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Modeling the energy saving potential of typical office building rooftop PV system in Guangzhou

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ABSTRACT

Rooftop photovoltaic (PV) system is a common utilization of renewable energy in Guangzhou with considerable energy saving potential, which not only produces electricity but also has an impact on building energy consumption system. There are still deficiencies in models for quickly assessing the energy saving potential for rooftop PV system, which makes it more difficult for architects to determine the installed area of rooftop PV in the design stage. This article, therefore, aims to establish the energy saving potential model of a typical office building Rooftop PV system in Guangzhou through experiment and simulation. The results revealed that the most energy-saving potential of the rooftop PV system comes from its electricity generation capacity. Especially for high-rise buildings with high-performance air conditioning systems, the impact of the rooftop PV system on the building HVAC energy consumption is almost negligible.

Keywords: rooftop PV system, impact on the building energy consumption, electricity generation, energy saving potential model

NONMENCLATURE

Abbreviations	
PV	Photovoltaic
I_r	Incident solar radiation received on the roof (before the PV installation) [W/m^2]
$I_{r,pv}$	Incident solar radiation received on the roof (after the PV installation) [W/m^2]
I_t	Incident solar radiation received on the PV panel [W/m^2]
q_{br}	Additional long-wave radiation (after the PV installation) [W/m^2]
T_b	PV back sheet temperature [℃]
T_r	Roof surface temperature (before the PV installation) [℃]
$T_{r,pv}$	Roof surface temperature (after the PV installation) [℃]
T_a	Ambient air temperature (before the PV installation) [℃]
$T_{a,pv}$	PV cavity air temperature (after the PV installation) [℃]
ε_{br}	Effective emissivity between the PV back sheet and the external roof surface
σ_b	Stefan Boltzmann constants, σ_b = 5.67×10^{-8}W/m^2·K^4
ε_b	PV back sheet emissivity
ε_r	External roof surface emissivity
X_{br}	Radiation angle coefficient between PV back sheet and roof
α	External roof solar absorptance
h_1	External roof convection heat transfer coefficient (before the PV installation) [W/(m^2·K)]
h_2	External roof convection heat transfer coefficient (after the PV installation) [W/(m^2·K)]
q_{lw}	Net radiant heat dissipation from the external roof surface (before the PV installation) [W/m^2]
$q_{lw,pv}$	Net radiant heat dissipation from the external roof surface (after the PV installation) [W/m^2]
Q	The heat gain from the external roof surface (before the PV installation) [W/m^2]
Q_{pv}	The heat gain from the external roof surface (after the PV installation) [W/m^2]
ΔQ	Annual building load change [kWh/m^2]
ΔE	Annual building HVAC energy consumption change [kWh/m^2]
E_h	Building HVAC energy consumption [kWh/m^2]
E_h'	Modified building HVAC energy consumption [kWh/m^2]
COP	Energy efficiency ratio of air conditioning systems
N_f	Number of floors
E_s	PV electricity generation [kWh/m^2]
A_{pv}	PV installation area [m^2]

A_{sf}	Standard floor area [m^2]

1. INTRODUCTION

The renewable energy application in buildings is a mandatory for new buildings in China after April 2022, which is also one of the most important means to reduce energy consumption and carbon emission [1]. Taking into account the differences in the building characteristics and their site resources, renewable energy can be used in a variety of ways, with an emphasis on adapting to local conditions. PV systems can be installed, attached to or integrated in buildings within a short time frame and are expected to receive wide social acceptance in contrast to wind and hydro power plants, which occupy public space [2]. Rooftop PV system installation has increased significantly in different countries during the past ten years. This increase was powered first by generous local governments' feed-in tariff schemes, followed by falling costs of PV systems and increasing grid electricity tariffs [3]. Considering sufficient daylight with long summer period, rooftop PV system is a common form of renewable energy utilization for office buildings in Guangzhou.

Rooftop PV system not only produces electricity but also has an impact on the building energy consumption system, which has also spotlighted the efforts of many scholars on research. Ban-Weiss [4] assessed the effects of installing a building integrated photovoltaic (BIPV) roof on an office building in Yuma, AZ, and the results showed that the average daily temperature of the upper surface of the roof was decreased and daily PV energy production was about 25% of building electrical energy use in the summer. The measurements of the thermal conditions throughout a roof profile on a building partially covered by solar photovoltaic (PV) panels were conducted in San Diego, California by Anthony [5]. The simulations showed no benefit (but also no disadvantage) of the PV covered roof for the annual heating load, but a 5.9 kWh/m^2 (or 38%) reduction in annual cooling load. Yoo et al [6] conducted a year analysis of the BIPV system performance at the Samsung Institute of Engineering & Construction Technology (SIECT) in Korea, which showed that the PV modules facilitated building shading and reduced cooling loads in summer. V. Kapsalis[7] developed a rooftop photovoltaic heat transfer model by TRNSYS and found a 6.7% increase in seasonal heating load and a 17.8% decrease in cooling load. The test in Albuquerque conducted by Shukla [8] showed no evidence of an adverse thermal impact of the adhesive-mounted PV system on roofing materials, while demonstrating a potential for a notable reduction in space conditioning energy requirements.

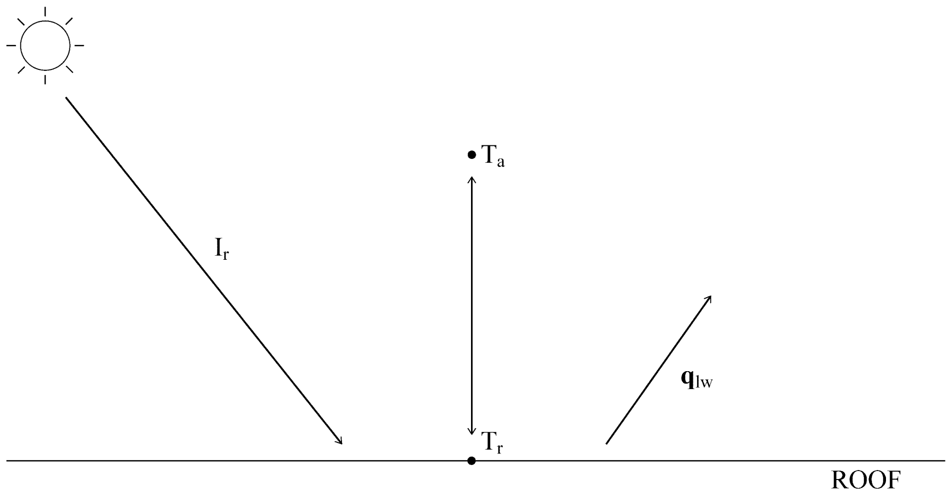
From previous studies, it is clear that the energy saving effect of rooftop PV system consists of two main aspects. Firstly, the PV modules convert solar energy into electrical energy, reducing the overall energy consumption of the building; secondly, the original energy balance of the roof is broken, and the additional PV modules change the heat transfer process of the roof, which in turn causes changes in the cooling and heating loads, ultimately affecting the overall energy consumption of the building. Existing heat transfer models for photovoltaic roofs can already describe the heat transfer process accurately, but its boundary conditions are complex and not suitable for the estimation of the energy saving effect of rooftop PV system in the early stage of building design.

This paper investigated the energy saving potential of a typical office building rooftop PV system in Guangzhou through experiments and simulations. Considering the impact of rooftop PV system on building HVAC energy consumption, the previous developed model for predicting building energy consumption[9] is revised. In addition, the relationship between PV utilization area, building information, PV system performance parameters and electricity generation is established, which provides a rapid and accurate model for architects to estimate the energy saving potential of rooftop PV system in the early building design stage.

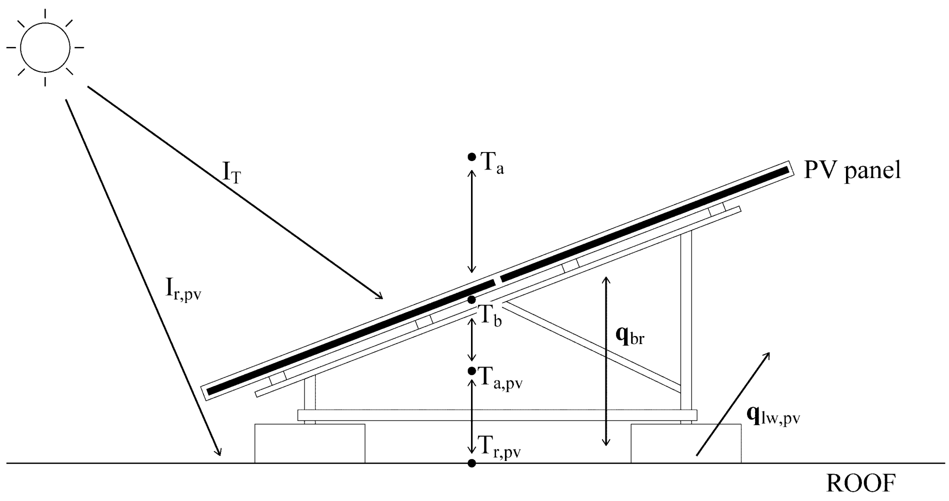
The remainder of this paper is structured as follows: Section 2 derives the theory of rooftop PV system. The method is introduced in Section 3. The results are provided in Section 4. Section 5 provides the conclusion and elaborates on suggestions for potential future research topics in this field.

2. THEORY

The impact of rooftop PV system on building energy consumption is due to the change in the heat transfer process on the roof. Office buildings have no HVAC energy demand at night, so only the change of the roof heat transfer process during daylight is analyzed. As shown in Fig. 1, before PV installation, the heat transfer process on the external surface of a normal roof mainly consists of incident solar radiation, convective heat transfer between the external roof surface and the ambient air, long-wave radiation heat dissipation from the roof to the outside. After PV installation, most of the incident solar radiation is blocked. At the same time, additional long-wave radiation is generated between the PV back sheet and the roof outer surface due to the rising temperature caused by the PV generation. Therefore, the effect on the heat transfer process and building load of the rooftop PV system is mainly in the following areas.



(a) Before the PV installation



(b) After the PV installation

Fig. 1. The change in the heat transfer process on the external roof surface

（1）With the installation of PV system, the external roof surface is not exposed to solar radiation directly, thus reducing the surface temperature of the roof and the heat gain of the room.

（2）Long-wave radiant heat dissipation from the external roof surface consists of three main aspects: the ground, ambient air and sky. The installation of rooftop PV system reduces roof heat loss by blocking long-wave radiation from the roof to the surroundings.

（3）When PV modules are converted from light energy to electricity, they also generate heat, which increases the temperature of the PV panel cells and the back sheet, resulting in a large temperature difference between the PV back sheet and the external roof surface, thus generating additional long-wave radiation (q_{br}) and increasing the heat gain to the roof. The q_{br} is related to the temperature of the PV back sheet (T_b), the temperature of the external roof surface, the emissivity and the angular coefficient, as shown in equation (1).

$$q_{\mathrm{br}} = \varepsilon_{br}\sigma_b\left({T_b}^4 - {T_{r,pv}}^4\right) \quad (1)$$

$$\varepsilon_{br} = 1/(1/\varepsilon_b + 1/\varepsilon_r + 1/X_{br} - 2) \quad (2)$$

The radiation angle coefficient is determined by the angle between the PV panel and the roof plane. The best orientation of the PV system in Guangzhou is south, the best inclination angle is 19° referring to Wang [10], X_{br} = 0.67. Therefore, equation (2) can be simplified as equation (3).

$$\varepsilon_{br} = 1/(1/\varepsilon_b + 1/\varepsilon_r - 0.5) \quad (3)$$

In summary, the heat gain from the external roof surface before and after the PV installation can be simplified as equation (4) and equation (5).

$$Q = h_1(T_a - T_r) + \alpha I_r - q_{lw} \quad (4)$$

$$Q_{\mathrm{pv}} = h_2\left(T_{a,pv} - T_{r,pv}\right) + \alpha I_{\mathrm{r,pv}} - q_{lw,pv} + q_{br} \quad (5)$$

3. METHODOLOGY

The overview of the research process is presented in Fig. 2. There are two aspects to be considered in the energy saving potential of office building rooftop PV system: one is the electricity generated by the photovoltaic (Es) and the other is the impact on the building HVAC energy consumption (ΔE). ΔE due to the change in the heat transfer process can be divided into two main components: one is the shading effect of the PV panels, which can be simulated by EnergyPlus; the other is the additional long-wave radiation due to the increase in temperature of the PV panels, which is not considered by the simulation software. Therefore, experiments are carried out to calculate the additional long-wave radiation.

3.1 Experimental setup

Experiments on the rooftop PV system of a high-rise office building in Guangzhou were conducted from 2021.09.03 to 2021.09.05. The test time period was a continuous sunny period from 8:00 to 18:00 over three days and the office room temperature was controlled at 26°C during the test time. The PV array was oriented in the south, tilted at 19°, the thermal physical parameters of the roof and PV system are shown in Table 1.

PV back sheet temperature, External roof surface temperature, Incident solar radiation intensity, Ambient air temperature, PV cavity air temperature, ambient wind speed and wind speed inside the power generation cavity are measured in this test. The main instrument information is shown in Table 2. The experimental field records are shown in Fig. 3.

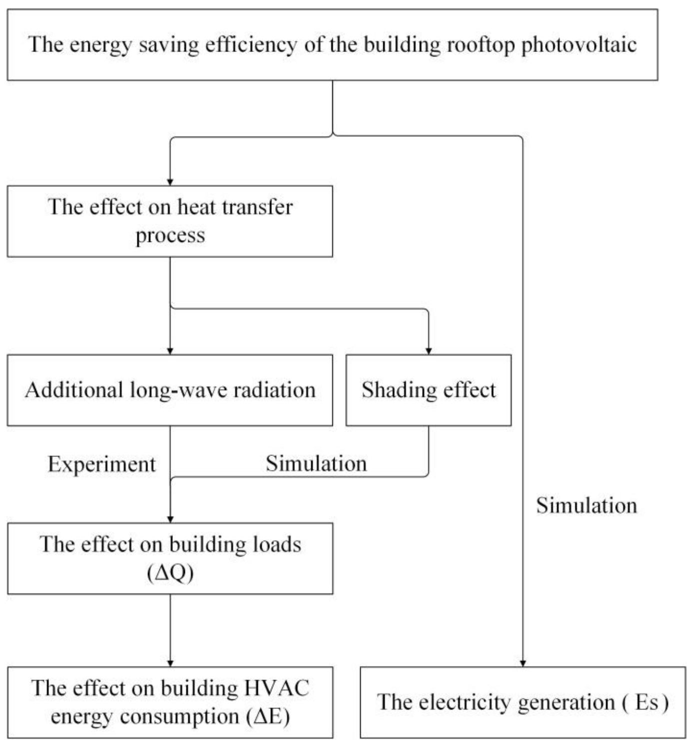


Fig. 2. Overview of the research process.

Table 1. Roof and PV array thermal physical parameters

Category	Parameters
PV type	Monocrystalline modules
PV panel size （mm）	1658×992×6
Maximum module power output （W）	285
Maximum component efficiency	17.3%
PV back sheet emissivity	0.9
Roof heat transfer coefficient [W/(m^2·K)]	0.76
External roof surface solar radiation absorptance	0.7
External roof surface emissivity	0.9

Table 2. Introduction to test instruments

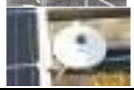
instrument	Image	Range	Accuracy	Measurement
Thermocouple		-200~120℃	±0.5℃	$T_{r,pv}$ T_b
HOBO		-40~70℃	±2.5%	T_a $T_{a,pv}$
Short-wave radiometer		0-2000W/m^2	±5%	I_t

Fig. 3. Experimental field records

3.2 Simulation setup

Ideally, assuming that all the roof area of a high-rise office building is used for PV system, taking the standard floor geometric model of a typical office building *established* by Chen [9] as an example, PV panels are installed on the building roof at an inclination angle of 19° towards the south, with an installation gap of 0.5m between each row of PV panels, as shown in Fig. 4. As shown in table 1, PV modules used on rooftops are monocrystalline silicon PV panels, so the Equivalent One-Diode in EnergyPlus[11] is chosen for the simulations below.

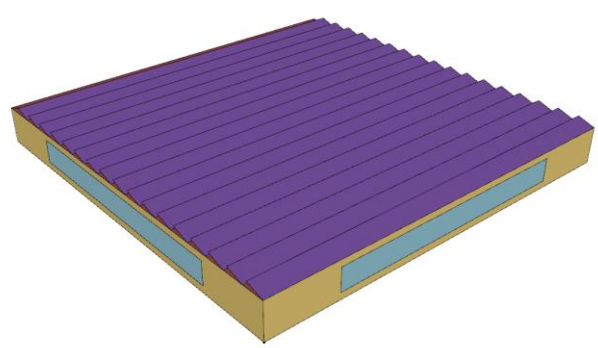


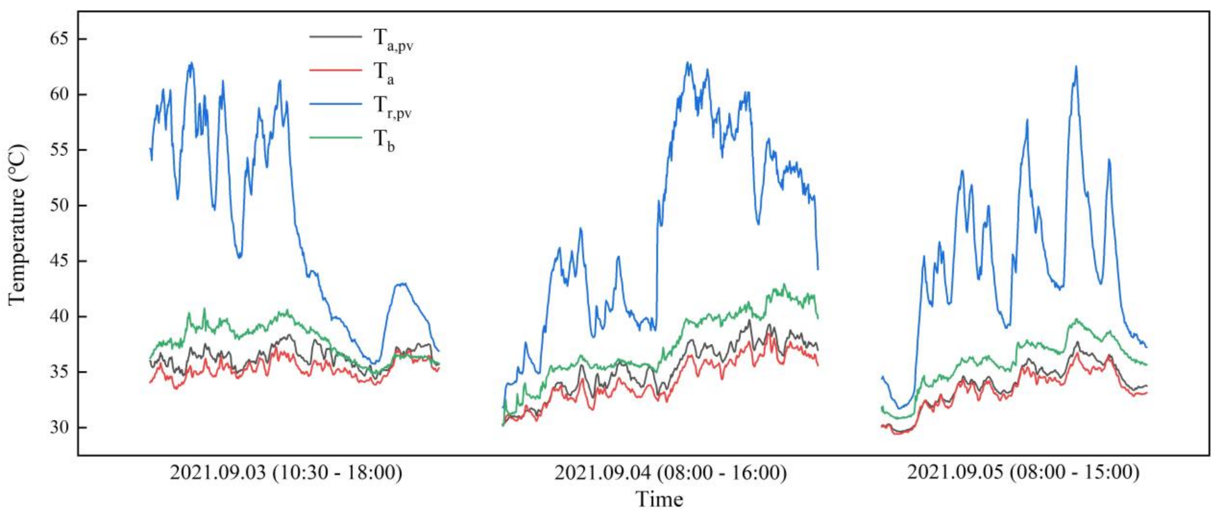
Fig. 4. Model of a typical office building roof with PV system

4. RESULT

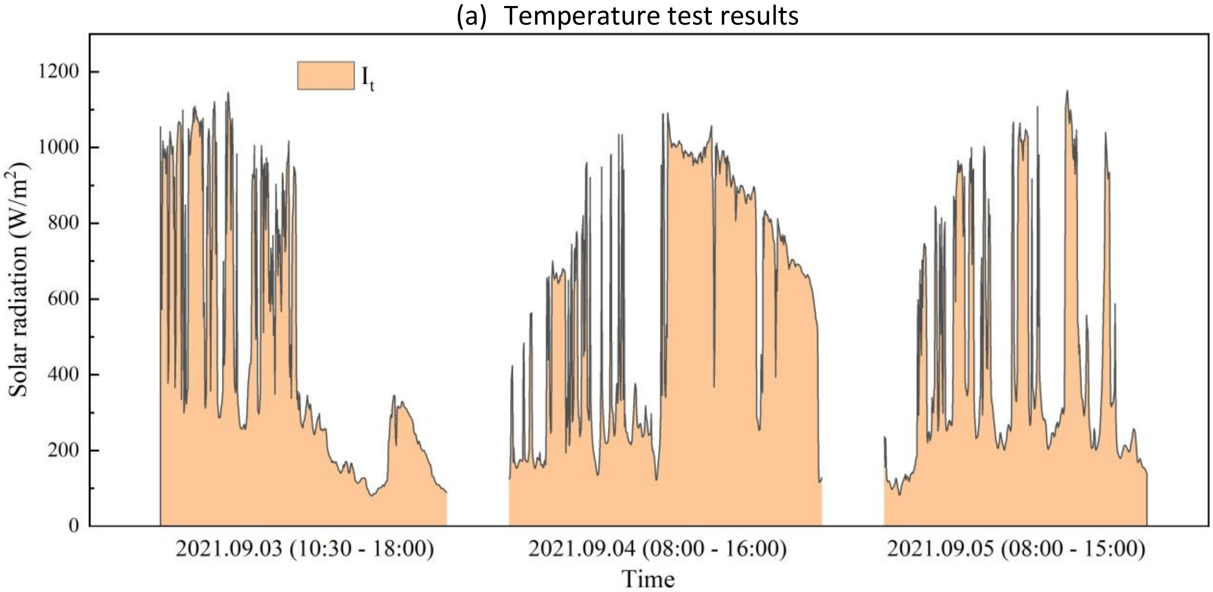
4.1 Experiment results

The test results for the sunny time period from 2021.09.03 to 2021.09.05 are illustrated in Fig. 5. The variation in T_b, $T_{r,PV}$ T_a and $T_{a,PV}$ over the test time period is shown in Fig. 5 (a). T_b is directly influenced by the PV power generation effect, with higher temperatures and more pronounced fluctuations. On cloudy days, when the solar radiation is low, the temperature difference between the PV panel back sheet and the roof surface is not significant, at this time, the power generation and additional long wave radiation of the PV system are negligible; when the solar radiation received by the PV panel reaches 1000W/m^2, the temperature of the PV panel back sheet is as high as 60℃. Overall, the PV cavity air temperature is slightly higher than the ambient air temperature, the wind speed is low and does not fluctuate greatly, so the impact on the flow heat exchange process on the external roof surface before and after the PV system installation is not significant. Only the changes in the radiative heat exchange process will be considered in the paper.

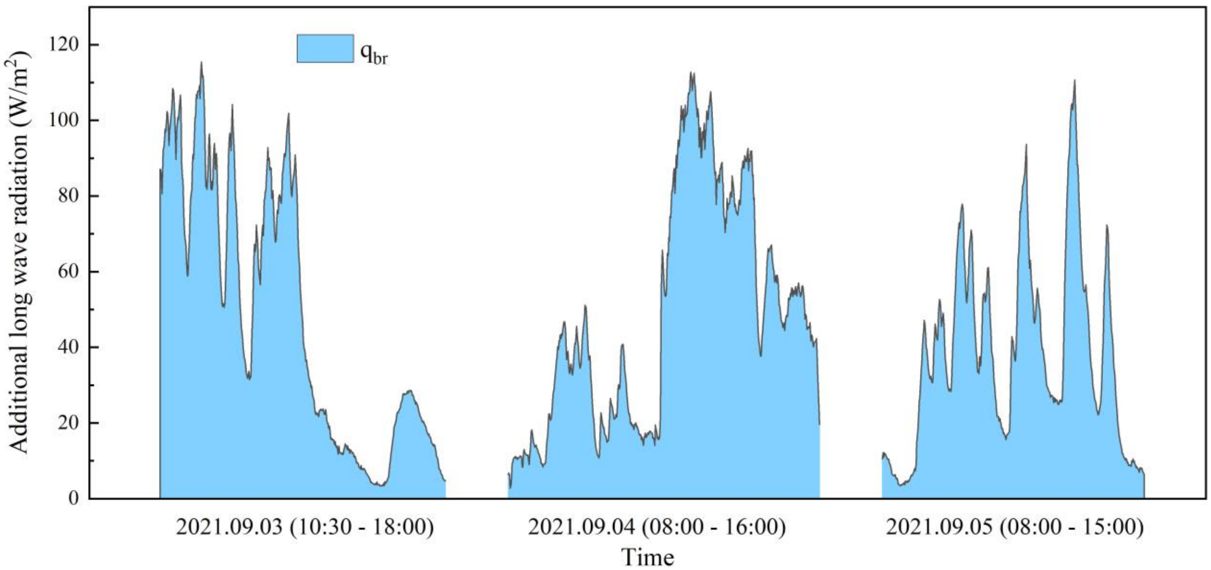
Substituting the emissivity of the PV back sheet and the external roof surface, as well as the experimentally measured temperatures of the PV back sheet and the external roof surface into Equation (1) and Equation (3), the additional longwave radiation, can be calculated as shown in Fig. 5 (c). Comparing Fig. 5 (b) and Fig. 5 (c), it can be seen that the additional long-wave radiation is correlated with the incident solar radiation of the PV panel. The Pearson coefficients and the Spearman coefficients are 0.78 and 0.85 respectively. According to the measured data, when the weather is clear, the amount of solar radiation incident on the photovoltaic panels is more stable, and the amount of additional long-wave radiation at the corresponding moment is one tenth of it.



(a) Temperature test results



(b) Results of the incident solar radiation intensity test on photovoltaic panels.



(c) Calculation of additional longwave radiation

Fig. 5. Experimental test results

4.2 Simulation results

Before the PV system installation, the cooling load is 53.45 kWh/m^2. From typical annual meteorological data, the annual incident solar radiation in the 19° south-facing plane in Guangzhou is 1483kWh/m^2. Based on the experimental results, it can be inferred that the annual additional long-wave radiation gain from the installation of PV panels on the roof is 148.3kWh/m^2. Taking into account the shading effect of the PV panels and the additional long-wave radiation, the cooling load of the building is 46.86 kWh/m^2. Therefore, the installation of rooftop PV system is beneficial for reducing the building cooling load, ΔQ = 6.6 kWh/m^2. The reduction in building HVAC energy consumption (ΔE) is shown in equation (6). When rooftop PV system is installed, the predictive model for air conditioning energy consumption in a typical office building[9] needs to be revised, as shown in equation (7). When the number of floors is high, the impact of rooftop PV system on building air conditioning energy consumption is almost negligible.

$$\Delta E = \Delta Q / COP \tag{6}$$

$$E_h{}' = E_h - \Delta E / N_f \tag{7}$$

What's more, the annual electricity generation of a typical building rooftop PV system was simulated by EnergyPlus, 128.6kWh/m^2. Therefore, the electricity generation prediction model of the typical building rooftop PV system is shown in Equation (8).

$$E_s = (128.6 \cdot A_{pv}) / (N_f \cdot A_{sf}) \tag{8}$$

5. CONCLUSION AND DISCUSSION

The rooftop PV system, a common form of BIPV, is of great significance for saving energy and reducing carbon emissions in the building sector. Although research on the energy saving potential of rooftop PV system is relatively mature, few studies have taken into account the impact of rooftop PV systems on building HVAC energy consumption at the early stage of building design, which has resulted in the inaccurate assessment of the rooftop PV system energy saving potential at the early stage of building design, thus affecting the determination of the installation area of rooftop PV system. Given this gap, through experiments and simulations, this paper presented a revised model for predicting building HVAC energy consumption, which considers the impact of the rooftop PV system, as well as a model for predicting building rooftop PV system electricity generation.

Firstly, the installation of rooftop PV system has changed the heat transfer process of the roof. In simple terms, it can be divided into two main aspects, one is the shading effect of the PV, the other is the additional long-wave radiation generated by the increased temperature of the PV panels. According to the experiment result, it can be concluded that the additional long-wave radiation is one tenth of solar radiation incident on the PV panels. What's more, the model for typical high-rise office building HVAC energy consumption prediction model in Guangzhou was revised according to the above effects, in relation to the COP of the air-conditioning system and the number of building floors. Finally, the simulation result shows that the annual power generation of rooftop PV system is 128.6kWh/m^2. From the electricity generation prediction model of the typical building rooftop PV system, the larger the proportion of PV installation area to the roof area, the greater the power generation; the higher the number of building floors, the smaller the power generation. The results revealed that the most energy saving potential of the rooftop PV system comes from its electricity generation capacity. Especially for high-rise buildings with high-performance air conditioning system, the impact of rooftop PV system on the building HVAC energy consumption is almost negligible.

When it comes to the possibility of offsetting the energy consumption with the generation of renewable energy, the roof space becomes extremely limited with the consideration of window cleaner, cooling towers and other outdoor equipment, instead of adding photovoltaic panels on the roof, building integrated photovoltaic façade could be an alternative for further investigation in future.

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