Approaching nearly zero energy of PV direct air conditioners by integrating building design, load flexibility and PCM

Li, Sihui; Peng, Jinqing; Wang, Meng; Wang, Kai; Li, Houpei; Lu, Chujie

DOI
10.1016/j.renene.2023.119637

Publication date
2024

Document Version
Final published version

Published in
Renewable Energy

Citation (APA)
Li, S., Peng, J., Wang, M., Wang, K., Li, H., & Lu, C. (2024). Approaching nearly zero energy of PV direct air conditioners by integrating building design, load flexibility and PCM. *Renewable Energy*, *221*, Article 119637. https://doi.org/10.1016/j.renene.2023.119637

Renewable Energy 221 (2024) 119637

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Approaching nearly zero energy of PV direct air conditioners by integrating building design, load flexibility and PCM

Sihui Li [a], Jinqing Peng [b,c,*], Meng Wang [a], Kai Wang [b], Houpei Li [b,c], Chujie Lu [d]

[a] College of Energy and Power Engineering, Changsha University of Science and Technology, Changsha, 410082, China
[b] College of Civil Engineering, Hunan University, Changsha, 410082, China
[c] Key Laboratory of Building Safety and Energy Efficiency of Ministry of Education, Hunan University, Changsha, Hunan, China
[d] Faculty of Architecture and the Built Environment, Delft University of Technology, the Netherlands

ARTICLE INFO

Keywords:
PV direct driven air conditioner (PVAC)
Zero energy buildings
Load flexibility
Building design

ABSTRACT

The energy matching of PV driven air conditioners is influenced by building load demand and PV generation. Merely increasing energy performance of building or PV capacity separately may improve the energy balance on a large time resolution, the real-time energy mismatching problem is still serious. In this study, a coordinated optimization method of PV capacity, building design, and load flexibility is proposed for improving the real-time energy matching of PVAC system. Then, a methodology integrating data mining method (XG Boost) and parametric simulation was developed to identify the determinant parameters of PV system and building design, exploring feature importance and correlations. The results of XG Boost indicate that the PV capacity, shape factor, and SHGC are the most critical factors. Finally, based on the optimized building design, the PCM layer was applied to improve the real time energy matching. To achieve a goal of 90 % ZEP, the PCM capacity can be decreased by 50.4 % and 62.8 % in Guangzhou and Shanghai in the optimized building. Moreover, the PV capacity can be reduced by 23 % in Guangzhou. The findings of this study provide practical guidance for designing PVAC system coupling with building design and energy storage devices.

1. Introduction

Energy consumption of buildings accounts for a significant portion of the global energy consumption [1]. With the indoor thermal comfort demand, the air conditioner (AC) system contributes to more than 50 % of the energy consumption of building [2]. Approaching a zero-energy goal of AC is an effective method to decrease the energy consumption of buildings in recent years. Previous research on reducing the energy consumption of AC in building mainly focused on three aspects: designing an energy efficient building [3], implementing renewable energy system [4], and optimizing of building design with renewable energy system [5].

The energy efficient building can be effectively reached by means of optimizing building design parameters [6]. Building design optimization can alter the building thermal performance to change the load demand, thereby improving the energy matching between the PV generation and energy consumption of AC [7]. Common building design optimization methods include the application of thermal insulation [8,9], glazing [10], building shape [11], phase change material (PCM) [12,13], shading [14], natural ventilation [15] and Trombe wall [16]. In above methodologies, Zhao et al. and Xu et al. argued that the heat loss by the building envelope accounted for 50 % of the building's total load demand, the optimization of building design is the first step for minimizing the load demand of buildings [17,18]. The building shape ratio, window type, window-to-wall ratio, wall type, wall layer and roof type have critical impacts on building performance [19]. These parameters of building envelope can be divided into building physical design parameters (e.g., shape factor [20] and WWR [21]), transparent envelope parameters (e.g., SHGC [22] and thermal conductivity [23]), and opaque envelope parameters (e.g., thermal conductivity [24] and thermal resistance [25]). While the above efforts in optimization studies are significant to explore the energy saving potential of the building, the renewable energy system was seldom considered. Actually, the installation of renewable energy system has grown continuously, building design optimization should be coupled with renewable energy capacity design, in which the purpose is changed to improve the energy matching of load demand and renewable energy system generation.

Among the various types of air conditioners with renewable energy,

---

[*] Corresponding author. College of Civil Engineering, Hunan University, Changsha, 410082, China.
E-mail address: jallenpeng@gmail.com (J. Peng).

https://doi.org/10.1016/j.renene.2023.119637
Received 14 July 2023; Received in revised form 22 September 2023; Accepted 13 November 2023
Available online 15 November 2023

PV driven AC (PVAC) are an appealing solution to reduce the energy consumption of air conditioners due to the good consistency between the PV generation and AC's energy consumption in summer and the lower investments [26]. The simple design method of PV capacity is that the total PV generation is equal to the total energy consumption of AC [27,28]. However, due to the fluctuations of solar irradiation, the PV generation may not always fully satisfy the energy consumption of AC. Taking an office building in Tianjin as an example, the annual PV generation was 120 % of the total energy consumption of ACs, but only 29.5 % of the energy consumption was supplied directly by PV system during actual operation periods [29]. Increasing PV capacity has limited effect on the real-time energy matching of PVAC system.

Considering load flexibility of AC is an effective method to further improve the energy matching degree [30]. The common methods of utilizing load flexibility involve switching the ON/OFF state of AC and changing the temperature setpoints [31,32]. Switching the ON/OFF state of AC can achieve immediate energy consumption growth or reduction. Some problems would also be caused, such as the indoor temperature exceeding thermal comfort temperature range, poor adjustability of AC energy consumption, and shorter the unit operation period [33]. Mohammed et al. illustrated that the dynamic changing temperature setpoint as the load flexibility control strategy can reduce energy consumption of AC by 15.23 %–17.33 % during the peak period [34]. However, during the temperature regulation process, the indoor temperature may take 1~2 h to reach the temperature setpoint [35]. The real-time indoor thermal comfort still cannot be fully satisfied. In addition, the accurate building thermal model and AC model are important for predicting the indoor temperature, but both modeling and computing process are complex and time-consuming. Thus, to improve the real-time energy matching of PVAC, changing temperature setpoint is not well applied [36].

A review of the literature reveals that optimizing building design, renewable energy systems and load flexibility control individually has limited effects on reaching real-time zero energy goal of air conditioners in buildings. The coordinated optimization of building design and renewable energy attracts increasing attention. In a building, the energy matching between PV generation and energy consumption of AC is shown in Fig. 1. The PV system determines the energy supply of the air conditioners in the building, while the building design have dominant influence on the load demands. The AC is the component to regulate the indoor thermal environment and consume the energy [8].

As shown in Fig. 1, to approach zero energy goal of AC, the PV generation should be equal to the energy consumption while maintaining the indoor temperature within the human thermal comfort temperature range. In traditional optimization method, the zero-energy goal of AC has relied on the building design optimization from an energy saving perspective, a PV system is designed to cover the total load demand of the optimized building [37,40,41]. In this method, the energy generation of a PV system with a small to medium scale can meet the total load demand of the optimized building [38,39]. However, with the continuous decline in PV system investment, the capacity of PV system has grown rapidly. Increasing PV capacity may result in a waste problem of PV generation in the traditional method, placing strain on utility grids that should receive excess PV generation. The PV generation is highly dependent on the weather conditions, which creates a real-time energy mismatching problem with the energy consumption of AC. Therefore, improving the real-time energy matching between PV generation and energy consumption of ACs is more and more essential in recent years, which can maximize the self-consumption and self-sufficiency of the PVAC system and minimize the burden of utility grid. A coordinated optimization of building design, PV capacity, load flexibility and energy storage are essential to reaching real-time energy matching of PVAC system. Li et al. showed that the PVACs coupled with load flexibility and PCM wall in a standard office building can achieve 90 % real-time zero energy probability [42]. However, in this study, this building design parameters were not optimized, leading to large capacities of PCM and PV system.

According to Table 1, various studies investigated the energy matching of PV generation and AC consumption from different perspectives, which include optimizing the building design to change the load demand curve, increasing PV generation to change the energy generation curve, and considering the load flexibility to change the rigid energy matching of PVAC system. Nevertheless, studies on improving energy matching are limited, because these studies mainly focus on improving energy matching just from one perspective of energy saving at a large time resolution. However, with the ever-increasing PV installed capacity, the reviewed optimization method may result in a waste problem of PV generation, placing strain on utility grids that should receive excess PV generation. Hence, the real-time energy matching between PV generation and energy consumption of AC is more important for designing PVAC system, which can be beneficial to maximize the self-consumption of PV generation and increase the self-sufficiency of AC at the same time.

This paper aims to develop a coordinated optimization method of the PVAC coupling with building design, PCM wall, load flexibility of AC to approach the real-time energy matching of PVAC in different climatic

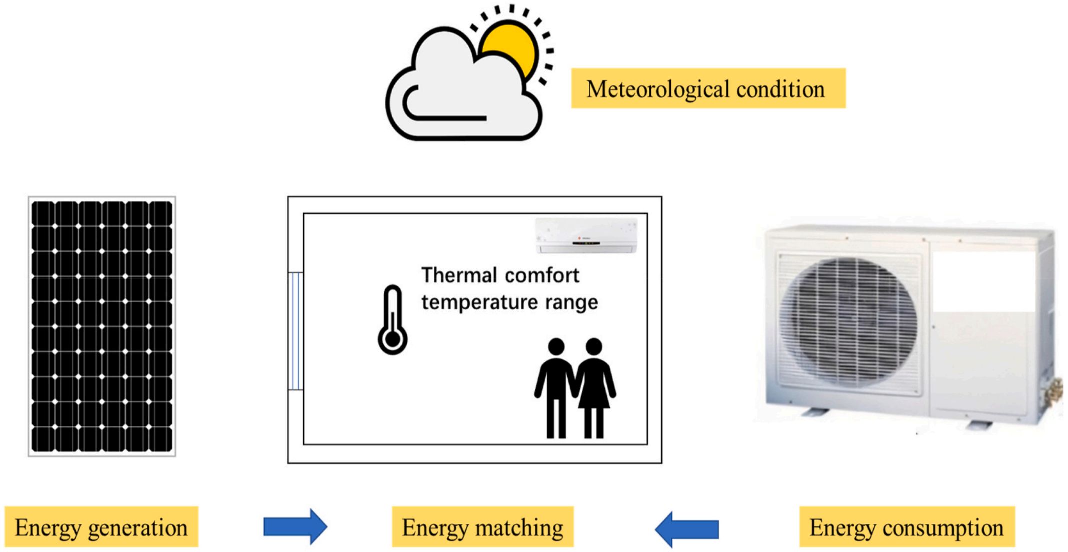

Fig. 1. The energy matching schematic diagram of PVAC in buildings.

Table 1
A summary of articles on the energy matching between PV generation and AC consumption in buildings.

Source	Building design					PV design	Load flexibility	
	Change building load demand					Change energy generation	Changing rigid energy matching of PVAC	
	f	WWR	SHGC	K	thermal resistance	Increasing PV capacity	ON/OFF of AC	Change temperature setpoints
[19]	✓	✓		✓				
[20]	✓							
[21]		✓						
[22]			✓					
[23]				✓				
[24]				✓				
[25]					✓			
[28]						✓		
[29]						✓		
[37]						✓		
[38]						✓		
[39]						✓		
[31]								✓
[32]								✓
[33]								✓
[34]								✓
[35]								✓
[43]						✓		✓

regions. In this paper, Section 2 presents the model of PVACs coupled with building design and load flexibility. The load flexibility was mainly achieved by means of a thermal comfortable temperature range (TCTR) of human. Section 3 provides a real-time ZEP evaluation method and calculation framework for the PVAC coupling system. Section 4 introduces the experimental platform of PVAC coupling system. In section 5, the synergistic effect on real-time ZEP of PVACs, building design, and load flexibility was investigated with the key factors. The optimization methods and results can offer guidance for system designers and users to create a well-designed system of PVAC and building for a higher real-time energy matching degree by itself.

2. Model

2.1. PVAC model

In this study, the PVAC system was implemented in an office building with dimension of 20m × 15m × 8.4m. In traditional AC operation strategy, the electricity consumed by AC is mainly determined the temperature setpoints, indoor and outdoor thermal environments. In this PVAC system, the real-time energy consumption is not dependent on the temperature setpoints of AC. The AC consumes the real-time electricity generated by the PV system as much as possible. The indoor temperature, conditioned by the PVAC, mainly depends on the real-time PV generation. Only when the indoor temperature conditioned is over the thermal comfort temperature range, the mismatching energy problem could be solved by the utility grid or batteries. In the simulation process, the AC model was regarded as an ideal air conditioning system. The nominal coefficient of performance (COP) was 3.99 for cooling and 4.12 for heating. The real-time output energy of PVAC is the product of the real-time PV generation value and the COP of AC.

2.2. Building model

For the large cooling demand in summer, two climatic regions in China were selected in the study, namely a Hot-summer and Warm-winter region, and a Hot-summer and Cold-winter region. The representative cities of the selected regions were Guangzhou and Shanghai, respectively. The selected key building design parameters included shape factor (f), window to wall ratio (WWR), K value of opaque construction, K value of transparent construction, and solar heat gain coefficient (SHGC). The building envelope parameters were based on the public energy efficiency design standard and general codes for energy efficiency and renewable energy application in buildings in China. To determine the optimal building design, the parameters mentioned above were not assigned constant values. The variation range for each building parameter during the optimization process was shown in Table 2.

To improve the real-time energy matching between the PV generation and energy consumption of AC, the Phase Change Material (PCM) layer was placed on the inner surface of the wall. In summer, when the indoor temperature is lower than the melting temperature of PCMs, the excess cooling energy can be stored by the PCM layer. When the indoor temperature is higher than the melting temperature, the cooling energy can be released from the PCM layer. Form the previous research on PVAC coupled with PCM layer, it was found that PCM-26 is more suitable to improve energy matching of PVAC in the two regions. The key thermophysical properties of A26 are shown in Table 3. In the optimization process of the energy system, the thickness of the PCM layers ranged from 0.02 m to 0.2 m, with a step of 0.02 m (See Fig. 2).

3. Methodology

In this study, a Zero Energy Probability (ZEP) evaluation method of the PVAC coupling system, considering building design, load flexibility and PCMs, was proposed from the perspective of real-time energy matching. The time resolution of the energy simulation is 1 h. The calculation process of ZEP is formulated as Eq. (1).

$$\mathrm{ZEP} = \frac{t_c}{t_{operation}} \tag{1}$$

where t_c are the zero energy hours during which the real-time indoor operative temperature can meet the thermal comfort requirement; $t_{operation}$ are the total PVACs operation hours.

To assess the impact of building design parameters on the real-time energy matching of PVAC and investigate the real-time zero energy potential of PVAC coupled with building design and load flexibility, an optimization of PVAC coupled with building design and load flexibility was conducted. The coordinated optimal design of PVACs to approach the real-time zero energy goal is shown in Fig. 3. The coordinated optimal design of PVACs in this study can be divided into three steps to achieve a nearly zero energy goal.

At stage 1, a parametric study of building parameters and PV capacity was conducted. The parametric simulation process was based on EnergyPlus and JePlus which can rapidly generate energy simulation results containing multiple design parameters. In the simulation, real-time PV generation was calculated and transferred into the real-time

Table 2
Input variable values.

Input variable	Abbreviation	Climatic regions	Lower limit	Upper limit	Increment	Unit
Shape factor	f	Hot-summer and Warm-winter	0.3	1.1	0.4	
		Hot-summer and Cold-winter				
Window to wall ratio	WWR	Hot-summer and Warm-winter	0.3	0.7	0.1	
		Hot-summer and Cold-winter	0.3	0.7	0.1	
Solar heat gain coefficient	SHGC	Hot-summer and Warm-winter	0.1	0.6	0.05	–
		Hot-summer and Cold-winter	0.1	0.6	0.05	–
K value of window	K_{window}	Hot-summer and Warm-winter	2.5	6	0.05	W/m^2K
		Hot-summer and Cold-winter	1.5	4	0.05	W/m^2K
K value of roof	K_{roof}	Hot-summer and Warm-winter	0.3	1	0.05	W/m^2K
		Hot-summer and Cold-winter	0.2	0.8	0.05	W/m^2K
K value of wall	K_{wall}	Hot-summer and Warm-winter	0.6	1	0.05	W/m^2K
		Hot-summer and Cold-winter	0.5	0.9	0.05	W/m^2K

Table 3
Thermophysical properties of A26.

Product	Manufacturer	Melting temperature (°C)	Latent heat (kJ/kg)	Specific heat (kJ/kgK)	Thermal conductivity (W/mK)
A26	China Materials Institute	26~27	160	1.95	0.6

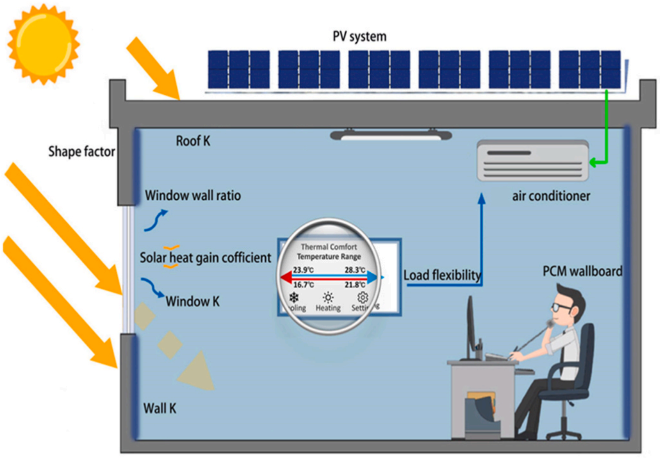

Fig. 2. The PVAC coupled with load flexibility, PCM and building design.

cooling/heating energy provided by PVAC with varying PV capacity. Then, the real-time indoor temperature associated with different building design and PVAC was simulated. Based on the real-time indoor temperature conditioned by the PVAC in the building and thermal comfort temperature requirements, the ZEP values of the system were calculated under different values of building design parameters and PV capacities. In the parametric simulation process, a data set containing 4,752,000 cases were generated for the data mining task.

At stage 2, XG Boost, a scalable machine learning system for tree boosting, was used to identify the significance of each parameter of the building design and PV system. XG boost is the primary method to model the complex non-linear relationship between these factors and related real-time ZEP values of each combination of parameters. Then, the parameters studied were ranked by XG Boost based on the feature importance score (IS). The higher the IS, the greater influence on the ZEP.

At stage 3, based on the optimized building design and PV capacity, the PCM layer was adopted to further improve the real-time energy matching of PVAC. Finally, the optimal design of building with PCM and PVACs were provided for achieving nearly zero energy goal.

4. Validation of PVAC model

4.1. System description of the experimental setup

To validate the simulation method and the proposed PVAC control strategy, an experimental room was constructed in Hunan, China. The experimental room had dimensions of 8.5m × 2.3m × 3m. To find a better control strategy to consume the real-time PV generation and maintain indoor thermal comfort, a PVAC system was set into the experimental room. The PVAC system consists of the variable speed air conditioner, PV system, inverter, utility grid, intelligent power distribution cabinets (IPDC) and data acquisition and control devices. The PV system was placed in the front of the room, positioned at the optimum tilt angle for PV generation in this area. The rated power of PV system is 2.4 kW. The electricity distribution of the PVAC was managed by the inverter. The actual weather data was obtained by the meteorological station in the experimental platform, and all data was recorded by the data platform. The experimental room and platform are shown in Figs. 4 and 5. The parameters of air conditioner are presented in Table 4. In the PVAC system, the speed of AC compressor can be controlled according to the real-time PV generation. By conducting comparative experiments, researchers could validate the effectiveness of the PVAC model, and the power control strategy proposed in the study. This validation process is essential to ensure that the model and control strategy can be applied in real-world situations and achieve the desired outcomes of improved energy efficiency and thermal comfort in buildings.

4.2. Model validation

The model validation of the PVAC system mainly focused on the cooling load and PV generation in this paper. In this simulation, the ideal air conditioning model was used to obtain the energy consumption of AC. The cooling load is calculated as the product of the power consumed by AC and its coefficient. In the process, the indoor temperature and the setting temperature of AC were 26 °C. The equivalent One-Diode model was employed to simulate the electrical performance of PV system. To verify the validity of the model, the relative error (RE) is used to measure the deviation between the experimental and simulated data, which is calculated by Eq (3):

$$\mathrm{RE} = \left| \frac{X_{sim} - X_{exp}}{X_{exp}} \right| \times 100\% \tag{2}$$

Where X_{sim} is the simulated data, X_{exp} is the experimental data.

The comparison of experimental and simulated results of cooling load is shown in Fig. 6. The changing trend of the cooling load was basically the same in both cases. The average RE of cooling load was 8.64 %. The large gap between experimental and simulated data occurred at the beginning of the operation. When the indoor temperature approaches to the setpoint of AC, the power consumed by AC decreased significantly. However, the power of a specific air conditioner

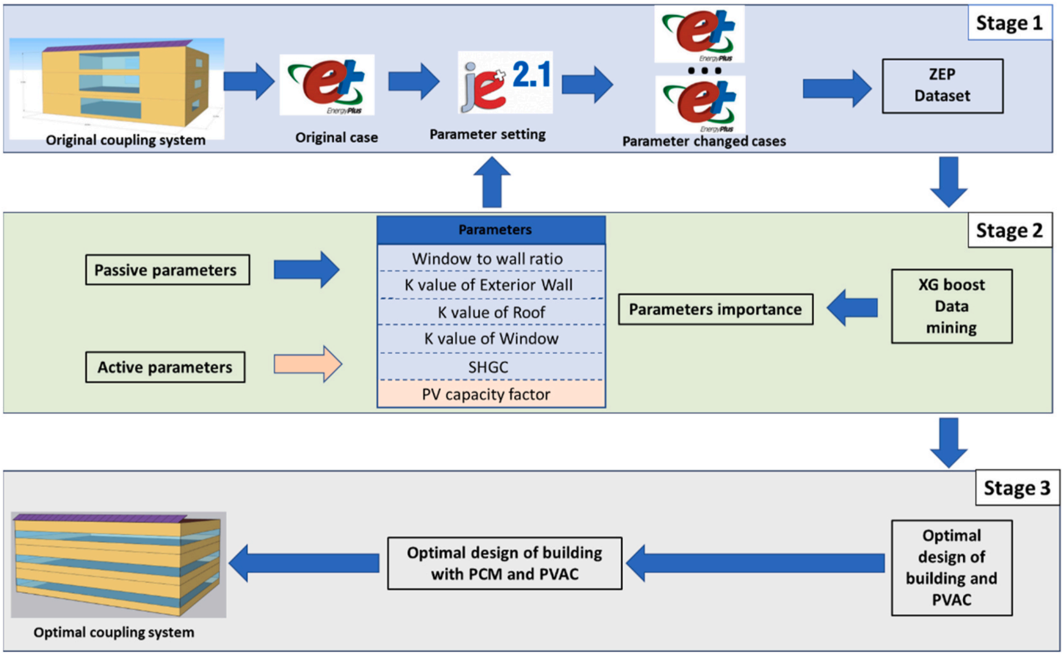

Fig. 3. The optimization framework of PVAC coupled with building design and load flexibility.

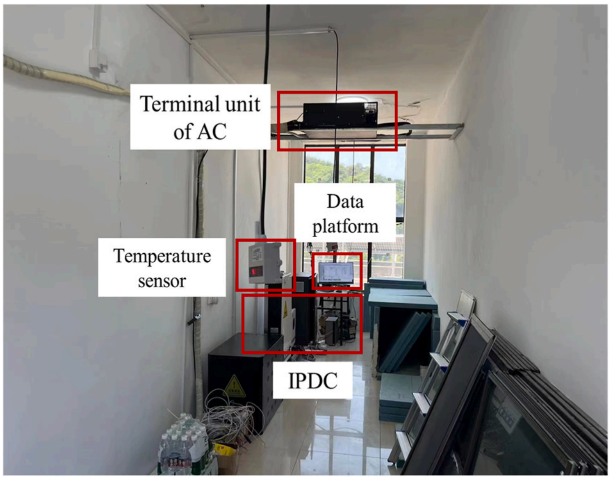

Fig. 4. Experimental room of PVAC.

did not decrease smoothly, resulting in a in a large gap. The average RE of PV generation was 8.64 %. In general, the simulated results of PVAC by EnergyPlus are valid and accurate.

4.3. Feasibility comparison of the PVAC control methods

In this study, the AC consumes all of the real-time electricity generated by the PV system. The indoor temperature, conditioned by the PVAC, is mainly determined by the real-time PV generation. To realize the control strategy, an experimental platform was established. To consume the real-time PV generation as much as possible, we employed a variable-speed compressor in the PVAC system and utilized the Proportional Integral Differential (PID) control method, a classical control technique in air conditioning systems. The PID control adjusts the compressor speed in 1-min intervals, ensuring that the power consumption of the AC system matches the PV generation in real time. When the PV generation is higher than the max value of AC output power, the compressor speed maintains the max value and the excess PV generation can be upload to the utility grid. When the PV generation is lower than the min value of AC output power, the compressor speed maintains the min value and the insufficient electricity can be supplemented by the utility grid.

In this study, the experiment was conducted on two summer days (cloudy and sunny weather conditions) with a time interval of 1 min. The real-time energy matching of PVAC and indoor temperature of two typical day were shown in Fig. 7. The corresponding weather data were recorded in Fig. 8. The outdoor temperature ranges in the test periods were 34.18 °C–39.6 °C and 36.03 °C–39.95 °C. The solar irradiation was also very high in the experimental days.

As shown in Fig. 7, the energy consumption of AC can be regulated timely according to the PV generation at 1 min interval. In the morning, the real-time energy consumption of AC was equal to the PV generation. In the cloudy day, when the PV generation suddenly drops or increases, the AC can quickly adjust the compressor speed to change the energy consumption.

To maximize the self-consumption of the PV generation, the indoor temperature is difficult to maintaining a fixed temperature value. As shown in Fig. 7, The indoor temperatures are lower than the upper limit of TCTR in summer from 9:00 to 16:00. According to Eq (1), the ZEPs of PVAC with fixed indoor temperature were 50 % and 0 in the two days. However, when considering the load flexibility (thermal comfort temperature range), the ZEPs can be correspondingly increased to 70 % and 90 %. In general, the control strategy can effectively improve the real-time energy matching of PVAC in actual application. In the speed range of compressor, the real-time self-consumption of PV system can be close to 100 % while the indoor thermal comfort can be maintained by the PVAC.

Additionally, indoor temperatures were low around noon and gradually rose in the afternoon due to the unreasonable design of building. The area of western surface of the experimental room is 24 m^2. A large area of western wall and window in the room was exposed to significant solar radiation, resulting in higher indoor temperatures during this period. With a suitable building design, the indoor thermal comfort could be satisfied by the PVAC. This phenomenon highlights the importance of building and PV system design optimization.

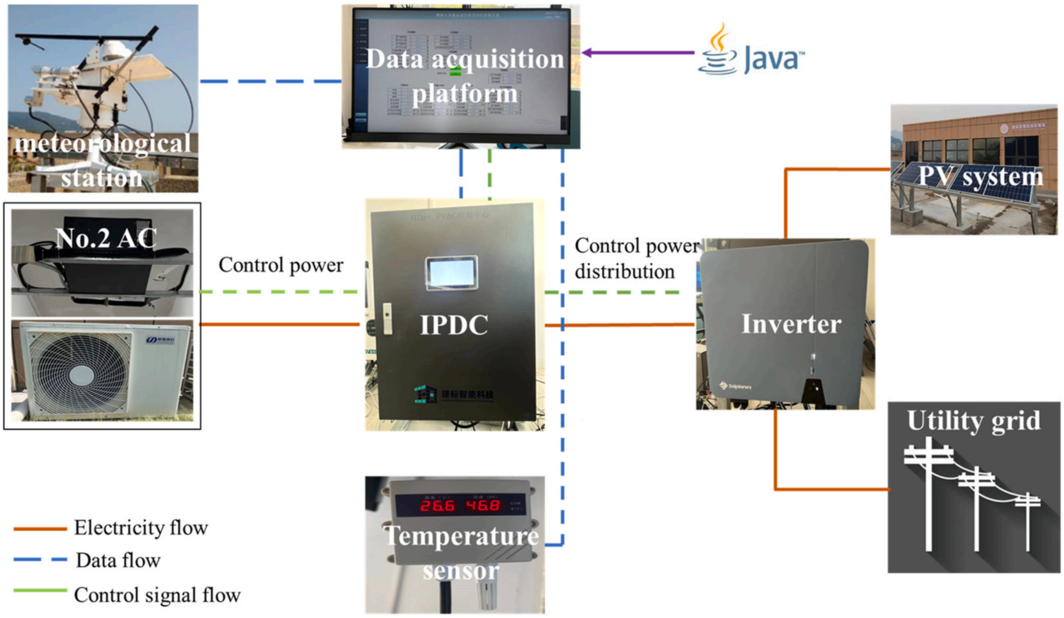

Fig. 5. The scheme and diagrammatic sketch of PVAC system.

Table 4
pecific parameters of air conditioner.

Parameter	Value
Rated cooling capacity (kW)	3.5
Rated air volume （m^3/h）	1000
Rated input power (kW)	1.3

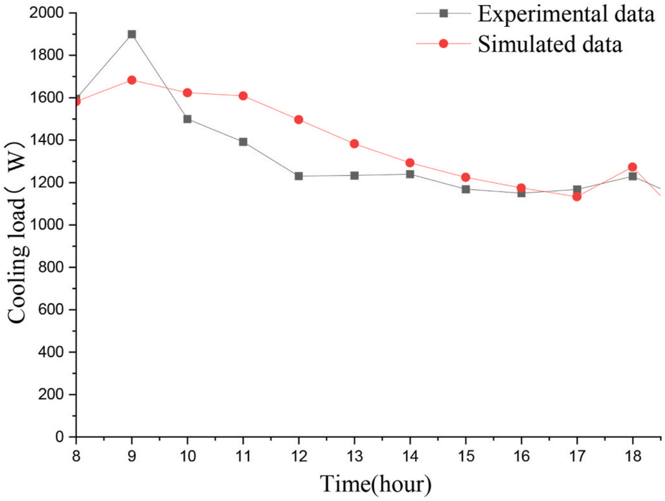

Fig. 6. The comparison of experimental and simulation data of cooling load.

5. Results and discussions

5.1. Sensitivity analysis results

The important score (IS) by XG boost was used to identify the significance of each parameter of the building design and PV capacity. The IS of each parameter in different climatic regions is shown in Fig. 9. According to the data mining results, PV capacity factor (PVF), shape factor (f), and SHGC have the most significant impact on the ZEP of PVAC. In PVAC system applications, a larger PV capacity usually leads to a lower indoor temperature and a higher ZEP value. Comparing the importance scores of PVF in different regions, the impact of PVF on the ZEP in Guangzhou is much higher than that of Shanghai. With a stronger consistency between PV generation and energy consumption of AC, increasing PVF can directly increase the ZEP of PVAC in Guangzhou.

Among building design parameters, the shape factor is the most critical factor for ZEP of the PVAC. A larger shape factor indicates a larger the external surface area per volume, which results in a higher cooling load demand of the building. Under the same PVF, the ZEP value decreases due to the larger shape factor. Except for the shape factor, SHGC of the transparent envelope is another important parameter affecting the ZEP of PVAC. The transparent envelope with a low SHGC may reduce excessive cooling caused by solar radiation heat, which aligns with the findings by Li et al. [48].

In summary, since the consistency between the PV generation and energy consumption of AC is stronger in Guangzhou, the increased PV generation can be directly consumed by AC in time. Enhancing the PV capacity of PVAC is the premier choice to improve the real-time energy matching between the PV system and air conditioners in Guangzhou. In contrast, the consistency has weakened in Shanghai, the increased PV generation cannot be easily consumed by air conditioners in some times. In this region, adjusting building design parameters to change the energy consumption curve can improve the real-time energy matching between the PV system and air conditioners, which is the preferred approach.

Figs. 10–12 quantify the effect of single parameters like PVF, shape factor, and SHGC on ZEP improvement. As shown in Fig. 10, the black and red points represent the PVF and ZEP values, respectively. When the PVF is equal to 1, the ZEP value can increase by 21.3 % and 35.6 % in Guangzhou and Shanghai, respectively, by optimizing the building design in general. When the PVF is 2, the ZEP value can increase by 60 % and 70.7 % in Guangzhou and Shanghai, respectively. The ZEP increasement of the PVAC with a larger PV capacity can be offset by the unreasonable building design. With the same PV capacity, the ZEP value in Guangzhou is lower than that in Shanghai. However, the ZEP growth rate in Guangzhou is higher by increasing same PV capacity. The reason is that the cooling demand is larger and the consistency between PV generation and energy consumption of AC is stronger in Guangzhou. Increasing PV capacity is a more effective method for improving real-time energy matching in Guangzhou.

From Fig. 11, when the shape factor is 0.3, the ZEP value can be

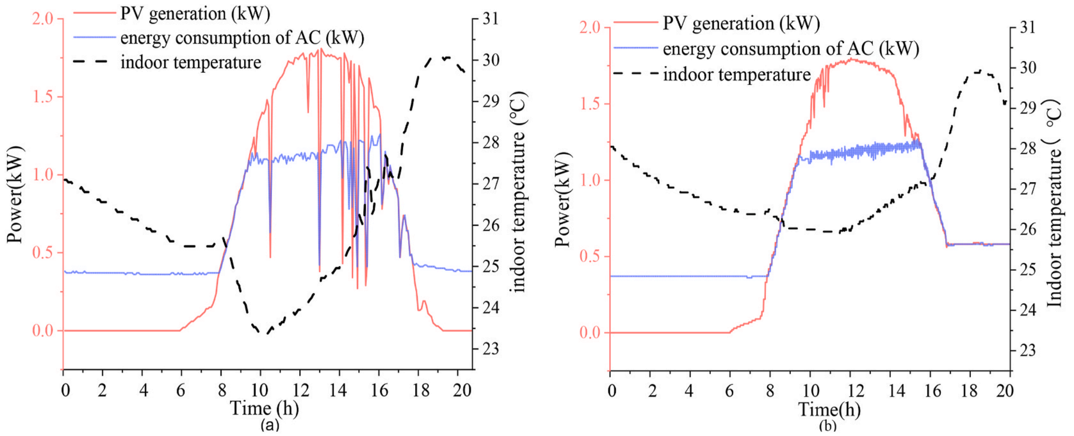

Fig. 7. The variation of P_{pv}, P_{AC}, and indoor temperature (a) Cloudy; (b)Sunny.

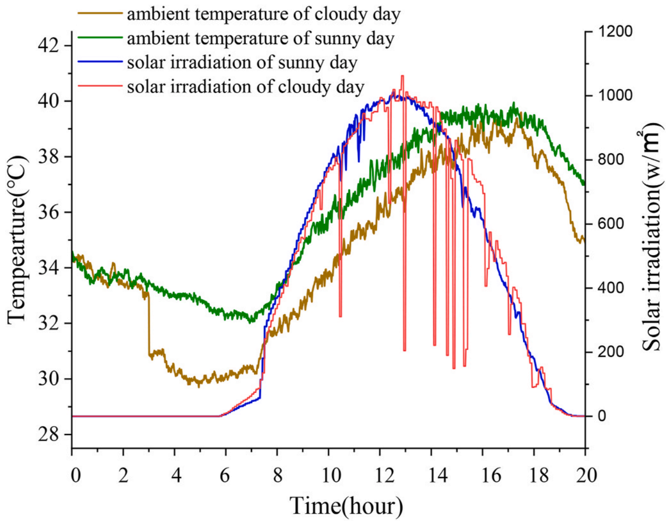

Fig. 8. The actual weather data in test period.

increased by 60 % and 70.7 % in Guangzhou and Shanghai, respectively. When the shape factor reaches 1.1, the ZEP value can only increase by 23.9 % and 39.2 %. With the increase of shape factor, the ZEP values decrease significantly in two regions. Moreover, the ZEP difference of PVAC system in Guangzhou and Shanghai reduce as the shape factor grows. In the simulation, under the fixed height and floor area of the building, the shape factor is changed by gradually increasing the aspect ratio of the building floor. Increasing the shape factor means that the length of the north-south direction increases. The growth of the shape factor greatly increases the heat gain of the building, weakening the effect of increasing PV capacity or optimizing other building parameters on improving real-time energy matching of PVACs. In Guangzhou, the ZEP values decreased significantly by the decrease of PV capacity. For the poor consistency between PV generation and energy consumption of AC, optimizing the building design parameters has greater effect on improving the real-time energy matching of PVACs in Shanghai.

Fig. 12 reveals the effect of SHGC on ZEP improvement. the black and red points represent the SHGC and ZEP values, respectively. The effect of SHGC on ZEP is like the effect of shape factor. The increase of the SHGC allows the windows on the south side to receive more heat, resulting in a corresponding decrease in the ZEP value. Compared to the shape factor, the ZEP value of the system decreases slighter with the increase of SHGC.

In summary, among various building design parameters, shape factor and SHGC have a more significant effect on the real-time energy matching of PVACs in the building. However, as the PV capacity increases, the energy performance of building does not have to be improved to high energy-efficient with a high investment. Under a small

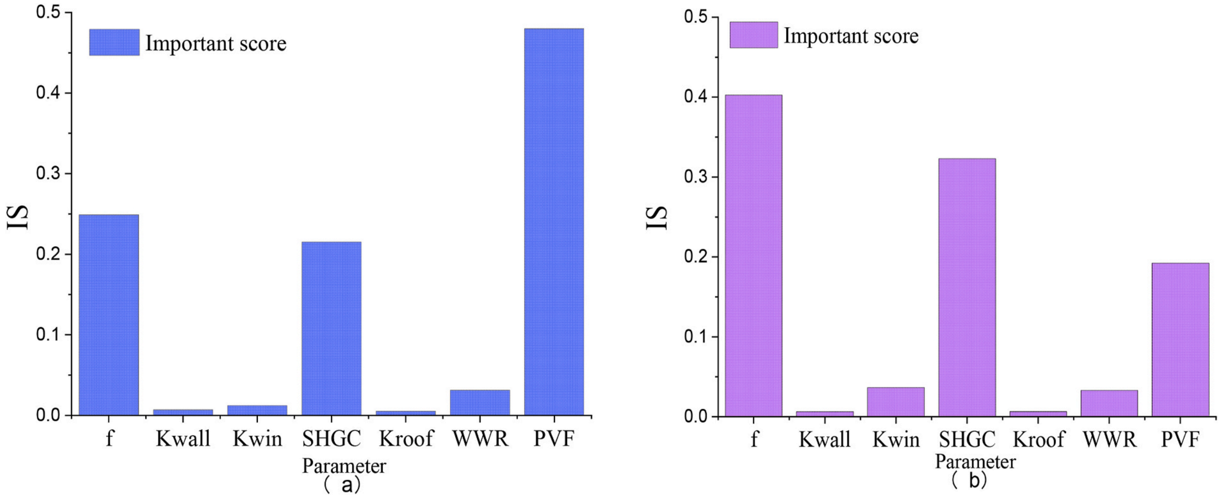

Fig. 9. Importance scores of different parameters by XG boost
(a) Guangzhou; (b) Shanghai.

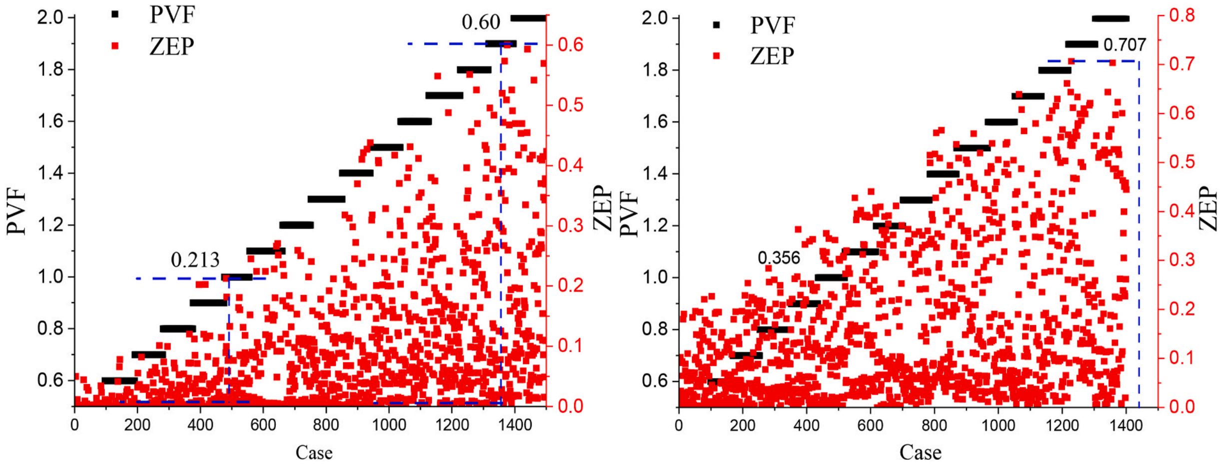

Fig. 10. Influence of PV capacity in different regions.

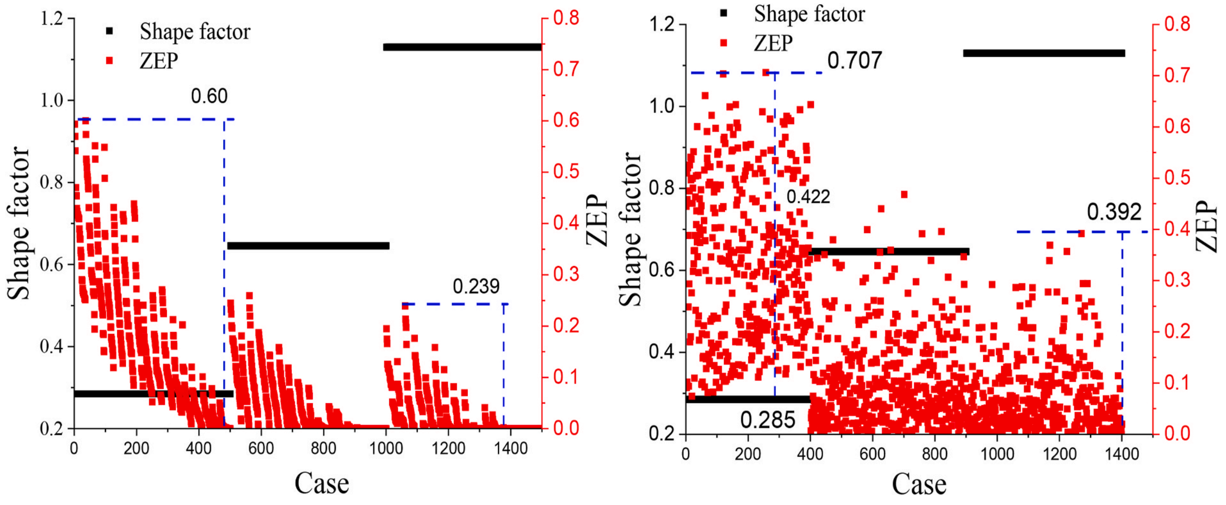

Fig. 11. Influence of shape factor in different regions.

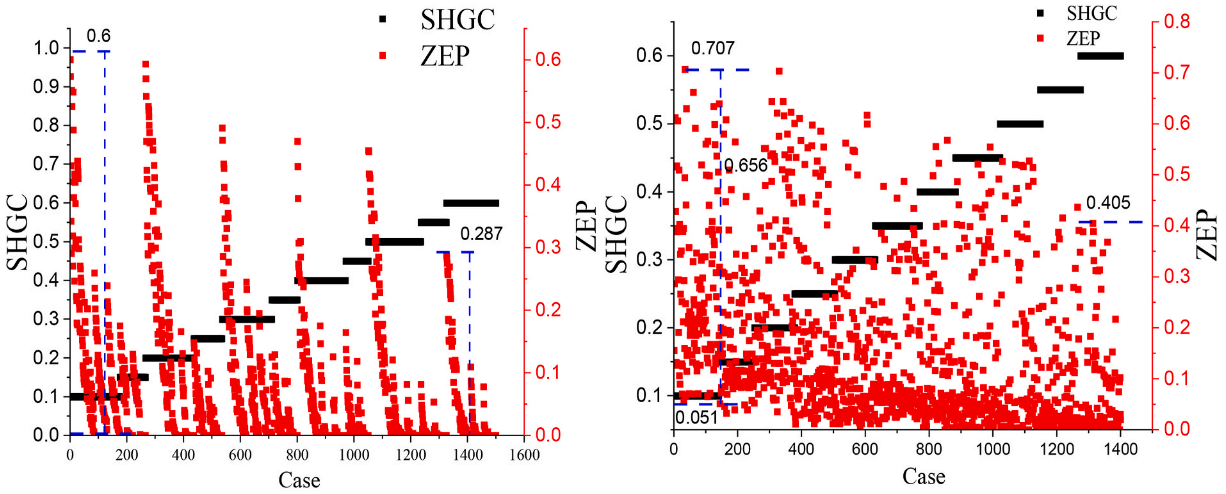

Fig. 12. Influence of SHGC in different regions.

or medium shape factor, there is no need for a strict requirement of other design parameters. The large PV generation can satisfy the energy consumption of AC. Hence, the coordinated optimization for the PV capacity and building design is important to improve the real-time energy matching of PVACs in the building and reduce the burden of utility grid.

5.2. Optimization results with different systems

To improve the real-time energy matching between the PV generation and energy consumption of air conditioner, common choices include considering load flexibility, increasing PV capacity, adding energy storage devices (PCM layer), and changing building design. In the previous studies, the zero energy potential of PVAC coupling with the load flexibility and PCM layers was investigated [47]. The suitable installed place of PCM layer is the interior surface of external wall in the building. To achieve 90 % ZEP, the PVF and the thickness of PCM layer were 1.3 and 0.14m in Guangzhou. In Shanghai, the value of PVF and PCM layer thickness were 1 and 0.12m. The study found that a large amount of PCM was required to achieve 90 % ZEP in both Guangzhou and Shanghai. If the building design parameters can be changed reasonably, the capacity of PCM and PV could be reduced and achieve the same ZEP value.

To conduct a more comprehensive optimization, a comparative analysis of ZEP for different PVAC coupling system were carried out in Guangzhou and Shanghai. In this study, the building type is divided into original and optimized building design. The original building design parameters were determined based on the building standards. The optimized building parameters were obtained by the data mining. Based on different building type, the PVAC coupling system is divided into two types: PVAC coupling with building design and load flexibility (PVAC-B-L) and PVAC coupling with building design, load flexibility and PCM layer (PVAC-B-L-P). The ZEP values of different PVAC coupling system are show in Table 5. In this table, the PVF is 1 in both regions.

As shown in Table 5, the ZEP of PVAC system without any assistance is only 21.8 % in the original office building in Guangzhou. When the building design parameters were optimized, the ZEP value can be increased to 28.1 %. In Shanghai, the ZEP value can be enhanced from 25.7 % to 35.6 % by optimizing building design parameters. Compared with Guangzhou, optimizing the building design parameters has a more obvious effect on increasing ZEP of PVAC system in Shanghai. Based on the original building, the ZEP value can only be improved by 27.7 % and 27.4 % with considering the load flexibility of AC in Guangzhou and Shanghai. Based on the optimized building, the ZEP value can be increased by 55.5 % and 47.4 % in the two regions. In the optimized building, the effect of load flexibility on improving ZEP of PVAC system is more significant. In other words, the optimized building design provides a larger load flexibility to reach a higher ZEP value. Based on the fixed PV capacity, changing the load curve is an efficient method to improve the real-time energy matching in this region. After optimizing the building design parameters and considering load flexibility, the ZEP value of PVACs is close to 90 %. Compared the PVAC coupling with load flexibility and PCM layers in original building, the material usage of PCM should be reduced in the optimized building.

Compared with the original building, the window to wall ratio (WWR) and shaper factor will be changed in the optimized building. Changes in the WWR and shape factor of the building will lead to the application area variation of PCM layer. To investigate the effect of building design optimization on the capacity of PV and PCM, the PVF, PCM thickness and application area were calculated to achieve 90 % ZEP in different regions. As shown in Table 6, the PCM thickness and application area are significantly reduced in both regions. Compared with PVAC coupling system in original building, the PCM capacity can be decreased by 50.4 % and 62.8 % in Guangzhou and Shanghai. Since the cooling load demand in Guangzhou is larger, the PVAC coupling system cannot achieve 90 % ZEP when the PVF is 1 in the original building. Only in the optimized building, the PVAC coupling system can realize nearly zero energy when the PVF is 1.

Table 5
ZEP comparison between different PVAC coupling system.

Region	Building type	ZEP		
		PVAC-B	PVAC-B-L	PVAC-B-L-P
Guangzhou	Original	21.8 %	49.5 %	82.5 %
Guangzhou	Optimized	28.1 %	83.6 %	91.4 %
Shanghai	Original	25.7 %	53.1 %	90.0 %
Shanghai	Optimized	35.6 %	83 %	91.5 %

Table 6
Comparison of PV capacity and PCM of different PVAC coupling system.

Region	Building type	PVF	PCM thickness	PCM area
Guangzhou	Original	1.3	0.14	411.6
Guangzhou	Optimized	1	0.12	294
Shanghai	Original	1	0.12	411.6
Shanghai	Optimized	1	0.1	294

In conclusion, the building design parameters optimization is an efficient method to improve the real-time energy matching of PVAC and reduced the capacity of PV and energy storage. For building types with insufficient PV installed area, such as office buildings, the importance of building parameter design is apparent.

5.3. Economic analysis of different PVAC coupling systems

In this paper, the payback period (PBP) is used to evaluate the economy of different PVAC coupling systems in two climatic regions. The PBP is the length of time it takes to recover the cost of an investment or the length of time an investor needs to reach a breakeven point. The PV installed capacity is 15 kW and 14 kW in Guangzhou and Shanghai. Table 7 shows the PBP of different PVAC coupling system in Guangzhou and Shanghai. Considering the load flexibility control strategy, the payback period of PVAC can be shortened. Compared with Shanghai, the payback period of PVAC system is shorter in Guangzhou for the higher consistency between solar radiation and outdoor temperature. To Shanghai, the payback period PVAC in the optimized building is shorter than that in Guangzhou. The reason is that the building design optimization can improve the real-time energy matching in Shanghai to a large extent. In general, building optimization and considering load flexibility have positive effect increase the system economy.

6. Conclusion

Optimizing the building design, PV capacity, PCM capacity, and considering load flexibility are the common methods to improve energy matching between the PV generation and load demand of building. However, most of studies mainly focus on improving energy matching just from one perspective of energy saving at a large time resolution. With the ever-increasing PV installed capacity, these optimization methods may result in a serious energy mismatching problem between PV generation and energy consumption of AC, placing strain on utility grids or energy storage devices that should receive frequent fluctuation of PV generation. In the new energy background, improving the real-time energy matching of PVAC can be the new goal for the building design optimization. To achieve nearly zero energy of PVAC system, this study proposed a comprehensive optimization method of building design, PV capacity, PCM capacity, and load flexibility, identified the key parameters affecting the real-time ZEP of the building design by XG Boost method, analyzed the coupling characteristics between the

Table 7
Payback period comparison of different PVAC coupling systems.

Region	Building type	Payback Period	
		PVAC-B	PVAC-B-L
Guangzhou	Original	6.33	5.06
Guangzhou	Optimized	6.24	4.64
Shanghai	Original	6.76	5.35
Shanghai	Optimized	5.61	4.99

building design, PV capacity, load flexibility and PCM. The main findings of this research can be summarized as follows.

(1) Building design optimization has proven to be effective to improve the zero energy probability of PVAC system in a building. Since the consistency between the PV generation and energy consumption of air conditioner is not strong in Shanghai, optimizing the building design parameters from the perspective of improving energy matching of PVAC is more important.
(2) Shape factor, SHGC and WWR are the most important factors affecting the real-time energy matching between the PV generation and energy consumption of AC. Notably, the important score of PV capacity in Guangzhou is much higher than that in Shanghai, Increasing PV capacity is the prior method to improve the energy matching of PVAC system.
(3) The optimization of building design is suitable to couple with load flexibility to improve the real-time energy matching of PVAC. Based on the original building, the ZEP value can only be improved by 27.7 % and 27.4 % with considering the load flexibility of AC in Guangzhou and Shanghai. Based on the optimized building, the ZEP value can be increased by 55.5 % and 47.4 % in the two regions.
(4) In general, the building design parameters optimization is an efficient method to improve the real-time energy matching of PVAC and reduced the capacity of PV and energy storage.

The findings from this study can provide invaluable guidance for designing a PVAC system with building design, load flexibility and PCM storage. Identification of important building parameters helps with the prioritization of design factors in the design process.

CRediT authorship contribution statement

Sihui Li: Investigation, Software, Visualization, Writing – original draft. **Jinqing Peng:** Conceptualization, Methodology, Supervision, Project administration. **Meng Wang:** Writing – review & editing. **Kai Wang:** Supervision, Writing – review & editing. **Houpei Li:** Visualization. **Chujie Lu:** Data curation.

Declaration of competing interest

Dear Editor:

The authors declared that they have no conflict of interest to this manuscript. We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

Acknowledgement

This work was supported by Hunan Provincial Natural Science Foundation of China under Grant No. 2023JJ40038 and No. 2022JJ40497, National Natural Science Foundation of China under Grant No. 52108070, National Key R&D Program of China under Grant No. 2022YFB4201003.

References

[1] K. Amasyali, N.M. El-Gohary, A review of data-driven building energy consumption prediction studies, Renew. Sustain. Energy Rev. 81 (2018) 1192–1205, https://doi.org/10.1016/j.rser.2017.04.095.
[2] Y. Chen, Y. Liu, J. Liu, X. Luo, D. Wang, Y. Wang, et al., Design and adaptability of photovoltaic air conditioning system based on office buildings, Sol. Energy 202 (2020) 17–24, https://doi.org/10.1016/j.solener.2020.03.055.
[3] S.M. Bambrook, A.B. Sproul, D. Jacob, Design optimisation for a low energy home in Sydney, Energy Build. 43 (2011) 1702–1711, https://doi.org/10.1016/j.enbuild.2011.03.013.
[4] Y. Lu, S. Wang, Y. Zhao, C. Yan, Renewable energy system optimization of low/zero energy buildings using single-objective and multi-objective optimization methods, Energy Build. 89 (2015) 61–75, https://doi.org/10.1016/j.enbuild.2014.12.032.
[5] H. Li, S. Wang, Coordinated optimal design of zero/low energy buildings and their energy systems based on multi-stage design optimization, Energy 189 (2019), 116202, https://doi.org/10.1016/j.energy.2019.116202.
[6] M. Sahu, B. Bhattacharjee, S.C. Kaushik, Thermal design of air-conditioned building for tropical climate using admittance method and genetic algorithm, Energy Build. 53 (2012) 1–6, https://doi.org/10.1016/j.enbuild.2012.06.003.
[7] Y. Elaouzy, A. El Fadar, Energy, economic and environmental benefits of integrating passive design strategies into buildings: a review, Renew. Sustain. Energy Rev. 167 (2022), 112828, https://doi.org/10.1016/j.rser.2022.112828.
[8] M. Abdul Mujeebu, F. Bano, Integration of passive energy conservation measures in a detached residential building design in warm humid climate, Energy 255 (2022), 124587, https://doi.org/10.1016/j.energy.2022.124587.
[9] M. Ertürk, A. Keçebaş, Prediction of the effect of insulation thickness and emission on heating energy requirements of cities in the future, Sustain. Cities Soc. 75 (2021), https://doi.org/10.1016/j.scs.2021.103270.
[10] H. Teixeira, M. Glória Gomes, A. Moret Rodrigues, D. Aelenei, Assessment of the visual, thermal and energy performance of static vs thermochromic double-glazing under different European climates, Build. Environ. 217 (2022), https://doi.org/10.1016/j.buildenv.2022.109115.
[11] J. Feng, X. Luo, M. Gao, A. Abbas, Y.P. Xu, S. Pouramini, Minimization of energy consumption by building shape optimization using an improved Manta-Ray Foraging Optimization algorithm, Energy Rep. 7 (2021) 1068–1078, https://doi.org/10.1016/j.egyr.2021.02.028.
[12] Q. Al-Yasiri, M. Szabó, Phase change material coupled building envelope for thermal comfort and energy-saving: effect of natural night ventilation under hot climate, J. Clean. Prod. 365 (2022), https://doi.org/10.1016/j.jclepro.2022.132839.
[13] A. Takudzwa Muzhanje, M.A. Hassan, H. Hassan, Phase change material based thermal energy storage applications for air conditioning: review, Appl. Therm. Eng. 214 (2022), 118832, https://doi.org/10.1016/j.applthermaleng.2022.118832.
[14] H. Liu, Y. Pan, Y. Yang, Z. Huang, Evaluating the impact of shading from surrounding buildings on heating/cooling energy demands of different community forms, Build. Environ. 206 (2021), 108322, https://doi.org/10.1016/j.buildenv.2021.108322.
[15] E. Bay, A. Martinez-Molina, W.A. Dupont, Assessment of natural ventilation strategies in historical buildings in a hot and humid climate using energy and CFD simulations, J. Build. Eng. 51 (2022), 104287, https://doi.org/10.1016/j.jobe.2022.104287.
[16] L. Xiao, L.L. Qin, S.Y. Wu, Proposal and application of comprehensive thermal comfort evaluation model in heating seasons for buildings with solar Trombe wall, Appl. Therm. Eng. 213 (2022), 118774, https://doi.org/10.1016/j.applthermaleng.2022.118774.
[17] Y. Lin, L. Zhao, W. Yang, et al., A review on research and development of passive building in China, J. Build. Eng. 42 (8) (2021), 102509.
[18] J. Xu, J.H. Kim, H. Hong, J. Koo, A systematic approach for energy efficient building design factors optimization, Energy Build. 89 (2015) 87–96, https://doi.org/10.1016/j.enbuild.2014.12.022.
[19] W. Wang, R. Zmeureanu, H. Rivard, Applying multi-objective genetic algorithms in green building design optimization, Build. Environ. 40 (2005) 1512–1525, https://doi.org/10.1016/j.buildenv.2004.11.017.
[20] J. Neale, M.H. Shamsi, E. Mangina, D. Finn, J. O'Donnell, Accurate identification of influential building parameters through an integration of global sensitivity and feature selection techniques, Appl. Energy 315 (2022), 118956, https://doi.org/10.1016/j.apenergy.2022.118956.
[21] Z. Zeng, J. Chen, G. Augenbroe, Movable window insulation as an instantiation of the adaptive building envelope: an investigation of its cost-effectiveness in the U.S, Energy Build. 247 (2021), 111138, https://doi.org/10.1016/j.enbuild.2021.111138.
[22] L. Vanhoutteghem, G.C.J. Skarning, C.A. Hviid, S. Svendsen, Impact of façade window design on energy, daylighting and thermal comfort in nearly zero-energy houses, Energy Build. 102 (2015) 149–156, https://doi.org/10.1016/j.enbuild.2015.05.018.
[23] F. Hassan, F. Jamil, A. Hussain, H.M. Ali, M.M. Janjua, S. Khushnood, et al., Recent advancements in latent heat phase change materials and their applications for thermal energy storage and buildings: a state of the art review, Sustain. Energy Technol. Assessments 49 (2022), 101646, https://doi.org/10.1016/j.seta.2021.101646.
[24] M.O.B.C. Melo, L.B. Da Silva, A.S. Coutinho, V. Sousa, N. Perazzo, Energy efficiency in building installations using thermal insulating materials in northeast Brazil, Energy Build. 47 (2012) 35–43, https://doi.org/10.1016/j.enbuild.2011.11.021.
[25] B. Park, W.V. Srubar, M. Krarti, Energy performance analysis of variable thermal resistance envelopes in residential buildings, Energy Build. 103 (2015) 317–325, https://doi.org/10.1016/j.enbuild.2015.06.061.
[26] Y. Chen, Y. Liu, D. Wang, X. Luo, J. Liu, J. Liu, et al., Performance and optimization of a novel solar-driven liquid desiccant air conditioning system suitable for extremely hot and humid climates, Energy Convers. Manag. 215 (2020), 112899, https://doi.org/10.1016/j.enconman.2020.112899.
[27] H. Wu, D. Wang, Y. Liu, et al., Study on the effect of building envelope on cooling load and life-cycle cost in low latitude and hot-humid climate, Procedia Eng. 205 (2017) 975–982.
[28] G.B. Shrestha, L. Goel, A study on optimal sizing of stand-alone photovoltaic stations, IEEE Trans. Energy Convers. 13 (1998) 373–378.

[29] Z. Zhou, L. Feng, S. Zhang, C. Wang, G. Chen, T. Du, et al., The operational performance of "net zero energy building": a study in China, Appl. Energy 177 (2016) 716–728, https://doi.org/10.1016/j.apenergy.2016.05.093.

[30] S. Li, J. Peng, B. Zou, B. Li, C. Lu, J. Cao, et al., Zero energy potential of photovoltaic direct-driven air conditioners with considering the load flexibility of air conditioners, Appl. Energy 304 (2021), 117821, https://doi.org/10.1016/j.apenergy.2021.117821.

[31] R. Yin, E.C. Kara, Y. Li, N. DeForest, K. Wang, T. Yong, et al., Quantifying flexibility of commercial and residential loads for demand response using setpoint changes, Appl. Energy 177 (2016) 149–164, https://doi.org/10.1016/j.apenergy.2016.05.090.

[32] B.Y. Zhao, Z.G. Zhao, Y. Li, R.Z. Wang, R.A. Taylor, An adaptive PID control method to improve the power tracking performance of solar photovoltaic air-conditioning systems, Renew. Sustain. Energy Rev. 113 (2019), https://doi.org/10.1016/j.rser.2019.109250.

[33] S. Wang, D.C. Gao, R. Tang, F. Xiao, Cooling supply-based HVAC system control for Fast demand response of buildings to Urgent Requests of smart grids, Energy Proc. 103 (2016) 34–39, https://doi.org/10.1016/j.egypro.2016.11.245.

[34] N. Mohammad, A. Rahman, Transactive control of industrial heating–ventilation–air-conditioning units in cold-storage warehouses for demand response, Sustain Energy, Grids Networks 18 (2019), 100201, https://doi.org/10.1016/j.segan.2019.100201.

[35] Z. Jiang, J. Peng, R. Yin, M. Hu, J. Cao, B. Zou, Stochastic modelling of flexible load characteristics of split-type air conditioners using grey-box modelling and random forest method, Energy Build. 273 (2022), 112370, https://doi.org/10.1016/j.enbuild.2022.112370.

[36] M. Hu, F. Xiao, L. Wang, Investigation of demand response potentials of residential air conditioners in smart grids using grey-box room thermal model, Appl. Energy 207 (2017) 324–335, https://doi.org/10.1016/j.apenergy.2017.05.099.

[37] F. Ascione, N. Bianco, C.D. Stasio, et al., Multi-stage and multi-objective optimization for energy retrofitting a developed hospital reference building: a new approach to assess cost-optimality, Appl. Energy 174 (jul.15) (2016) 37–68.

[38] M. Hamdy, A. Hasan, K. Siren, A multi-stage optimization method for cost-optimal and nearly-zero-energy building solutions in line with the EPBD-recast 2010, Energy Build. 56 (2013) 189–203.

[39] F. Ascione, N. Bianco, G.M. Mauro, et al., A new comprehensive framework for the multi-objective optimization of building energy design: Harlequin, Appl. Energy 241 (MAY1) (2019) 331–361.

[40] M.S. Javed, J. Jurasz, M. McPherson, Y. Dai, T. Ma, Quantitative evaluation of renewable-energy-based remote microgrids: curtailment, load shifting, and reliability, Renew. Sustain. Energy Rev. 164 (2022), 112516, https://doi.org/10.1016/j.rser.2022.112516.

[41] D. A D, P. B D, A framework for the cost-optimal design of nearly zero energy buildings (NZEBs) in representative climates across Europe, Energy 149 (2018) 814–829.

[42] S. Li, J. Peng, H. Li, B. Zou, J. Song, T. Ma, et al., Zero energy potential of PV direct-driven air conditioners coupled with phase change materials and load flexibility, Renew. Energy 200 (2022) 419–432, https://doi.org/10.1016/j.renene.2022.09.088.

[43] C. Li, J. Tan, T.T. Chow, Z. Qiu, Experimental and theoretical study on the effect of window films on building energy consumption, Energy Build. 102 (2015) 129–138, https://doi.org/10.1016/j.enbuild.2015.04.025.