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The Impact of Wall Structure with Photovoltaic Function on Prefabricated Buildings

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Abstract. The wall structure is the main load-bearing component of the prefabricated building, which plays an important role in the stability and aesthetics of the building. With the deepening of the application of new energy in the construction field, the application of photovoltaic wall with photovoltaic function is becoming more and more extensive. However, there is still controversy about whether the photovoltaic function can meet the requirements of the building. On this basis, this paper discusses the wall structure with photovoltaic function in depth, and analyzes its energy consumption, heat preservation, ventilation and cost indicators. The results show that the wall structure of photovoltaic function can improve the aesthetics of prefabricated buildings, meet customer demand rate of more than 75%, save energy consumption by 25%~30%, increase indoor temperature by 1~3 degrees, and ventilate at 1.2 levels. It can be inferred that the load-bearing wall of photovoltaic function is suitable for prefabricated buildings and has the potential and role of vigorous development.

Key words. Photovoltaic Function, Wall Structure; Prefabricated Buildings, Energy Conservation, Airy, Keep Warm.

1. Introduction

The 13th Five-Year Plan for Prefabricated Buildings released by the Ministry of Housing and Urban-Rural Development clearly states that it is expected that in the next 10 years, the proportion of prefabricated buildings in China's new buildings will increase by 30% [1], [2]. It can be seen that the construction speed and scale are the main problems to be solved in the construction field at present, and the prefabricated building has the advantages of fast speed, low cost and complete design functions, which can meet the construction requirements of the Ministry of Housing and Urban-Rural Development. However, after the completion of the building, its warmth and ventilation are insufficient, so it is necessary to increase light, ventilation and thermal equipment. In order to save the construction cost of prefabricated buildings and the later use costs, some scholars suggest that photovoltaic functional walls should be used as building supports to provide heating for buildings through renewable energy. Some scholars also believe that the PV functional wall itself is unstable, and there is a lack of case support for the energy-saving role of prefabricated buildings [3], [4]. At present, it is only at the theoretical level, so there are doubts about this method. The photovoltaic functional wall absorbs light energy through polysilicon and converts it into electrons, which has the characteristics of cleanliness and high efficiency, and integrates with the wall structure of prefabricated buildings, which has considerable value in theory [5], [6]. Therefore, some scholars have found that the photovoltaic functional wall has the phenomenon of power flow and voltage instability, and the integration effect with the prefabricated building is poor, so it is believed that the influence of the photovoltaic functional wall structure in the prefabricated building is limited [7], [8]. However, the above research only stays at the level of individual cases, and lacks actual mathematical analysis and model construction, so some scholars believe that the mathematical algorithm is combined with photovoltaic functional walls, and the role of photovoltaic functional walls is analyzed from the perspective of renewable energy. The effectiveness of the method has been verified by continuous tracking of construction cost, thermal insulation and thermal insulation. On the basis of the above background, this paper makes a comprehensive judgment on the power generation of the photovoltaic matrix [9], [10], collects the parameters and data of the prefabricated building, and quantifies the photovoltaic function by using mathematical description. Then, the relationship between the structure of the photovoltaic functional wall and the prefabricated building was calculated, the factors affecting the performance of the photovoltaic functional wall were identified, and the indicators of thermal insulation, warmth preservation and energy consumption of the prefabricated building were evaluated, aiming to expand the scope of application of the photovoltaic functional wall and meet the needs of future buildings.

2. Construction of Wall Structure and Prefabricated Building with Photovoltaic Function

How to solve the problem of energy supply in the building is an effective way to expand the scope of use of prefabricated buildings, photovoltaic function is strong, by absorbing the functions in nature to enhance the overall hope of the wall, and transforming it into limited resources to meet the lighting and ventilation needs in reality, the effectiveness of the prefabricated building can be improved, so the analysis of the wall structure of the photovoltaic function is the main problem of this paper.

A. The Functional Structure of the Photovoltaic Functional Wall

First of all, the structure of the photovoltaic functional wall should be analyzed, the data collection points should be found, and the qualitative and quantitative data in the data should be classified to realize the transformation between the two, so as to facilitate the later model analysis.The photovoltaic functional wall needs to assume different functions *xi*, and the corresponding function of each function is *fi* [11], and the result function of the impact of the assembled building caused by it is *fi*, so the demand function of the functional wall is as follows:

$$f_i \to f_j = \sum (M_{xi} - {}^N P_{xi}) \cdot (M_{yi} - {}^N P_{yi}) \tag{1}$$

The analysis of photovoltaic function is not only the analysis of the wall structure, but also the judgment of the gap between the photovoltaic solar panel and the photovoltaic solar energy, so as to study the needs of different types of light energy conversion, and eliminate the differences between the wall structures, so as to lay the foundation for the accuracy of later data analysis.In equation (8): M_{Xi} the role of photovoltaic energy in the building; M_{Yi} for the release of energy in stages; ${}^N P_{xi}$ and ${}^N P_{yi}$ role in the assembly process.

Let it ω_{a0} be the rate of change of photovoltaic energy, the *FR* utilization rate of wall function [12], *Me* the energy consumption of the wall structure, and *I* the energy matrix of the prefabricated building. The equation for the balance between the performance of photovoltaic functions and the energy demand of the building is

$$\begin{cases} f_i + F_R + \Delta m g \approx 0 \\ r_i \cdot f_i + \boldsymbol{M}_{\mathrm{e}} - \boldsymbol{I} \dot{\omega}_{a0} \approx 0, \\ i \in n \end{cases} \tag{2}$$

In equation (2): ***ri*** for the function of the wall; *m* for the current of photovoltaic energy; $\dot{\omega}_{a0}$ acceleration adjusted for photovoltaics; $\dot{V}_{a0}$ is the voltage of the photovoltaic functional wall.

The photovoltaic functional wall can be converted into a matrix form:

$$\boldsymbol{W}_{\mathrm{s}} = \boldsymbol{K} \cdot \boldsymbol{F}_i = [e_i \to r_{ai} \cdot e_{i+1}]^T \cdot \begin{bmatrix} F_{\mathrm{R}} + mg - m\dot{V}_{a_0} \\ \boldsymbol{I}\dot{\omega}_{a0} + \omega_{a0}(\boldsymbol{I}\omega_{a0}) - \boldsymbol{M}_{\mathrm{e}} \end{bmatrix} \tag{3}$$

The assembly effect of the wall structure y(t) can be expressed as:

$$y_{(t)} = K_{\mathrm{C}} \left[e + \frac{1}{T_1} \int_0^t e(t)\, \mathrm{d}t + T_{\mathrm{D}} \frac{\mathrm{d}e(t)}{\mathrm{d}t} \right] \tag{4}$$

In equation (4): *y(t)* the output signal of power flow and voltage; *e* deviations in the implementation of functions; *Kc* the proportion of electricity supplied to photovoltaics; *T1* is a standard for the building structure of the wall; *TD* It is the self-structure of the prefabricated building.

B. Impact on Prefabricated Buildings

The $x - y$ change matrix of the assembled building is obtained in the order of the axes ${}_0^1\boldsymbol{R}$, and the calculation process is as follows

$${}_0^1\boldsymbol{R} = \boldsymbol{LM} = [\cos\beta_i \cdot \sin\alpha_i \cdot k] \tag{5}$$

In equation (5): ***L*** is the photovoltaic functional wall matrix; ***M*** It is a prefabricated building matrix, and the relationship between the two is:

$$\sum_{i=1}^{4} \boldsymbol{r}_i \times f_i + \boldsymbol{M}_{\mathrm{e}} = \boldsymbol{I} \cdot \dot{\omega}_{a0} + \Delta \boldsymbol{I} \tag{6}$$

In Eq. (14): α is the angular displacement of the photovoltaic function travel; β The angular displacement of the prefabricated building completed.

$$\begin{cases} \boldsymbol{I}_i = [I_{xi \cdot xi} \quad I_{xi \cdot yi} \quad I_{xi \cdot zi}] \\ I_{xi \cdot xi} = m_i a_i^2 b_i^2 / i + j \end{cases} \tag{7}$$

Equation (6) and (7) adjust the relationship between photovoltaic functional wall and prefabricated building.

Assuming that the influence of photovoltaic function is positive during the day, ***Pi*** is the degree of photovoltaic function. ***R*** is the electrical conversion rate of light energy; $\boldsymbol{\theta}_i$ is the angle vector of insolation; ***Ji*** for thermal inertia; ***Ci*** It is a ventilation damping coefficient matrix, including ventilation motor, reducer, etc.; ***Mi*** for the lighting matrix.

Then the influence equation of photovoltaic functional wall on prefabricated building is

$$\boldsymbol{M}_i = J_i \ddot{\boldsymbol{\theta}}_i + \boldsymbol{C}_i \dot{\boldsymbol{\theta}}_i + R\boldsymbol{P}_i \tag{8}$$

When the light time is long, the wall structure will change, and the relationship between the influence of the wall structure on the prefabricated building is

$$\boldsymbol{\theta}_i = \frac{\Delta I_i}{R} \qquad (9)$$

In equation (9): *li* is the influence of lighting on prefabricated buildings.

The derivation of both sides at the same time *xi* can obtain the final influence result of the prefabricated building

$$\ddot{\boldsymbol{\theta}}_i = \frac{\mathrm{d}}{\mathrm{d}x_i}\left(\frac{\partial \boldsymbol{\theta}_i}{\partial \boldsymbol{W}}\right)\overrightarrow{\boldsymbol{W}} + \left(\frac{\partial \boldsymbol{\theta}_i}{\partial \boldsymbol{W}}\right)\overleftarrow{\boldsymbol{W}} \qquad (10)$$

where: *W* is 6-dimensional variables such as insulation, ventilation, lighting, current, voltage and power flow.

C. Constraints on the Influence of Wall Structure on Prefabricated Buildings

Any wall assembly needs to be constrained, otherwise it is difficult to determine the corresponding effects. Under the influence of current, voltage, power flow and weather, the role of photovoltaic functional wall is not obvious, so it should be constrained and analyzed, as follows:

$$\boldsymbol{F}_i = R_i^{-1}\left(\boldsymbol{M}_i - \boldsymbol{J}_i \frac{\boldsymbol{i}_i}{R} - \mathbf{C}_i \frac{\boldsymbol{i}_i}{R}\right) \qquad (11)$$

The influence constraints of the wall structure on the prefabricated building are obtained by the simultaneous power flow equilibrium equation (2) and the photovoltaic function evaluation equation (2), ***K•Fi*** which are calculated as follows.

$$\boldsymbol{K}\cdot\boldsymbol{F}_i = \boldsymbol{K}\cdot R_i^{-1} \to \left(\boldsymbol{M}_i - \boldsymbol{J}_i \cdot \frac{\boldsymbol{i}_i}{R} - \mathbf{C}_i \cdot \frac{\boldsymbol{i}_i}{R}\right) \simeq \boldsymbol{W}_s \qquad (12)$$

The constraints of the wall structure of the photovoltaic function are mainly the sunshine time, and they show periodic changes, so the constraints are mainly the introduction of the sinusoidal function, as follows.

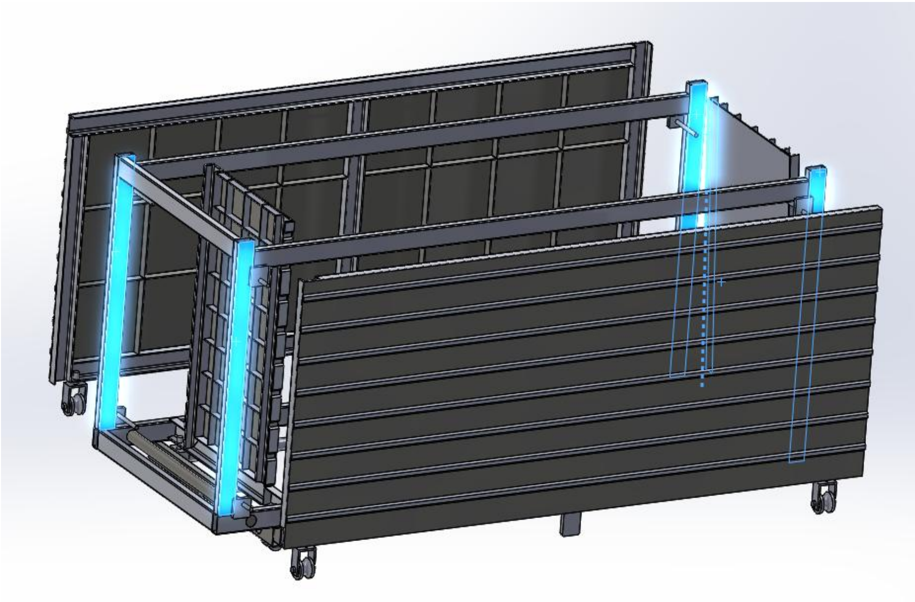
$$\beta = f_i \cdot \sin(\theta / 24) \qquad (13)$$

The above-mentioned photovoltaic functional wall has a theoretical impact on the prefabricated building, so it is necessary to analyze its publicity, quantify and mathematically describe the current, voltage, power flow and thermal insulation and ventilation and other indicators as the basis for the later research and the proof and identification of actual cases, in addition, it is necessary to do a good job in the transformation between different data, collect photovoltaic data throughout the day to avoid the problem of abnormal data and differential data, and then carry out the early data standardization process, analyze the key data values or abnormal data values, find out the reasons and make notes, so as to improve the rationality and accuracy of the later analysis.

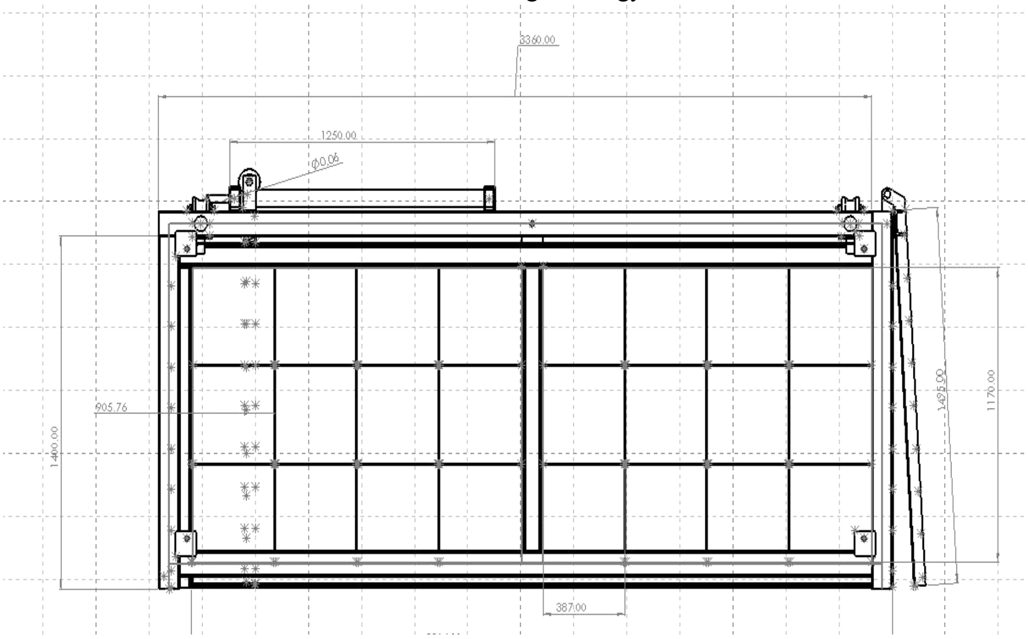
3. Case Study of the Influence of Photovoltaic Wall Structure on Prefabricated Buildings

A. Frame Wall Structure

This paper takes the prefabricated building on the construction site as an example for analysis, and the building includes: photovoltaic functional wall and prefabricated building construction, mainly including aluminum alloy columns, aluminum alloy beams, aluminum alloy pressing plates, photovoltaic glass, photovoltaic cables and stainless steel spring pins Photovoltaic solar panels are distributed structures, with solar panels on the roof and roof, and electrical energy stored in mobile wall panels; Nickel-chromium batteries with high stability; The photovoltaic functional capacity parameters are: 14~20mH/m2, 0.24KW/h, 10 ohms, 2A; The wall structure is mainly brick-concrete structure, mainly hollow brick, cement grade C30, strength of 102N/m2; The insulation board is: perlite, aluminum alloy interlayer.



Wall Structure with Light Energy Function



CAD Sketches

Figure 1. Schematic Diagram of Frame Wall Structure

From the analysis in Figure 1, it can be seen that the wall structure adopts a frame structure, and photovoltaic panels are set to form a stable wall structure, and the focus points of the wall structure are as follows.

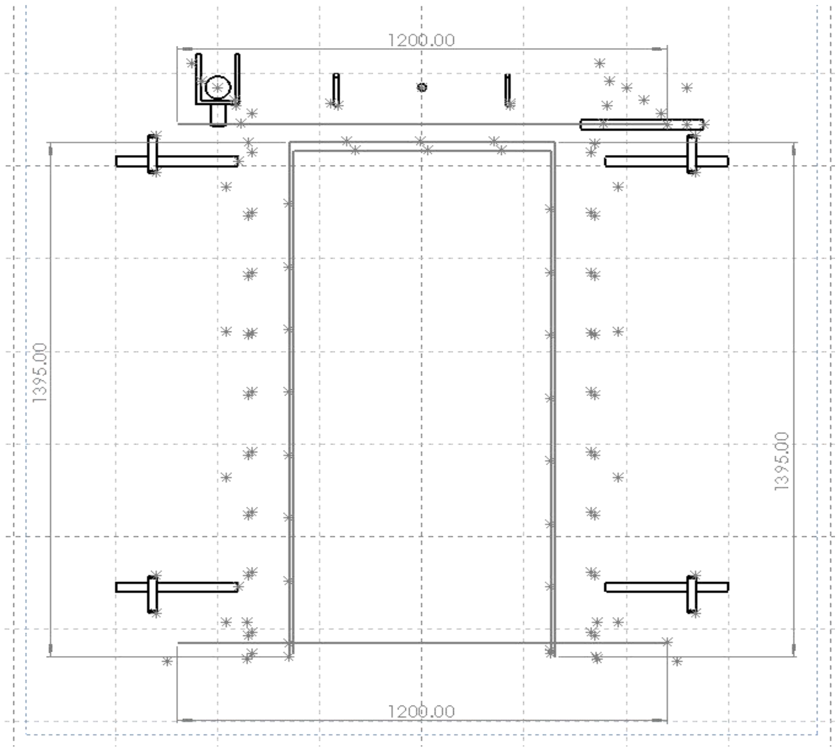


Figure 2. The Focus Point of the Photovoltaic Wall Structure

From the drawing structure of Figure 2 and Figure 1, it can be seen that the wall structure is constructed with the surrounding embedded nodes as the focus point. In the wall, photovoltaic panels are respectively set up to collect and convert the light energy of the wall, and provide electricity for the insulation, warmth and ventilation of the prefabricated building structure. Due to the embedded assembly, it can bear more installation force, so the gravity of its steel frame, light steel partitions, light steel roof and walls can be loaded. The design of the double-layer sealing system makes high-performance integrated houses possible. After the installation is completed, in the external maintenance structure of the unitized wall structure, the composite photovoltaic panels and the inside of the photovoltaic panels, due to the use of environmentally friendly and energy-saving insulation panels, as well as the bolts of the broken bridge material, the appearance of cold bridges can be reduced, which has great benefits for the insulation and energy saving of the building. With this type of photovoltaic insulation composite panel, the research can be applied to efficiently integrate the walls and roofs of buildings. In the joint part of the composite panel, a unique hole design is adopted, and some space is reserved for the edge of the plate to cut the seam more efficiently, which improves its complete structural stability and air tightness. In addition, the study achieved accuracy by adjusting the position of the embedded parts and installing them accordingly. In addition, the photovoltaic functional wall itself adopts screws and fixings with airtight characteristics and broken bridge materials, which can ensure the reasonable setting of the drive motor and photovoltaic pipeline. Embedded assembly can use adhesives with airtight characteristics to improve the airtightness characteristics of functional wall structures, and realize the integrated construction of broken bridge beads to ensure the stability of photovoltaic cells and solar panels. It can be seen that the installation of embedded photovoltaic functional panels is more solid and reasonable, and the rationality analysis of the data collected in the early stage is shown in Table 1.

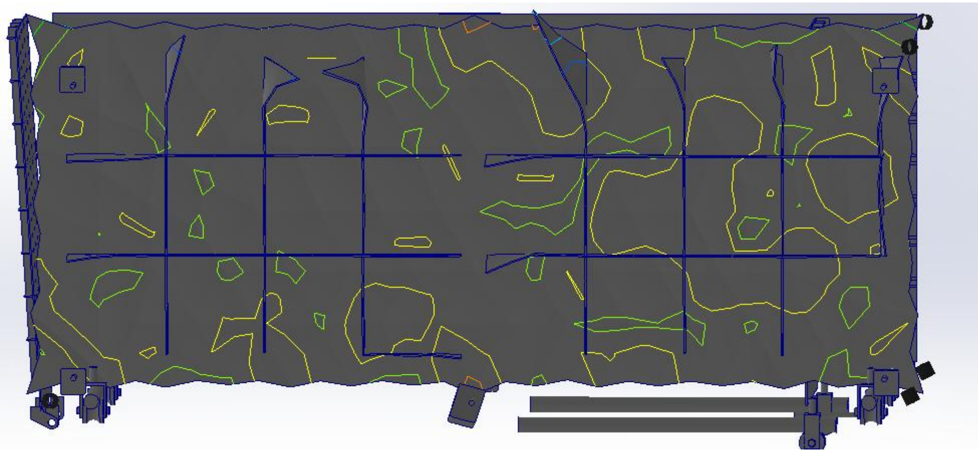
Table 1. Rationale for Data Collection

Index	Photovoltaic Functional Walls	Prefabricated Structure	Data Convergence
Voltage	0.045	0.007	0.005
Current	-0.361	-0.393	
Tidal Current	0.092	-0.236	
Energy Consumption	0.280	-1.086	
Note: Normalized Cronbach α coefficient = 0.105			

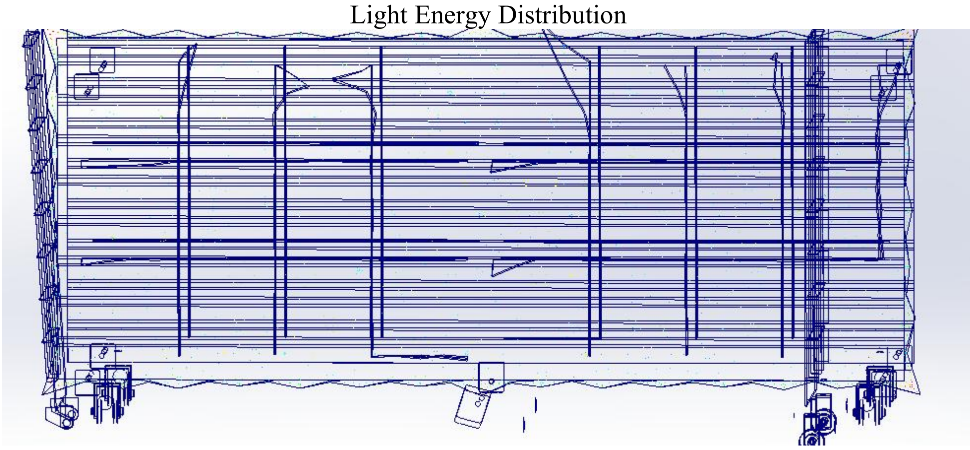
From the data analysis in Table 1, it can be seen that the data between the photovoltaic functional wall and the prefabricated building are more reasonable. Among them, there is a negative correlation between current and power flow, as well as energy consumption, mainly because of the combination of photovoltaic power generation and standard voltage power generation, current and power flow are reversed. There is a negative correlation between energy consumption, mainly because the prefabricated structure belongs to the traditional building, while the photovoltaic functional wall structure adopts the new green environmental protection technology, and there is a reverse energy consumption relationship between the two.

B. *Energy Consumption of Prefabricated Buildings*

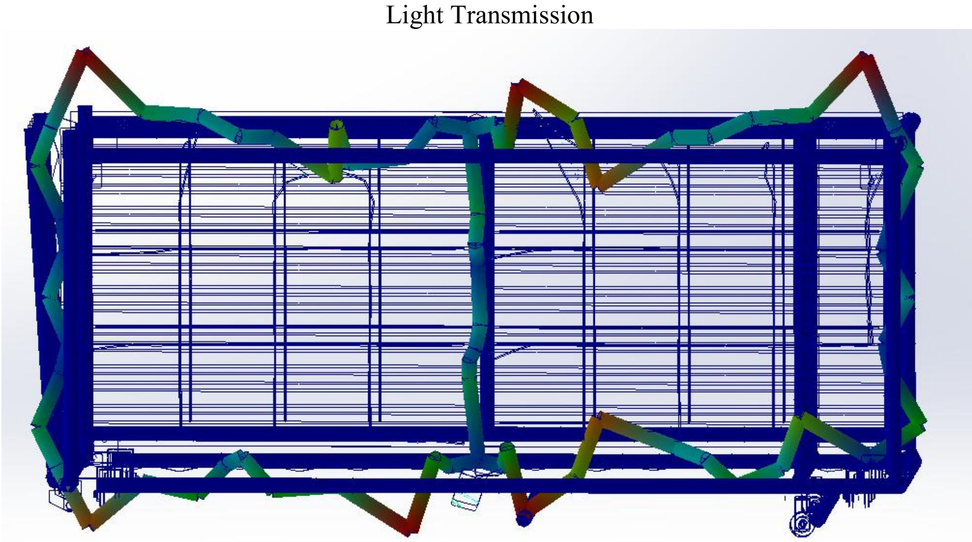
In the photovoltaic functional wall structure, doors and windows, photovoltaic equipment, and their parts or other materials can be assembled by the processing plant, which can shorten the construction period, and can save a lot of on-site operation content and manual machinery costs, thereby improving the implementation time of prefabricated buildings. Since the various components of the photovoltaic functional wall structure are assembled in the manufacturing plant, it is very convenient to carry out inspections, which is conducive to ensuring the diversity and overall quality of the prefabricated building, as well as facilitating transportation and on-site installation, and the energy consumption of the prefabricated building is analyzed below, and the results are as follows.



Light Energy Distribution



Light Transmission



Ventilation

Figure 3. Calculation of Energy Consumption of Prefabricated Buildings

From the data analysis in Figure 3, it can be seen that the photon distribution is relatively uniform, and the state presented on the photovoltaic panel is discrete, and there is no large photon concentration problem, indicating that the photon absorption ability is relatively strong. When the light transmittance analysis of the obstacle is carried out, it is found that the light transmittance of the wall structure is high, and its light transmittance area accounts for 70~80% of the whole, but there is no random obstacle. Therefore, the light level of the wall structure is relatively uniform, and the light evenly passes through the photovoltaic panels, showing the result of scattering. In the analysis of the ventilation effect, it is found that the wind mainly enters the prefabricated building through the upper and lower sides of the photovoltaic panels, and does not enter directly, indicating that the ventilation method is reasonable. Upper and lower ventilation has the effect of increasing indoor air velocity and reducing indoor heat loss. On the whole, the photovoltaic functional wall structure can improve the rationality of the prefabricated building, and has superior performance in ventilation, light and thermal insulation. In addition, through the thermal energy analysis of the solar panel's light energy, it can be indirectly found that the power flow and voltage of the solar panel are stable, and there is no large fluctuation, otherwise the temperature will be too high. The energy consumption and cost are calculated below as follows.

Table 2. Energy Saving of Photovoltaic Function on Prefabricated Buildings[Unit: KJ/s]

Index	Illuminating			Heat Preservation			Airy		
	Average Energy Consumption	Night	Daytime	Average Energy Consumption	Night	Daytime	Average Energy Consumption	Night	Daytime
Bedchamber	1.562	0.019*	-	1.463	0.001**	-	1.233	0.000**	-
Living Room	-0.163	0.296	-0.289	-0.042	0.429	-0.075	-0.007	0.639	-0.013
Corridor	0.067	0.688	0.094	-0.012	0.820	-0.018	-0.020	0.262	-0.028
Kitchen	-0.935	0.022*	-0.738	-0.187	0.263	-0.148	-0.177	0.022*	-0.140
F=10.252，R2=0.2421									

As can be seen from Table 2, the average energy consumption in areas such as kitchens, bedrooms, living rooms and corridors is relatively low, the overall energy consumption has decreased significantly, and the energy consumption savings in ventilation and lighting are also relatively high, indicating that the structural predecessor of photovoltaic function can provide continuous energy for prefabricated buildings and reduce their dependence on thermal power generation. The first floor of the prefabricated building constitutes a complete unit module, which can be assembled directly in the factory, and the living room, kitchen and bedroom can be regarded as a unit module, which is then produced in the factory and transported to the site for assembly, and is powered by photovoltaic modules. The mechanical and electrical equipment and pipelines that have been installed in the plant can also reserve a place according to the actual demand, and the type and quantity of modules can be increased according to the demand, and then assembled on site to ensure the independence and sealing of the wall structure. The photovoltaic functional wall converts energy consumption into electrical energy consumption, and through its own design, it can continuously supply energy, which can reduce energy consumption by 75% compared to traditional buildings. In addition, photovoltaic panels in prefabricated buildings can regulate the amount of sunlight passing through and realize the regulation of temperature, surface temperature, airflow and air.

C. The Working State of the Photovoltaic Functional Wall Structure in the Prefabricated Building

In the prefabricated building, the photovoltaic functional wall structure should be combined with the standard 220-volt power grid to ensure the stability of the power supply of the prefabricated building, so it is necessary to judge the stability of the photovoltaic functional wall structure, so as to find the integration effect between the photovoltaic energy and the standard energy in the wall structure, as well as the power supply stability of the entire prefabricated building, as shown in the following table.

Table 3. Working Status of Photovoltaic Functions

Index	Illuminating	Heat Preservation	Airy
Tidal Current	1.562*(3.398)	1.463**(9.926)	1.233**(23.362)
Voltage	-0.163(-1.166)	-0.042(-0.880)	-0.007(-0.520)
Instantaneous Trends	0.067(0.426)	-0.012(-0.243)	-0.020(-1.378)
Current	-0.935*(-3.272)	-0.187(-1.301)	-0.177*(-4.410)
Instantaneous Voltage	\	89.478**(6.721)	85.042**(22.525)
Instantaneous Current	\	\	-36.015**(-6.943)
Volatility	0.807	0.984	0.999

Index	Illuminating	Heat Preservation	Airy
Adjustment Rate	0.691	0.969	0.998
Evenly Distributed	F (3,5)=6.968,P=0.031	F (4,4)=62.691,P=0.001	F (5,3)=651.640,P=0.000
Overall Adjustments	0.807	0.177	0.015
Transient Distribution	F (3,5)=6.968,P=0.031	F (1,4)=45.173,P=0.003	F (1,3)=48.204,P=0.006
Note: Dependent Variable = Photovoltaic Power Generation			
* P<0.05 ** P<0.01			

From the data analysis in Table 3, it can be seen that the power flow voltage, instantaneous current and voltage of the wall structure with photovoltaic functions in terms of lighting, illumination and ventilation show stable changes. The instantaneous voltage and current both change negatively, mainly due to weather and other reasons, and the phenomenon of power loss in photovoltaic power generation. In this case, a standard voltage is required as a supplement to ensure the overall stability of the power supply. Therefore, it is normal for negative values to occur, and the distribution adjustment of voltage and power flow is more reasonable, and there is no major change. It shows that the integration between the photovoltaic function and the standard voltage is good, especially the difference between the instantaneous distribution and the average distribution is small. On the one hand, there is a small difference in power supply, mainly because in the process of photovoltaic power generation, the voltage and current are adjusted through the battery to ensure the stability of photovoltaic power supply. With the assistance of standard voltage, photovoltaic power generation can continuously carry out lighting, ventilation and thermal insulation, and ensure the stability of power supply of the entire prefabricated building. The following compares the overall changes of power flow in the process of photovoltaic power supply, analyzes the role of photovoltaic functional walls, and analyzes the impact of multi-prefabricated buildings, as follows.

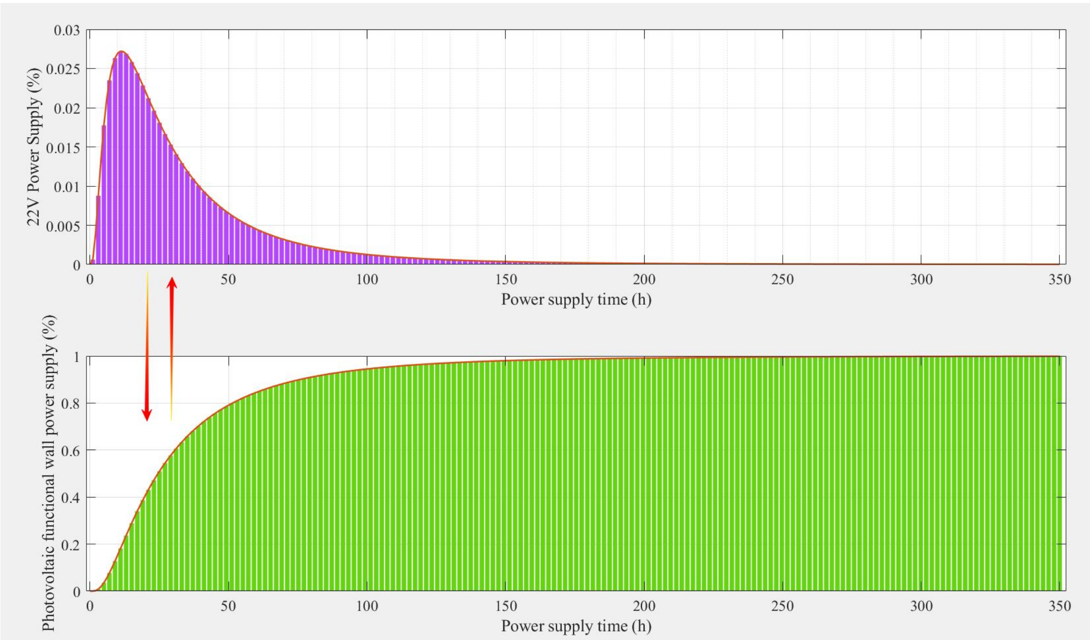


Figure 4. Power Supply between the PV Functional Wall and the Standard Voltage

From the analysis in Figure 4, it can be seen that the photovoltaic functional wall structure and the standard voltage are complementary, and when the power generation of the photovoltaic functional wall structure increases, the power supply of the standard voltage will be reduced, so as to maintain the stability of the power supply of the entire prefabricated building. In terms of fluctuation changes, there is a linear change between the two, and there is no large fluctuation anomaly, indicating that the two are linearly complementary in the process of voltage regulation. Moreover, there is no interference from other factors, mainly because the photovoltaic function reserves energy through nickel-chromium cells when collecting electric energy, so as to ensure the stability of the power supply of the photovoltaic functional wall structure.

4. Conclusion

Photovoltaic functional wall is the main form of photovoltaic power generation in the construction field, which integrates photovoltaic power generation with traditional buildings through photovoltaic panels, and effectively installs the two to achieve rapid wall installation and energy saving. In the process of installation, the voltage, current and power flow and other indicators of the photovoltaic functional wall should be integrated with the requirements of lighting, ventilation and other equipment in the building, and used in conjunction with the standard voltage to ensure the stability of the power supply of the prefabricated building. Through the research of simulation results, it is found that the photovoltaic functional wall structure has the effect of stability, can provide stable current and voltage, and ensure the power supply demand of the prefabricated building, with a satisfaction rate of 72%. Photovoltaic can not only realize the conversion of light energy, but also provide clean energy, and reduce the overall energy consumption of the building by 25%. Moreover, its own design is more reasonable, which can improve the light transmittance and ventilation rate, and the increase range is between 20~30%. In addition, the wall structure of photovoltaic function can use battery power to keep warm and heat, and increase the indoor temperature by 1~2 C. The photovoltaic functional wall adopts a prefabricated structure, which has fewer joint points and bearing points, which can greatly improve the efficiency of building construction, play the role of the original sealing, and ensure the overall sealing of the prefabricated building structure. Therefore, the photovoltaic functional wall can give full play to the advantages of the prefabricated building structure, expand the application range of photovoltaic energy, and reduce the energy consumption of building construction. There are also some shortcomings in this study, if the data collected in the process of photovoltaic functional wall light energy conversion is too simple, it will continue to be monitored in the future to analyze the photovoltaic light energy conversion rate and the utilization rate of electric energy.

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