



Calculation and Numerical Simulation of Building Integrated Photovoltaic System Based on BIM Technology

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Abstract. With the development of photovoltaic technology, the number of building integrated photovoltaic (BIPV) systems is increasing. Differing from the traditional design of BIPV systems based on the experience of experts, which suffers from high cost and non-maximum efficiency of equipment due to the information lack of buildings, this paper proposes a novel calculation approach based on building information modeling (BIM) technology. Taking a BIPV building located in Hainan, China as a example, the modelling process is given, which description is 1:1 to the real system. Besides, the geographic information attribute of Hainan and the thermal radiation of the building are considered, respectively. Numerical simulation validates the effectiveness of the proposed approach with advantages of high-accuracy and practicability.

Keywords: Smart building · Building Information Modeling (BIM) · Building Integrated Photovoltaic (BIPV) · Thermal analysis

1 Introduction

With the development of the whole society, the issue of energy consumption has become important. For the traditional fossil energy, it has been gradually exhausted. besides its use and discharge has caused serious environmental pollution, destroying the ecological balance, and further posing a serious threat to the life and health of human beings [1]. As an alternative solution, the building integrated photovoltaic (BIPV) technology has arisen to replace the traditional fossil energy by the solar energy. The advantages of BIPV lies on the savings of energy and cost due to the combination of the building and the photovoltaic systems [2]. On the one side, the building can provide enough area for the photovoltaic systems so that the support structure and transmission cost of the photovoltaic systems can be saved; while on the other side, the utilization of the distributed power generation system located in building can reduce the investment and maintenance cost of power. Therefore, BIPV technology has been attractive and the number of BIPV systems is increasing.

With the integration of photovoltaic architecture makes the building from the past independent power consumption to power generation complex, it can effectively reduce the energy consumption of the building, but also brings a series of new demands for the architectural design, i.e., architectural appearance, optimization deployment, photovoltaic building optimization, etc. However, it should be noted that, BIPV is a combination of photovoltaic modules and building materials (such as windows, building exterior walls, sun shading facilities, outer roofs, etc.) to form a new building material [1, 3]. Compared with the traditional photovoltaic architecture design method based on expert experience. The advantage of BIPV is that photovoltaic modules can not only generate photovoltaic power, but also play a role as building materials. For photovoltaic system, most photovoltaic modules are installed on the roof and wall, and are often affected by the building structure and external environment, and the complexity is not the same today [4]. The influence of the top edge and shape of the building on the photovoltaic array must be fully considered. The traditional method will be very complicated to face such problems.

For the BIPV system, the traditional methods are mostly on the basis of the experience of experts and ignore the connection between the building and the photovoltaic system [5]. On the one hand, if the photovoltaic system is introduced into the building, the photovoltaic module will change the appearance and structure of the building. Besides, the addition of photovoltaic will change the building from the original single power supply to multi power supply, and the electrical characteristics of the building will also change accordingly. On the other hand, due to the variety of architectural shapes, the installation of photovoltaic modules will be limited, and the photovoltaic modules can't play the maximum performance. Therefore, these factors should be considered in in the design of BIPV system [6, 7].

It is worth noticing that, some specific situations concerning the local climate and geologic conditions are also needed to be considered for the buildings. However, the research of BIPV systems often ignores these influences, leading to the degradation of accuracy [5]. Meanwhile, due to the existence of too many building information, it is difficult to cover all of these information. In order to solve the above problems, the building information modeling (BIM) technology has arisen [8]. By using BIM technology, the local geographic and meteorological information is introduced into the BIPV systems and further is used to analyze different conditions by changing the parameters. Therefore, the reliability of the electrical system can be guaranteed, and the optimal energy efficiency of the whole building system under any special circumstances can be realized.

BIM technology is a new technology in the construction industry in recent years. Revit is a BIM design software launched by Autodesk company. It is the most widely used in BIM market [5]. Many software companies have carried out the secondary development based on the platform of Revit. With the rapid development of BIM in the construction industry, BIM is more and more used in all stages of the whole construction life cycle. During the system design, the photovoltaic system and the building are both needed to be modelled by BIM software [9, 10]. However, although some professional software of distributed photovoltaic design as Pvsyst and Retscreen can provide the analysis functions related to photovoltaic, yet they can hardly support the

application of BIM so that its shadow radiation analysis function is difficult to reflect the complex shape and environment of the building accurately.

In this paper, taking a hospital with BIPV system located in Hainan of China as an example, a novel calculation approach by combining BIM technology and the software Ecotect is proposed to realize the calculation and numerical simulation of BIPV systems. The structure of the paper is organized as follows. In Sect. 1, the modelling and parameter setting of the system is given; in Sect. 2, the solar model, shadow model and radiation model are established respectively for the solar radiation analysis. In Sect. 3, the numerical simulations concerning the thermal analysis, radiation, photovoltaic power generation are carried out. And the final conclusion of this paper is given in Sect. 4.

2 System Description and BIM Modelling

In this paper, we take a hospital with BIPV system located in Hainan of China as an example to investigate the calculation approach for its photovoltaic system. And the total construction area of this building is 51335.75 m². Figure 1 shows its 2D plane by AutoCAD software, which represents the traditional system description of this building. Innovatively, this paper introduces BIM technology to establish a 3D plane for this building, shown in Fig. 2. And the geographical characteristics of Hainan are directly considered and the thermal parameters of the building are shown in Table 1.



Fig. 1. Traditional 2D plane of the building based on AutoCAD

Table 1. Thermal parameter of the building

Texture	Number	Thermal conductivity
Crack resistant mortar	34	0.930
TF inorganic insulation mortar	22	0.030
Cement mortar	1	0.930
Aerated concrete block	30	0.240
Lime mortar	18	0.810

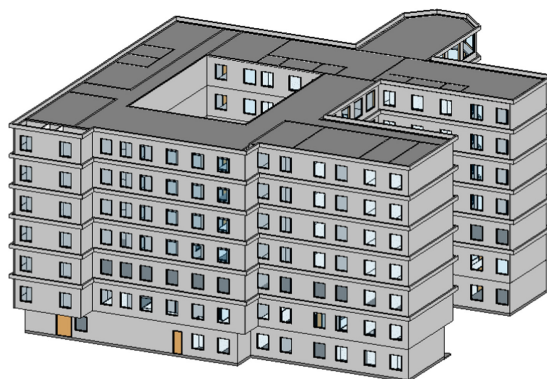


Fig. 2. 3D plane of the building based on BIM

Based on the thermal parameter of construction materials in Table 1, we further use Revit software to calculate its corresponding parameters, seen in Table 2. By combining the BIM model in Fig. 2 and the construction materials thermal parameter in Table 2, the Ecotect software is further introduced to simulate the geographical characteristics of Hainan. And the environmental humidity is set as 60%, the wind speed is set as 0.5 m/s, and the crowd density and clothing activities in the building are set as well for the accuracy of the simulation, seen in Fig. 3. And the parameter settings of the wall and window are given in Table 3 and Table 4.

Table 2. Revit calculation of thermal parameters

Function	Texture	Thickness(mm)
Structure 1	Crack resistant mortar	5.0
Structure 1	TF inorganic insulation mortar	20.0
Structure 1	Cement mortar	20.0
Structure 1	Aerated concrete block	200.0
Structure 1	Lime mortar	20.0

Table 3. Thermal parameter setting of the wall

Parameter	Data
U-Value (W/m^2K)	1.552
Admittance (W/m^2K)	4.220
Solar Absorption	0.428
Visible Transmittance	0
Thermal Decrement	0.41



Fig. 3. Thermal parameter setting in Ecotect software

Table 4. Thermal parameter setting of the windows

Parameter	Data
U-Value (W/m ² K)	3.440
Admittance (W/m ² K)	2.800
Solar Absorption	0.403
Visible Transmittance	0.43
Thermal Decrement	-

3 Solar Radiation Analysis

3.1 Solar Model

In order to simulate the impact of climate environment on buildings, we first establish a solar motion model to calculate the shadow and solar radiation of photovoltaic system in Fig. 2. Declination, solar elevation angle and the azimuth of the sun are three key factors to be addressed in modeling. For the declination, it is the angle between the equatorial plane of the earth and the line connecting the sun and the center of the earth [11]. It is a phenomenon caused by the earth’s orbit around the sun, which changes with time, with a cycle of years, reaching a maximum of 23.45° on June 22, the value reached -23.45° on December 22. For the solar elevation angle, it refers to the angle between the light of a certain place and the tangent line of the earth’s surface connected with the earth’s center. And for the azimuth of the sun, it refers to the angle between the sun’s projection on the horizon plane and the local meridian. It is generally measured in a clockwise direction with the north direction of the target as the starting direction and

the incident direction of the sun as the ending direction. Therefore, the declination angle δ , altitude angle α and azimuth angle φ_s can be calculated respectively as [12]

$$\delta = 23.45^\circ \times \sin\left(360 \times \frac{284 + n}{365}\right) \tag{1}$$

$$\alpha = \sin^{-1}(\sin \delta \sin \varphi + \cos \delta \cos \varphi \cos \tau) \tag{2}$$

$$\varphi_s = \cos^{-1}\left(\frac{\sin \alpha \cos \varphi - \cos \alpha \sin \varphi \cos \tau}{\cos \alpha}\right) \tag{3}$$

where n represents the accumulated day, φ is the local latitude, τ is the solar hour angle. When the sun's noon is zero, the clockwise direction is positive, while the counterclockwise direction is negative.

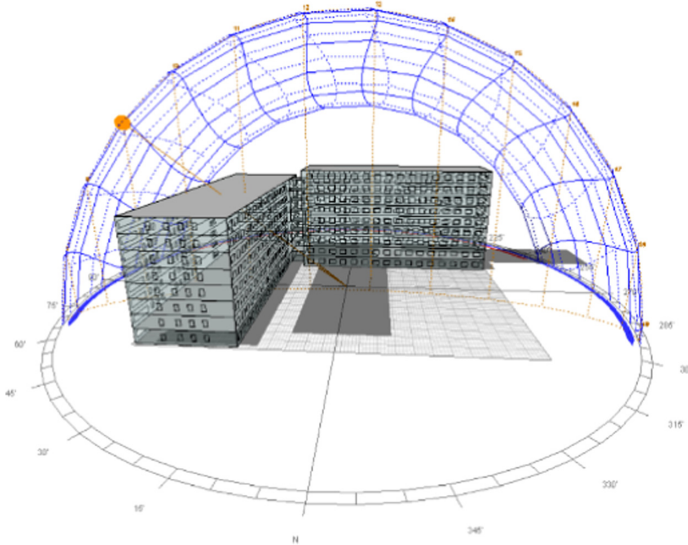


Fig. 4. Shadow analysis by Ecotect software

3.2 Shadow Model

Differing from the traditional shadow analysis such as instrumental measurement, theoretical formula approach, software simulation approach, which suffers from complex determination of the photovoltaic panel, this paper proposes a novel approach based on Ecotect software, shown in Fig. 4, which is simple and easy implementation. Based on the solar model in (1)–(3), the shadow analysis will be carried out by adding the solar meteorological data of a place in Hainan.

3.3 Radiation Model

In the following, we continue to establish a radiation model for the building in Fig. 2. Since the solar radiation energy received by objects on the surface is mainly composed of direct radiation, scattered radiation and reflected radiation, the direct solar radiation refers to the solar radiation that reaches the earth surface in the form of parallel light without changing the direction of radiation [13]. Therefore, the intensity of extraterrestrial solar radiation A can be calculated as [14]

$$A = 1160 + 75 \sin \left[\frac{360}{365} (n - 275) \right] \quad (4)$$

The optical thickness coefficient k is given as

$$k = 0.7 + 0.035 \sin \left[\frac{360}{365} (n - 100) \right] \quad (5)$$

The air mass m is given as

$$m = \frac{1}{\sin \alpha} \quad (6)$$

where α is the altitude angle defined in (2).

The solar radiation intensity I_B and I_{BC} are given respectively as [15]

$$I_B = Ae^{-km} \quad (7)$$

$$I_{BC} = I_B \times (\cos \alpha \sin \beta \cos(\varphi_m - \varphi_s) + \sin \alpha \cos \beta) \quad (8)$$

where β is the tilt angle of the photovoltaic array, φ_m is the azimuth of the PV array.

It is worth noticing that the solar scattered radiation is also called sky scattered radiation. When the solar radiation meets the gas molecules and dust in the atmosphere, it scatters and reaches the surface of the earth in the form of diffusion. Therefore, the sky diffuse scattering coefficient C can be calculated as [16]

$$C = 0.095 + 0.04 \sin \left[\frac{360}{365} (n - 100) \right] \quad (9)$$

By combining (7) and (9), the intensity of solar scattering radiation I_D can be calculated as

$$I_D = CI_B \quad (10)$$

And the solar scattered radiation intensity I_{DC} is given as [17]

$$I_{DC} = I_D \left(\frac{1 - \cos \beta}{2} \right) \quad (11)$$

Solar reflected radiation refers to the solar radiation reflected by objects. Radiation usually accounts for a small proportion of the total radiation. Therefore, the solar reflected radiation intensity I_R can be calculated as [17]

$$I_R = \rho I_B(\sin \beta + C) \tag{12}$$

Where ρ Is the reflection coefficient of the object surface.

And the radiation intensity of horizontal solar reflection on inclined plane I_{RC} can be calculated as [18]

$$I_{RC} = I_R \left(\frac{1 - \cos \beta}{2} \right) \tag{13}$$

Based on the established solar model, shadow model and radiation model, the local meteorological data got by the Ecotect software can be introduced to the BIM model of the hospital in Fig. 2. By comparing with the traditional 2D plane of the building based on AutoCAD, the proposed approach based on BIM and Ecotect can improve the selection and placement of photovoltaic panels and the photoelectric efficiency.

4 Numerical Simulation

In order to test the proposed calculation approach based on BIM and Ecotect, we take the hospital located in Hainan as an example to realize its thermal analysis. In Fig. 5 and Fig. 6, the temperature change on the hottest day and coldest day of one year can be got by Ecotect software based on the local meteorological data of Hainan.

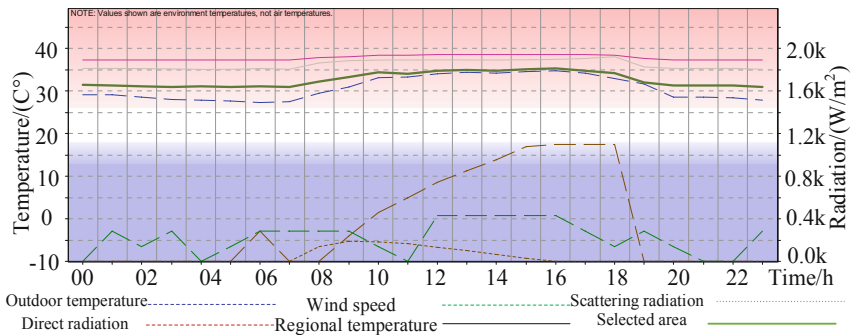


Fig. 5. Temperature change on the hottest day of the year

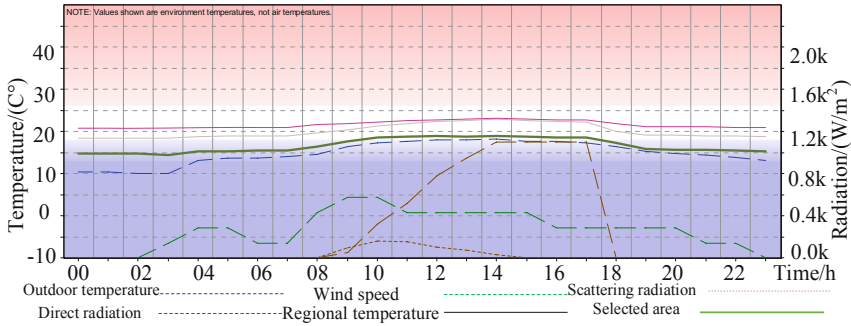


Fig. 6. Temperature change on the coldest day of the year

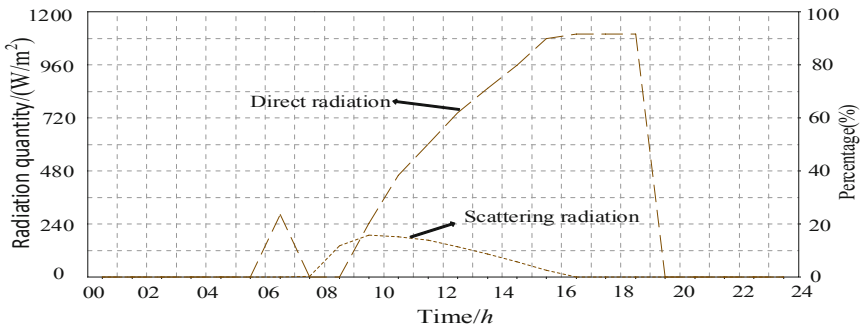


Fig. 7. Average solar radiation on the hottest day

From (4)–(13) and the parameter settings in Table 3, Table 4, we can further get the average solar radiation on the hottest day, the coldest day, the clearest day and the darkest day respectively in Fig. 7–Fig. 10. And in Fig. 11, the monthly mean direct radiation of Hainan can also be achieved by Ecotect.

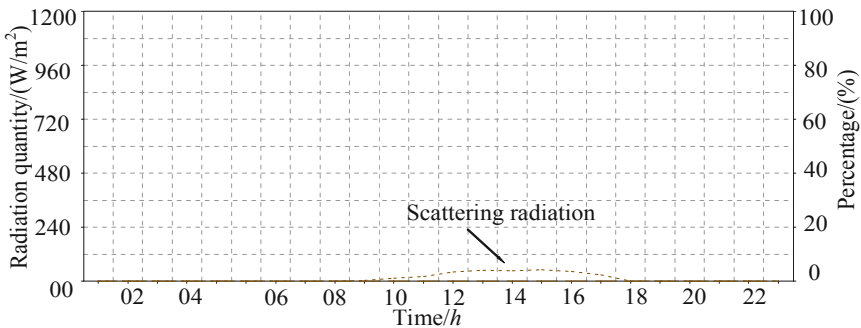


Fig. 8. Average solar radiation on the coldest day

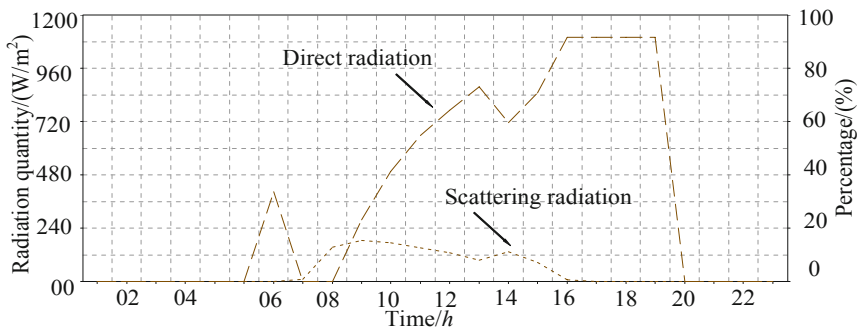


Fig. 9. Average solar radiation on the clearest day

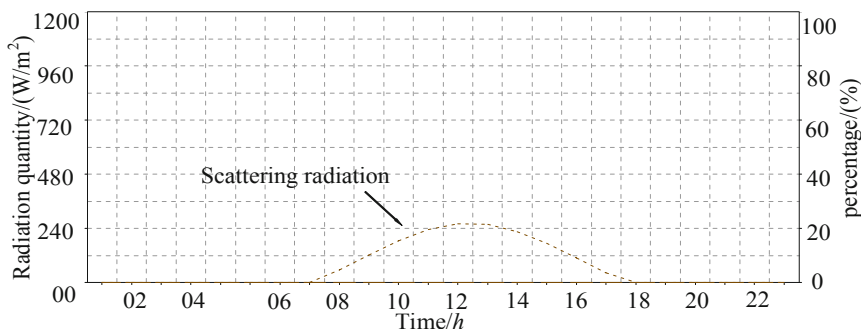


Fig. 10. Average solar radiation on the darkest day

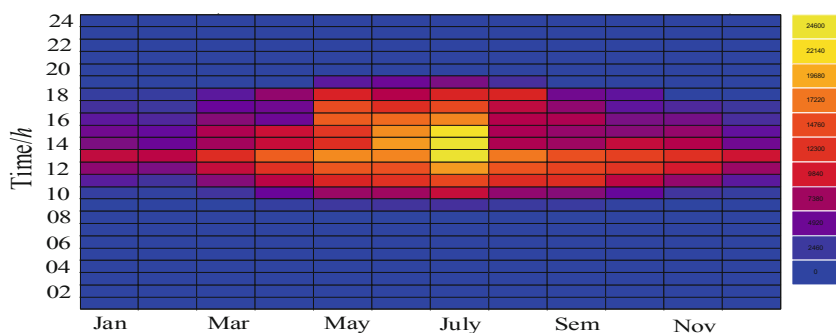


Fig. 11. Monthly mean direct solar radiation

Based on the above analysis of solar radiation data in Fig. 7–Fig. 11, we can get the amount of gain and loss of radiation, which is helpful for the calculation of photovoltaic power generation. And the solar radiation accumulation on the hottest day, coldest day, the day with the most abundant light and the radiation accumulation on the day with the least light of a year can be simulated in Fig. 12–Fig. 15. In conclusion, the solar radiation accumulations in different cases can be seen in Table 5, which are suitable for photovoltaic power generation. The total annual solar radiation per unit area is

991.575 kw, and the comprehensive efficiency is 15%. And the installed capacity of 100 kW modules, the annual photovoltaic power generation is 14873.625 kwh, which proves the fact that BIPV system is suitable in Hainan.

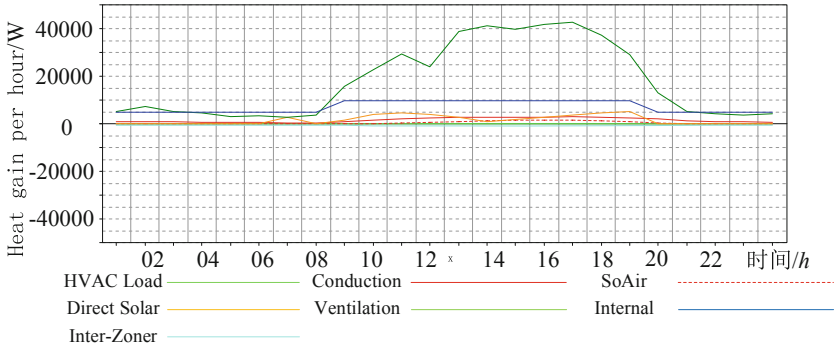


Fig. 12. Solar radiation accumulation on the hottest day

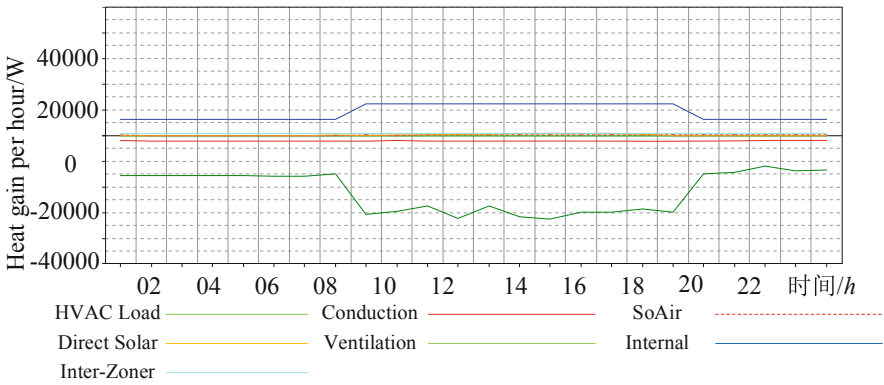


Fig. 13. Solar radiation accumulation on the hottest day

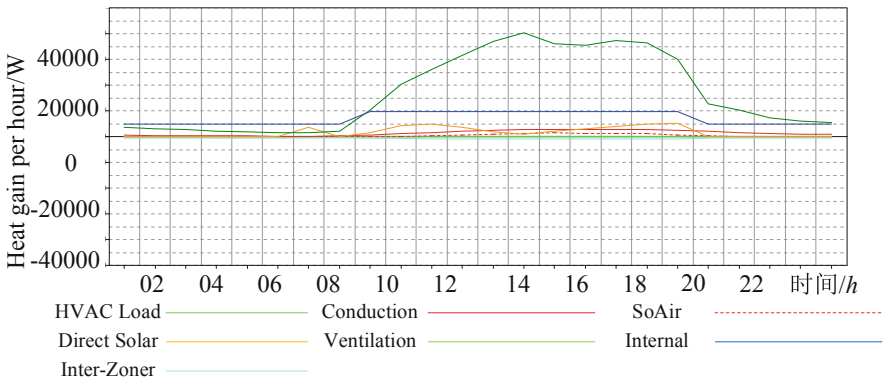


Fig. 14. Solar radiation accumulation on the hottest day

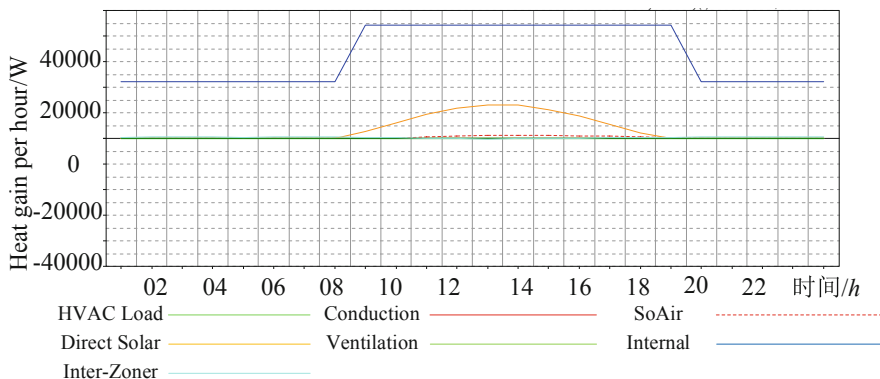


Fig. 15. Solar radiation accumulation on the hottest day

Table 5. Annual cumulative radiation data

	Avail	Average	Incident
Month	Wh/m ²	SHADE	Wh/m ²
January	92380	53%	41826
February	83595	52%	37185
March	117517	44%	62738
April	129005	41%	78718
May	173757	11%	124037
June	155111	0%	136761
July	199414	3%	165943
August	160981	30%	96198
September	138195	48%	84119
October	129062	45%	71468
November	87172	41%	54282
December	95216	49%	38263
Total	1563169		991575

5 Conclusion

In this paper, a novel calculation approach is proposed by BIPV systems. Differing from the traditional design based on 2D plane and experience of experts, the BIM technology and Ecotect are introduced so that 3D plane of the building and the local geographical characteristics. And taking a hospital in Hainan as an example, the numerical simulations are carried out to validate the proposed approach. Specially, the solar model, shadow model and radiation model have been established. It provides a reference for the application of photovoltaic power generation.

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