buildings

MDPI

Article

A Study on the Effect of Dynamic Photovoltaic Shading Devices on Energy Consumption and Daylighting of an Office Building

Yan Jiang [1,2], Zongxin Qi [1], Shenglin Ran [1] and Qingsong Ma [1,*]

[1] Innovation Institute for Sustainable Maritime Architecture Research and Technology, Qingdao University of Technology, Qingdao 266033, China; coastdesign@163.com (Y.J.); 17864271803@163.com (Z.Q.); ran.shenglin@outlook.com (S.R.)
[2] Faculty of Environmental Engineering, The University of Kitakyushu, Kitakyushu 808-0135, Japan
* Correspondence: maqingsong@qut.edu.cn

Abstract: Photovoltaic shading devices (PVSDs) have the dual function of providing shade and generating electricity, which can reduce building energy consumption and improve indoor daylighting levels. This study adopts a parametric performance design method and establishes a one-click simulation process by using the Grasshopper platform and Ladybugtools. The research focuses on the effect of dynamic PVSDs on daylighting and energy consumption in an office building in Qingdao. The optimal configuration of PVSDs for each month under three dynamic strategies (rotation, sliding, and hybrid) is determined here. Additionally, different control strategies and fixed PVSDs are compared to clarify the impact of various control strategies on daylighting and energy consumption. The findings reveal that, compared to no shading, dynamic PVSDs in the rotation strategy, sliding strategy, and hybrid strategy can achieve energy savings of 32.13%, 47.22%, and 50.38%, respectively. They can also increase the annual average UDI by 1.39%, 2.8%, and 3.1%, respectively. Dynamic PVSDs can significantly reduce the energy consumption of office buildings in Qingdao while improving indoor daylighting levels. A flexible control strategy that adapts to climate change can significantly improve building performance. This research can provide theoretical, methodological, and data support for the application of the PVSD in cold-climate regions in China.

Keywords: photovoltaic shading devices (PVSDs); dynamic; fixed; energy consumption; daylighting

check for updates

Citation: Jiang, Y.; Qi, Z.; Ran, S.; Ma, Q. A Study on the Effect of Dynamic Photovoltaic Shading Devices on Energy Consumption and Daylighting of an Office Building. *Buildings* **2024**, *14*, 596. https://doi.org/10.3390/buildings14030596

Academic Editor: Constantinos A. Balaras

Received: 25 January 2024
Revised: 19 February 2024
Accepted: 20 February 2024
Published: 23 February 2024

Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

The global issues of energy consumption and environmental pollution have become significant challenges that hinder human development. In 2020, China made a commitment to peak carbon emissions by 2030 and achieve carbon neutrality by 2060 [1]. Subsequently, in 2021, China released the "Action Plan to Peak Carbon Before 2030", which outlined the goal that non-fossil energy consumption will reach 20% and 25% by 2025 and 2030, respectively [2]. Faced with rising energy demand and environmental degradation, renewable energy may efficiently cut fossil fuel use and carbon emissions while also having significant application value. In 2020, China's energy consumption in the entire building process accounted for 45.5% of the country's energy consumption, energy consumption in the building operation stage accounted for 21.3% of the country's energy consumption, and carbon emissions in the building operation stage accounted for 21.7% of the total carbon emissions [3]. Therefore, using clean energy to reduce energy consumption in the building operation phase is of great significance to achieve the goal of carbon neutrality.

Photovoltaic technology can generate electricity for buildings, reduce the reliance on traditional urban power networks, and lower urban carbon emissions [4]. With the advancement of photovoltaic technologies, building-integrated photovoltaics (BIPVs) have been applied to building facades and roofs, as well as integrated into the architectural design to become a functional component of the building [5]. The first BIPV system was

introduced in the 1980s, but its high cost initially limited its application market [6]. It was not until the advancement of photovoltaic technology and the demand for low-carbon buildings that BIPVs became popular [7]. Photovoltaic shading devices (PVSDs) not only provide shade, but also collect solar energy, converting the sunlight with restricted access to the building into electricity [8]. However, as part of the building envelope, PVSDs will also strongly affect the indoor daylighting environment and energy consumption. Therefore, when designing PVSDs, it is necessary to find the right balance between indoor daylighting and energy consumption as much as possible. Excessive solar radiation can cause indoor overheating and glare problems. However, if too much solar radiation is blocked, the energy demands for heating and artificial lighting will increase [9].

A PVSD combines shading and photovoltaic functions to improve the internal daylight and thermal environment [10], lower the building cooling load [11], improve indoor visual comfort [12], and fulfill a portion of the building's energy demands [13]. Many studies have demonstrated the energy-saving potential of PVSDs [14,15]. Compared with traditional shading devices and unshaded windows, PVSDs perform better in terms of energy use and daylighting [16]. For instance, Mostafa et al. [17] used an educational facility at the GUC University in Cairo to investigate the daylighting and energy-saving benefits of installing PVSDs in the south and east. Sadatifar et al. [18] optimized the design of PVSDs for five different climate zones from the perspective of energy use and daylighting. Ellika et al. [8] proposed a design method for fixed PVSDs based on multi-objective optimization (MOO). The inclination angle and the number of PVSDs louvers on the south side of an office building in Northern Europe were optimized with the goals of net energy consumption, power generation, and daylighting. Chen et al. [19] investigated the daylighting and power generation performance of PVSDs in China's hot summers and cold winters. The results found that the proportion of indoor space illumination between 450 lx and 2000 lx, and exceeding 50% of the time, was about 85%, and the power generation amount ranged from 9.18 kWh to 22.46 kWh.

However, most of these studies seek to achieve a balance between power generation and shading, as well as to optimize the design of fixed PVSDs with one or more of the following objectives: daylighting, energy consumption, visual comfort, and electricity generation. The sun's altitude and azimuth angles continuously change throughout the year. A dynamic PVSD can greatly enhance the potential of power generation and shading and improve indoor daylighting and the thermal environment. However, there are only a few studies on dynamic PVSDs. Ayca et al. [20] classified dynamic PVSD control strategies into the following three categories: soft control, hard control, and other technologies (hybrid strategies), based on the implementation method of the control strategy and the tools used. Svetozarevic et al. [21] presented a dynamic PVSD that can increase power generation by 50% compared to a fixed PVSD and can meet 115% of office net energy requirements in temperate and arid climate conditions. Meysam et al. [22] compared the difference in power generation and building heating load between south-facing dynamic PVSDs and static PVSDs in an apartment in Tehran. The study found that changing the angle and position of the PVSD twice a year can significantly improve energy efficiency, and more changes have little impact on energy consumption. Krarti et al. [23] investigated the impact of a dynamic PVSD on building energy consumption in four U.S. cities. The study found that, while hourly control strategies had better energy-saving potential, daily and monthly control strategies gained most of the advantages of dynamic PVSDs. Compared with having no PVSD, controlling a PVSD on a monthly basis can reduce greenhouse gas emissions by 87%.

From these studies, it is evident that the optimal shading system is closely related to building characteristics [24] (building function, building orientation, building form coefficient, and envelope heat transfer coefficient), geographical location [25] (longitude, latitude, altitude, and climate), type of shading device [16], and control strategies, etc. [26]. Due to the complexity of influencing factors, it is difficult for architects to judge the performance of PVSDs through experimental methods and rules of thumb. Simulation can help designers to make decisions quickly and accurately. The simulation software

commonly used in the past (EnergyPlus, DoE-2, and TRNsys) not only required users to master a large amount of relevant professional knowledge, but also required programming abilities. Moreover, multiple simulation software options are independent of each other, which undoubtedly increases the difficulty for designers to evaluate PVSD performance through software simulation. Ladybugtools in the Grasshopper platform integrate a variety of commonly used simulation engines, including daylighting and energy consumption simulations, which can be used to evaluate building performance in many aspects and form a simple and flexible parametric performance evaluation process. Architects and users can simply adjust the corresponding parameters to evaluate a PVSD under different conditions and further export visual graphics for analysis [27], thereby expanding the boundaries of the design [28].

In this study, the following three control strategies for PVSDs were considered: rotation, sliding, and hybrid (rotation + sliding). By rotating the PVSD, the power generation, indoor daylighting, and visual comfort can be adjusted. Sliding the PVSD up and down can effectively adjust whether sunlight can enter the room. Of course, it can also control the sunlight entering the room from the upper or lower part of the window. Presently, there are few studies on dynamic PVSDs in China, especially for office buildings in cold-climate areas. This study has established a flexible and simple parametric performance simulation process for PVSDs based on Ladybugtools and the Grasshopper platform. The design and control strategies of PVSD are evaluated using daylighting and energy consumption as optimization objectives. The main purposes of this paper are twofold, as follows: (1) To study the impact of three control strategies of PVSDs on building daylighting and energy consumption throughout the year. (2) To explore the energy-saving and daylighting application value of three control strategies of PVSDs in office buildings in cold areas. It is hoped that this study can provide theoretical, methodological, and data support for the promotion and application of dynamic PVSDs in cold-climate areas.

2. Methodology

2.1. Case Study Description

This case study is located in Qingdao, China. The research room on the sixth floor of the office building covers an area of 71 m^2. It is usually used for multi-person offices. The length, width, and height of the room are 8 m, 9 m, and 3.4 m, respectively. This room has three casement windows facing south. Each window has a height of 1.8 m and a width of 1.45 m. The windowsill height is 0.9 m. Three PVSDs are installed on the outside of the three windows. Each PVSD panel is independent. There are no other surrounding buildings or landscaping blocking sunlight from entering the room. The north wall of the room adjacent to the internal corridor made of glass. There is also the same type of multi-person office on the east and west sides of the room. Figure 1 shows an overview of the case room. Among them, a represents the corridor perspective, b represents the indoor perspective of the case room, and c represents the case room seen from the outside.

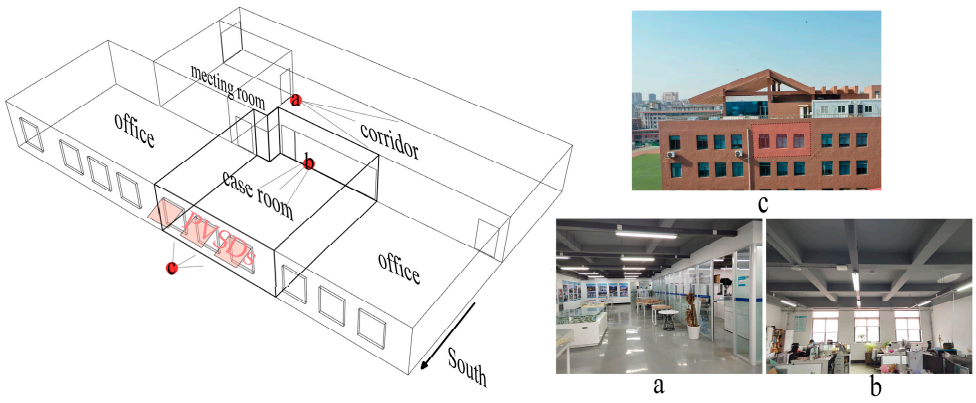


Figure 1. An overview of the case room.

Qingdao is located in the southern part of the Shandong Peninsula, located at 119°30′–121°00′ east longitude and 35°35′–37°09′ north latitude. Qingdao faces the sea on three sides. Affected by the southeast monsoon, ocean currents, and water masses, Qingdao has significant maritime climate characteristics. Generally speaking, Qingdao has four distinct seasons throughout the year, with hot, humid, and rainy summers and is windy with low temperatures in the winter. The meteorological data used in this study are Qingdao meteorological data from 2007 to 2021 (https://climate.onebuilding.org/, accessed on 25 January 2024). Figure 2 shows the changes in dry bulb temperature and global horizontal radiation in Qingdao.

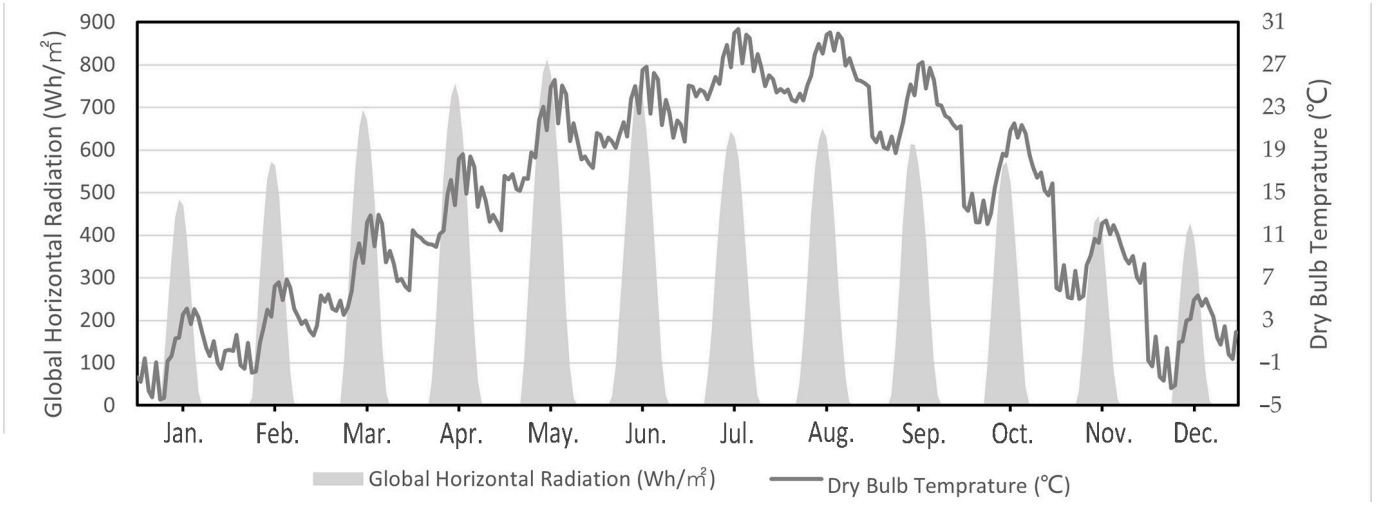


Figure 2. Dry bulb temperature and global horizontal radiation.

2.2. Baseline Model Settings

Based on the Grasshopper platform, a parametric model of the room and its surrounding elements was constructed according to the actual situation. Parametric models of energy consumption and daylight were established through Ladybugtools. The established model was verified in Section 3. According to the actual structure of the building and the requirements for school buildings in the "General code for energy efficiency and renewable energy application in buildings" [29], the thermal parameters of the walls, windows, and roofs, as well as the internal loads of the building, are set. The thermal properties of the building envelope are detailed in Table 1. The optical properties are outlined in Table 2. The air conditioning temperature control schedule is shown in Figure 3. In the daylighting model, indoor illumination test points are distributed in a grid (1 m × 1 m) with a height of 0.75 m. The minimum illumination of the indoor working surfaces is controlled at 300 lux. When the working surface does not reach 300 lux, artificial lighting is turned on.

Table 1. Thermal properties of the building.

Component	Value	Unit
External wall U-value	0.36	$W/(m^2K)$
Roof U-value	0.47	$W/(m^2K)$
Window U-value	2.58	$W/(m^2K)$
Airtightness	0.0003	$m^3/s\text{-}m^2$
Lighting load	8	W/m^2
Equipment load	15	W/m^2
Ventilation per person	0.0084	$m^3/s\text{-}ppl$

Table 2. Optical properties of the surfaces.

Building Elements	RGB Reflectance	Roughness	Specularity	Transmissivity
Opaque wall	0.85, 0.85, 0.85	0.05	0.0013	-
Ceiling	0.16, 0.17, 0.17	0.005	0.008	-
Floor	0.4, 0.45, 0.41	0.002	0.05	-
Window	-	-	-	0.65
Glass wall	-	-	-	0.65

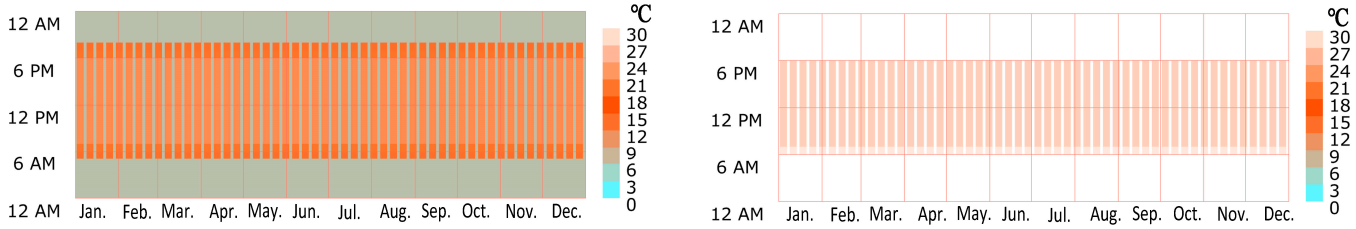


Figure 3. Air conditioning schedule: (**a**) Heating setpoint schedule; (**b**) Cooling setpoint schedule.

2.3. PVSD Control Strategies

Figure 4 shows the dynamic photovoltaic shading devices (PVSDs) installed on the south wall. Among them, the red arrow represents the solar altitude angle at the summer solstice, and the blue arrow represents the solar altitude angle at the winter solstice. There are three design variables for PVSDs, namely the width, tilt angle, and sliding height. The range and interval control of the variables are shown in Table 3. This study considers the impact of three dynamic strategies of PVSDs (rotation, sliding up and down, and hybrid) on indoor daylighting and energy consumption. In the case of the rotation strategy, the width and installation height of the PVSD are fixed and can be rotated at intervals of 5°, between 0° and 70°. In the case of the sliding strategy, the width and tilt angle of the PVSD are fixed and can slide up and down along the guide rails. The highest point can slide to 1 m above the upper eaves of the window, and the lowest point can slide to the lower eaves of the window. The interval between each slide is 0.2 m (the upper eave of the window is 0 m, and the lower eave of the window is −1.8 m). A hybrid strategy is a combination of a rotation strategy and a sliding strategy. The PVSD has a fixed width and can rotate at the same time that it slides. These three dynamic strategies are controlled by a set schedule and are activated monthly. The rotation and sliding of the PVSD panels are realized through gears and slide rails. The PVSD panel has three layers, the glass on the outside, the silicon wafer in the middle, and the base plate (plastic) at the back. The three layers are held together by an aluminum frame and are fixed and sealed with some adhesive. In the simulation, the power generation capacity of each square meter of photovoltaic panel is set at 160 W.

Table 3. The range and interval control of variables.

Variables	Range of Values	Value Interval	Unit
Width	0.2~1.2	0.2	Meter
Sliding height	−1.8~1	0.2	Meter
Tilt angle	0~70	5	Degree

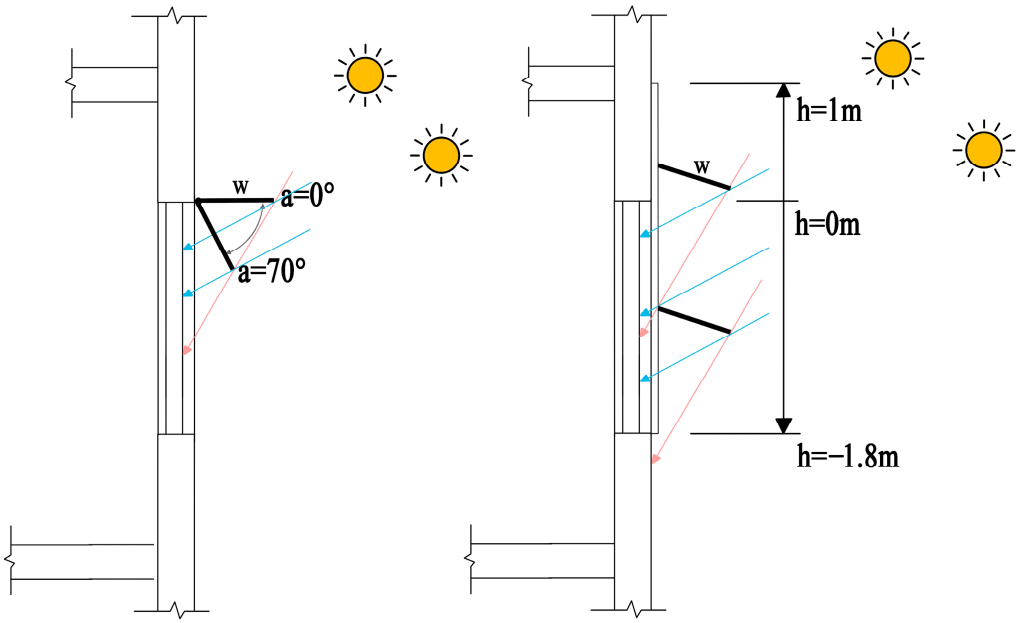


Figure 4. Schematic diagram of PVSDs.

2.4. Parametric Performance Design Method

The parametric performance design method integrates parametric models and performance evaluation to provide non-professionals with a visual toolbox to optimize and evaluate design solutions. The parametric performance design method allows designers to modify algorithms or rules, prompting the computer to generate multiple design solutions and evaluate the performance of the solutions so that the designer can choose the best design solution. In parametric performance design thinking, the generation, modification, and evaluation of solutions are combined into a cyclic process that can be driven by performance. This allows designers to pay attention to the relationship between parameters and goals and the feasibility of the solution during the design process, thereby improving the quality and efficiency of the design. The parametric performance design process of dynamic PVSDs is shown in Figure 5. As shown in Figure 5 (left), given certain ideas, an architect or designer can input a large number of rules and parameters and let the computer algorithmically generate and evaluate a large number of potential designs. Architects or designers can choose reasonable and better design solutions from the calculated results. Figure 5 (right) is a flowchart demonstrating the design generation process in more detail. Firstly, fixed parameters (including meteorological data, loads and schedules, HVAC systems, building construction, and building geometry) and dynamic parameters (including PVSD geometry, rotation angle, and movement height) are set to create a parametric simulation model. The generated PVSD solutions are then evaluated based on the evaluation metrics (energy consumption, power generation, and UDI). Finally, architects or designers can choose reasonable and better solutions from the output results.

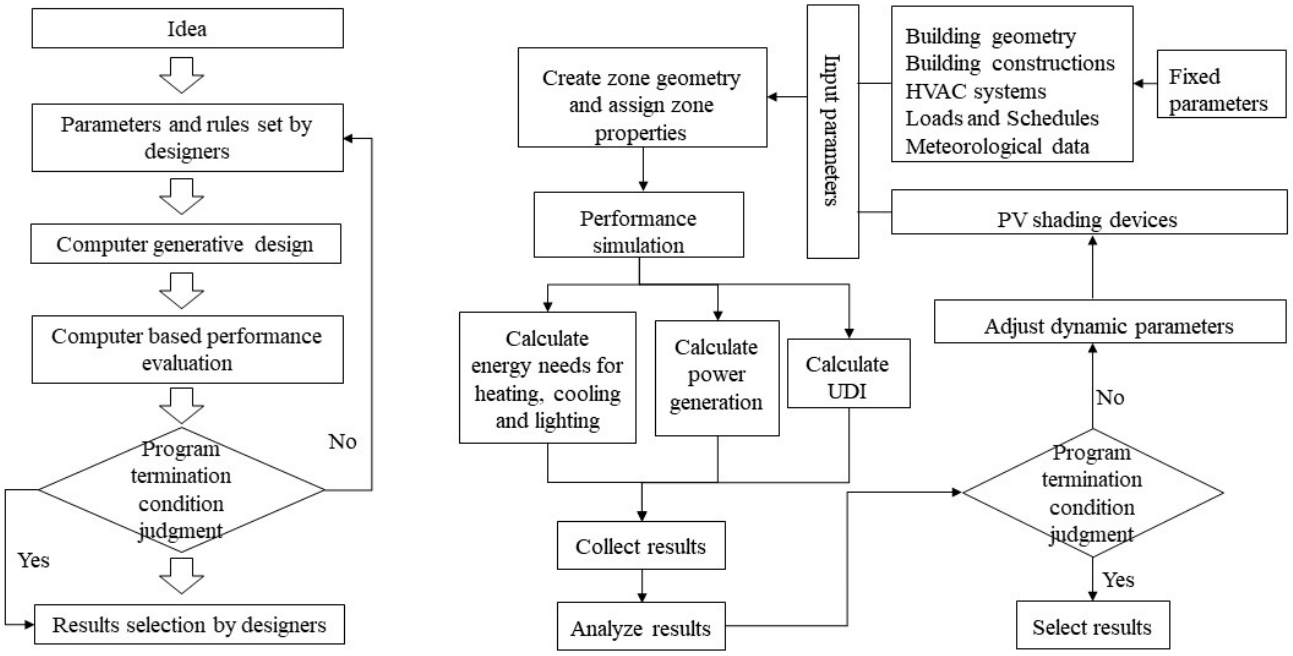


Figure 5. Parametric performance design flow chart.

2.5. Evaluation Indicators

2.5.1. Daylighting Evaluation Indicators

The evaluation of indoor daylighting commonly utilizes the following two indicators in China: the daylight factor (DF) and the illuminance (lux). While illuminance is a local short-term indicator, evaluating the daylighting performance of the entire space over a long period requires a lot of additional work [30]. DF is a ratio and does not show the absolute value of illumination [31]. It ignores the impact of changes in climate conditions, building orientation, location, etc., on daylighting [32]. Furthermore, neither illuminance nor DF consider the impact of glare. To address these issues, a series of dynamic daylighting evaluation indicators has been proposed. The most commonly used ones are daylight autonomy (DA) and useful daylight illuminance (UDI). DA is defined as the percentage of occupied hours of the year during which daylight meets a minimum illuminance threshold [33]. Based on daylight autonomy, continuous daylight autonomy (cDA) [34] and spatial daylight autonomy [35] have also been derived to describe the proportion of time below the minimum illumination threshold and the adequacy of ambient daylight levels in indoor environments, respectively.

UDI is the percentage of time during a period when indoor illumination levels are within a certain range [30]. In comparison with DA, UDI sets upper and lower limits for indoor illumination levels, allowing for the evaluation of indoor illumination levels and limitation of glare occurrence [36]. The given illuminance range on a typical work plane was originally suggested to be 100–2000 lux, which was later revised to 100–3000 lux [37]. According to Mardaljevic's research, the need for indoor artificial lighting can be largely eliminated when the UDI is in the range of 300–3000 lux [37]. When the illumination value of the working plane is below 100 lux, it is difficult to perform basic visual tasks. When the illumination value of the working surface is greater than 3000 lux, glare is likely to occur [38]. As a result, the UDI target range for this study is set to 100–3000 lux, divided into two parts, as follows: the supplementary useful illumination range of 100–300 lux and the autonomous useful illumination range of 300–3000 lux, recorded as UDIlow (<100 lux),

UDIsup (100–300 lux), UDIauto (300–3000 lux), and UDIup (>3000 lux). The calculation equation for UDI is as follows:

$$UDI = \frac{\sum_i fi * ti}{\sum_i ti} \in [0,1] \begin{cases} UDIlow : fi = \begin{cases} 1 & Ei < 100 \\ 0 & Ei \geq 100 \end{cases} \\ UDIsup : fi = \begin{cases} 1 & 100 \leq Ei \leq 300 \\ 0 & Ei < 100, Ei > 300 \end{cases} \\ UDIauto : fi = \begin{cases} 1 & 300 \leq Ei \leq 3000 \\ 0 & Ei < 300, Ei > 3000 \end{cases} \\ UDIup : fi = \begin{cases} 1 & Ei > 3000 \\ 0 & Ei \leq 3000 \end{cases} \end{cases} \quad (1)$$

where *ti* represents each occupied hour in the calculation time, *fi* is a weighting factor, and *Ei* represents the illuminance value of each hour.

2.5.2. Energy Consumption Indicators

This paper uses energy use intensity (EUI) as the basic indicator to evaluate energy consumption, intuitively quantifies the building's energy consumption, and eliminates the impact of room area on this indicator. EUI represents the ratio of building energy consumption to the total building area within a certain period, in kWh/m^2 [39]. The energy consumption calculated in this paper includes lighting energy consumption and air conditioning energy consumption (cooling energy consumption and heating energy consumption). In the following sections, EUI-a will be used to represent the annual energy consumption intensity, and EUI-m will be used to represent the monthly energy consumption intensity.

2.5.3. Model Validation Indicators

This paper uses the following two indicators to check the model's accuracy: mean bias error (MBE) and coefficient of variation of the root mean squared error (CV_RMSE). The calculation equations for the MBE and CV_RMSE are listed in Equations (2) and (3) [39], as follows:

$$MBE = \frac{\sum_{i=1}^{n}(M_i - S_i)}{\sum_{i=1}^{n} M_i}(\%) \quad (2)$$

$$CV(RMS\ E) = \frac{1}{\overline{y}}\sqrt{\frac{\sum_{i=1}^{n}(M_i - S_i)^2}{n}}(\%) \quad (3)$$

where S_i and M_i refer to the time intervals (i) of simulation and measurement, respectively, $\overline{y}$ is the average value of measurement, and n is the total value for calculation.

3. Results

3.1. Model Validation

Figure 6 shows the measured and simulated temperatures inside the building during the test period. The MRE and CV(RMSE) values are 0.33% and 1.58%, respectively. According to the requirements of the ASHRAE Guideline (14-2014) [40], if the hourly MBE value is within ±10% and the hourly CV (RMSE) value is within 30%, the energy consumption simulation model verification is considered successful. Therefore, the error of the simulation model used in this study is within the acceptable range.

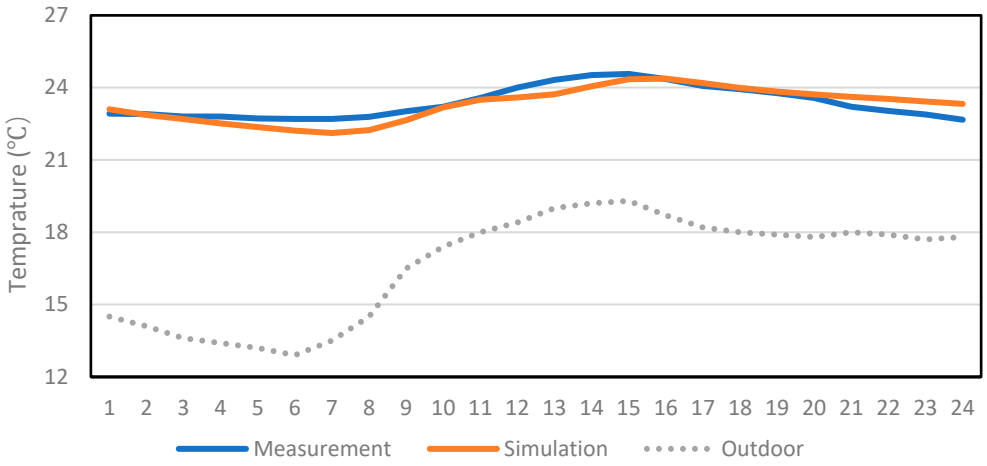


Figure 6. Comparison between measured and simulated indoor temperatures.

Table 4 shows the measured and simulated illumination distribution of the indoor working plane at 10:30 and 12:30 on 16 December. The illumination of all of the grids in the measured and simulated data is greater than 100 lux, and the distribution of illumination values is also reasonable. Judging by existing research, Merghani et al. [41] considered an MBE of 20% and an RMSE of 32% to be acceptable in illumination simulation. In a study of classroom daylight performance optimization in hot and dry areas, Khaoula [42] found that the MBE and CV (RMSE) were −19.57% and 26.01%, respectivley. Yoon et al. [43] studied six simulation algorithms and found that the CV (RMSE) of the daylighting model ranged from 25.36% to 42.05%. The error can be reduced by using more optimized modeling and measurement techniques [33]. These errors in the daylighting model are acceptable due to the influence of measuring instruments, field tests, and various parameters in the modeling process (sky conditions, building materials, etc.). Therefore, these models and related parameters will be used in the following research.

Table 4. Visualization of simulated and measured illuminance levels and their distribution at the work plane level.

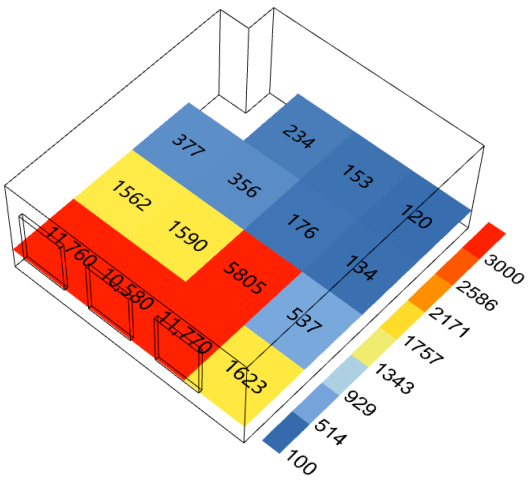
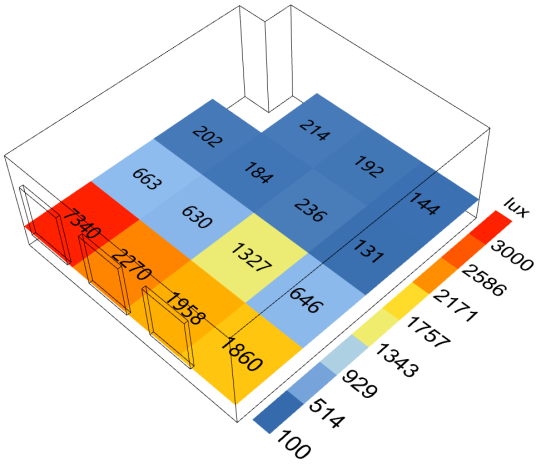
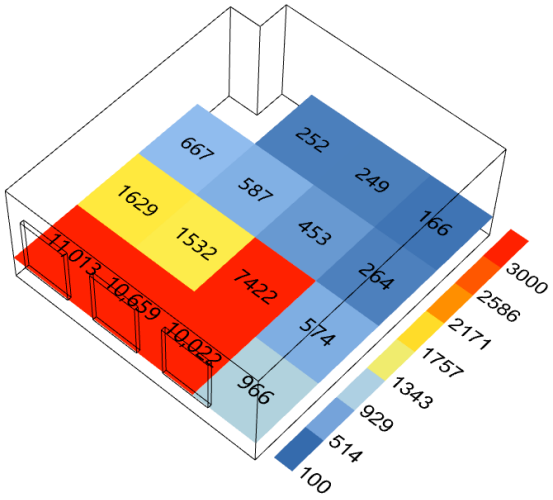
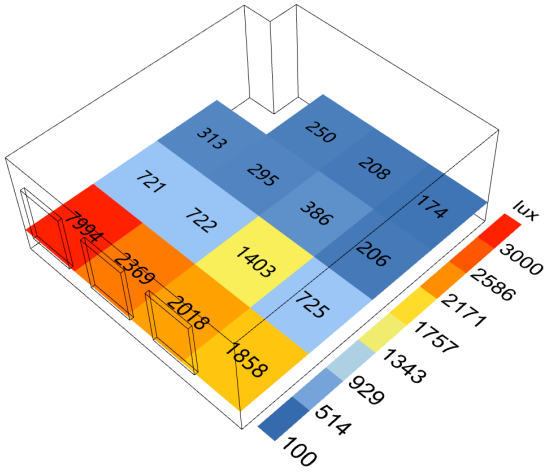
	10:30	**12:30**
Measured		
	Average illumination: 3118.47 lux	Average illumination: 1199.8 lux

Table 4. *Cont.*

	10:30	12:30
Simulated		
	Average illumination: 3096.91 lux	Average illumination: 1309.63 lux
MBE	0.69%	−9.15%
CV (RMSE)	21.78	15.53%

3.2. Energy Consumption and Daylighting Performance of Fixed PVSDs

3.2.1. The Impact of Fixed PVSDs on Building Energy Consumption and Daylighting

Figure 7 shows the impact of year-round fixed PVSDs on indoor energy consumption. It has been found that, as the width of the PVSDs increases, the average annual net energy use intensity (EUI) throughout the year gradually decreases. The panel width increased from 0.2 m to 1.2 m, and the average annual net EUI of the PVSDs decreased from 42.89 kWh/m^2 to 30.57 kWh/m^2. This also shows that, in Qingdao, PVSD power generation capacity plays a leading role in the annual energy consumption. At the same time, it can also be seen that, as the panel tilt angle increases from 0° to 70°, the average annual net EUI of PVSDs first decreases and then increases. When the panel tilt angle is 20°, the average annual net EUI of all shading solutions is the lowest, at 36.1 kWh/m^2. The influence of the panel installation height on the annual net EUI shows different trends on the above and below the reference position (0 m). As the panel installation position arises from the bottom of the window frame (−1.8 m) to the top of the window frame (0 m), the annual average net EUI of PVSDs continues to increase. As the panel installation position arises from the top of the window frame (0 m) to 1 m above the window, the average annual net EUI continues to decrease. When the PVSDs are installed at the bottom of the window frame (−1.8 m), the average annual net EUI is the lowest, at 34.53 kWh/m^2. When the installation position is at the top of the window frame (0 m), the maximum average annual net EUI is 38.82 kWh/m^2.

The influence of PVSDs on indoor UDI (100 lux < Illuminance < 3000 lux) is shown in Figure 8. It can be seen from the figure that the influence trends of PVSDs on UDI throughout the year are different. When the panel width is large, the panel tilt angle is large, or the PVSD installation position is close to the upper edge of the window (0 m), the UDI distribution is more discrete. As the panel width increases, the average annual UDI first increases and then decreases. When the panel width is 0.4 m, the maximum average annual UDI is 79.92%. As the panel tilt angle increases, the average annual UDI gradually decreases. When the panel tilt angle is 0°, the maximum average annual UDI is 80.52%. The influence of PVSD installation height on UDI is the same on the above and below the reference position (0 m). The average UDI throughout the year first increases and then decreases as the installation height increases. When installed at the reference position (0 m),

the average annual UDI is the lowest, at 76.49%, and when the installation height is −1.2 m, the average annual UDI is at the maximum of 80.77%.

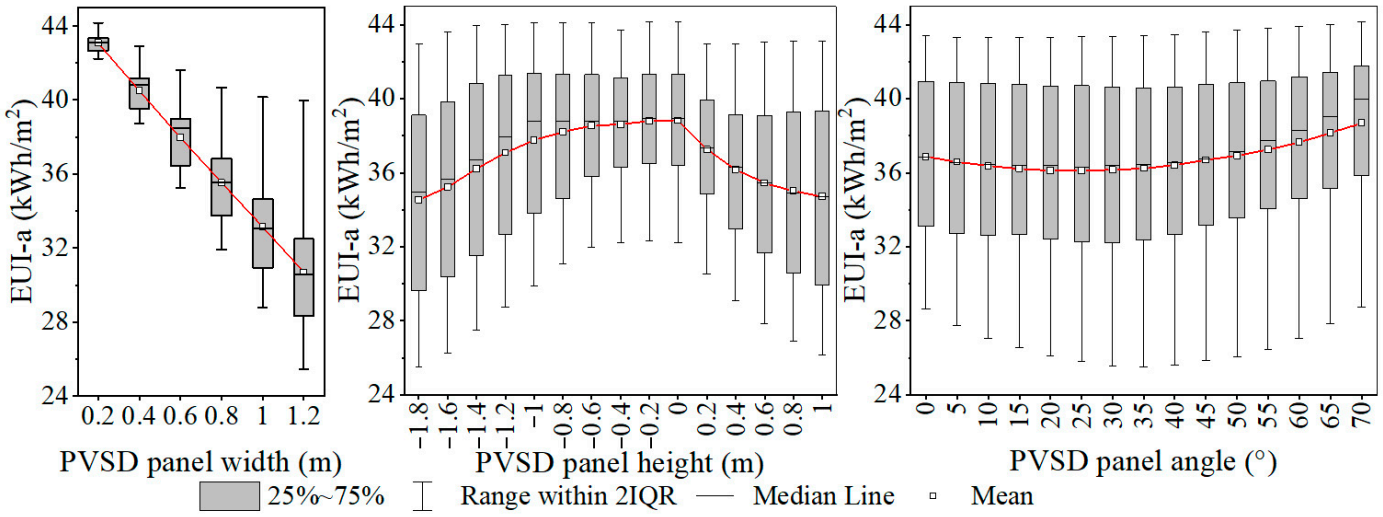


Figure 7. Impact of PVSDs on energy consumption.

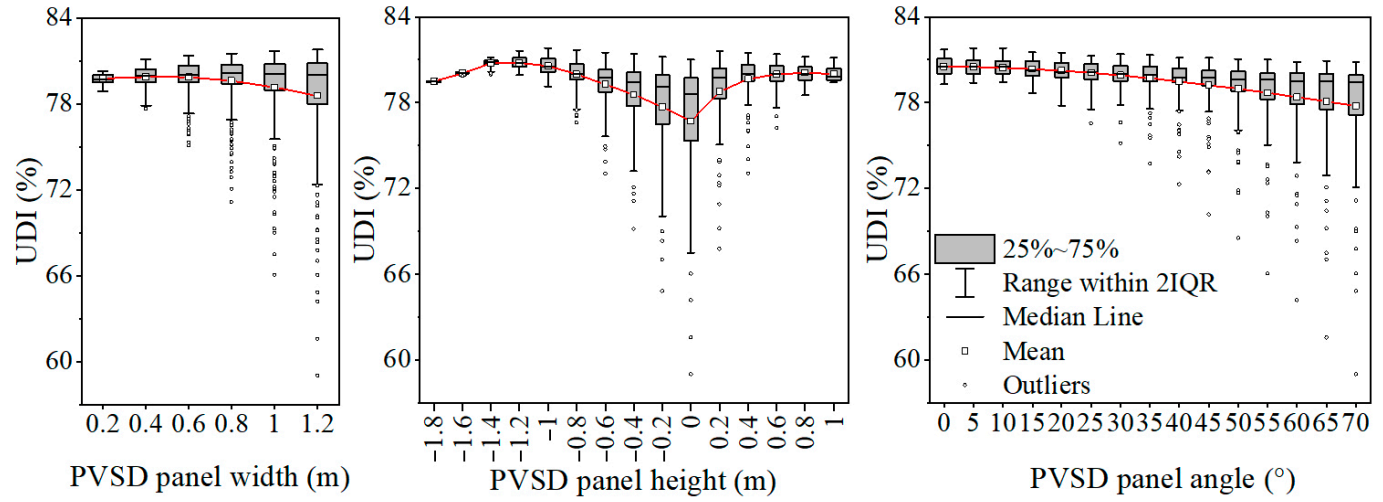


Figure 8. The impact of PVSDs on daylighting.

Generally speaking, PVSDs have different trends and influences on the indoor daylighting and energy consumption of buildings. For the annual net EUI, PVSD width has the greatest impact, followed by the installation height, and the panel tilt angle has the least impact. For UDI, the installation height of PVSDs has the greatest impact, followed by the panel tilt angle, and the panel width has the smallest impact.

3.2.2. Energy-Saving and Daylighting Potential of Fixed PVSDs

The simulation results of all 1350 solutions were sorted, and we found that, when the width is 1.2 m, the installation height is −1.8 m, the tilt angle is 35°, and the net EUI of the fixed PVSDs throughout the year is the lowest, at 25.49 kWh/m^2. At this time, PVSDs only have the function of generating electricity and do not have the function of shading. Comparing the cooling, heating, and lighting energy consumption of buildings with and without photovoltaic shading devices, the differences are small. This shows that, in Qingdao, fixed shading throughout the year has no energy-saving effect. Although the Qingdao area has a relatively large demand for cooling in summer, it also has a large demand for heating in winter. The fixed shading cannot avoid increasing the heating

energy in winter. It can also be seen from Figure 9 that PV power generation can account for 44% of the total energy consumption throughout the year. In March and April, PV power generation still has residual power after offsetting the cooling load, heating load, and artificial lighting load. This also confirms that Qingdao has abundant solar energy resources and that PVSDs have huge application prospects in Qingdao.

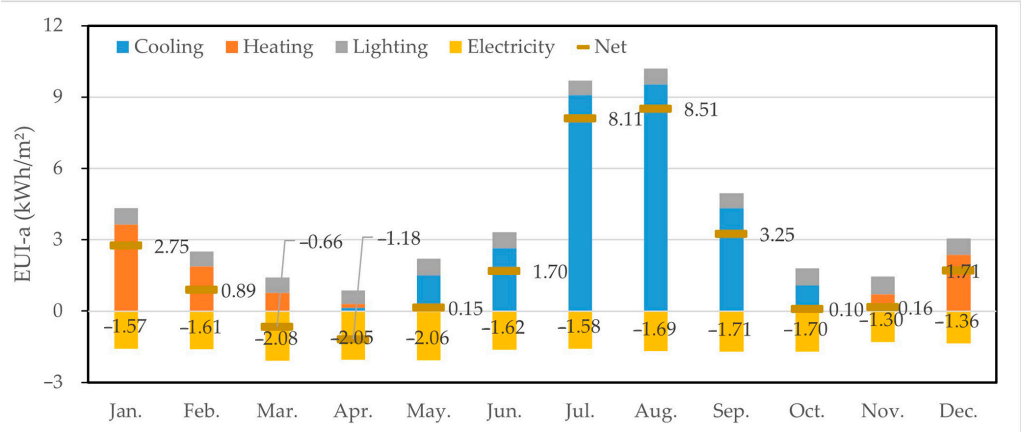


Figure 9. Monthly energy consumption of fixed PVSDs.

In terms of daylighting, when the width of fixed PVSDs is 1.2 m, the installation height is −1 m, and the tilt angle is 10° throughout the year, indoor daylighting is the best. This is because PVSDs allow sunlight to enter the room from the upper part of the window and block sunlight from entering the room from the lower part of the window. This not only reduces excess daylighting near the windows, but also contributes to indoor daylighting uniformity. Compared with having no PVSDs, fixed PVSDs with optimal daylighting throughout the year reduced indoor UDIup (>3000 lux) by 4.2%. They also reduced UDIauto (300–3000 lux) by 2.8%, increased UDIlow (<100 lux) by 2%, and increased UDIsup (100–300 lux) by 5%. Figure 10 shows the visualization of daylighting without PVSDs and optimal daylighting throughout the year with fixed PVSDs. It can also be seen from the figure that PVSDs greatly reduce the proportion of excessive illumination in areas near windows. At the same time, they also increase the proportion of insufficient illumination deep in the room, reducing the risk of glare and direct exposure. The indoor illumination distribution is more even, and the UDI (100–3000 lux) increases by 2.2%.

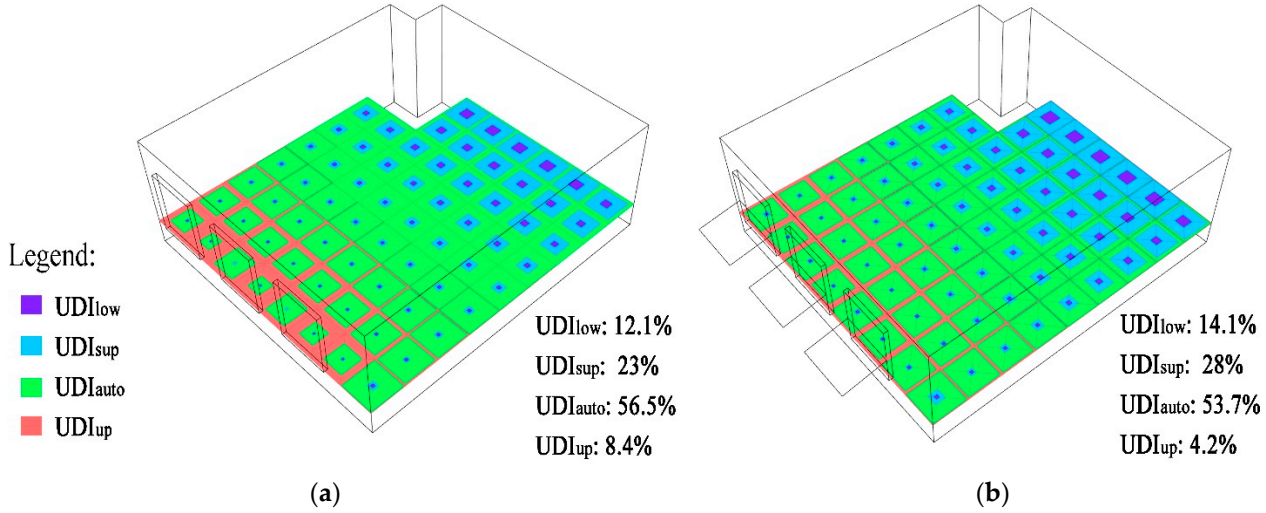


Figure 10. Daylighting visualization: (**a**) Visualization of daylighting throughout the year without shading; (**b**) Visualization of daylighting throughout the year under fixed PVSD conditions.

3.3. The Impact of Dynamic PVSDs on Daylighting

3.3.1. The Impact of Rotation Strategy on Daylighting

By rotating the tilt angle of PVSDs, they can better adapt to the impact of changes in the sun's altitude angle on indoor daylighting, effectively improving the indoor daylighting levels. Figure 11 shows the impact of adjusting the tilt angle of PVSDs at different installation heights on indoor daylighting in January and July when the width of the PVSDs is 1.2 m. It can be seen from the figure that changes in the panel tilt angle at different installation heights have different effects on the indoor daylighting. When the installation height is 0 m, changes in the panel tilt angle have the greatest impact on indoor daylighting. Taking the PVSD installation height of 0 m as an example, as the panel tilt angle increases, UDIauto and UDIup can decrease by a maximum of 25.6% and 5%, respectively, in January, while UDIsup and UDIlow can increase by a maximum of 17.4% and 14.6%, respectively. In July, UDIlow increased by 33.7%, while UDIup, UDIauto, and UDIsup decreased by a maximum of 0.5%, 25.2%, and 8.6%, respectively. This shows that the rotation strategy has a greater impact on indoor daylighting in July and will significantly increase the proportion of areas with insufficient illumination. In January, it can effectively limit the proportion of excessive illumination and also increase the proportion of supplementary useful illumination.

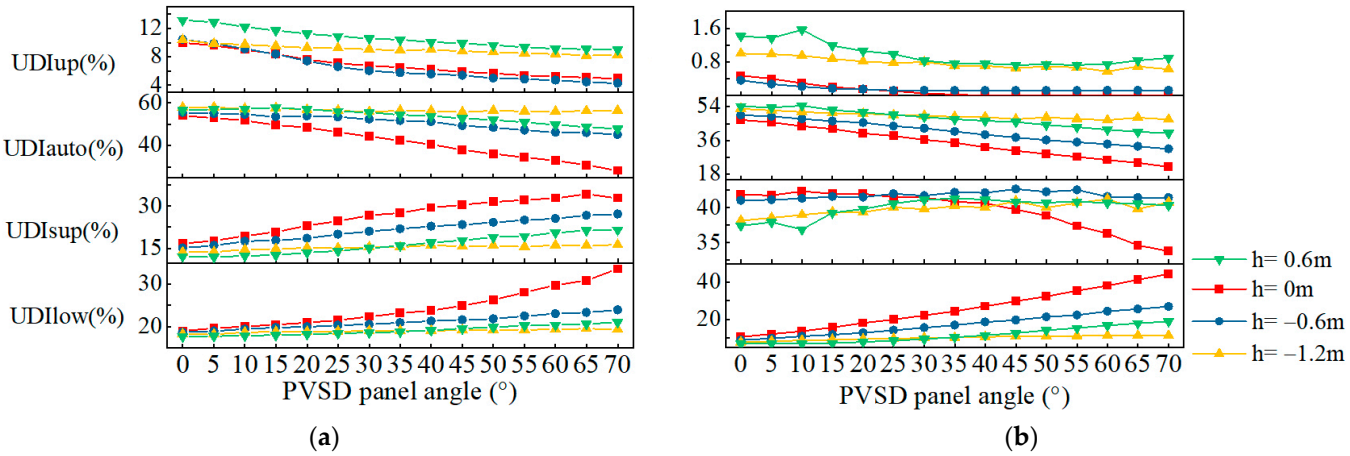


Figure 11. The impact of rotation strategy on daylighting: (**a**) January; (**b**) July.

3.3.2. The Impact of Sliding Strategy on Daylighting

By sliding the PVSD up and down, the position of sunlight entering the room can be controlled, and the level of daylighting in the room increases. Of course, this sliding strategy will also be affected by the tilt angle of the PVSDs. Figure 12 shows the impact of adjusting the PVSD height on indoor daylighting at different inclination angles when the width of the PVSD is 1.2 m in January and July. It has been found that the larger the panel tilt angle, the more obvious the effect of the sliding strategy on daylighting. In July, as the sliding height increases, the changing trends of UDIsup at different inclination angles are different. When the tilt angle is 60°, the positions above and below 0 m show a trend of first increasing and then decreasing, which is the result of the joint influence of the tilt angle and the height. When the height slides from −1.8 m to 0 m, UDIlow increases by 31.5% and UDIauto decreases by 29.6%. When the height is −1.8 m, UDI (100–3000 lux) achieves the optimal value. In January, when the inclination angle is 60° and the height is −0.4 m, UDIsup achieves the minimum value, which is 10.6% lower than that found without shading. When the height is −1 m, UDI (100–3000 lux) achieves a maximum value of 73.2%, which is 4.7% higher than that found without shading.

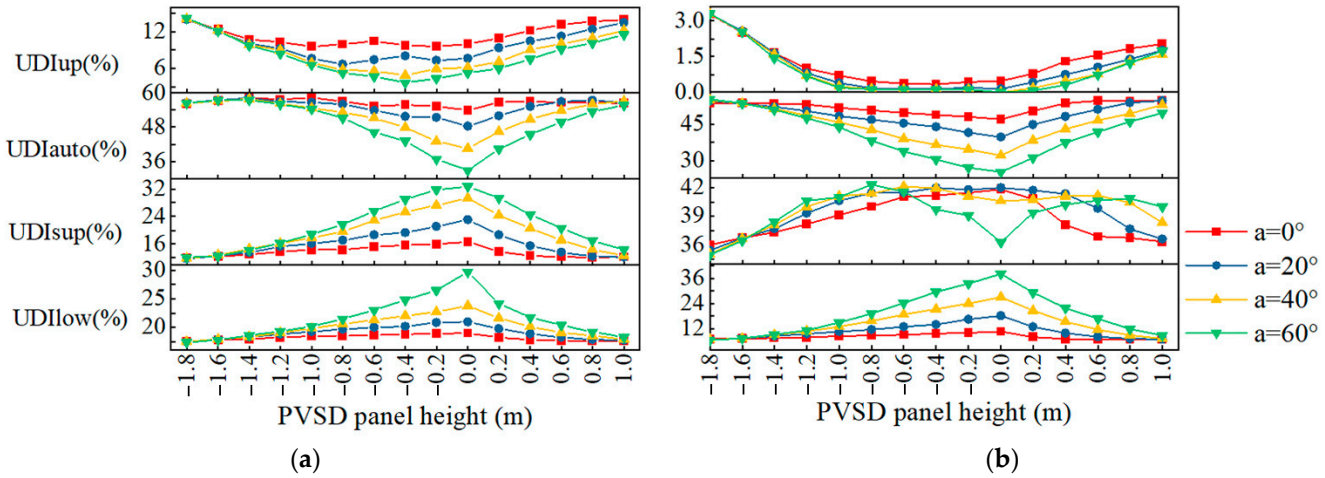


Figure 12. The impact of sliding strategy on daylighting: (**a**) January; (**b**) July.

3.3.3. The Impact of Hybrid Strategy on Daylighting

The hybrid strategy is a shading control strategy that combines rotation and sliding. It can combine the advantages of the rotation strategy and the sliding strategy to control indoor daylighting more flexibly. In Figure 13, the impact of the rotation angle and the sliding height on UDI is shown in the form of a heat map. It has been found that, no matter whether the results are taken in January or July, when the tilt angle is 70° and the installation height is 0 m, the UDI is the smallest. The difference is that, in July, the UDI expanded outward from the minimum. In January, the distribution of larger UDI values was more discrete, and mainly concentrated at −1 m. Therefore, it can be judged that, in January, the impact of the height on UDI is greater than that of the tilt angle. Blocking the daylighting from the lower part of the windows is more conducive to improving UDI. In July, PVSDs will reduce UDI, while having no PVSDs will achieve better daylighting.

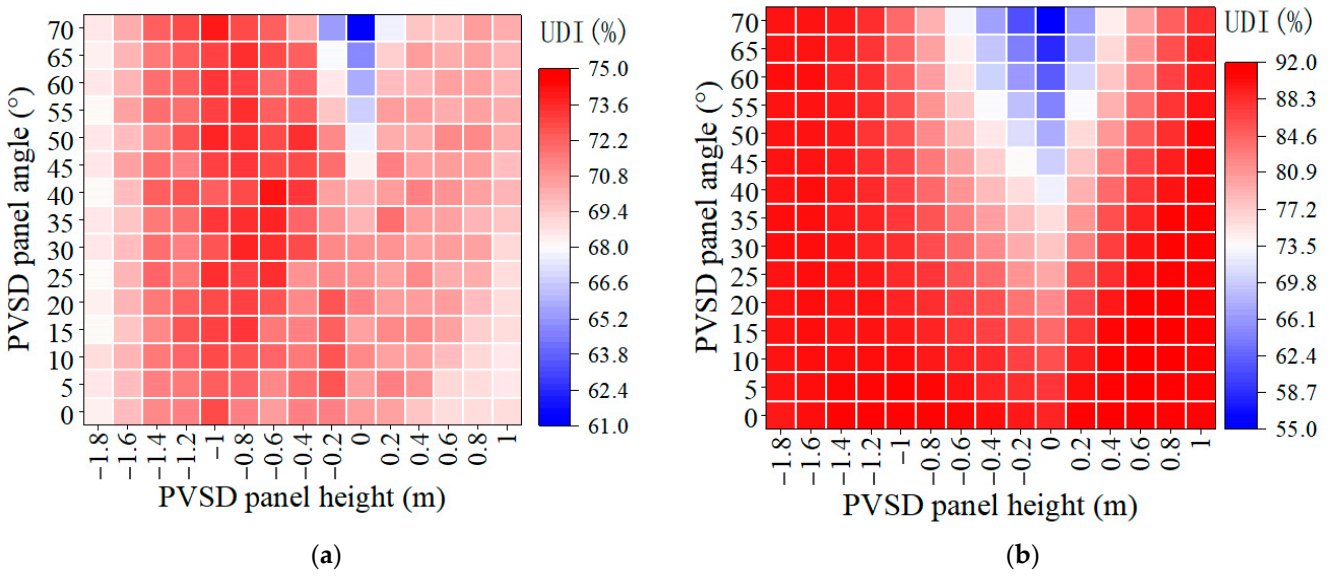


Figure 13. The impact of hybrid strategy on daylighting: (**a**) January; (**b**) July.

3.4. Impact of Dynamic PVSDs on Energy Consumption

3.4.1. The Impact of Dynamic PVSDs on Power Generation

The PVSD power generation is affected by the photovoltaic area, tilt angle, solar radiation, and shading factors. In this study, photovoltaic power generation is mainly affected by the tilt angle and solar radiation. Figure 14 shows the optimal monthly power

generation and the corresponding shading parameters for the three strategies of dynamic PVSDs. The annual photovoltaic power generation in a rotating (height is 0 m), sliding (tilt angle is 35°), and hybrid strategy are 20.6 kWh/m^2, 20.46 kWh/m^2, and 21.25 kWh/m^2, respectively. Among them, since the amount of solar radiation is the largest from March to May, the photovoltaic power generation is the largest, which is consistent with the results of the meteorological data analysis. In the rotation strategy, the PVSD can be rotated to the most suitable angle for power generation in the current month, as shown in Figure 14a. The tilt angle suitable for power generation is smaller in summer and larger in winter, which is related to the changes in the solar altitude angle throughout the year. In the sliding strategy, the direct solar radiation received by the PVSD changes slightly. However, the difference in the reflective capabilities of the building exterior walls and window glass materials can affect the indirect solar radiation received by the PVSDs. This also results in different heights corresponding to different power generation amounts (but this effect is small), as shown in Figure 14b. In the hybrid strategy, due to the influence of the sliding height, the monthly optimal power generation angle changes slightly, but the annual trend remains unchanged, as shown in Figure 14c.

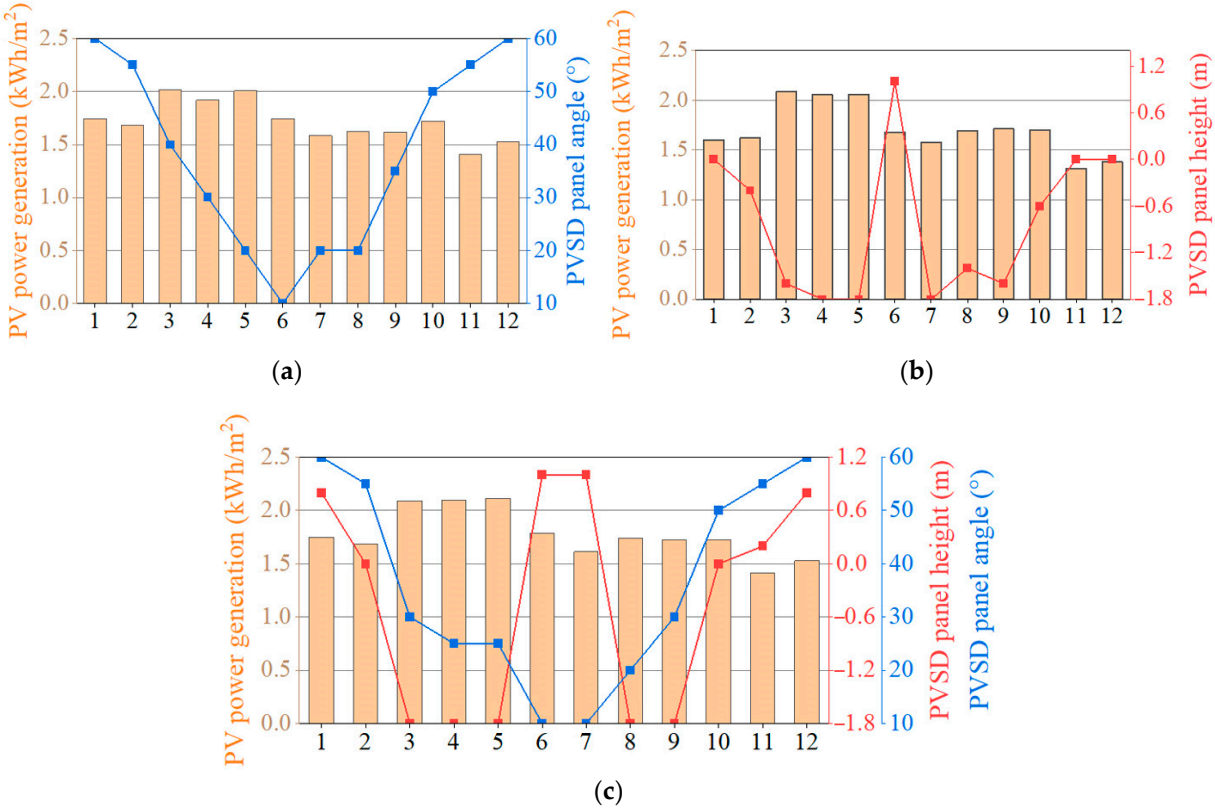


Figure 14. The impact of dynamic PVSDs on photovoltaic power generation: (**a**) The impact of rotation strategy on photovoltaic power generation; (**b**) The impact of sliding strategy on photovoltaic power generation; (**c**) The impact of hybrid strategy on photovoltaic power generation.

3.4.2. The Impact of Dynamic PVSDs on Energy Consumption

In the Qingdao area, the heating load dominates from November to April, and the cooling load dominates from May to October. PVSDs can reduce indoor heat gain, which is beneficial in summer but harmful in winter in terms of energy consumption. PVSDs will also increase the use of artificial lighting, which will also have an impact on energy consumption, although the impact is small. Figure 15 shows the optimal monthly energy consumption for the three strategies of dynamic PVSDs. In the figure, "a" represents the rotation strategy (the height is 0 m), "b" represents the sliding strategy (the tilt angle is 0°), and "c" represents the hybrid strategy. The total annual energy consumption of the

three strategies is 38.91 kWh/m^2, 35.38 kWh/m^2, and 34.04 kWh/m^2, respectively. In summer, the rotation strategy has a greater impact on cooling energy consumption than the sliding strategy, while in winter the sliding strategy has a greater impact on heating energy consumption than the rotation strategy.

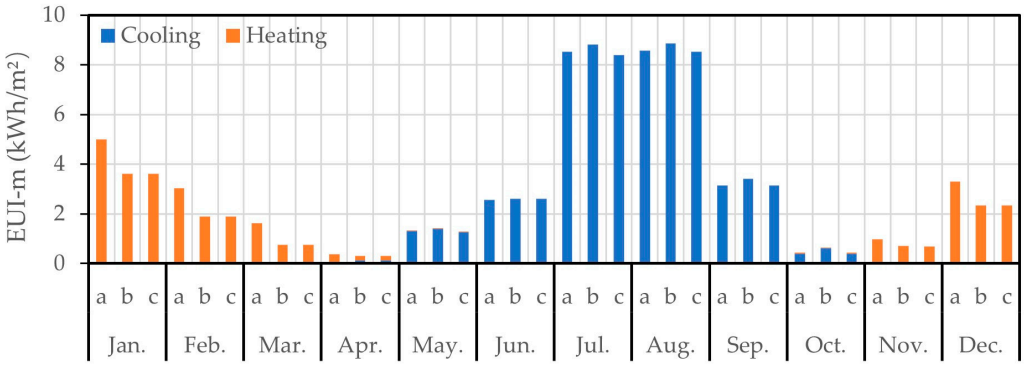


Figure 15. The impact of dynamic PVSDs on energy consumption.

3.4.3. The Impact of Dynamic PVSDs on Lighting Energy Consumption

Artificial lighting is a supplement to daylighting. In Qingdao, although PVSDs can adjust the level of indoor daylighting, they will also increase the proportion of insufficient indoor illumination (especially deep in a room). Figure 16 shows the impact of dynamic PVSDs on lighting energy consumption. It has been found that, when the dynamic PVSDs are at a height of 0 m and a tilt angle of 70° in January and July, the lighting energy consumption reaches the maximum value and decreases diffusely to the surrounding areas. The lighting energy consumption increases with the angle. Taking the height of 0 m as an example, as the tilt angle increases, the lighting energy consumption increases by 0.2 kWh/m^2 and 0.29 kWh/m^2 in January and July, respectively. The lighting energy consumption first increases and then decreases with the increase in height, reaching the maximum value at 0 m. In general, dynamic PVSDs have a greater impact on lighting energy consumption in July. This is determined by the indoor daylighting conditions. The greater the PVSD angle and the closer the PVSD height is to the upper eaves of the window (0 m), the lower the indoor daylighting illumination and the greater the lighting energy consumption.

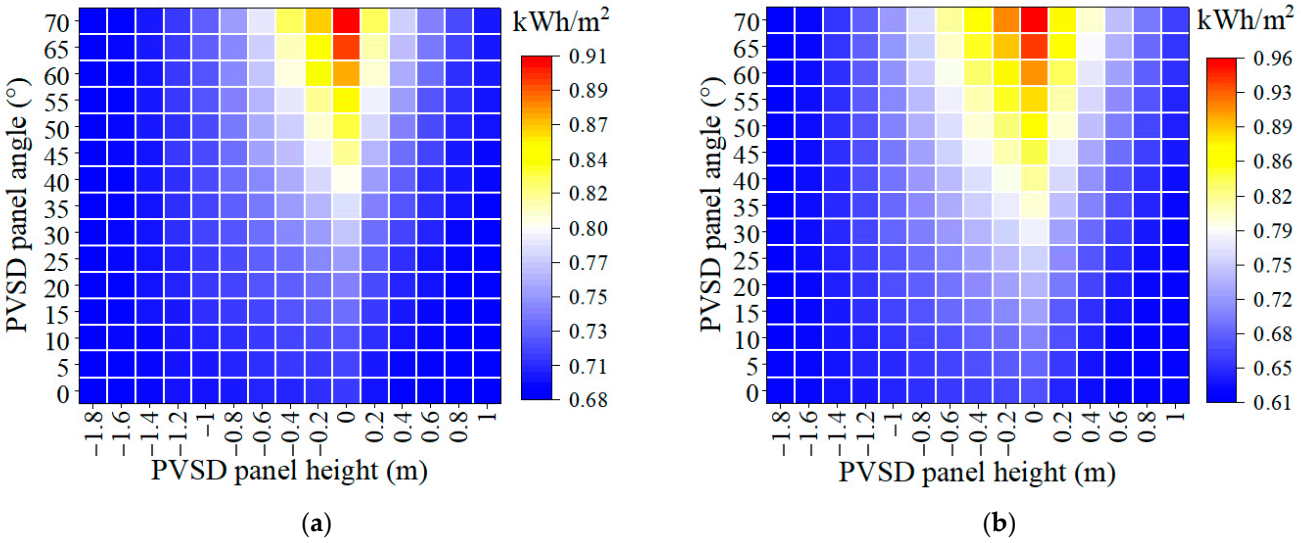


Figure 16. The impact of dynamic PVSDs on lighting energy consumption: (**a**) January; (**b**) July.

3.5. Energy-Saving and Daylighting Potential of Dynamic PVSDs

3.5.1. Energy-Saving Potential of Dynamic PVSDs

In this section, we use net EUI as the evaluation index to explore the energy-saving potential of the three strategies. In Section 3.2, it can be seen that the wider the width, the more energy-saving potential it has; therefore, the width selected in this section is 1.2 m. When the installation height is 0 m, the rotation strategy is adopted. When the panel tilt angle is 20°, the sliding strategy is adopted. The optimal net energy consumption of the three strategies is shown in Figure 17. From the perspective of energy saving, the annual net EUI of the three strategies are 31.09 kWh/m^2, 24.18 kWh/m^2, and 22.73 kWh/m^2, respectively. The annual net EUI of the sliding strategy and the hybrid strategy are both smaller than the annual net EUI of the fixed PVSD (25.49 kWh/m^2). It is worth mentioning that the position of the fixed PVSD is −1.8 m and has no shading effect. In the rotation strategy, the height of the PVSD is 0 m, which has a shading effect, thus increasing the heating energy consumption. Compared with the sliding and hybrid strategies, the rotation strategy reduces the cooling energy consumption but increases the heating and artificial lighting energy consumption. However, the photovoltaic power generation is small, and the energy-saving effect of the rotation strategy is not ideal. In the rotation strategy, the PVSD tilt angle is smaller in winter, which is not conducive to power generation, but is beneficial to reducing the heating energy consumption. This shows that the impact of heating energy consumption on the net energy consumption is greater than that of photovoltaic power generation at this time. In the sliding strategy, the PVSD is located at the lower eaves of the windows from November to May, indicating that shading is detrimental to energy conservation in these months. In the hybrid strategy, the tilt angle of the PVSD becomes the most beneficial to power generation in winter, which is why the hybrid strategy is better than the rotating and sliding strategies.

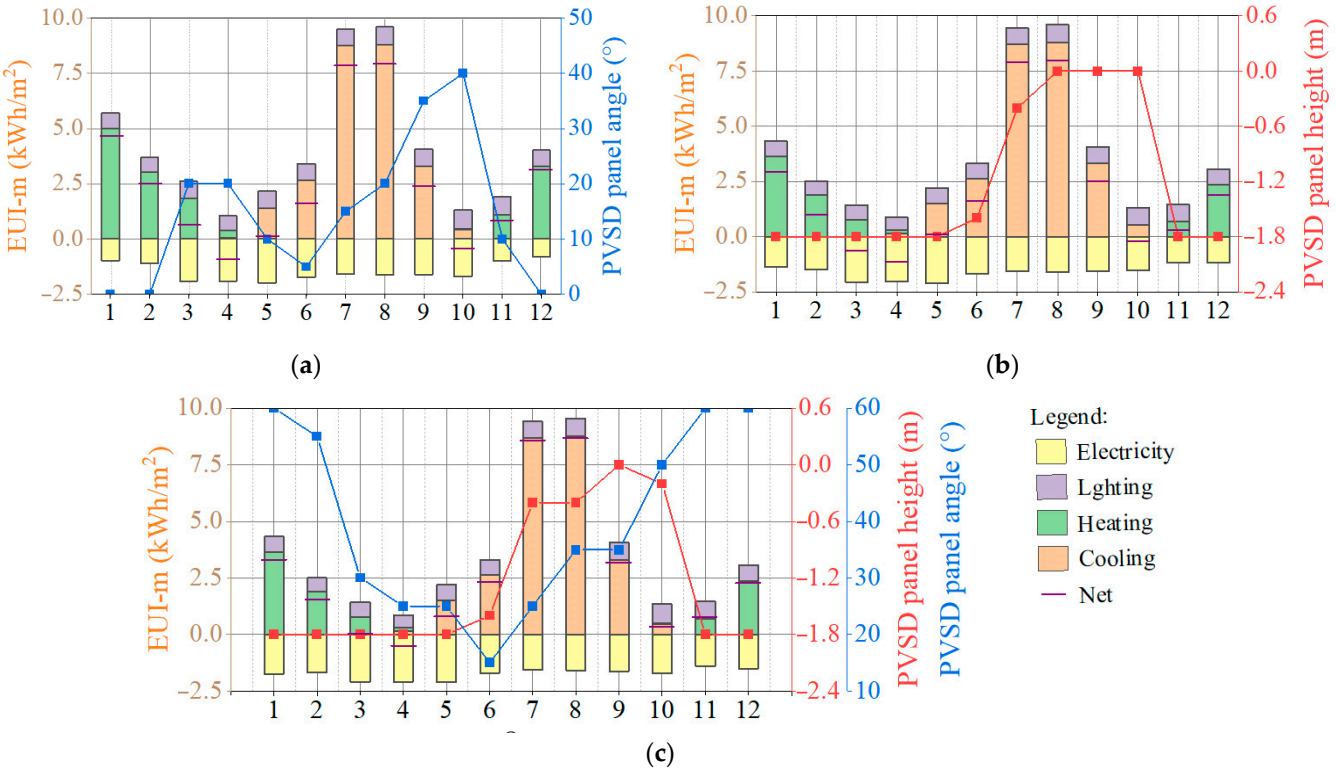


Figure 17. Energy-saving potential of dynamic PVSDs: (**a**) Rotation strategy; (**b**) Sliding strategy; (**c**) Hybrid strategy.

3.5.2. Dynamic PVSD Daylighting Potential

This section explores the potential of dynamic PVSDs to improve daylighting with the goal of UDI. Referring to the results in Section 3.2, this section takes the width of 1.2 m as an example. The rotation strategy is adopted when the installation height is −1.2 m, and the sliding strategy is adopted when the inclination angle is 20°. The optimal UDI of the three strategies is shown in Figure 18. The optimal average UDI of the three strategies throughout the year is 81.8%, 82.3%, and 82.6%, respectively. Compared with the fixed PVSD (81.7%) and having no PVSD (79.5%), the indoor daylighting level has improved. Compared with having no PVSD, the three strategies reduce UDIup in each month, and the reduction rate is the largest in January. The three strategies of rotation, sliding, and mixing reduce UDIup by 6%, 7.6%, and 8.7%, respectively. The reduction rate of UDIup in summer is smaller than that observed in winter. The three strategies improve UDIlow in each month, and the improvement rate in winter is greater than that observed in summer. This is due to the fact that the sun has a lower altitude angle and shorter sunshine hours in winter, therefore, direct sunlight has a greater impact on indoor daylighting. PVSDs can block a large amount of direct sunlight from entering the room.

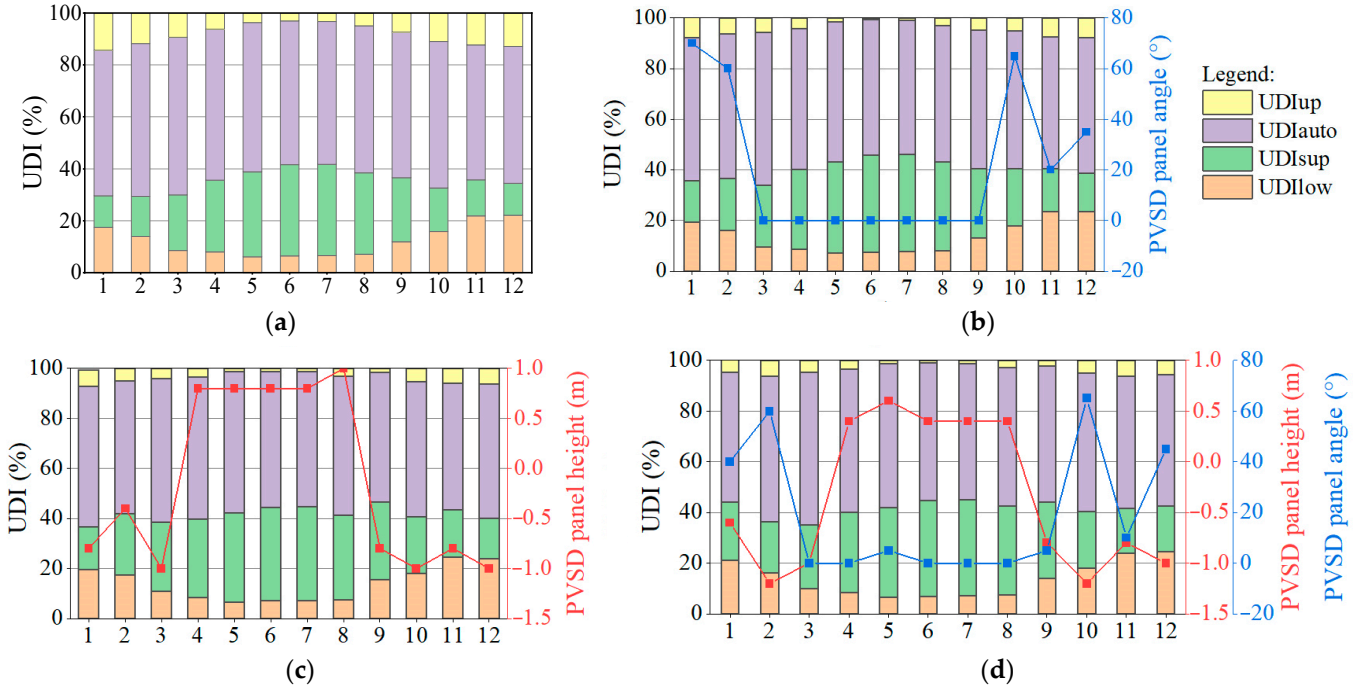


Figure 18. Dynamic PVSD daylighting potential: (**a**) Daylighting potential without PVSDs; (**b**) Rotation strategy; (**c**) Sliding strategy; (**d**) Hybrid strategy.

4. Discussion

From the analysis of the results, in Qingdao, the main effect of PVSDs on indoor energy consumption is reflected in their power generation capacity. Although it is possible to reduce a certain amount of cooling energy, the effect is limited. For indoor daylighting, the biggest role of dynamic PVSDs is to significantly reduce the proportion of excessive illumination, thereby effectively reducing the risk of glare. Of course, this will also increase the proportion of insufficient indoor illumination, and a good control strategy can weaken this deficiency. Therefore, in office buildings in cold areas, flexible and appropriate dynamic control strategies can effectively enhance the application potential of PVSDs in terms of energy saving and daylighting.

However, in dynamic PVSD design, it is often necessary to consider the costs of various dynamic control strategies. More flexible control often means higher costs. The performance improvements brought by more complex control strategies are sometimes not

directly proportional to the cost. For example, in this study, the hybrid strategy and the sliding strategy only reduced the net EUI by 2.76 kWh/m^2 and 1.31 kWh/m^2, respectivley, compared with the optimized fixed PVSD. Of course, the fixed PVSD at this time cannot improve indoor daylighting. The energy-saving performance of dynamic PVSDs will be improved in other building types in other climate zones. Krarti [23] studied the energy-saving performance of sliding (left–right sliding) and rotating strategies in US apartment buildings and found that, in San Francisco, California, the use of dynamic PVSDs could meet the entire energy needs of the apartments. Meysam [22] studied the performance of movable PVSDs on the south windows of an apartment in Tehran and found that the building's annual heating load was 12% lower with movable PVSDs than with fixed PVSDs. Their power generation can also meet part of the energy consumption needs of the apartment. Only the dynamic control strategy of PVSDs adapted to local conditions can meet the design requirements.

In addition, dynamic PVSDs can better adjust the contradiction between daylighting and energy saving. Although traditional fixed PVSDs can prevent glare in winter, they will also significantly reduce the indoor heat gain and increase heating load. In summer, although the cooling energy can be reduced, the proportion of insufficient illumination will increase. Figure 19 shows a comparison of daylighting and energy consumption between fixed PVSDs (height 0 m, tilt angle 20°) and dynamic PVSDs. In terms of daylighting, the best UDI scenario for dynamic PVSDs in January reduced UDIup by 2.02% and increased UDIauto by 2.8%, compared with fixed PVSDs. In terms of energy consumption, although heating energy consumption increased by 0.32 kWh/m^2, photovoltaic power generation also increased by 0.25 kWh/m^2. Therefore, the best UDI scenario for dynamic PVSDs in January not only improved indoor daylighting, but also reduced energy consumption. In July, the optimal dynamic PVSDs for energy consumption also increased UDIsup and UDIauto by 0.27% and 1.96%, respectively.

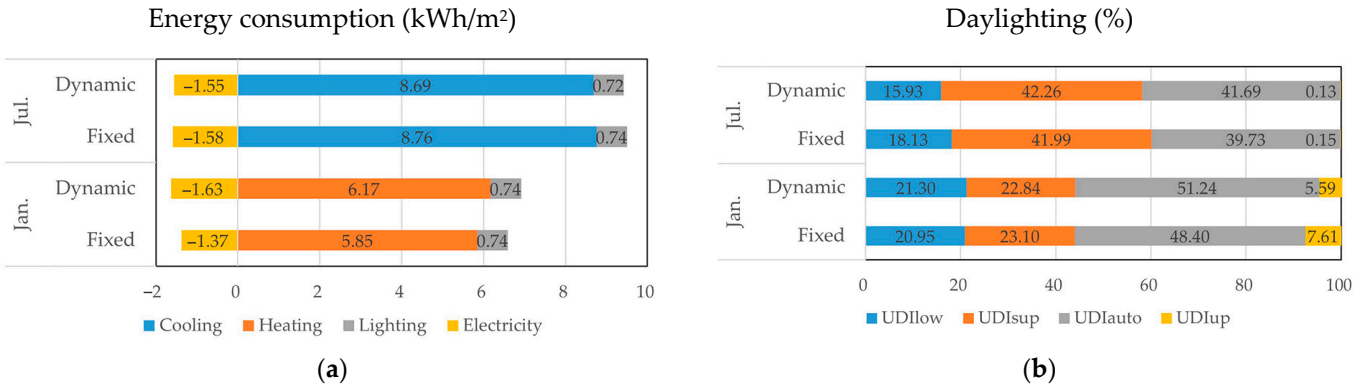


Figure 19. Comparison of energy consumption and daylighting between fixed PVSD and dynamic PVSD: (**a**) Energy consumption; (**b**) Daylighting.

Generally speaking, the application of dynamic PVSDs in office buildings in cold areas meets the needs of office buildings. On the basis of energy saving, it reduces the risk of glare, improves the uniformity of indoor daylighting, and also meets the needs of visual comfort. If the PVSD is used in other cities in cold regions of China, the PVDS is suitable for cities with sufficient radiation and cooling needs.

5. Conclusions

Compared with existing research, the novelty of this paper is the creation of a dynamic PVSD performance evaluation method that integrates parametric design and performance evaluation. This parametric performance design method can provide non-professionals with a visual toolbox to optimize and evaluate PVSD design solutions. In this paper, we use this method to analyze the dynamic PVSD potential of Qingdao, providing a good

reference for the evaluation and optimization of PVSDs in other cities in different climate zones. This research can provide theoretical, methodological, and data support for the application of the PVSD in cold-climate regions in China. In this paper, we investigate the daylighting and energy-saving performance of a south-facing dynamic PVSD in an office building located in Qingdao, a cold region in China. The impact of three strategies (rotation, sliding, and hybrid) on daylighting and energy consumption was investigated. The main results of this study are summarized below, as follows:

(1) The fixed PVSD in Qingdao can increase the annual average UDI by 2.2% and reduce the annual average UDIup by 4.2%. When the fixed PVSD is installed at an angle of 35° and installed under the window eaves, the net EUI is the lowest, at 25.49 kWh/m^2. This is caused by the climate environment (winter dominance).

(2) The simulation results show that the dynamic PVSD is superior to the fixed PVSD and the photovoltaic panel in terms of energy performance, and it can also effectively improve the indoor daylighting environment. This is due to the flexibility of the hybrid strategy, which can better adapt to changes in the building environment and user needs.

(3) Simultaneous changes in height and tilt angle (hybrid strategy) can achieve maximum energy-saving efficiency and higher daylighting levels.

(4) In terms of daylighting, the greater the tilt angle of the PVSD and the closer it is to the upper eaves of the window (height is 0 m), the lower the indoor daylighting level will be. In terms of energy consumption, when the PVSD area is constant, the tilt angle has the greatest impact on power generation, while the height has a greater impact on energy consumption.

(5) Compared with having no PVSD, the rotation strategy (installation height is 0 m), sliding strategy (tilt angle is 20°), and hybrid strategy can save energy by 32.13%, 47.22%, and 50.38%, respectively. The three strategies increase the average UDI by 1.39%, 2.8%, and 3.1%, respectively.

This study also has some limitations. In this paper, we only studied the application of dynamic PVSDs in office buildings in cold-climate areas in China, and the paper lacks research on other climate areas and other types of buildings. We only studied the performance of south-facing PVSDs, and the paper lacks research on other orientations. In future studies, it may be necessary to consider dynamic control strategies for PVSDs in multiple types of buildings in different climate zones under future climate conditions.

Author Contributions: Conceptualization, Q.M. and Y.J.; methodology, Y.J. and Q.M.; software, S.R. and Z.Q.; validation, Z.Q. and S.R.; writing—original draft preparation, Z.Q. and S.R.; writing—review and editing, Y.J. and Q.M.; visualization, Z.Q. and S.R.; funding acquisition, Q.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China, grant number 52108015.

Data Availability Statement: The data presented in this study are available upon request from the corresponding author. The data are not publicly available due to privacy.

Acknowledgments: We would like to express our gratitude to the editors and reviewers for their thoughtful comments and constructive suggestions on improving the quality of this paper.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Building on the Past and Starting a New Journey to Address Climate Change Globally. Available online: http://www.gov.cn/gongbao/content/2020/content_5570055.htm (accessed on 12 December 2023).
2. National Development and Reform Commission. Action Plan to Peak Carbon Emissions before 2030. Available online: https://en.ndrc.gov.cn/policies/202110/t20211027_1301020.html (accessed on 19 February 2024).

3. China Association of Building Energy Efficiency. 2022 Research Report of China Building Energy Consumption and Carbon Emissions. 2022. Available online: https://www.cabee.org/upload/file/20230104/1672820934145324.pdf (accessed on 19 February 2024).
4. Hao, D.; Qi, L.; Tairab, A.M.; Ahmed, A.; Azam, A.; Luo, D.; Pan, Y.; Zhang, Z.; Yan, J. Solar energy harvesting technologies for PV self-powered applications: A comprehensive review. *Renew. Energy* **2022**, *188*, 678–697. [CrossRef]
5. Peng, C.; Huang, Y.; Wu, Z. Building-integrated photovoltaics (BIPV) in architectural design in China. *Energy Build.* **2011**, *43*, 3592–3598. [CrossRef]
6. Ekoe A Akata, A.M.; Njomo, D.; Agrawal, B. Assessment of Building Integrated Photovoltaic (BIPV) for sustainable energy performance in tropical regions of Cameroon. *Renew. Sustain. Energy Rev.* **2017**, *80*, 1138–1152. [CrossRef]
7. Jakica, N. State-of-the-art review of solar design tools and methods for assessing daylighting and solar potential for building-integrated photovoltaics. *Renew. Sustain. Energy Rev.* **2018**, *81*, 1296–1328. [CrossRef]
8. Taveres-Cachat, E.; Lobaccaro, G.; Goia, F.; Chaudhary, G. A methodology to improve the performance of PV integrated shading devices using multi-objective optimization. *Appl. Energy* **2019**, *247*, 731–744. [CrossRef]
9. Tzempelikos, A.; Athienitis, A.K. The impact of shading design and control on building cooling and lighting demand. *Sol. Energy* **2007**, *81*, 369–382. [CrossRef]
10. Yu, G.; Yang, H.; Luo, D.; Cheng, X.; Ansah, M.K. A review on developments and researches of building integrated photovoltaic (BIPV) windows and shading blinds. *Renew. Sustain. Energy Rev.* **2021**, *149*, 111355. [CrossRef]
11. Skandalos, N.; Karamanis, D. An optimization approach to photovoltaic building integration towards low energy buildings in different climate zones. *Appl. Energy* **2021**, *295*, 117017. [CrossRef]
12. Noorzai, E.; Bakmohammadi, P.; Garmaroudi, M.A. Optimizing daylight, energy and occupant comfort performance of classrooms with photovoltaic integrated vertical shading devices. *Archit. Eng. Des. Manag.* **2023**, *19*, 394–418. [CrossRef]
13. Liu, J.; Bi, G.; Gao, G.; Zhao, L. Optimal design method for photovoltaic shading devices (PVSDs) by combining geometric optimization and adaptive control model. *J. Build. Eng.* **2023**, *69*, 106101. [CrossRef]
14. Long, W.; Chen, X.; Ma, Q.; Wei, X.; Xi, Q. An Evaluation of the PV Integrated Dynamic Overhangs Based on Parametric Performance Design Method: A Case Study of a Student Apartment in China. *Sustainability* **2022**, *14*, 7808. [CrossRef]
15. Ma, Q.; Ran, S.; Chen, X.; Li, L.; Gao, W.; Wei, X. Study on the effect of photovoltaic louver shading and lighting control system on building energy consumption and daylighting. *Energy Sources Part A Recovery Util. Environ. Eff.* **2023**, *45*, 10873–10889. [CrossRef]
16. Mandalaki, M.; Zervas, K.; Tsoutsos, T.; Vazakas, A. Assessment of fixed shading devices with integrated PV for efficient energy use. *Sol. Energy* **2012**, *86*, 2561–2575. [CrossRef]
17. Marzouk, M.A.; Atwa, M. Daylighting and Energy Performance of PVSDs. *Sci. Res. J.* **2020**, *8*, 69–75. [CrossRef]
18. Sadatifar, S.; Johlin, E. Multi-objective optimization of building integrated photovoltaic solar shades. *Sol. Energy* **2022**, *242*, 191–200. [CrossRef]
19. Chen, H.; Cai, B.; Yang, H.; Wang, Y.; Yang, J. Study on natural lighting and electrical performance of louvered photovoltaic windows in hot summer and cold winter areas. *Energy Build.* **2022**, *271*, 112313. [CrossRef]
20. Kirimtat, A.; Tasgetiren, M.F.; Brida, P.; Krejcar, O. Control of PV integrated shading devices in buildings: A review. *Build. Environ.* **2022**, *214*, 108961. [CrossRef]
21. Svetozarevic, B.; Begle, M.; Jayathissa, P.; Caranovic, S.; Shepherd, R.F.; Nagy, Z.; Hischier, I.; Hofer, J.; Schlueter, A. Dynamic photovoltaic building envelopes for adaptive energy and comfort management. *Nat. Energy* **2019**, *4*, 671–682. [CrossRef]
22. Akbari Paydar, M. Optimum design of building integrated PV module as a movable shading device. *Sustain. Cities Soc.* **2020**, *62*, 102368. [CrossRef]
23. Krarti, M. Evaluation of PV integrated sliding-rotating overhangs for US apartment buildings. *Appl. Energy* **2021**, *293*, 116942. [CrossRef]
24. Kim, M.; Konstantzos, I.; Tzempelikos, A. Real-time daylight glare control using a low-cost, window-mounted HDRI sensor. *Build. Environ.* **2020**, *177*, 106912. [CrossRef]
25. Huo, H.; Xu, W.; Li, A.; Lv, Y.; Liu, C. Analysis and optimization of external venetian blind shading for nearly zero-energy buildings in different climate regions of China. *Sol. Energy* **2021**, *223*, 54–71. [CrossRef]
26. Grynning, S.; Lolli, N.; Wågø, S.; Risholt, B. Solar Shading in Low Energy Office Buildings—Design Strategy and User Perception. *J. Daylighting* **2017**, *4*, 1–14. [CrossRef]
27. Barzegar Ganji, H.; Utzinger, D.M.; Bradley, D.E. Create and Validate Hybrid Ventilation Components in Simulation Using Grasshopper and Python in Rhinoceros. In Proceedings of the Building Simulation 2019: 16th Conference of IBPSA, Roma, Italy, 2–4 September 2019; pp. 4345–4352.
28. Feng, K.; Lu, W.; Wang, Y. Assessing environmental performance in early building design stage: An integrated parametric design and machine learning method. *Sustain. Cities Soc.* **2019**, *50*, 101596. [CrossRef]
29. Ministry of Housing and Urban-Rural Development of the People's Republic of China. General Code for Energy Efficiency and Renewable Energy Application in Buildings. 2021. Available online: http://www.jianbiaoku.com/webarbs/book/160785/4739756.shtml (accessed on 19 February 2024).
30. Carlucci, S.; Causone, F.; De Rosa, F.; Pagliano, L. A review of indices for assessing visual comfort with a view to their use in optimization processes to support building integrated design. *Renew. Sustain. Energy Rev.* **2015**, *47*, 1016–1033. [CrossRef]
31. Mardaljevic, J.; Heschong, L.; Lee, E. Daylight metrics and energy savings. *Light. Res. Technol.* **2009**, *41*, 261–283. [CrossRef]

32. Reinhart, C.F.; Mardaljevic, J.; Rogers, Z. Dynamic daylight performance metrics for sustainable building design. *Leukos* **2006**, *3*, 7–31. [CrossRef]
33. Reinhart, C.F.; Walkenhorst, O. Validation of dynamic RADIANCE-based daylight simulations for a test office with external blinds. *Energy Build.* **2001**, *33*, 683–697. [CrossRef]
34. Rogers, Z.; Goldman, D.; Daylighting Metric Development Using Daylight Autonomy Calculations in the Sensor Placement Optimization Tool. Boulder, Colorado, USA: Architectural Energy Corporation. 2006. Available online: http://dayinnov.demo.pcr-webdesign.com/system/public_assets/original/SPOT_Daylight%20Autonomy%20Report.pdf (accessed on 19 February 2024).
35. IES Daylight Metrics Committee. Approved Method: IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE). *Illum. Eng. Soc. North Am.* **2012**, 2–3.
36. Nabil, A.; Mardaljevic, J. Useful daylight illuminances: A replacement for daylight factors. *Energy Build.* **2006**, *38*, 905–913. [CrossRef]
37. Mardaljevic, J. *Climate-Based Daylight Modelling and Its Discontents*; CIBSE Technical Symposium: London, UK, 2015; pp. 1–12.
38. Mardaljevic, J.; Andersen, M.; Roy, N.; Christoffersen, J. Daylighting metrics: Is there a relation between useful daylight illuminance and daylight glare probabilty? In Proceedings of the Building Simulation and Optimization Conference BSO12, Loughborough, UK, 10–11 September 2012.
39. Energy Star. What Is Energy Use Intensity (EUI). Available online: https://www.energystar.gov/buildings/benchmark/understand_metrics/what_eui (accessed on 19 February 2024).
40. *Guideline 14-2014*; Measurement of Energy, Demand, and Water Savings. ASHRAE Guideline: Peachtree Corners, GA, USA, 2014; Volume 4, pp. 1–150.
41. Merghani, A.H.; Bahloul, S.A. Comparison between Radiance Daylight Simulation Software Results andMeasured on-Site Data. *J. Build. Road Res.* **2017**, *20*, 48–69. [CrossRef]
42. Lakhdari, K.; Sriti, L.; Painter, B. Parametric optimization of daylight, thermal and energy performance of middle school classrooms, case of hot and dry regions. *Build. Environ.* **2021**, *204*, 108173. [CrossRef]
43. Yoon, Y.; Moon, J.W.; Kim, S. Development of annual daylight simulation algorithms for prediction of indoor daylight illuminance. *Energy Build.* **2016**, *118*, 1–17. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.