

## Article

# Structural Design and Photoelectric Performance of Vertical Sunlight-Tracking Mid-Pane Photovoltaic Louver Window

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## Abstract

To address the bottleneck that traditional building blinds struggle with, namely synergistically achieve shading control and energy recovery, a vertical mid-pane photovoltaic (PV) louver based on a self-powered feedback mechanism was designed. This system utilizes the voltage difference generated by differential light exposure on photovoltaic thin-film cells to drive a motor, realizing zero-energy automatic tracking of the solar azimuth and dynamic adjustment of component angles. By establishing a mathematical model for sunlight-tracking power generation and combining it with COMSOL multiphysics simulation, the coupling effects of the PV louver angle, operating conditions, and solar terms on photoelectric performance were thoroughly analyzed. The research results indicate that when the PV louver angle increases from 60° to 150°, the power generation significantly improves by 80%. Compared with the non-tracking mode, the all-day power generation efficiency gain of the vertical tracking center-mounted PV louver can reach up to 19.68%. Driven by the seasonal evolution of the solar elevation angle, the direct radiation irradiance during the tracking period across four typical solar terms exhibits a distribution pattern characterized as “higher in winter, lower in summer, and intermediate in spring and autumn.” These findings provide a technical pathway integrating dynamic shading, passive photothermal regulation, and clean power generation for south-facing facades in hot summer and cold winter zones, offering significant reference value for enhancing the energy autonomy and low-carbon level of building envelopes.

**Keywords:** vertical centrally mounted photovoltaic louvers; light-tracking; structural design; mathematical model; photoelectric performance; power generation

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## 1. Introduction

Under the context of the “dual carbon” strategy (i.e., carbon peaking and carbon neutrality), the integration and utilization of renewable energy in buildings have become a research focus. Building-integrated photovoltaic (BIPV) curtain walls [1] can convert the vast exterior surface areas of urban buildings into clean energy production bases without occupying additional land, representing one of the key technological pathways towards low-carbon and zero-carbon buildings. Among these, photovoltaic-integrated shading systems—particularly photovoltaic louver windows—exhibit substantial application potential due to their combined functions of dynamic shading, daylighting regulation, and

solar power generation, as well as their compatibility with modern glass curtain walls and window-wall systems [2–4].

Early research mainly focused on the energy-saving potential of fixed shading panels [5]. In recent years, the focus has shifted to adjustable dynamic photovoltaic shading systems, especially photovoltaic louver windows, focusing on performance evaluation [6–9], control strategy optimization [10–12], and integration with new structures such as double-layer curtain walls [13]. However, there are still obvious challenges in the existing research: in terms of structural design, most of the automatic sunlight-tracking systems rely on external meteorological data or complex sensor networks, with complex structure and high cost, which restricts the large-scale application of engineering [14]; in the theoretical model, the mathematical model of the power generation of the mid-pane PV louvers mainly focuses on the influence of the calculation of the effective light-receiving area of the fixed louvers on the power generation performance, and there is no dynamic sunlight-tracking power generation mathematical model; in terms of application suitability, the existing research is mostly limited to specific climatic regions [15], and there is a lack of research on the photoelectric performance of dynamic light in hot summer and cold winter areas such as Nanjing.

Most existing studies have focused primarily on horizontal photovoltaic louvers. In contrast, vertical photovoltaic shading louvers offer significant comprehensive advantages under the high solar altitude angle conditions typical of Nanjing. In terms of photovoltaic safety, they effectively mitigate the hot-spot effect caused by the superposition of shadows from adjacent louvers, thereby ensuring the long-term reliability and power generation stability of the PV modules. With regard to environmental regulation, they dynamically respond to variations in solar azimuth, achieving a synergistic balance between summer cooling load reduction and daylighting optimization on overcast days. In terms of spatial experience, they avoid the visual fragmentation and esthetic drawbacks resulting from the limited slat length inherent in horizontal-axis louvers, providing a more transparent visual connection between the interior and exterior. In architectural expression, they embody both technical rationality and formal esthetics, aligning with the design vocabulary of contemporary green architecture.

Current mainstream solar tracking technologies can be categorized into three types according to their control strategies. The first is centralized programmed tracking based on photosensitive sensors and microprocessors, which relies on microcontroller computations and an external power supply. The second is analog tracking employing photoreistors and comparator circuits; although this approach simplifies the programming requirements, it still necessitates peripheral circuitry such as driver chips. The third is spatiotemporal program control based on the solar trajectory, which, while immune to weather disturbances, is characterized by high system complexity and cost. The common essence of these three types of technology lies in a three-stage decoupled chain of “sensing–processing–actuation”, where the photosensitive element is only responsible for signal acquisition, which must then be processed by an independent circuit or chip before the motor is driven to execute the corresponding action.

In fundamental contrast, the self-sensing and self-actuating tracking technology designed in this paper integrates the functions of light sensing and drive power supply into a single unified entity. Specifically, two photovoltaic thin-film cells with their positive and negative terminals reversely connected serve simultaneously as both the sensing elements and the driving power source. When a voltage difference arises between the two cells due to uneven illumination, this differential voltage is directly applied across the terminals of a DC motor, thereby enabling forward and reverse rotation control—without the need for any sensors, control chips, comparators, driver circuits, or external power supply. This

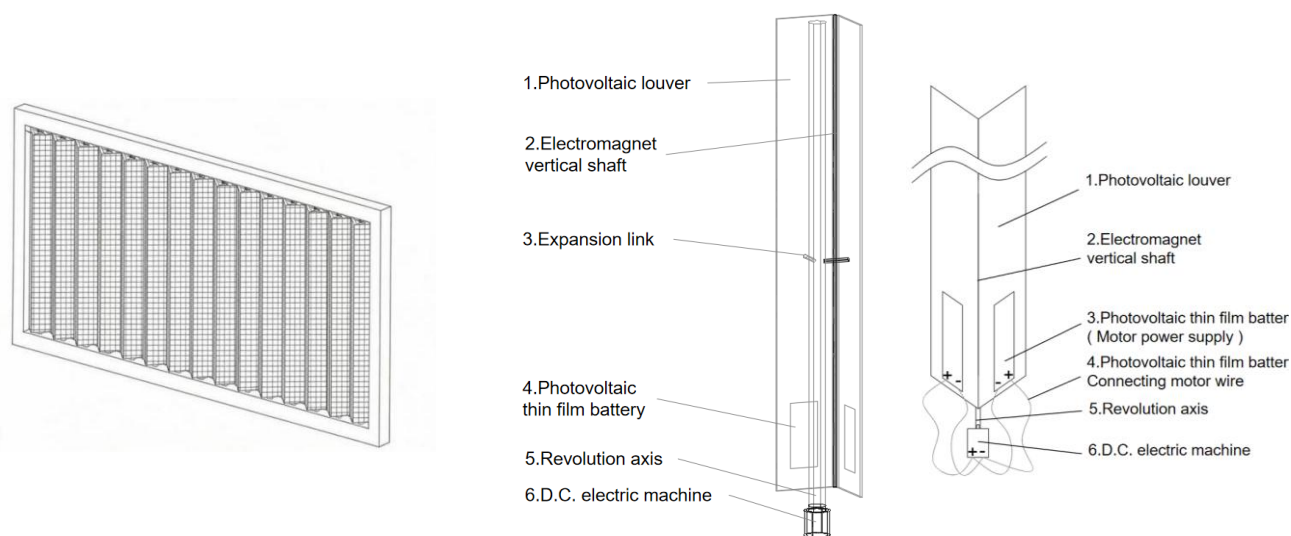
realizes truly “zero-energy” tracking with distributed and independent closed-loop control. It is this elegantly simple architecture of “sensing-driving integration” that constitutes the most essential innovation of the present design. To the best of our knowledge, there is no existing research on comparable sensorless tracking methods.

In view of the above shortcomings, this paper proposes a vertical sunlight-tracking central photovoltaic louver window based on the principle of self-powered feedback. It aims to provide a reference for the optimal design and performance evaluation of such systems in hot summer and cold winter areas through structural optimization and photo-electric performance coupling analysis.

## 2. Structure Design

The sunlight-tracking central photovoltaic louver encapsulates the photovoltaic louver module in the sealed cavity of the insulating glass. The rotation angle of the single pair (group) of photovoltaic louvers is adjusted by light control and electric control, and the photovoltaic louver module is formed by multiple pairs (groups) of photovoltaic louvers. Among them, each pair (group) of photovoltaic louvers is equipped with a pair (group) of two small photovoltaic thin-film batteries used to adjust the energy required for motor rotation. The battery is reversely connected to the DC motor through the positive and negative poles, which plays a role in controlling the positive and negative rotation of the DC motor. When the sunlight deviates from any direction of the two small photovoltaic thin-film batteries, the light intensity received by the photovoltaic thin-film battery is inconsistent, resulting in a voltage difference. The voltage difference makes the positive potential of the motor higher or lower than the negative potential, and the motor obtains positive voltage and positive rotation; otherwise, the motor reverses.

The voltage difference between the two small photovoltaic thin-film cells is controlled by the solar light from the solar azimuth angle to control the forward or reverse rotation of the motor so as to realize the rotation of each pair of (group) photovoltaic louvers and achieve automatic sunlight-tracking of the solar azimuth angle. Many pairs of (group) photovoltaic louvers are in a vertical state in the sealed cavity of the insulating glass, so they are also called vertical sunlight-tracking mid-pane photovoltaic louvers. The structural schematic diagram of vertical light-tracking centrally mounted photovoltaic louvers is shown in Figure 1.



(1) The overall structure of vertical sunlight-tracking mid-pane photovoltaic louver window

(2) Single pair (group) photovoltaic louver structure diagram

(3) The schematic diagram of the power supply principle of the optical motor

**Figure 1.** Structural schematic diagram of vertical light-tracking centrally mounted photovoltaic louvers.

### 3. Mathematical Model of Sunlight-Tracking Power Generation

#### 3.1. Establishment of Mathematical Model of Power Generation

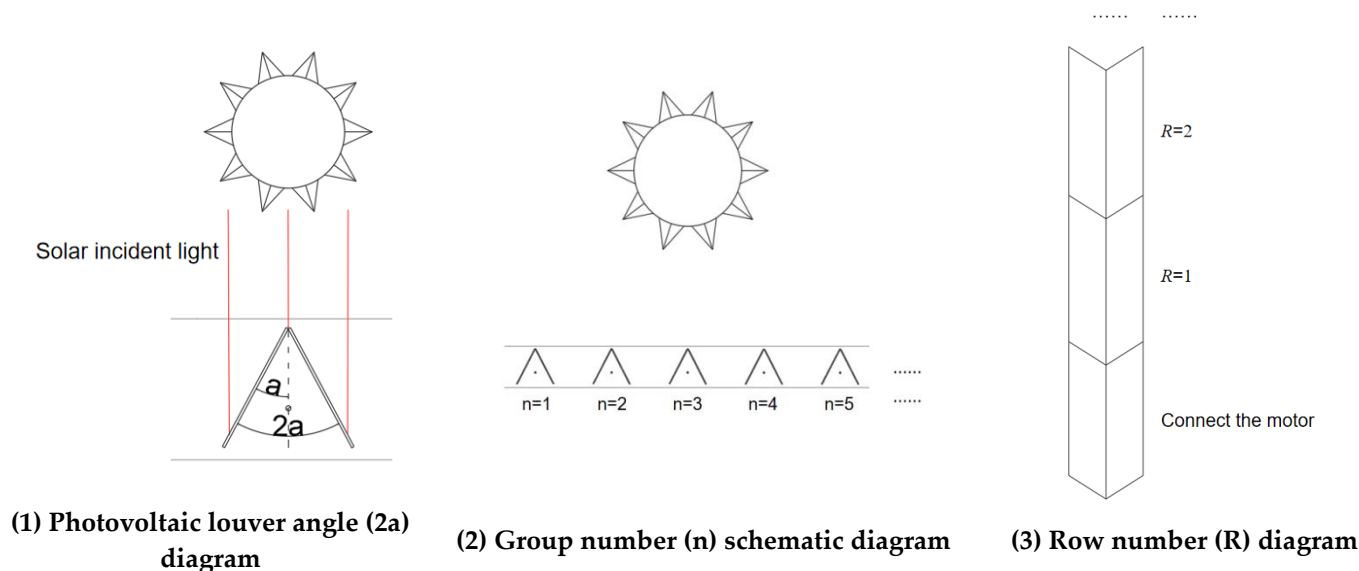
The power generation of a photovoltaic system is, in essence, the time-integrated amount of incident irradiance energy that has been converted via the photovoltaic conversion efficiency during the photoelectric conversion process. Its general fundamental formula is presented in Equation (1), and the fundamental formula for the photovoltaic conversion efficiency is given in Equation (2).

$$E = \eta \times S \times \left[ 1 - \beta_0 (T_{pv} - 25) \right] \times \int_{t_1}^{t_2} I_{eff}(t) dt \quad (1)$$

$$\eta = \frac{P_{max}}{P_{in}} \quad (2)$$

$E$  is the cumulative generated energy over the time interval  $[t_1, t_2]$  (Wh);  $\eta$  is the photovoltaic conversion efficiency of the module;  $S$  is the effective light-receiving area of the module ( $m^2$ );  $\beta_0$  is the temperature coefficient of the module;  $T_{pv}$  is the temperature of the module ( $^{\circ}C$ );  $I_{eff}(t)$  is the effective irradiance at time  $t$  ( $W/m^2$ );  $P_{max}$  is the maximum output power of the module (W); and  $P_{in}$  is the incident optical power (W).

The photovoltaic louver is composed of  $n$  groups of  $R$  rows of two photovoltaic cells with width  $W$  and height  $H$ , and the angle between a pair of photovoltaic louvers is the angle between photovoltaic louvers ( $2a$ ). A schematic diagram of the photovoltaic louver angle, group number, and row number is shown in Figure 2.



**Figure 2.** Schematic diagram of photovoltaic louver angle, number of groups, and number of rows.

When sunlight is incident along the symmetry axis of each pair (group) of vertical photovoltaic louvers, the effective light-receiving width of a single louver is the projection of its physical width onto the direction perpendicular to the incident rays, i.e.,  $W \sin a$ . Therefore, the total effective light-receiving area of each pair (group) of louvers is given by Equation (3).

$$S = 2 \times H \times W \times \sin a \times R \times n \quad (3)$$

$H$  is the height of the photovoltaic cell on each louver (m);  $W$  is the width of the photovoltaic cell on each louver (m);  $a$  is half of the louver angle (rad);  $R$  is the number of rows of photovoltaic cells on each pair (group) of vertical photovoltaic louvers; and  $n$  is the number of groups.

For the installed photovoltaic modules, the effective irradiance must account for the geometric relationship between the sun's position and the module's orientation. According to the cosine law of the incidence angle, as expressed in Equation (4), the effective irradiance incident on the module surface is given by Equation (5).

$$\cos \theta = \sin \beta \times \sin \alpha + \cos \beta \times \cos \alpha \times \cos (\gamma_s - \gamma) \quad (4)$$

$$I_{\text{eff}}(t) = I_{\text{DNI}}(t) \times \cos \theta + I_{\text{GHI}}(t) \times \rho \times \left( \frac{1 - \cos \alpha}{2} \right) + I_{\text{DHI}}(t) \times \left( \frac{1 + \cos \alpha}{2} \right) \quad (5)$$

$\theta$  is the solar incidence angle, i.e., the angle between the incoming solar rays and the normal to the PV module surface (rad);  $\beta$  is the solar altitude angle (rad);  $\alpha$  is the tilt angle of the PV module (rad);  $\gamma_s$  is the solar azimuth angle (rad);  $\gamma$  is the azimuth angle of the PV module (rad);  $I_{\text{DNI}}(t)$  is the direct normal irradiance at time " $t$ " ( $\text{W}/\text{m}^2$ );  $I_{\text{GHI}}(t)$  is the global horizontal irradiance at time " $t$ " ( $\text{W}/\text{m}^2$ );  $\rho$  is the average ground albedo (reflectance); and  $I_{\text{DHI}}(t)$  is the diffuse horizontal irradiance at time " $t$ " ( $\text{W}/\text{m}^2$ ).

When sunlight tracking is employed, if shading occurs between adjacent photovoltaic louvers, a portion of the irradiance is blocked. A shading coefficient  $k_{\text{oc}}(t)$  is therefore introduced (with  $k_{\text{oc}} = 1$  under no shading and  $0 < k_{\text{oc}} < 1$  under shading) to correct the effective irradiance, as shown in Equation (6).

$$I_{\text{eff}}(t) = \left( I_{\text{DNI}}(t) \times \cos \theta + I_{\text{GHI}}(t) \times \rho \times \left( \frac{1 - \cos \alpha}{2} \right) + I_{\text{DHI}}(t) \times \left( \frac{1 + \cos \alpha}{2} \right) \right) \times k_{\text{oc}}(t) \quad (6)$$

By substituting the photovoltaic conversion efficiency, the effective area of the PV louvers, and the effective irradiance under solar-tracking conditions into the fundamental model, the cumulative power generation formula for the center-mounted photovoltaic louver window under solar tracking is finally obtained, as shown in Equation (7).

$$\begin{aligned} E = & \frac{P_{\text{max}}}{P_{\text{in}}} \times 2HW \sin a \times R \times n \times k_{\text{oc}}(t) \times [1 - \beta_0(T_{\text{pv}} - 25)] \\ & \times [(\sin \beta \sin \alpha + \cos \beta \cos \alpha \cos (\gamma_s - \gamma)) \int_{t_1}^{t_2} I_{\text{DNI}}(t) dt \\ & + \rho \frac{1 - \cos \alpha}{2} \int_{t_1}^{t_2} I_{\text{GHI}}(t) dt \\ & + \frac{1 + \cos \alpha}{2} \int_{t_1}^{t_2} I_{\text{DHI}}(t) dt] \end{aligned} \quad (7)$$

The photovoltaic louver module with photovoltaic louvers in the vertical sunlight-tracking center changes with the change in the solar azimuth angle and realizes the azimuth angle sunlight-tracking. The rotation angle of the photovoltaic louver module is always consistent with the solar azimuth, that is,  $\gamma_s = \gamma$ . Therefore, the mathematical model of the power generation of the vertical middle photovoltaic louver window is Equation (8):

$$\begin{aligned} E = & \frac{P_{\text{max}}}{P_{\text{in}}} \times 2HW \sin a \times R \times n \times k_{\text{oc}}(t) \times [1 - \beta_0(T_{\text{pv}} - 25)] \\ & \times \left[ \sin \beta \int_{t_1}^{t_2} I_{\text{DNI}}(t) dt + \frac{\rho}{2} \int_{t_1}^{t_2} I_{\text{GHI}}(t) dt + \frac{1}{2} \int_{t_1}^{t_2} I_{\text{DHI}}(t) dt \right] \end{aligned} \quad (8)$$

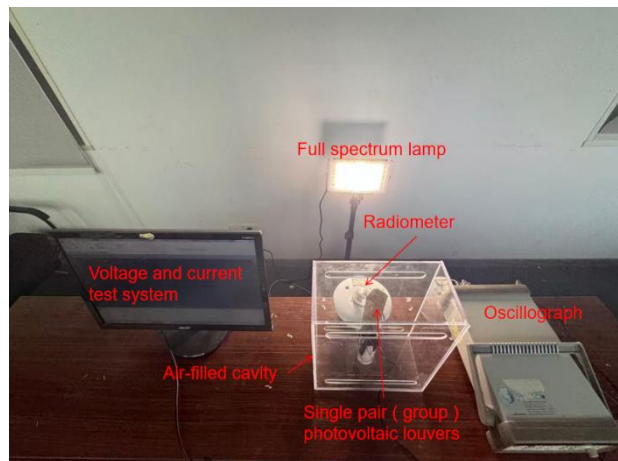
### 3.2. Single-Pair (Group) Photovoltaic Louver Power

#### 3.2.1. Experimental Platform Construction and Test Results Analysis

The experimental platform consists of a full spectrum lamp, a single (group) photovoltaic louver, a DC motor, and an experimental test instrument, in which the test instrument includes an oscilloscope, an irradiation meter, etc. The single-pair (group) photovoltaic louver device is shown in Figure 3(1), and the power generation device test bench is shown in Figure 3(2).



(1) Single-pair (group) photovoltaic louver device diagram

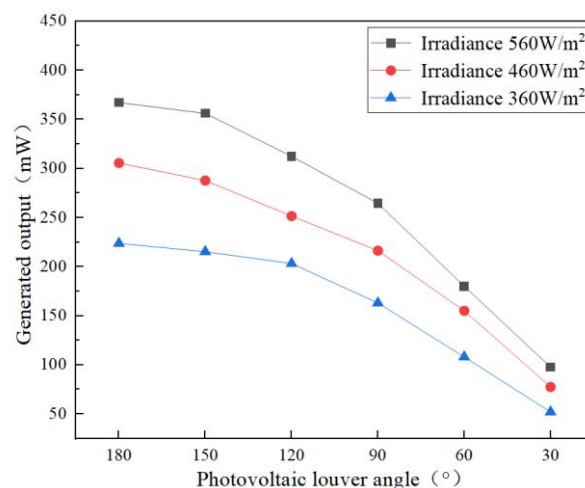


(2) Single-pair (group) photovoltaic louver power generation device test bench diagram

**Figure 3.** Schematic diagram of the experimental setup for a single pair (group) of photovoltaic louvers and power generation devices.

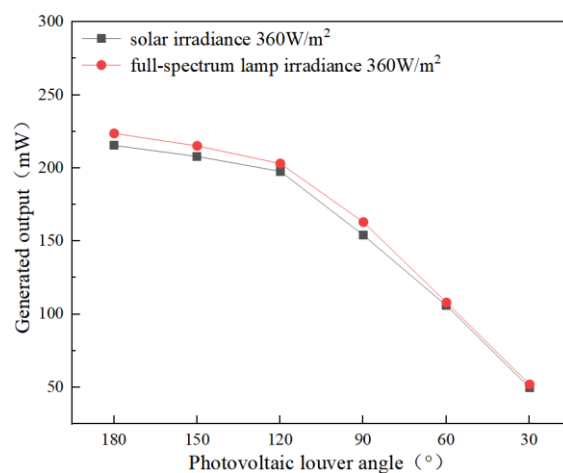
The 200 W full-spectrum lamp was employed to simulate solar irradiation. The photovoltaic thin-film cells generated electricity to drive a DC motor, enabling automatic solar tracking of the PV louver assembly. By varying the distance between the full-spectrum lamp and a single pair (group) of PV louvers, the irradiance levels of 360 W/m<sup>2</sup>, 460 W/m<sup>2</sup>, and 560 W/m<sup>2</sup> were simulated. Under these three irradiance conditions, the electrical power output of the single louver pair was measured at six different louver included angles, namely 180°, 150°, 120°, 90°, 60°, and 30°. The measured power outputs corresponding to each louver angle are presented in Figure 4.

With a gradual decrease in the louver included angle from 180° to 30°, the power generation exhibited a consistent declining trend. Peak outputs at 180° reached 367.1 mW, 305.6 mW, and 223.8 mW under the three irradiance levels, whereas at 30°, they fell to 97.7 mW, 77.6 mW, and 52.1 mW, respectively. Of particular note, the rate of decline increased substantially once the angle fell below 120°, suggesting that smaller included angles impose a significantly greater penalty on the optical capture efficiency of the PV louvers.



**Figure 4.** Power output graph of a single PV louver pair (group) for different angles.

In order to explore the effect of laboratory full-spectrum lamps versus outdoor natural illumination on the electrical performance of photovoltaic louvers, this study carried out both outdoor experiments under natural sunlight and indoor simulations using a full-spectrum lamp, with the irradiance fixed at 360 W/m<sup>2</sup> in both cases. The power generation of the photovoltaic louvers was measured at different inclination angles, as shown in Figure 5. Comparing the two datasets shows that the power output under the full-spectrum lamp consistently exceeds that under outdoor sunlight by about 10 mW, corresponding to relative differences between 4.3% and 6.5%. The observed deviations are primarily ascribed to the spectral mismatch between the solar spectrum and the lamp spectrum, the rise in module operating temperature, and the extra reflective losses caused by diffuse light.



**Figure 5.** Experimental setup of outdoor natural light and indoor full-spectrum lamp simulation.

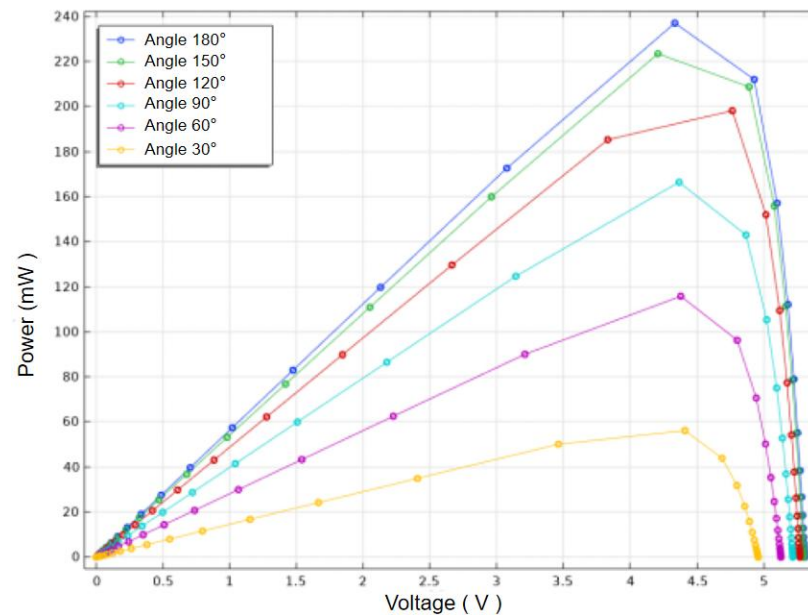
### 3.2.2. Simulation Calculation

Dynamic simulations were performed in the COMSOL Multiphysics 6.1 software, and the operational steps are as follows:

1. Study creation: Using the Model Wizard, a three-dimensional model was first created with the Geometrical Optics physics interface selected, and the study type was set to transient ray tracing. Subsequently, a second three-dimensional model was established with the Semiconductor physics interface, and the study type was set to transient.

2. Model import: Under the Geometry 1 and Geometry 2 menus, the corresponding models were established to simulate the solar trajectory and the current–voltage output of the photovoltaic cells under solar irradiation, respectively. The drawing units were first set to meters, after which the respective geometric domains were generated using the primitive shapes available in COMSOL. The height and width of the two PV louvers were set to 0.214 m and 0.026 m, respectively.
3. Material selection and parameter assignment: Under the Materials menu, air and silicon were assigned to the corresponding domains. For silicon, the relative permittivity was set to 11.7, and the electron mobility was specified as 1450 [cm<sup>2</sup>/(V·s)]. The thermal conductivity is 131 W/(m·K), and the density is 2329 kg/m<sup>3</sup>.
4. Setting of physical field boundary conditions: A solar radiation boundary condition was added to the domain under the Geometrical Optics interface, with its position defined by the following coordinates: latitude 32.08°, longitude 118.46°, time zone UTC+8, and altitude 67 m. For the Semiconductor interface, an analytical doping model was assigned to the domain, with the impurity type set to donor doping (n-type) and a donor concentration of  $1 \times 10^{16}$  [1/cm<sup>3</sup>]. A geometric doping model was also added, with a Gaussian distribution away from the boundary, the impurity type set to donor doping (p-type)—as per the original description—and a concentration of  $1 \times 10^{19}$  [1/cm<sup>3</sup>]. The trap model for trap-assisted recombination was selected as the Shockley–Read–Hall model. Finally, metal contacts were applied to the boundaries of Domain 2. In the Semiconductor physics settings, because the model involves heavy doping, the carrier statistics were chosen to follow the Fermi–Dirac distribution. The principal doping model equations include both the analytical doping model and the geometric doping model, as presented below.
5. Meshing: The sequence type “Physics-controlled mesh” was initially selected, with the element size set to “Finer”. The physics-guided sequence was then edited to refine the element size in the metal-contact regions to “Extra fine”.
6. Study computation: The output time steps were defined as “0,  $0.9 \times 10^{-3}$ ,  $10^{\{\text{range}(-3, 8/50, 5)\}}$ ”, meaning that the output voltage, current, and power of the photovoltaic cell are computed at time instants 0,  $0.9 \times 10^{-3}$  s and the times generated by the exponential sequence  $10^{\{\text{range}(-3, 8/50, 5)\}}$ .

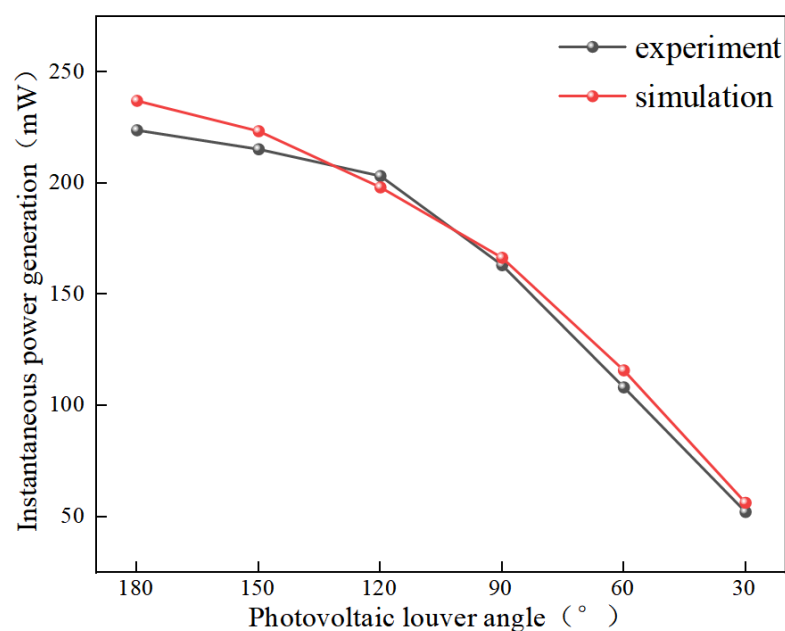
Under the fixed solar irradiance of 360 W/m<sup>2</sup>, the power–voltage curves of different PV louver angles are simulated, as shown in Figure 6. When the angle of photovoltaic louver is reduced from 180° to 30°, the angle of the normal line of photovoltaic louver deviating from the main direction of the sun increases, the effective irradiance decreases, the peak power decreases from 237.02 mW to 56.2 mW, and the power generation decreases monotonously.



**Figure 6.** Simulation diagram of output voltage and power for a single PV louver pair (group) at different angles.

### 3.2.3. Results Comparison

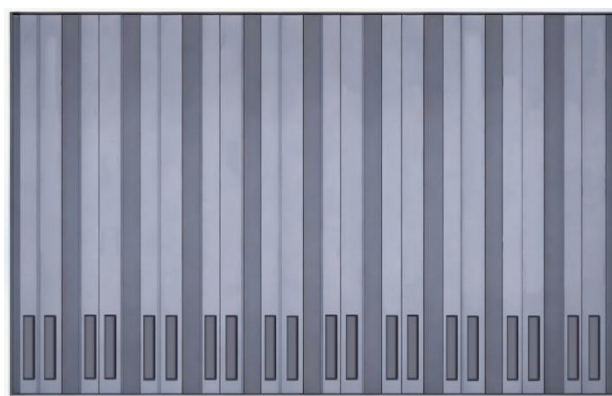
Under the condition of solar irradiance of  $360 \text{ W/m}^2$ , the variation trend of experimental and simulated power generation is compared, as shown in Figure 7. Both of them decrease continuously with the decrease in the angle of the photovoltaic louver from  $180^\circ$  to  $30^\circ$ , which is consistent with the angle response law of the radiation utilization rate of the photovoltaic louver, and the overall fit is good. Based on comparative verification under six operating conditions, the results indicate that the mean absolute error (MAE) is 6.92 mW, the root mean square error (RMSE) is 7.68 mW, and the coefficient of determination ( $R^2$ ) reaches as high as 0.9848. The relative error of power generation attains its maximum value of 7.86% at a louver included angle of  $30^\circ$  and decreases to its minimum of 2.03% at  $90^\circ$ . The deviation is mainly due to the ideal assumption of the model during simulation (photoelectric perfect conversion, no energy loss, uniform illumination) and the practical factors such as reflection loss, circuit loss, irradiance fluctuation, measurement, and angle deviation in the actual test. The overall change trend of the experiment and the simulation is highly consistent, which verifies the regulation effect of the photovoltaic louver angle on the power generation and realizes the mutual verification of the experimental and simulation results.



**Figure 7.** Comparison chart of power generation for a single pair (group) of photovoltaic louvers at various angles.

### 3.3. Model Construction and Working Condition Setting

The vertical sunlight-tracking central photovoltaic louver window consists of 20 photovoltaic thin-film cells with a height of 10.7 cm and a width of 2.6 cm and 10 pairs of photovoltaic louver windows with an area of 0.025 m<sup>2</sup>. At this time, the row R is set to 1. The physical model of the vertical sunlight-tracking central photovoltaic louver window is shown in Figure 8. This study only considers the effect of direct solar radiation irradiation, ignoring the effects of solar scattering irradiation and surface reflection irradiation. For the Nanjing area on 3 December at a 90° louver angle and southward, COMSOL software was used to simulate and analyze the power generation performance of photovoltaic louvers under the influence of photovoltaic louver angle (2a), sunlight-tracking, and typical solar terms. Four sunlight-tracking conditions (Table 1) were set in the study. When multiple pairs (groups) of vertical PV louvers under different working conditions are not in the corresponding solar azimuth range, mutual occlusion will occur between vertical PV louvers, which is called the solar azimuth range.



**Figure 8.** Schematic diagram of angle, group number, and row number of vertical photovoltaic louvers.

**Table 1.** Light-tracking conditions under different solar azimuth angle intervals.

| Working Condition | Photovoltaic Louver Angle | Light-Chasing Solar Azimuth Interval | Non-Light-Chasing Solar Azimuth Interval              |
|-------------------|---------------------------|--------------------------------------|-------------------------------------------------------|
| 1                 | 60°                       | 120°~240°                            | Sunrise solar azimuth~119°, 241°~Sunset solar azimuth |
| 2                 | 90°                       | 135°~225°                            | Sunrise solar azimuth~134°, 226°~Sunset solar azimuth |
| 3                 | 120°                      | 150°~210°                            | Sunrise solar azimuth~149°, 211°~Sunset solar azimuth |
| 4                 | 150°                      | 165°~195°                            | Sunrise solar azimuth~164°, 196°~Sunset solar azimuth |

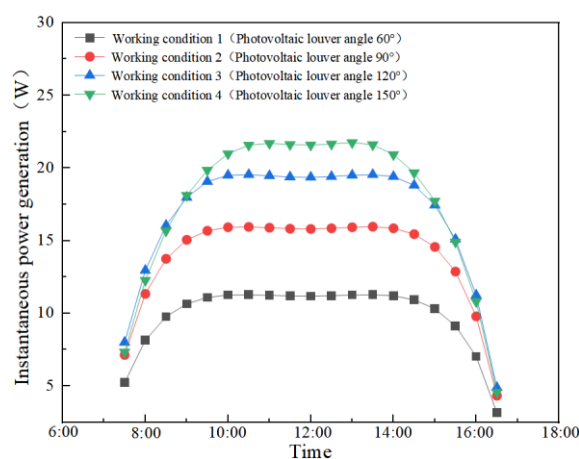
It can be seen from the table that as the angle of the photovoltaic louver increases, the angle range of the sunlight-tracking solar azimuth interval gradually decreases.

## 4. Analysis and Discussion of Simulation Results

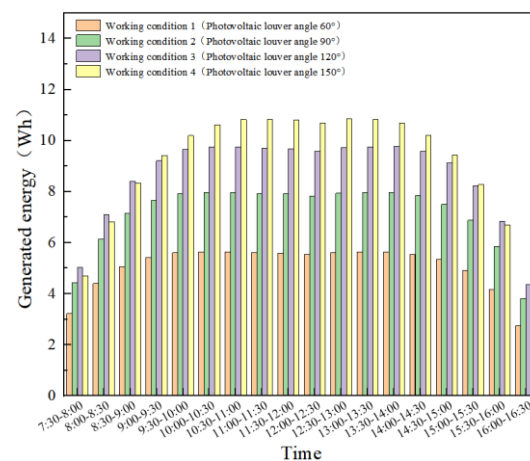
### 4.1. The Influence of the Louver Angle on the Power Generation Performance of Photovoltaic Louvers

The instantaneous power generation and power generation of vertical sunlight-tracking mid-pane photovoltaic louvers under four working conditions of a 60° louver angle (working condition 1), 90° louver angle (working condition 2), 120° louver angle (working condition 3), and 150° louver angle (working condition 4) are compared. The change trend is shown in Figures 9 and 10.

In the sunlight-tracking mode, the power generation performance of the large angle condition (condition 3, condition 4) has significant advantages, and its instantaneous power generation is significantly higher than that of the small angle condition (condition 1, condition 2). The instantaneous power of the large angle condition is stable at more than 17 W at 10~14 o'clock, and the peak of condition 4 is close to 22 W; the power of the small angle condition is low. The instantaneous power of condition 1 is always lower than 12 W, and the peak value of condition 2 is only 15 W. This difference is mainly due to the fact that the large angle can effectively expand the light-receiving range of the photovoltaic louver window and reduce the angle loss. The power generation law is consistent with the instantaneous power. The power generation advantage of the large angle condition is outstanding. The full-day power generation of the four working conditions is 91.31 Wh, 128.69 Wh, 155.29 Wh, and 164.38 Wh, respectively. The full-day power generation of the working condition 2 is 40.9% higher than that of the working condition 1, and the full-day power generation of the large angle condition (working condition 3 and working condition 4) is increased by 70.1% and 80.0%, respectively.



**Figure 9.** Comparison chart of hourly instantaneous power generation of light-following windows under different working conditions.



**Figure 10.** Comparison chart of power generation by time period of light-following windows under different working conditions.

#### 4.2. Effect of Sunlight-Tracking on the Power Generation Performance of Photovoltaic Louver Windows

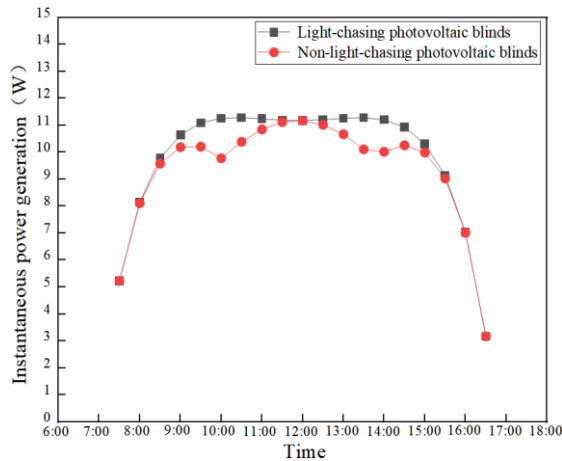
The variation in instantaneous power and power generation of non-sunlight-tracking windows and sunlight-tracking windows is shown in Figure 11.

The photovoltaic louvers that are not positioned in the photovoltaic window are fixed and do not rotate with the azimuth of the sun. When the orientation is determined to be southward, there is an upward trend from morning to noon, the instantaneous power reaches its maximum at 12:00, and there is a downward trend from noon to afternoon. When the louver angle is  $60^\circ$ , the instantaneous power change in the non-light-by-window is as follows: the instantaneous power gradually increases from 7:30 to 9:00, decreases to 10:00, gradually increases to 12:00, gradually decreases to 14:00, then begins to rise to 14:30 and gradually decreases. The whole day power generation is 86.98 Wh. When the louver angle is  $90^\circ$ ,  $120^\circ$ , and  $150^\circ$ , the instantaneous power peak of the non-sunlight-tracking window is concentrated, and the attenuation at both ends is significant in the morning and evening. The daily power generation is 108.56 Wh, 129.75 Wh, and 144.73 Wh, respectively.

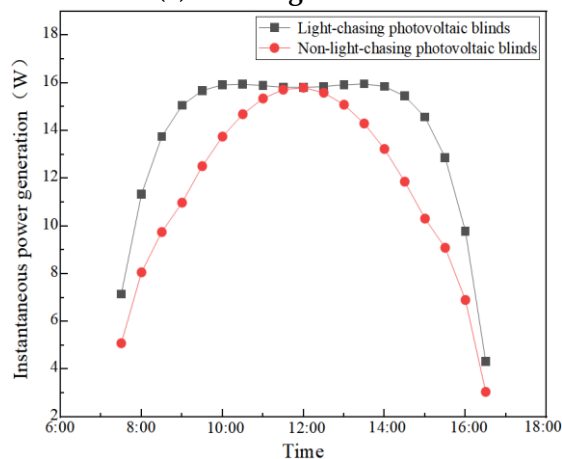
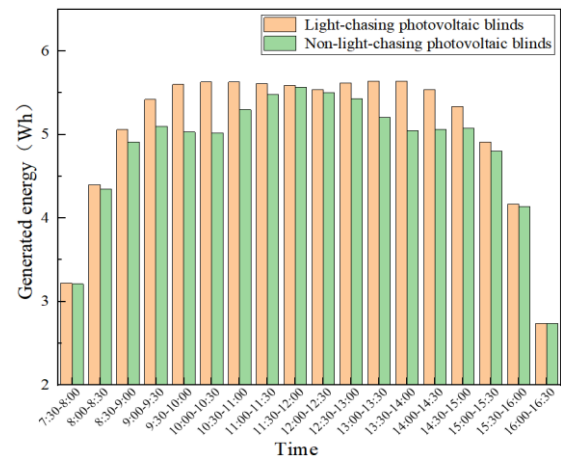
The light-receiving angle can be adjusted adaptively in real time by the light window. The instantaneous power generation shows an upward trend in the morning, enters a stable range when it reaches the maximum value, and then shows a downward trend. The power generation is consistent with the trend of instantaneous power generation. When the louver angle is  $60^\circ$ , the instantaneous power fluctuation is gentle and maintains a high level from 9:30 to 14:30, which is stable at 11~12 W, and the daily power generation is 91.31 Wh; when the louver angle is  $90^\circ$ , the instantaneous power fluctuation from 9:00 to 14:00 is gentle and maintains a high level, which is stable at 15~16 W, and the daily power generation is 128.69 Wh; when the louver angle is  $120^\circ$ , the instantaneous power is stable at 19~20 W from 9:30 to 14:30, and the daily power generation is 155.29 Wh. When the louver angle is  $150^\circ$ , the instantaneous power is stable at 22~23 W from 10:30 to 14:00, and the daily power generation is 164.38 Wh.

Overall, the instantaneous power and power generation of window-by-light and non-window-by-light show a trend of first increasing to the maximum value and then decreasing. The instantaneous power of the non-sunlight-tracking window reaches its maximum at about 12:00, and this high value is maintained in a period of about 3.5–5 h before and after noon. The instantaneous power value and power generation of the full-time power generation of the sunlight-tracking window are higher than those of the non-sunlight-tracking window, and the advantage of the weak light period is more prominent.

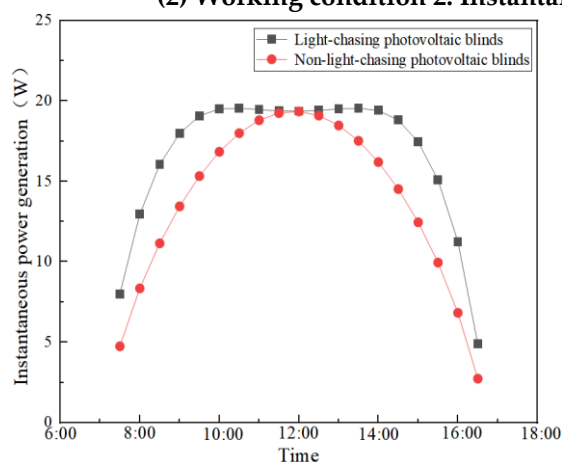
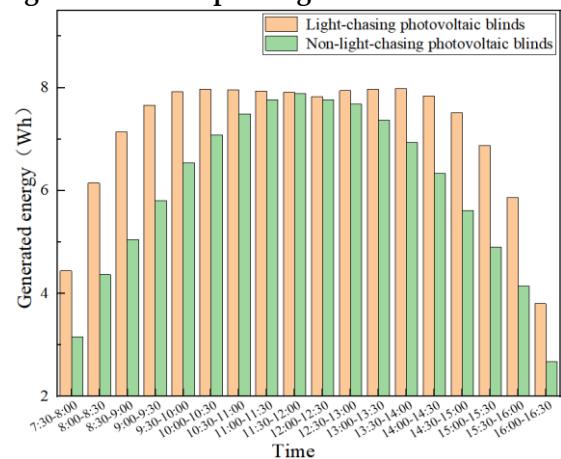
The power generation stability and daytime continuous power generation capacity of the light window are significantly higher than those of the non-light window. The power generation of the four working conditions is 4.98%, 18.54%, 19.68%, and 13.58% higher than that of the non-sunlight-tracking window, respectively, and the power generation gain effect is remarkable.



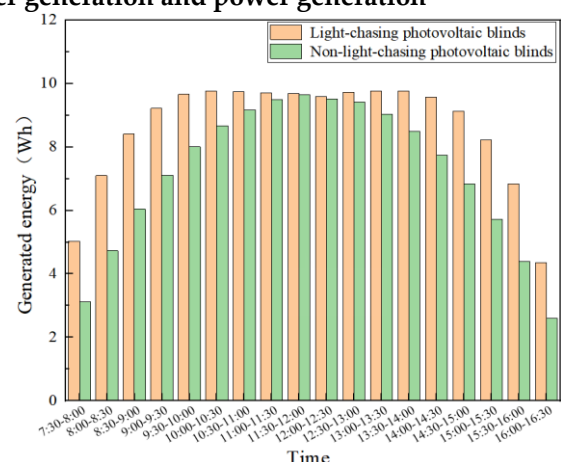
(1) Working condition 1: Instantaneous power generation and power generation

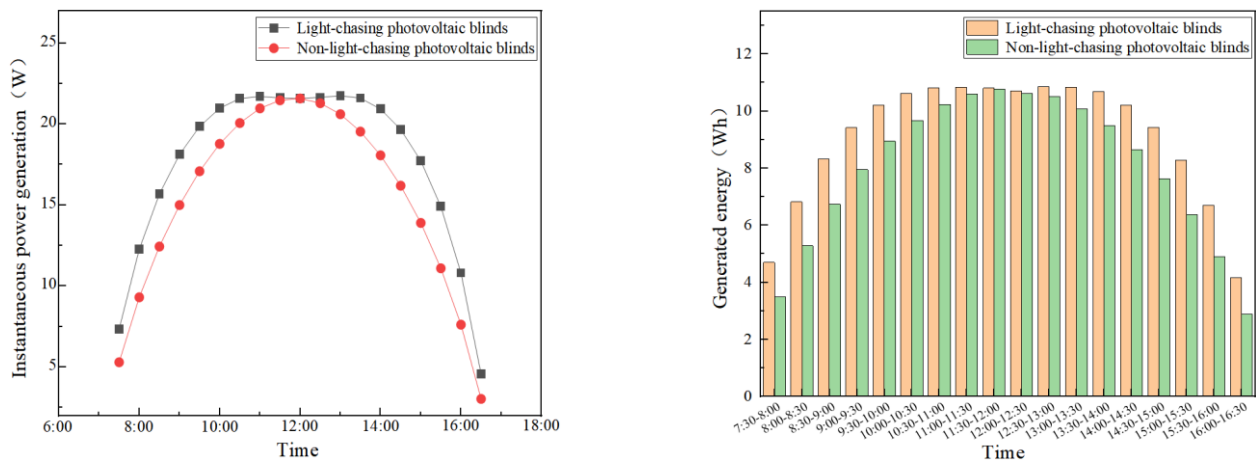


(2) Working condition 2: Instantaneous power generation and power generation



(3) Working condition 3: Instantaneous power generation and power generation





#### (4) Working condition 4: Instantaneous power generation and power generation

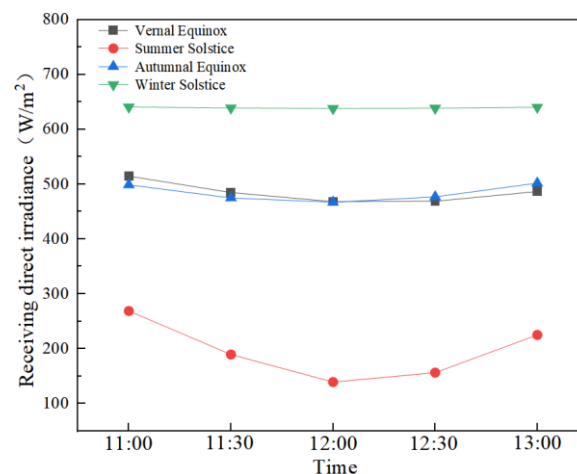
**Figure 11.** Comparison of instantaneous power generation and power output between light-following windows and non-light-following windows.

#### 4.3. The Power Generation Performance of Vertical Sunlight-Tracking Central Photovoltaic Louver Windows on Typical Solar Terms

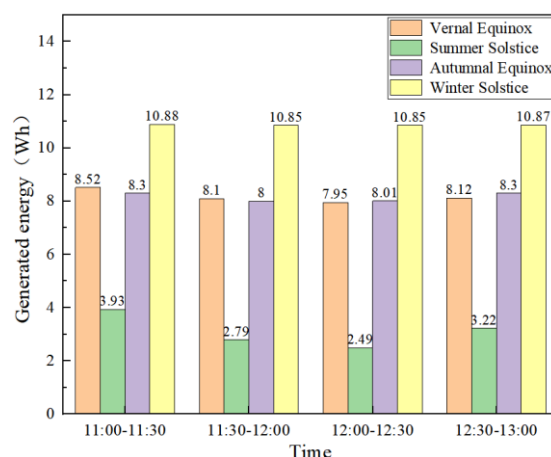
In order to analyze the influence of solar terms on the power generation performance of vertical photovoltaic mid-louvers, four typical solar terms (summer solstice, winter solstice, vernal equinox, and autumnal equinox) were selected to study the direct solar irradiance and power generation received on the surface of photovoltaic louvers.

The synergistic change in the solar elevation angle and azimuth angle directly determines the incident direction of solar light relative to the surface of vertical photovoltaic louvers. The size of the solar elevation angle is the main factor affecting the incident angle of light, which provides the key solar position parameter support for the subsequent analysis of the direct radiation irradiance receiving the law of vertical photovoltaic louvers. The solar elevation angles of the four solar terms are as follows: the peak value of the summer solstice is about  $82^\circ$  at noon, the winter solstice is about  $35^\circ$ , and the spring equinox and autumn equinox are close to  $57^\circ$ .

Based on the solar position data and the vertical photovoltaic louver structure parameters, the solar direct radiation irradiance and power generation received on the surface of the four solar terms during the sunlight-tracking period (11:00~13:00) are calculated, as shown in Figures 12 and 13.



**Figure 12.** Hourly direct solar irradiance incident on the photovoltaic cell surface.



**Figure 13.** Comparison diagram of power generation during light-following periods of vertical light-following central-mounted PV louver for the four solar terms.

The solar direct radiation irradiance received by the vertical sunlight-tracking photovoltaic louvers is characterized by being high in winter and low in summer and in the middle in spring and autumn. The average solar direct radiation irradiance received by the sunlight-tracking period is the highest on the winter solstice, which is  $639.4 \text{ W/m}^2$ . The lowest value is  $195 \text{ W/m}^2$  on the summer solstice. The spring equinox is similar to the autumn equinox at about  $484 \text{ W/m}^2$ . The solar elevation angle of the summer solstice is large, and the sunlight almost parallels the south vertical plane. The vertical photovoltaic louvers are small in terms of the light surface, and the direct solar radiation received is very low. On the winter solstice, the solar elevation angle is small, and the sunlight is almost vertically irradiated on the south vertical plane. The vertical photovoltaic louvers are large in light surface, and the direct solar radiation received is high. The spring and autumn seasons are between the two. The power generation of the four solar terms also shows the law of high in winter and low in summer. The highest value in the winter solstice is  $10.88 \text{ Wh}$ , and the lowest in the summer solstice is only  $2.79 \text{ Wh}$ . The spring equinox and autumn equinox are in the middle, and the value is close, at about  $8.3\text{--}8.5 \text{ Wh}$ . The fluctuation of power generation in each period of the same solar term is small, the fluctuation of the winter solstice is less than  $0.03 \text{ Wh}$ , and the fluctuation of the spring equinox and autumn equinox is less than  $0.6 \text{ Wh}$ .

The direct solar radiation irradiance received by the vertical mid-pane photovoltaic louver windows in the south vertical plane of the building is characterized by being high in the winter and low in summer, which is more favorable for energy utilization in hot-summer and cold-winter areas. In summer, efficient shading is formed, which greatly reduces indoor cooling load and significantly saves indoor air conditioning energy. In winter, low-angle sunlight can penetrate the louvers to increase the passive heat gain of the room, reduce heating energy consumption, and maximize the use of photovoltaic power generation.

## 5. Conclusions

Based on the self-powered feedback mechanism, a vertical sunlight-tracking mid-pane photovoltaic louver system is constructed. Through the coupling analysis of structural innovation and photoelectric performance, the dynamic balance between shading and power generation functions is realized. The main conclusions are as follows:

1. The mathematical model of a photovoltaic louver with a vertical louver is established, and the mapping relationship between the angle of a photovoltaic louver, the position of the sun, and power generation is revealed.

2. The influence of the photovoltaic louver angle on power generation performance is analyzed. It is confirmed that the large angle condition ( $150^\circ$ ) is better, and its instantaneous power generation and time period power generation are significantly higher than those of the  $60^\circ$  angle, and the whole day power generation is increased by 80%.
3. The efficiency advantage of the sunlight-tracking mode is verified. The sunlight-tracking mode with vertical central photovoltaic louvers shows more stable instantaneous power generation than the non-sunlight-tracking mode, and the power generation efficiency is increased by 4.98~19.68%.
4. The seasonal photoelectric response characteristics are revealed. The power generation of the four solar terms is the highest in the winter solstice, the lowest in the summer solstice, and in the middle in the spring and autumn.

Aiming at the south facade application of buildings in hot-summer and cold-winter areas, the system uses seasonal solar irradiance differences to construct a passive control strategy: in winter, solar radiation is introduced to assist heating by optimizing the blade angle, and in summer, it is automatically adjusted to the shading posture to block excessive heat gain so as to achieve adaptive energy-saving control of the building's light and thermal environment. This technology not only strengthens the energy initiative of the building skin but also provides a sustainable solution for reducing the energy consumption of building operation.

**Author Contributions:** Z.Z.: methodology, project administration, and writing—original draft; H.G.: conceptualization, supervision, and writing—review and editing; S.L.: conceptualization and supervision; Y.H.: validation and visualization. All authors have read and agreed to the published version of the manuscript.

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