298	265	488	0.54
	12.00 p.m.	861	853	732	594	479	398	352	610	0.58
	3.00 p.m.	2308	3020	1817	1080	751	590	515	1440	0.36
LSPV6	9.00 a.m.	750	616	507	407	325	268	238	444	0.54
	12.00 p.m.	3234	2170	1037	1006	793	641	563	1349	0.42
	3.00 p.m.	897	741	600	482	388	322	288	531	0.54
LSPV7	9.00 a.m.	821	685	560	443	351	290	259	487	0.53
	12.00 p.m.	945	945	808	648	518	427	377	667	0.57
	3.00 p.m.	2322	3085	1860	1127	800	633	551	1483	0.37
LSPV8	9.00 a.m.	772	640	523	418	332	273	242	457	0.53
	12.00 p.m.	3738	2335	1460	1062	825	670	586	1525	0.38
	3.00 p.m.	933	757	619	493	382	318	280	540	0.52

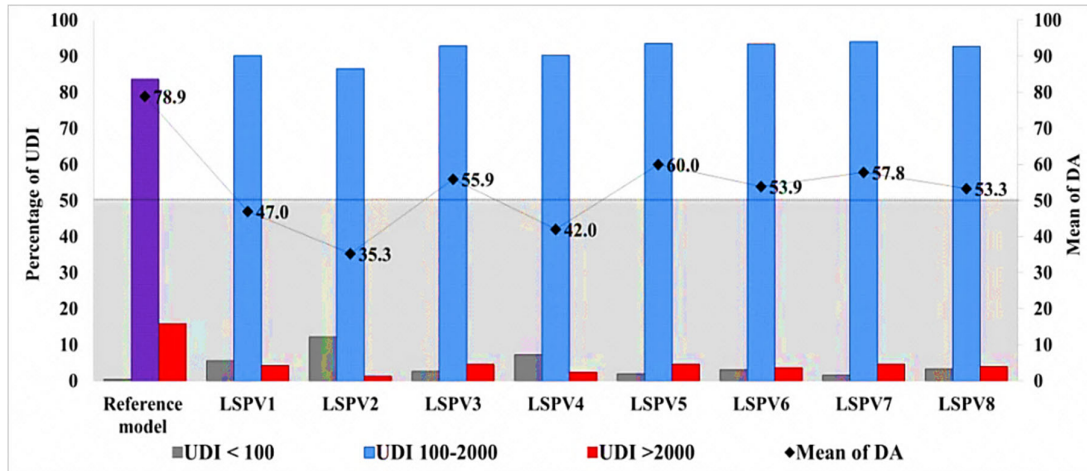
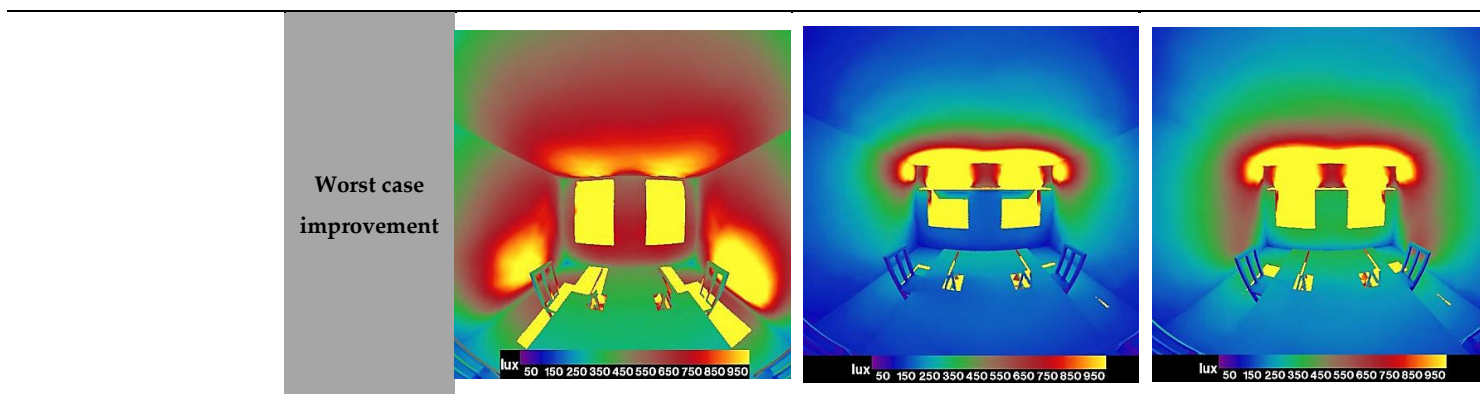


Figure 9. Annual climate-based analysis (UDI and mean of DA) of different configurations of light shelves integrated with photovoltaics.

Table 10. Illuminance contour maps of the reference model and the optimum LSPV configurations under clear sky at solstice winter at (9.00 a.m., 12.00 p.m., 3.00 p.m.).

		Reference Model	Optimum Case 1	Optimum Case 2
Solstice Winter (21 December)	9.00 a.m.	 lux 55100 49300 43500 37700 31900 26100 20300 14500 8700 2900	 lux 56050 50150 44250 38350 32450 26550 20650 14750 8850 2950	 lux 59850 53550 47250 40950 34650 28350 22050 15750 9450 3150
		DGP = 35	DGP = 25	DGP = 26
	12.00 p.m.	 lux 54150 48450 42750 37050 31350 25650 19950 14250 8550 2850	 lux 52250 46750 41250 35750 30250 24750 19250 13750 8250 2750	 lux 52250 46750 41250 35750 30250 24750 19250 13750 8250 2750
		DGP = 37	DGP = 27	DGP = 28
	3.00 p.m.	 lux 57950 51850 45750 39650 33550 27450 21350 15250 9150 3050	 lux 59850 53550 47250 40950 34650 28350 22050 15750 9450 3150	 lux 60800 54400 48000 41600 35200 28800 22400 16000 9600 3200
		DGP = 36	DGP = 26	DGP = 27



3.5. Analysis of Artificial Lighting Energy Consumption

Table 11 specifies the amount of energy production for the integrated LSPV and the total lighting energy consumption in each lighting control zone throughout the year pertaining to the climatic condition of Ha'il. For the analysis, it is assumed that lighting was switched on automatically after 8:00 a.m. and kept on until 5:00 p.m., with the dimming system set to 300 lux. The results show that the reference model (without LS) exhibited the lowest energy use compared to all LSPV configurations by a difference of only 20.6 kWh per year, while the lowest lighting energy consumption of 49.7 kWh was achieved for LSPV5, which is more than 50%. Peak lighting energy demand for the deep office reached up to 102 kWh for LSPV2.

On the other hand, the energy output due to PV use was much higher than the lighting energy consumption. PV energy output ranged between 107 kWh for LSPV7 to 686 kWh for LSPV2. Consequently, the annual lighting-specific energy savings were calculated for two tilt angles (horizontal and 30°) and four PV coverages. The net savings were computed relative to the energy output of PV and lighting energy demands. In all the cases, the results indicated a reduction of at least 63% and, in some cases, up to 89%. Considering these observations, a light shelf using a solar module is advantageous concerning energy savings for lighting. Furthermore, the energy production can also compensate for a considerable fraction of other domestic energy needs, such as that required for cooling.

Table 11. The yearly lighting energy consumption of various light shelf configurations compared to the base model.

Configuration of LS with PV	Lighting Energy Consumption (kWh)	PV Energy Production (kWh)	Net Energy Saving (kWh)	Percentage of Energy Saved with PV Light Shelves
Reference model	20.6	0	−20.6	0%
LSPV1	71.8	626	554	89%
LSPV2	102.9	686	583	85%
LSPV3	50.3	469	419	89%
LSPV4	93.8	514	420	82%
LSPV5	49.7	313	263	84%
LSPV6	53.6	343	289	84%
LSPV7	53.1	156	103	66%
LSPV8	63.1	171	108	63%

4. Conclusions

This study focused on the application of using integrated photovoltaic solar panels in light shelves to decrease the lighting energy requirement for office buildings and proposed a prototype of a modular unit composed of a light shelf combined with photovoltaic technology (LSPV) for deep office buildings in hot desert-like climatic conditions. In order to optimize the daylighting performance, three phases were carried out before the PV was attached to the LS to determine the appropriate height, reflector characteristics, and curved internal LS. The key findings of this study are specified below:

- The optimal height for a flat LS for enhancing WPI and the uniformity index determined in this study is 1.3 m above the floor with widths of 1.1 m and 0.7 m for the external and internal LS respectively, Configuration LS3H3 is challenging to use in high rise buildings.
- The use of a reflector with constant width of 30 cm at the top of the window, combined with external and internal LS configurations, is considered a good daylight strategy to improve the WPI in the back area of the model by 10%.
- The optimal specification for a flat external LS, combined with a curved internal LS, for improving daylighting distribution was found to be 10°, which increased the back daylit area by up to 5–11% at the summer and winter solstices, and less than 4% at the spring equinox.

- All LS configurations are observed to provide less daylight in the back daylit area compared to the reference model; however, there is uniformity of illumination.
- The integration of LSPV with a conversion efficiency of only 10% can completely compensate for the lighting-specific energy consumption in all LSPV configurations. At the same time, these configurations eliminate the discomfort caused due to glare, especially during the winter season. Also, LSPV1 with a flat and 30° tilt angle with 100% coverage shows a higher uniformity of illumination compared to a light shelf without a solar module.
- The optimal modular units of the LSPV that can achieve significantly greater savings and uniformity index within the office perimeter, close to the windows and the middle, along with the back area, are LSPV1 and LSPV2, as specified in Appendix D.

The focus of this study is limited to the energy required for lighting and daylight distribution for visual comfort. However, further studies are needed to evaluate the effect of the wall-to-window ratio (WWR) and other types of photovoltaic materials, specifically with respect to conversion efficiency, the effects of transparency on energy saving, and glare prevention. The effects of combined internal and external light shelves on window view also need further investigation. Moreover, the potential integration of LSPV had a significant impact on providing uniform daylight and preventing CO₂ emissions. Finally, such structures can be conveniently installed in buildings during renovation.

Author Contributions: Conceptualization, A.M. and A.G.; methodology, A.M.; software, A.M.; validation, A.M.; formal analysis, A.M.; investigation, A.M.; resources, A.M.; data curation, A.M. and A.G.; writing—original draft preparation, A.M.; writing—review and editing, A.G.; visualization, A.G.; supervision, A.G.; project administration, A.G.; funding acquisition, A.G. All authors have read and agreed to the published version of the manuscript.

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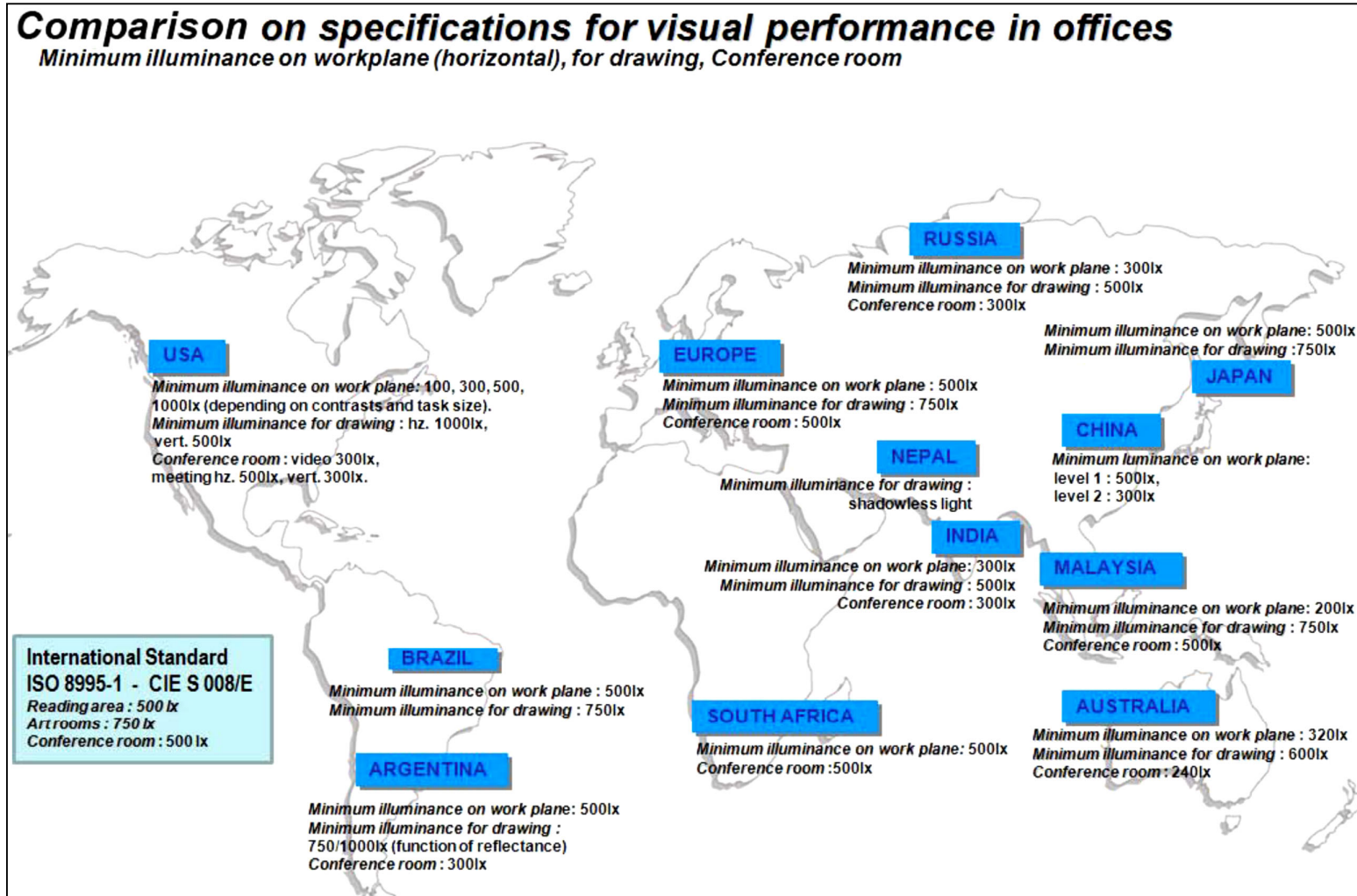
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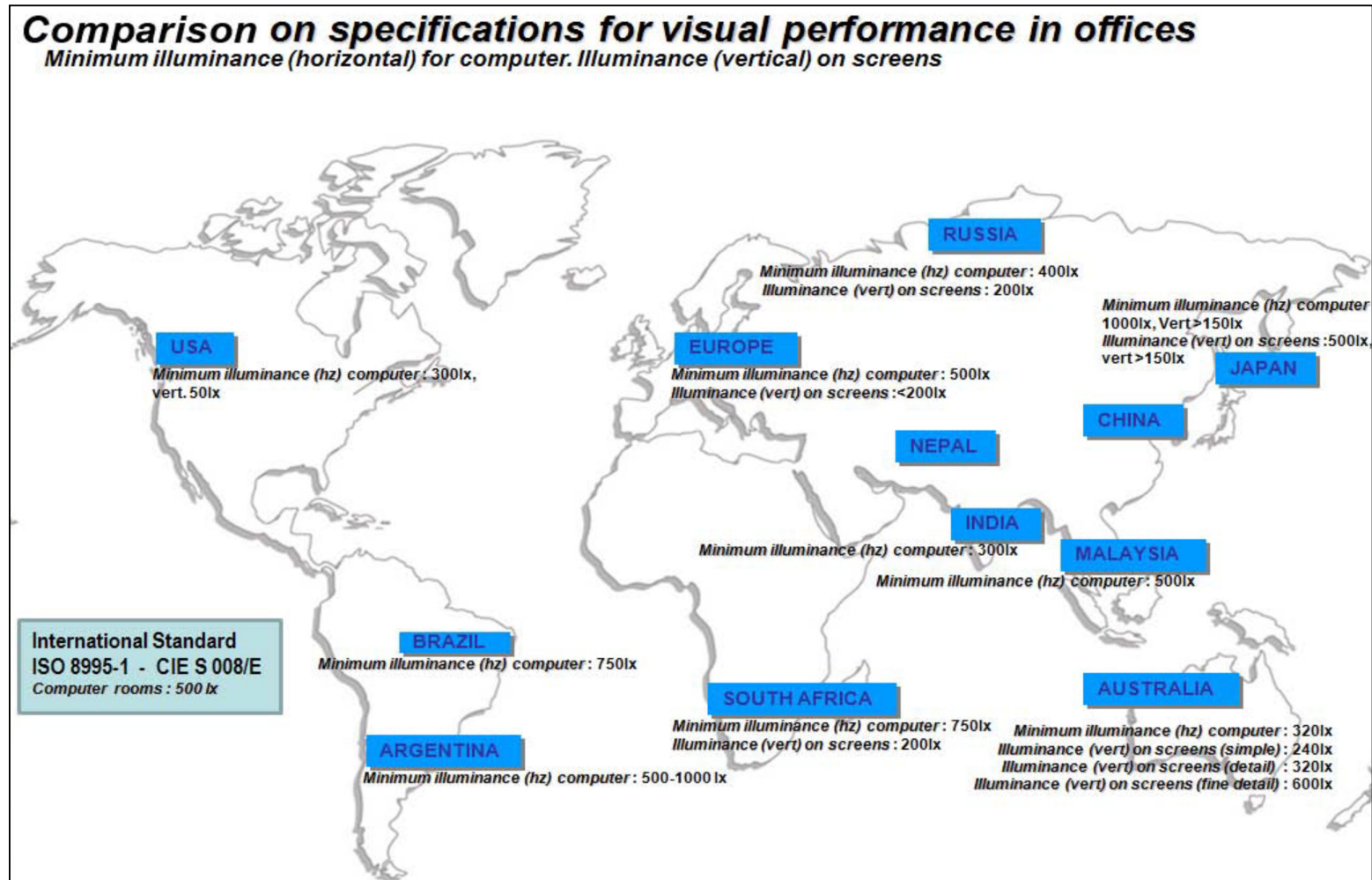
Nomenclature

LSPV	Light shelf photovoltaics
ILS	Internal light shelf
ELS	External light shelf
STPV	Semi-transparent photovoltaics
ISO	International Organization for Standardization
CEI	Commission International d'Eclairage
WPI	Work plane illuminance
TMY	Meteonorm metrological database
LS1H1	Light shelf height
LSC	Light shelf curved
LS2H2 + R	Light shelf height + reflector
VLT	Visible light transmittance
WWR	Window-to-wall ratio
UI	Uniformity index
UDI	Useful daylight illuminance
DA	Daylight autonomy
DGP	Daylight glare index
h _{clerestory}	Height of clerestory
d _{int} light shelf	Depth of internal light shelf
d _{ext} light shelf	Depth of external light shelf

Appendix A



(A)



(B)

Figure A1. The minimum illuminance level based on International Standard ISO 8995-1:2002 (CIE 2001/ISO 2002) for visual performance in office (A) WPI horizontal for a drawing task (B) for a computer task.

Appendix B

Table A1. The distribution of absolute work plan illuminance (WPI) and uniformity of the reference model compared to the optimized internal and external light shelves without integrating a solar module in (a) solstice summer, (b) equinox spring, and (c) solstice winter.

(a)										
Configurations	Solstice Summer	L1	L2	L3	L4	L5	L6	L7	Average	Uniformity
Reference Model	9.00 a.m.	441	432	363	292	236	196	177	305	0.58
	12.00 p.m.	1016	972	795	628	501	415	376	672	0.56
	3.00 p.m.	480	467	392	316	257	216	194	332	0.59
LS C1	9.00 a.m.	511	490	409	332	270	226	214	350	0.61
	12.00 p.m.	1196	1039	893	736	612	524	488	784	0.62
	3.00 p.m.	593	572	483	393	320	269	250	411	0.61
(b)										
Configurations	Equinox Spring	L1	L2	L3	L4	L5	L6	L7	Average	Uniformity
Reference Model	9.00 a.m.	1208	856	645	502	394	324	284	602	0.47
	12.00 p.m.	6507	2525	1366	993	769	626	540	1904	0.28
	3.00 p.m.	2154	1173	814	615	481	394	348	854	0.41
LS C1	9.00 a.m.	797	715	546	436	347	286	275	486	0.56
	12.00 p.m.	943	935	791	923	494	402	393	697	0.56
	3.00 p.m.	1023	841	690	550	437	362	340	606	0.56
(c)										
Configurations	Solstice Winter	L1	L2	L3	L4	L5	L6	L7	Average	Uniformity
Reference Model	9.00 a.m.	2434	3111	2501	1478	979	741	635	1697	0.37
	12.00 p.m.	7242	11,280	8307	2669	1880	1420	1185	4855	0.24
	3.00 p.m.	2932	3881	3089	1816	1112	827	702	2051	0.34
LS C1	9.00 a.m.	1984	2569	1747	1023	731	586	531	1310	0.41
	12.00 p.m.	4432	3210	1760	1267	985	801	695	1878	0.37
	3.00 p.m.	2338	3066	1866	1091	769	610	564	1472	0.38

Appendix C

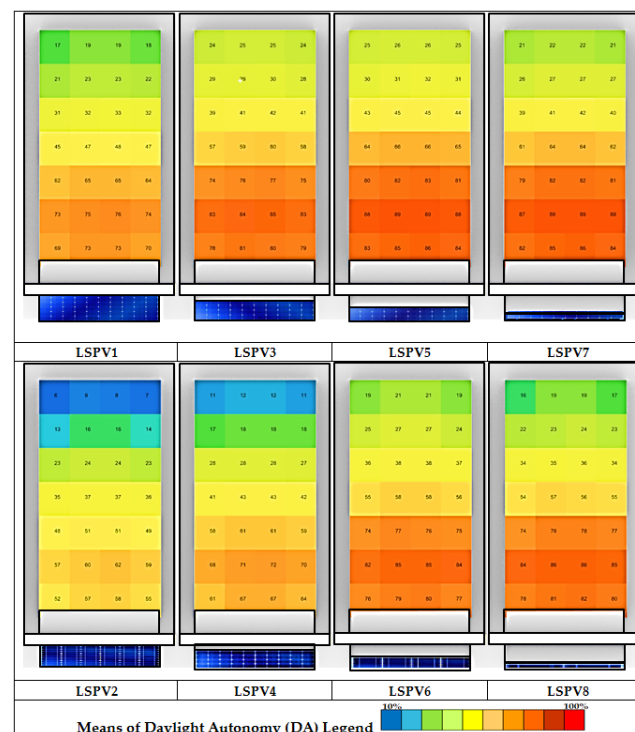


Figure A2. Daylight autonomy (DA) distribution of different LSPV configurations in each row.

Appendix D

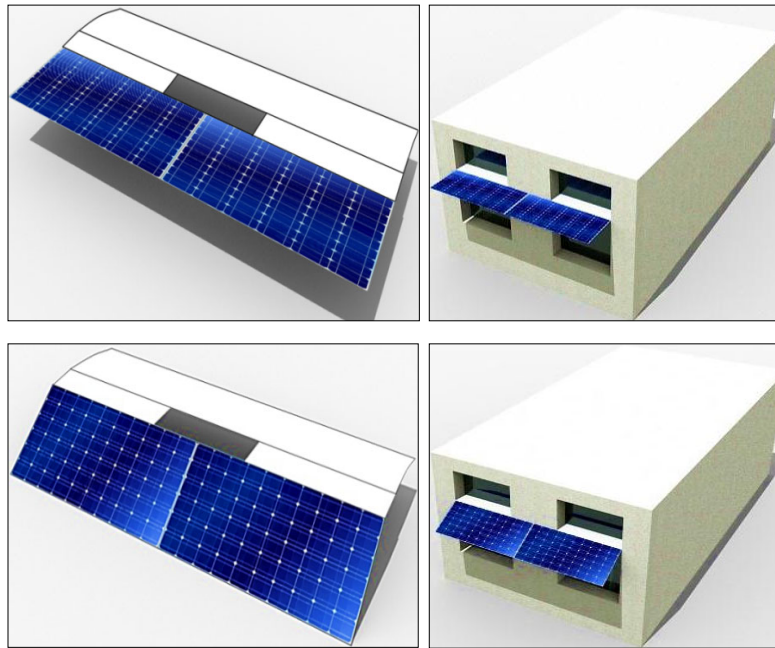


Figure A3. The optimum LSPV configuration design.

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