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Integrated design optimization of distributed photovoltaic systems in buildings with phase change materials

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ABSTRACT

This paper proposed a coupled application of phase change materials (PCMs) and distributed photovoltaic (PV) power generation systems for building energy efficiency. An experimental apparatus for buildings with PCMs and PV systems was constructed. The energy consumption and power generation of the experimental buildings was simulated using EnergyPlus and System Advisor Model (SAM) and verified against experimental data, respectively. The energy consumption was reduced by an average of 0.015 kW per hour and the peak load was delayed by an average of 1 h using PCMs. To realize the highest self-sufficiency rate, an additional 2 kWh battery was required for a reduction of 0.269 kWh air conditioning load. The more the PCMs of the buildings used, the larger the capacity of the battery was needed to be equipped.

Keywords: distributed photovoltaic power generation, phase change materials, building energy consumption, battery SOC

1. INTRODUCTION

Photovoltaic (PV) power generation is an important application of renewable energy as fossil fuels diminish. However, it has an intermittent supply in nature and the indoor load in buildings varies from time to time. Significant research is devoted to the use of PV in buildings.

In order to smooth the volatility of PV system output, it is usually equipped with a certain capacity energy storage system. Coupling the PV system with battery system can increase the self-consumption by 40% [1]. Ricardo et al. [2] mentioned that the electric energy storage system can decouple power generation and consumption, solve the intermittent defects of PV supply in the traditional power grid, and increase the potential penetration rate of PV in the distribution network. Luthander et al. [3] used demand-side management (DSM) to increase 2%-15% power generation per installed kilowatt of PV. At the same time, more and more scientific researchers are committed to improving the efficiency of PV power generation by reducing the temperature of the components [4-7]. It was proved that the use of phase change materials (PCMs) can keep the working temperature of PV systems at a higher efficiency [8]. Nada et al. [9] improved the average daily efficiency by 7.1% after integrating a building with PV modules and PCM. Although many studies have been conducted on PV thermal regulation using PCM, they are limited to reducing the temperature of the PV modules and do not take into account the fluctuations in indoor load and the matching of the PV system.

As PCM is increasingly used in buildings, the depth and breadth of its application research is expanding. Vinod and Rajat et al. [10, 11] found that the presence of the PCMs significantly reduced the peak load. Kissock et al. [12] conducted experimental studies on ordinary walls and phase change walls respectively, and showed that compared with rooms with phase change walls, the temperature fluctuations in ordinary rooms are much greater. Na et al. [13] proposed a new double-layered PCM panel of Trumbull walls, which resulted in a 9% and 15% reduction in the peak cooling and heating loads of the building, respectively, as well as a reduction in indoor temperature fluctuations and an increase in thermal comfort.

PCMs have excellent heat storage performance, which can uniformize the hourly load of buildings. The intermittent supply of solar energy can be effectively solved by using PCMs. The building energy consumption can be reduced further by using PCMs and PV systems together. An experimental apparatus for buildings with PV systems and PCMs was built. EnergyPlus and SAM softwares were used to simulate the building energy consumption and PV power generation, respectively. Corresponding battery control strategies were adopted to solve the problems of imbalance of system supply and demand as well as peak discrepancy.

2. METHODOLOGY

2.1 Experimental apparatus

Two light-weight buildings were constructed, of which building A was the reference building and building B was the building with PCMs. A composite PCM-insulation board used paraffin wax with phase transition temperature of 25 °C was designed and developed. The PCM accounted for 2.6 vol% of the insulation board. The two buildings are shown in Fig. 1. Building A and B was equipped with 540 W distributed PV system (Fig. 2). The PV panels were placed flat on the ground near buildings, with latitude and longitude of 112.87 °E and 28.23 °N respectively, facing south with a tilt angle of 30 °, in the form of a fixed axis, shaded by grass 50 cm to the south and shaded by trees within a radius of 4m. The entire experiment was conducted in the same location and under the same climatic conditions for both ordinary building A and phase change building B. Meteorological parameters were collected via a U30-GSM weather station.

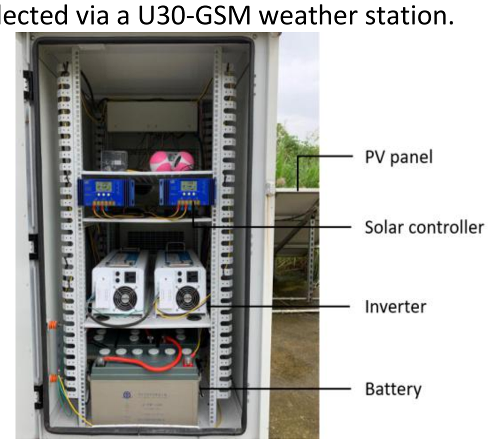

Fig 2 PV power generation system.

2.2 Physical model

EnergyPlus was used to simulate the energy consumption of buildings A and B. The building model was built using DesignBuilder, as shown in Fig. 3. The year-round indoor cooling/heating load data of PCMs

Fig 1 Building A and B.

with volume fraction of 2.6%, 3.9% and 5.2% were simulated by inputting outdoor weather, wall thermal conductivity and enthalpy of phase change materials into the software, respectively. The electrical loads were calculated based on a power energy conversion factor of 3.167 and a floor area of 19.34 m2. System Advisor Model (SAM) was used to simulate the power generation, as shown in Fig. 4. The climate file consists of total horizontal solar radiation, dry bulb temperature, dew point temperature, relative humidity, etc., collected from the weather station and calculated scattered horizontal radiation using the Berlage formula. The model design parameters were all consistent with the actual PV power generation system. Assume that the setting is 96% inverter efficiency loss, 5% module mismatch loss, 2% cable loss, and 0% snow loss. The soiling loss is set at 10% due to the PV panels being placed on the ground behind the grass, where they tend to accumulate dust. A simple PV shading model was constructed by the 3D shadow calculator and the shading loss of the system was calculated to be 4%.

The indoor air-conditioning electricity consumption was assumed to be the load of PV systems and was used as one of the input conditions for the system. Different volume fractions of PCMs in a phase-change building will generate different electricity consumption for air conditioning, thus combining the PV system with the phase change wall to construct an integrated photovoltaic phase change (PV-PCMs) system. The electricity consumption of PV-PCMs system is obtained from SAM simulations and compared with the experimental power generation data recorded using the solar controller to validate the model reliability. Changing the volume fraction of PCMs in buildings is to change the load side input of the model. Different building conditions have different load characteristics, which may have different effects on the same PV system. The effects of PCMs on the PV system and the optimization requirements of PV-PCMs system are obtained from the comparison.

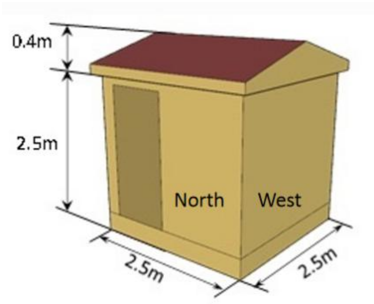

Fig 3 Phase change building.

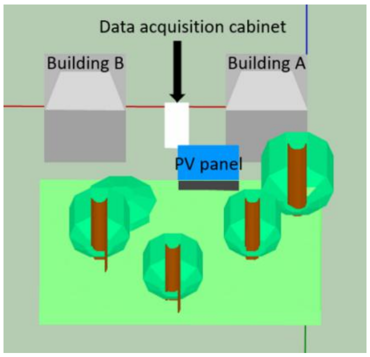

Fig 4 PV power generation system model.

3. RESULTS

3.1 Model verification

The simulated and measured results for building B from July 16-18 are shown in Fig. 5, where the average deviation of the simulated and measured values of the west-facing, south-facing and east-facing wall internal surface temperature is 6.48%, 4.05% and 8.77%, respectively. The simulated power generation of the PV system in different time periods were compared with the measured power generation in Fig. 6. The maximum error between the simulated and experimental data was 1.06 kWh and the minimum error is 0.0004 kWh for different time periods with an average error of 5.46%. The average daily simulation error by calculation is about 9.53%.

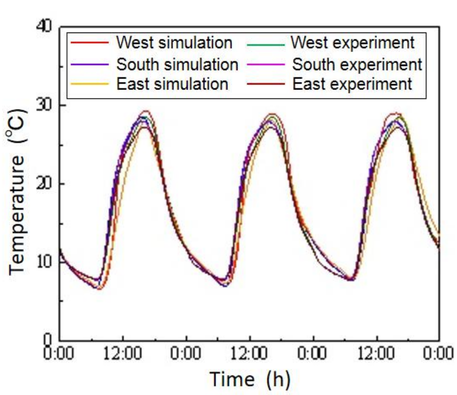

Fig 5 Internal wall temperature comparison.

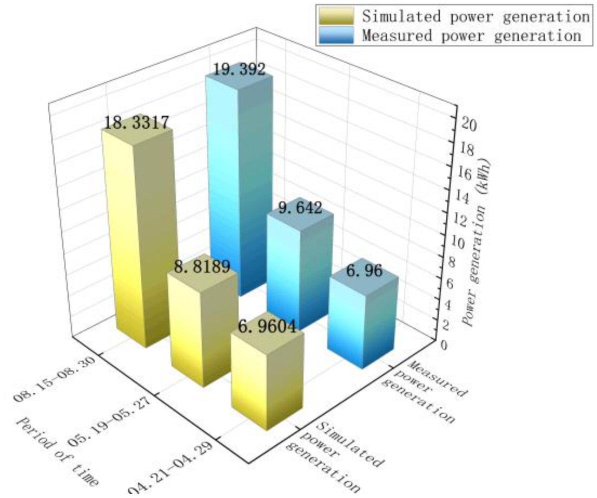

Fig 6 Power generation comparison.

3.2 Performance of PV-PCMs system

The system power generation and indoor electricity load from August 5 to August 8 were simulated by the residential PV power generation system model. The results are shown in Fig. 7. It should be noted that the electricity load simulated in this paper only refers to the indoor air-conditioning electricity load, not including the electricity consumption by lighting and household equipment. Fig. 7 showed that the hourly electricity load for reference building and building with PCMs were similar. However, on August 5 and August 6, the electricity load fluctuated with temperature because of the large fluctuation in outdoor temperature, showing an erratic trend.

Considering that cooling is required during the day and night in Changsha City in August, the PCMs in the walls of the building solidified and released the stored heat during nighttime when the temperature was decreasing, which increased the cooling load. The PCMs melted and absorbed heat during the daytime to reduce the cooling load. Therefore, the cooling load of the building with PCMs was lower than the load of the reference building from 6:00 to 17:00, but higher than the load of the reference building during nighttime. The maximum load reduction occurred around 9:00, with an average hourly load reduction of 0.015 kW, and the average hourly increase in electricity load at night is 0.007 kW. The peak load of the building with PCMs was significantly delayed compared to the reference building, with an average peak load delay of 1 h. In addition, the amount of PCMs that melted was large for the first peak load and the remaining amount decreased with time, so the peak delay was not obvious with time.

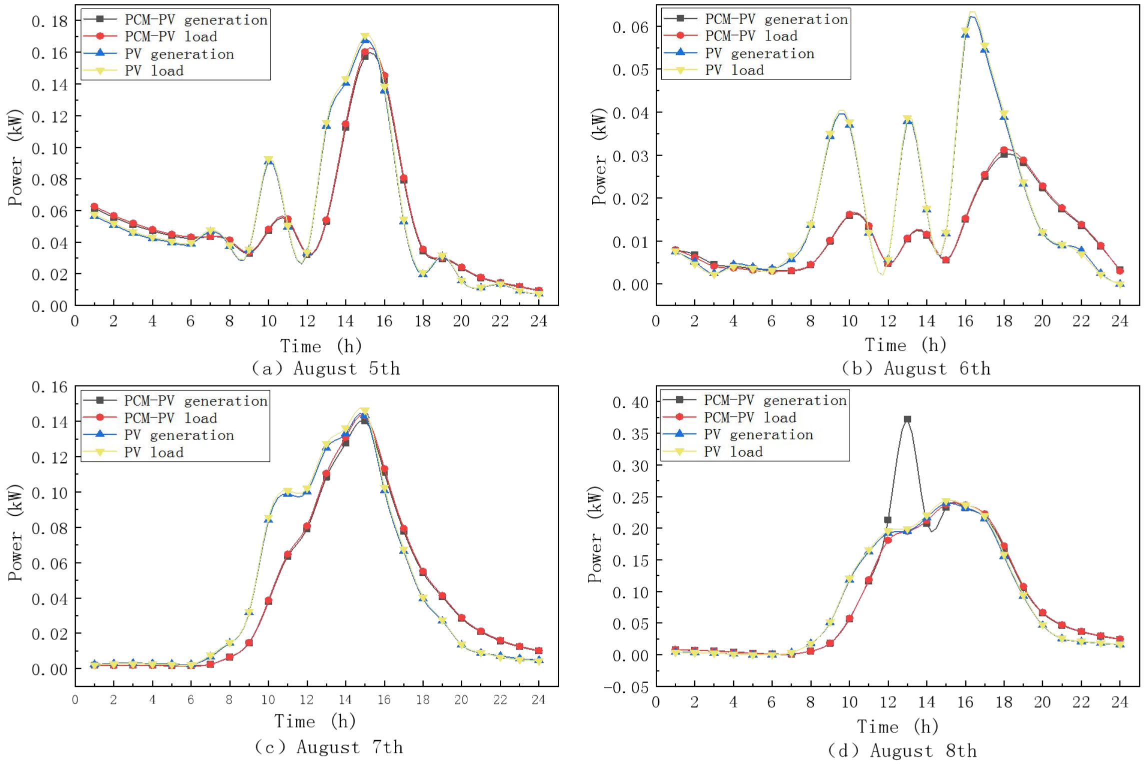

Fig 7 Supply and demand after optimization.

The building air-conditioning load decreased with the increase of PCMs volume fraction. The larger the amount of PCM used, the more heat was absorbed during the daytime and the lower the cooling load was, and vice versa during nighttime.

Although the load demand of the PV-PCMs was reduced and the peak value was delayed, the power generation curve did not match the electricity load curve, as shown in Fig. 7d. Outdoor climate and temperature variation were the main reasons for this situation. The power generation of the PV system mainly depended on the total solar radiation, which was generated directly from the solar cells through the panel glass, while the air-conditioning load of the building mainly depended on the outdoor temperature. In addition, there was no solar radiation at night, which generated 0 kWh of electricity. As a result, the system power generation was not able to meet the load demand continuously. Battery system was required.

4. DISCUSSIONS

The power supply and demand were not balanced in above results. Therefore, the size of the PV panel was adjusted and a 12 V, 120 Ah lead-acid battery was added. The battery capacity is 7 kWh with a maximum charge and discharge power of 0.5 kW. The control strategy of the battery was discharging from 19:00 to 5:00 and charging from 6:00 to 18:00. The battery state of charge (SOC) from August 5 to August 8 is shown in Fig. 8. Battery capacity was always maintained at 25-85%.

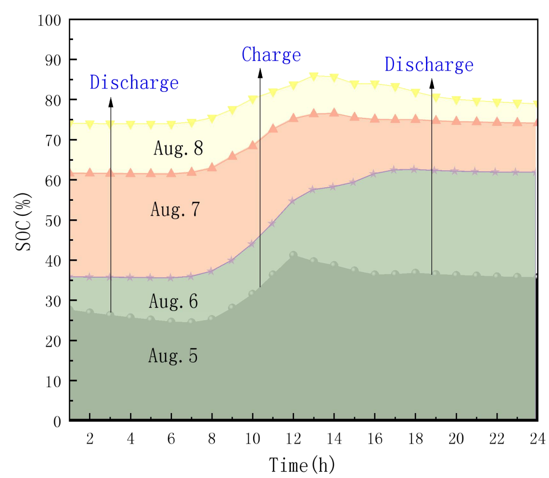

Fig 8 Battery state of charge.

After optimization, the power generation met the electricity load for the reference building. The peak electricity load was consistent. According to the subsidy standard for PV power generation in Changsha, the mode of self-sufficiency brings greater economic benefits than the electricity consumption model that generates electricity to the grid [14]. The power supply and demand matched, and the degree of self-sufficiency was the maximized with high economic benefits. However, for the building with 5.2 vol% PCMs the excess power after meeting the electricity load at noon on August 8 was not fully stored in the battery. Increasing the battery capacity to 9.4 kWh increased the self-sufficiency rate of building B to the maximum in the case of battery safety, as shown in Fig. 9. Therefore, for buildings with PCMs, larger battery capacity was required. A 2 kWh battery needed to be added for an average reduction of 0.269 kWh in indoor air-conditioning electricity load to achieve the maximum self-sufficiency rate.

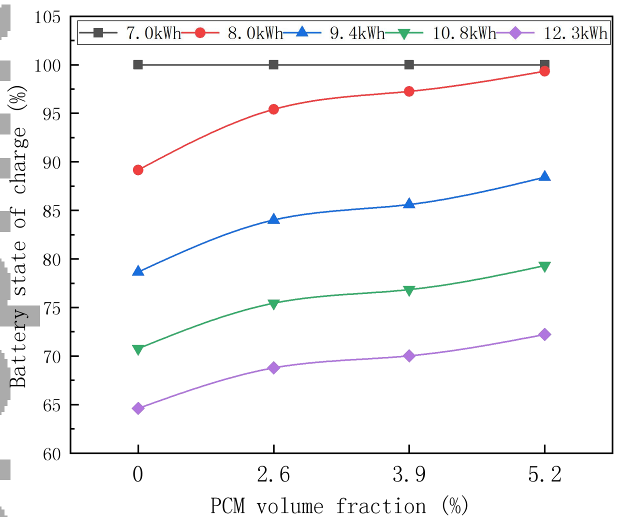

Fig 9 Hourly peak of battery SOC.

5. CONCLUSIONS

In this paper, a building with PCMs and PV systems was designed, tested, and simulated, compared with a reference building. The conclusions are as follows:

1. The maximum load reduction of the building with PCMs appeared at 9:00, with an average load reduction of 0.015 kW and an average peak load delay of 1h. The more the PCMs used, the greater the load was reduced.

2. The PV-PCMs system has the defect of imbalance between power supply and demand. Appropriate battery control strategy was required to realize the highest self-sufficiency rate.

3. With the aim of battery SOC within a safe range and the system highest self-sufficiency rate, the building with PCMs required a larger battery system. For an average reduction of 0.269 kWh in the cooling electricity load, an additional 2 kWh battery capacity was needed.

4. The battery SOC increases with the amount of PCMs used. A building with more PCMs had a higher potential for battery damage.

ACKNOWLEDGEMENT

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