DOI：10.11835/j.issn.2096-6717.2024.013
开放科学(资源服务)标识码 OSID:

The energy flexibility potential of short-term HVAC system management in office buildings under both typical and extreme weather conditions in China during the cooling season

HUANG Bingjie, LIU Meng, LI Ziqiao

(School of Civil Engineering; National Centre for International Research of Low-Carbon and Green Buildings (Ministry of Science and Technology), Chongqing University, Chongqing 400045, P. R. China)

Abstract: To meet the challenge of mismatches between power supply and demand, modern buildings must schedule flexible energy loads in order to improve the efficiency of power grids. Furthermore, it is essential to understand the effectiveness of flexibility management strategies under different climate conditions and extreme weather events. Using both typical and extreme weather data from cities in five major climate zones of China, this study investigates the energy flexibility potential of an office building under three short-term HVAC management strategies in the context of different climates. The results show that the peak load flexibility and overall energy performance of the three short-term strategies were affected by the surrounding climate conditions. The peak load reduction rate of the pre-cooling and zone temperature reset strategies declined linearly as outdoor temperature increased. Under extreme climate conditions, the daily peak-load time was found to be over two hours earlier than under typical conditions, and the intensive solar radiation found in the extreme conditions can weaken the correlation between peak load reduction and outdoor temperature, risking the ability of a building's HVAC system to maintain a comfortable indoor environment.

Keywords: energy flexibility; demand-side management; extreme weather; HVAC systems; thermal requirements

中国典型与极端天气下制冷季办公建筑空调系统短期管理柔性用能潜力

黄炳杰，刘猛，李子桥

（重庆大学 土木工程学院；国家级低碳绿色建筑国际联合研究中心，重庆 400045）

摘　要：在电力供需不匹配的挑战下，需要对建筑实行柔性负荷调度以改善电网的协调性。气候变化造成日益增多的极端天气和气候活动，了解不同气候条件下柔性管理策略的效果至关重要。采用中国五大气候区代表城市的典型与极端天气数据，研究办公建筑在3种短期暖通空调管理策略下的柔性用能潜力，旨在发掘不同策略在中国不同地区及室外气候条件下的效果。结果表明，3种短期策略下，峰值负荷柔性与总能耗表现受室外气候条件影响；预冷及温度调节策略的峰值负荷降低率随户外温度升高呈线性下降；在极端气候条件下，峰值负荷出现时间较典型情况提前2 h以上，极端条件下的强烈太阳辐射可能导致峰值负荷降低率与室外温度的相关性降低，同时降低

Received: 2023-11-11

Foundation item: National Key R & D Program of China of the 13th Five-Year Plan (No. 2018YFD1100704)

Author brief: HUANG Bingjie (1999-), main research interest: building energy flexibility, E-mail: 202116131370@stu.cqu.edu.cn.

LI Ziqiao (corresponding author), PhD, research associate, E-mail: z.li@cqu.edu.cn.

室内热舒适。

关键词:柔性用能;需求侧管理;极端天气;暖通空调系统;热需求

中图分类号:TU831.2 **文献标志码:**A **文章编号:**2096-6717(2025)04-0157-15

1 Introduction

The simultaneous growth in global population and urbanization has resulted in a marked increase in urban energy demand over the past several decades. Furthermore, many societies must now confront issues of sustainability and other problems caused by reliance on fossil fuels, such as energy shortages, greenhouse gas emissions and health problems[1]. Mitigating greenhouse gas emissions and reducing fossil fuel usage have become priorities for many countries, and more than 454 cities and 23 regions have committed to achieving zero carbon emissions by the 21st century[2]. China aims to reach its "carbon peak" by 2030 and carbon neutrality by 2060. As a result, renewable energy sources are being developed rapidly to replace conventional energy ones. However, the nature of many renewable energy sources can lead to undesirable changes in energy supply structures[3]. Due to its intrinsic variability, renewable energy often exacerbates the discrepancy between energy supply and demand and aggravates the fluctuations in net system load[4], causing unexpected curtailment rates[5]. To meet the challenge of this potential mismatching between supply and demand, flexible load scheduling is required in order to improve the efficiency of power grids[6].

Buildings represent a large portion of the world's energy consumption and associated CO_2 emissions, consuming around 40% of total energy usage in developed countries[7]. Since the energy demand of a building can be shifted in time, a large potential for energy flexibility can be achieved by low-carbon design and energy-efficient operation in buildings, which can in turn provide better power grid management. The term "building energy flexibility" is defined by Annex 67 as "the ability to manage a building's demand and power generation according to local climate conditions, user needs, and energy network requirements"[3]. Lu et al. [8] have summarized the general approach to achieving energy flexibility, including demand-side management, demand response, and the flexible control of resources. Under the building energy flexibility approach, Shan et al. [9] highlight four types of flexible management strategies that can be used in buildings' demand-response processes, including demand limiting, demand shedding, demand shifting and on-site generation. Identifying building power usage characteristics is one of the most critical steps for revealing a building's energy flexibility. To this end, with their large proportion of energy utilization and schedulable operation control, the ability of HVAC systems to shift on-peak electricity demand and alleviate short-term demand-supply mismatch events has attracted increasing research attention[10].

HVAC operation is regarded as the most influential energy consumer in buildings. In office buildings alone HVAC operation can create a −15% to 70% variation in building energy consumption annually[11]. Thus, applying different control strategies to building HVAC systems can lead to considerable benefits in demand side management, and this flexibility potential can be further enhanced by integrating HVAC systems with occupant behaviour control strategies, and building thermal mass and thermal energy storage systems[12]. For example, Malik et al. [13] found that more than half of the total air-conditioners monitored in Australia had shown intensive energy usage during on-peak periods, indicating a considerable demand response potential. Although the ability of HVAC systems to cut down peak-time power loads has been postulated, occupant thermal comfort ("user needs") should not be adversely compromised under building energy flexibility management. As a result, precooling/preheating and zone temperature resets are typical methods used in HVAC operation control that enable energy flexibility and ensure that room temperatures are within a comfortable range.

Existing studies have already reported on the benefits of precooling/preheating and zone temperature reset. As a natural thermal storage source, building thermal mass is often an integral part of energy flexibility strategies. As the most straight forward approach to achieving demand shedding, directly switching off HVAC cooling/heating units commonly responds quickly to a shedding signal without affecting occupants' short-term thermal comfort[14]. However, unbalanced cooling distribution issues and the instability of zone/space thermal environments should be considered in how to maintain spaces within the comfort range when HVAC systems is partly off[15].

To minimize the risk of unacceptable thermal environments during the demand-response period, researchers have looked into the effectiveness of zone temperature resets. Chen et al. [12] quantified the energy flexibility of a maximum peak power reduction by up to 25% of the maximum cooling power demand. Furthermore, by simultaneously resetting zone air temperature, supply air temperature, chilled water temperature and condenser water temperature, the short-term curtailment approach can reduce building cooling demand by 23%-47%, depending on occupant comfort limits[16]. Wang et al. [17] investigated the spinning reserve capacity of a rising room air temperature setpoint (up to 3 ℃) in Hong Kong and reported a link between reserve capacity and temperature rise that contributed more than 68% to the spinning reserve capacity required by the power grid in Hong Kong. In addition to HVAC systems and building thermal mass, outdoor weather is also a factor that influences a building's energy flexibility. For example, Yin et al. [18] simulated the hourly demand response potential of indoor air temperature setpoint resets in both commercial and residential buildings, and the results highlighted the decreased demand response potential in the presence of extreme outdoor air temperatures.

Additionally, one typical precooling/preheating strategy utilizes the thermal charging capacity of building thermal mass to shed/store heat before the occupied period or demand response period, and this is more commonly applied in commercial buildings with larger building thermal mass and more dynamic incentives to lower/shift peak demand[19]. Xu et al. [20] reported that the precooling strategies can reduce chiller power by 80% during on-peak hours in office buildings without thermal comfort complaints. Jiang et al. [21] likewise developed a deep reinforcement learning framework to reduce HVAC electricity cost and peak demand of a single-zone office building that was able to save 6%-8% of monthly electricity costs, and Hu et al. [22] developed a thermal-based self-learning model to examine the demand response potential of residential air conditioners. These latter results revealed that the combination of room temperature reset and precooling was able to reduce electricity consumption by 26% during the peak-time period of a typical summer day without sacrificing indoor thermal comfort. However, the effectiveness of precooling strategies on building load shifting is also influenced by contextual factors.

For example, Stopps et al. [23] examined the load-shifting capacity of a pre-conditioning strategy in high-rise residential buildings using HVAC runtime data and found that the overall impact on load demand reduction was not effective. However, the load-shifting potential of the pre-conditioning strategy varied in suites with different orientations. Similarly, Turner et al. [24] evaluated the electricity load-shifting potential of integrating precooling and building thermal mass. They found that although the precooling could effectively shift on-peak cooling load, its effectiveness was largely dependent on climate zone and local outdoor weather.

Growing numbers of extreme weather and climate events have been reported[25], especially high daily outdoor temperatures[26]. Dai et al. [27] compared the differences in AC usage behavior in China between the extremely hot summers and normal summers and found differences between both the frequency of use and the duration of operation by air conditioner users in each type of summer. Considering the theory of building thermal dynamics, HVAC energy consumption and indoor thermal conditions can be largely influenced by the outdoor thermal environment, which can result in the effectiveness of building energy flexibility that relies on precooling/preheating and zone temperature reset strategies.

Previous studies relevant to building energy flexibility and demand response mainly focus on the flexibility potential of a given strategy and its corresponding effects on indoor thermal comfort. Although the effects of certain energy flexibility strategies could be various due to the variation of climate and building structure, the performance and applicability of energy flexibility strategies under different climate conditions are nonetheless understudied. Hence, the novelty of this article is to evaluate building energy flexibility potential under different local outdoor climates and local building regulations on building envelops in China specifically, including one extreme weather condition. Three flexibility strategies are studied, including pre-cooling, zone-temperature reset, and partial shutdown. The energy flexibility under five typical climate zones and one extreme climate condition are compared. The following section first describes the details of simulation modeling and data input. Section 3 then analyzes the energy flexibility of three typical flexibility strategies under various local climates and extreme weather conditions, followed by a discussion regarding the effect of outdoor climate on building energy flexibility in Section 4.

2 Methods

To evaluate the energy flexibility of office buildings with typical HVAC flexibility management strategies in the different climate conditions of China, we simulated the HVAC power load shifting and shedding potential in the cooling season (July and August) of a real prototype office building in five major climate conditions and one extreme climate condition, considering three previously mentioned typical short-term HVAC flexibility management strategies.

2.1 Energy flexibility indicators

Methods of assessing energy flexibility have been established by existing studies to quantify building energy flexibility. However, the energy flexibility indicators used in these quantification methods vary depending on building control objectives. Lu et al. [8] have summarized the main energy flexibility indicators for evaluating flexibility capacity by considering building power/energy reduction[22], financial cost[28], CO_2 emission[29], building thermal mass[30], and renewable energy generation[31]. In this study we use three indicators to assess the energy flexibility of HVAC flexibility-management strategies under different outdoor climate conditions, including peak load reduction rate during the on-peak period, energy consumption reduction rate, and the ratio difference of peak load during the on-peak period. The parameters adopted to build the flexibility indicators are shown in Fig. 1.

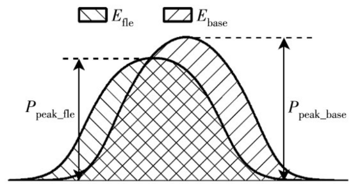


Fig. 1 The energy flexibility indicators used

Peak load reduction rate during the on-peak period (F_P is adopted to indicate the load shedding ability of a given flexibility control strategy (Eq. (1)), and energy consumption reduction rate (F_E) illustrates the difference in the overall HVAC energy consumption before and after applying flexibility management strategies (Eq. (2)).

$$F_P=\frac{P_{peak\_base}-P_{peak\_fle}}{P_{peak\_base}}\times 100\% \tag{1}$$

where, F_P is peak load reduction rate during the on-peak period (2:00 PM to 6:00 PM as identified in this study) (%), and P_{peak_base} and P_{peak_fle} are the peak loads of the baseline case and the flexibility case (kW), respectively.

$$F_E=\frac{E_{base}-E_{fle}}{E_{base}}\times 100\% \tag{2}$$

where, F_E is the rate of reduction of energy consumption of the HVAC system (%), and E_{base} and E_{fle} are the energy consumption of the HVAC system for the baseline case and the flexibility case (kW·h), respectively.

Apart from the potential of lowering peak load and overall energy consumption, a system's load-shifting ability is also an important indicator for assessing the effectiveness of a flexibility strategy. For this purpose we use "the reduction rate of peak load during the on-peak period" to present the energy flexibility of the peak load shifting of the baseline case and the flexibility case (Eq. (3)).

$$F_R=\frac{R_{on\text{-}peak\_base}-R_{on\text{-}peak\_fle}}{R_{on\text{-}peak\_base}}\times 100\% \tag{3}$$

where, F_R is the difference in the ratio of peak load during the on-peak period (2:00 PM to 6:00 PM as identified in this study) (%), and $R_{on\text{-}peak\_base}$ and $R_{on\text{-}peak\_fle}$ are the ratios of peak load during the on-peak period of the baseline case and the flexibility case, respectively.

2.2 Local weather conditions

China spans across several climate zones. Its national code *Code for Thermal Design of Civil Building* (GB 50176—2016) divides China into five major climate zones, the severe cold (SC) zone, the cold zone, the hot summer and cold winter (HSCW) zone, the hot summer and warm winter (HSWW) zone, and the temperate zone, which are classified by the average temperature of the coldest month (January) and the hottest month (July) historically. To evaluate the energy flexibility of office buildings in different climate zones under different flexibility control strategies, we used the average annual weather data of five typical cities in the five climate zones: Harbin for the SC zone, Beijing for the cold zone, Chongqing for the HSCW zone, Kunming for the temperate zone, and Guangzhou for the HSWW zone.

The Chinese Standard Weather Data (CSWD) was used for simulations of typical weather conditions as it has already been used extensively in building energy simulation studies in China. Although CSWD data represent the long-term means regarding weather variables, there certainly is real-world variance from year to year[32]. In addition, in order to assess the impact of extreme weather on building energy flexibility, we used the measured weather data collected in the extremely hot summer (July and August) of 2022 in Chongqing, China (HSCW zone), during which the consecutive days with a maximal outdoor temperature higher than 35 ℃ numbered 32. Researchers have yet to reach a consensus as to what constitutes the extremely hot period. However, the most common one adopted is the period of at least three consecutive days with a daily maximal outdoor temperature higher than 35 ℃ [27, 33].

2.3 Building and simulation description

A prototype building model was established in EnergyPlus software based on an actual office building. This building has 27 stories with an occupied area (HVAC operating) of 40 068 m^2. The model and floor layout are shown in Fig. 2.

To simplify the simulation process, we divided the building layout into eight occupied zones depending on four building orientations. The envelope structure thermal performance of this building prototype is based on the regulations for buildings that are subject to trade-off judgement in *General code for energy efficiency and renewable energy application in buildings* (GB 55015—2021)[34]. The simulated building's shape coefficient and window-wall ratio are 0.1 and 0.6, respectively, which satisfies the requirements in GB 55015—2021. Since the building design code is different for each climate zone, the thermal characteristics of the prototype building in each climate zone are listed in Table 1, and they all satisfy the local building energy efficiency standards in GB 55015—2021.

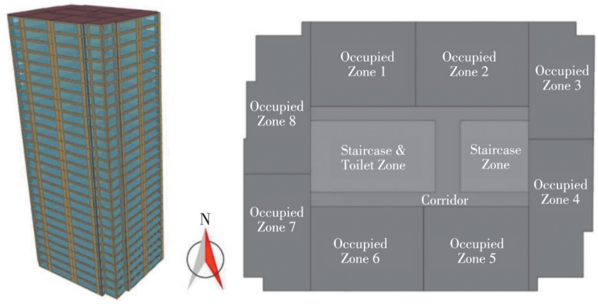


Fig. 2　Views of the building model and floor layout

The internal disturbance and schedule of this model also followed the regulations in GB 55015—2021. The occupant density was set to 10 m^2/person, and the power density of lighting and equipment are 9 W/m^2 and 8 W/m^2 respectively. The occupancy, lighting, and electrical equipment usage profile can be found in Fig. 3. Finally, the chiller and ventilation systems of the HVAC system were set to operate from 07:00 to 19:00 with the indoor temperature setpoint at 26 ℃ on working days.

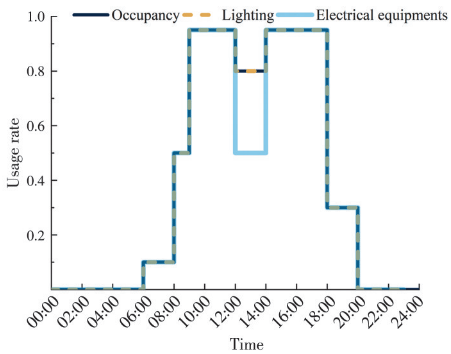


Fig. 3　Occupancy, lighting, and electrical equipment usage rate schedules

2.4 Energy flexibility strategies

As mentioned above, rescheduling an HVAC system's operation profile is an effective approach to achieve flexibility in load shifting and shedding, particularly when integrated with a passive thermal storage source such as building thermal mass[35]. To as-

Table 1 Thermal characteristics of the prototype building under different weather conditions

Climate zone	City condition	U/[W/(m²·K)]			Thermal inertia index D		Window Solar Heat Gain Coefficient
		External wall	Window	Roof	External wall	Roof	
SC	Harbin	0.34	1.4	0.25	3.59	3.24	0.35
	Harbin limit	≤0.35	≤1.4	≤0.25			
Cold	Beijing	0.48	1.8	0.4	3.22	2.74	0.35
	Beijing limit	≤0.5	≤1.8	≤0.4			≤0.35
HSCW	Chongqing	0.75	2.1	0.4	2.9	2.74	0.3
	Chongqing (extreme)	0.75	2.1	0.4	2.9	2.74	0.3
	Chongqing limit	≤0.8	≤2.1	≤0.4	>2.5	>2.5	≤0.3
HSWW	Guangzhou	1.45	2.4	0.4	2.61	2.74	0.2
	Guangzhou limit	≤1.5	≤2.4	≤0.4	>2.5	>2.5	≤0.2
Temperate	Kunming	1.45	2.5	0.55	2.61	2.52	0.3
	Kunming limit	≤1.5	≤2.5	≤0.8	>2.5	>2.5	≤0.3

sess the effect of outdoor climate on the energy flexibility potential of short-term HVAC management in office buildings, this study concentrates on three typical energy flexibility strategies under different local summer climate conditions, including pre-cooling, zone temperature reset, and partial shutdown. The requirement of indoor thermal comfort during the occupied period is considered in the analysis of the flexibility strategy application.

Under the baseline case, the office building is occupied from 08:00 to 18:00 from Monday to Friday. The chiller is operated from 07:00 to 18:00 on workdays, and the ventilation system is shut down one hour later (07:00 to 19:00) to secure indoor air quality. The indoor temperature setpoint is set to be 26 ℃ for occupied areas on working days during the cooling season (July and August).

The basic chiller and ventilation system operation schedules under the three flexibility strategies are the same as the baseline case. However, each flexibility case adopts one HVAC setting adjustment scheme, as shown in Table 2.

Table 2 HVAC settings for the different flexibility strategies

Flexibility strategy	07:00—13:00	13:00—18:00 (on-peak period)
Pre-cooling	24 ℃	28 ℃
Zone-temperature reset	26 ℃	28 ℃
Partial shutdown	26 ℃	Off

Current research mostly uses the time range prior to operating hours or the valley period before peak demand as the pre-cooling period[4, 20, 24]. For office buildings[20], the pre-cooling period is typically set to be from 05:00 to 14:00. Therefore, under the pre-cooling case, the indoor temperature setpoint in occupied areas was set to be 24 ℃ until 13:00, before the peak hours, then to 28 ℃ from 13:00 to 18:00 on workdays.

Under the zone-temperature reset case, the indoor temperature setpoint in occupied areas was automatically reset from 26 ℃ to 28 ℃ for 5 hours from 13:00.

Under the partial shutdown case, the simulated building was closed to deal with a simulated emergency event. Considering that the effect of solar heat gain and building thermal mass discharging on building flexibility can be impacted by building orientation and local solar radiation, we simulated the strategy of partially shutting down the HVAC systems of indoor zones facing west and occupancy in these zones was set to unoccupied. The shutdown schedule was from 13:00 until the end of the day, and the HVAC system operation schedule and occupancy in the remaining zones was unchanged relative to the baseline case.

2.5 Typical and extreme climate conditions

The hourly average outdoor dry bulb temperature of five major climate zones and one extreme hot condition in July and August is summarized and shown in Fig. 4. Based on this, Kunming in the temperate climate and Harbin in the SC climate present the lowest outdoor temperatures, and Chongqing, Guangzhou, and Beijing cities present the highest outdoor temperatures during the cooling season. As expected, the hourly average outdoor dry bulb temperature of the Chongqing extreme condition was the highest among all conditions. Fig. 5 demonstrates the hourly outdoor dry bulb temperature ratio of all conditions. Those above 35 ℃ account for nearly 40% of total summer hours in the Chongqing extreme summer condition. On the contrary, the outdoor dry bulb temperatures in the five typical climate conditions are mostly lower than 30 ℃.

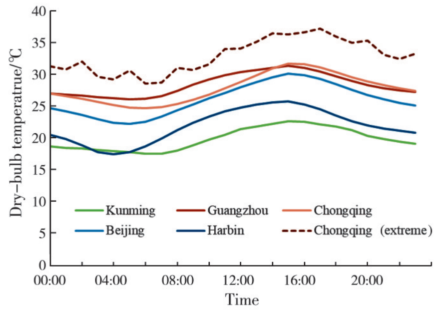


Fig. 4　Hourly average outdoor dry bulb temperature of five typical conditions and one extreme condition

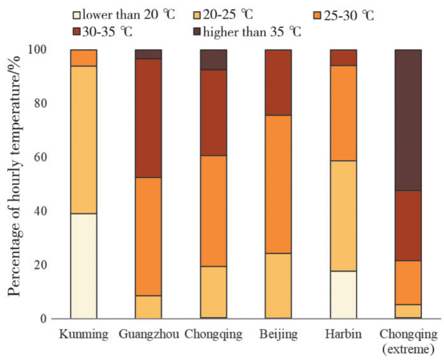


Fig. 5　Percentage of hourly outdoor dry bulb temperature of five typical conditions and one extreme condition

Fig. 6 compares the hourly average total solar radiation of all climate conditions in July and August, and we can see that the distribution of total solar radiation of five cities in typical climate conditions is similar. For the extreme condition case, the overall total solar radiation is obviously higher than other typical climate conditions; the peak total solar radiation at noon is over 200 W/m^2 higher than that of other conditions. Again, the extreme summer condition of Chongqing presents a proportion of total solar radiation higher than 550 W/m^2 than other conditions, as shown in Fig. 7.

To quantify the cooling demand of different climate conditions, the monthly cooling degree days during the cooling season (July and August) based on 26 ℃ (CDD26) are shown in Table 3. With the continuously hot outdoor condition, the cooling degree

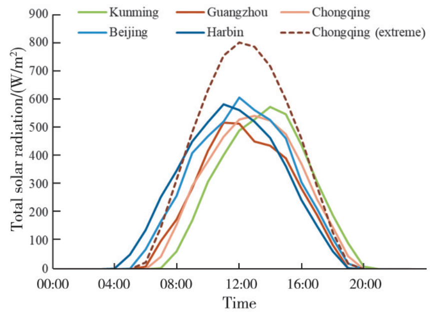


Fig. 6　Hourly average total solar radiation of five typical conditions and one extreme condition

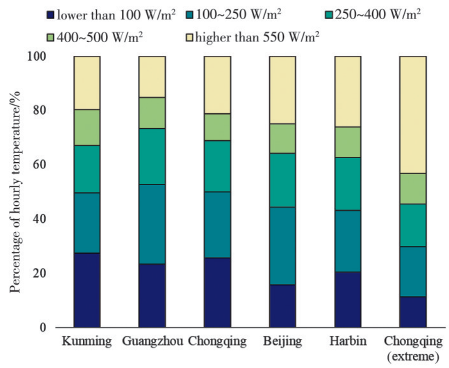


Fig. 7　Percentage of hourly average total solar radiation of five typical conditions and one extreme condition

Table 3　Cooling degree days in five cities with typical and extreme outdoor climates

City	Climate condition CDD26
Kunming	0
Guangzhou	155
Chongqing	133
Beijing	48
Harbin	6
Chongqing (extreme)	438

day in Chongqing extreme climate condition was much higher than the other conditions, which indicates a stronger cooling demand.

As previously mentioned, the outdoor thermal conditions of five cities in different climate zones present discrepancies in amplitude and temporal scale due to geographic location, which may potentially result in a difference in load shifting/shedding effectiveness when applying the same energy flexibility strategies. Furthermore, a considerable discrepancy was found in the outdoor temperature and solar radiation between Chongqing typical and extreme summer conditions. Thus, this intensive outdoor thermal condition may potentially impact the final performance of energy flexibility strategies.

3 Results

In this section, we compare the overall energy consumption characteristics in different climate zones in order to reveal the load shifting/shedding potential of the three flexibility management strategies (as in Fig. 3). The prototype building's baseline HVAC operation power loads in the five cities are shown in Fig. 8. The patterns of the HVAC power loads were similar, experiencing a surge at the beginning and reaching stable level during the occupied period. Since this study mainly investigates flexibility during the on-peak period, the focus is on the HVAC operation management during the occupied period (08:00 to 18:00).

In the baseline cases, the peak power load of HVAC systems mainly appeared in afternoons (the on-peak period), though a slight decrease in HVAC power load was observed at noon due to lower occupancy. Fig. 9 compares the differences in peak power load time, peak load, and energy consumption of the 6 total climate conditions. For Guangzhou, Chongqing, Beijing, and Harbin, peak power loads mostly appeared between 12:00 to 17:00, with the median time landing around 15:00. The peak loads in the Chongqing extreme condition occurred slightly earlier, and that of Kunming was later. The daily peak power loads of the HVAC systems were about 1 000 kW in Guangzhou, Chongqing, and Beijing, which were higher than those of Harbin and Kunming. The Chongqing extreme condition presented the highest peak loads at 1 157.21 kW. The trend of daily HVAC energy consumption in the five cities was similar to the trend of peak power load in the cooling season.

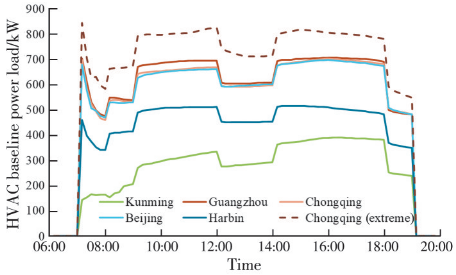
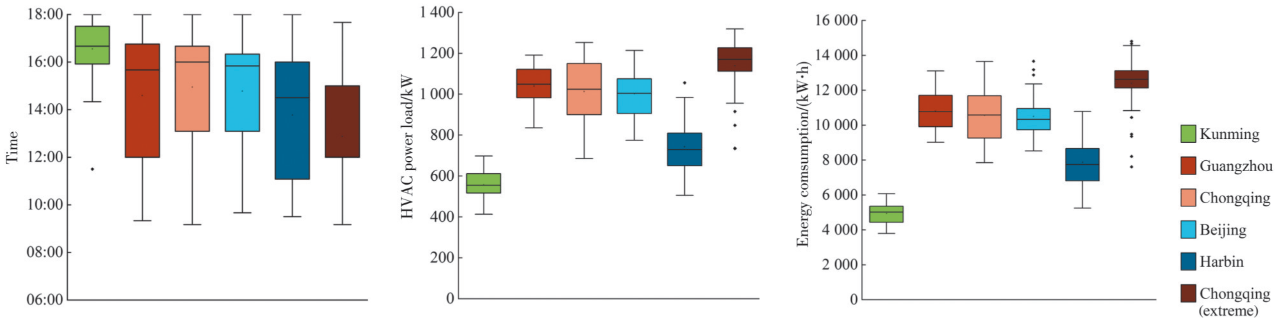


Fig. 8 Baseline power load of five cities with typical climate conditions during the cooling season



(a) Peak power load occuring time (b) Daily peak power load (c) Daily HVAC energy consumption

Fig. 9 Peak-load time, peak load and energy consumption under typical climate condition

3.1 The flexibility of pre-cooling strategy

The pre-cooling strategy sets the indoor temperature setpoint 2 ℃ lower until 13:00, then 2 ℃ higher from 13:00 to 18:00 on working days. Fig. 10 shows the corresponding seasonal average HVAC power load difference between the pre-cooling and baseline cases in the six climate conditions.

Based on loads in Fig. 10, with increased power load, the pre-cooling strategy reduced the HVAC power load during the on-peak period (14:00—18:00) in all climate conditions, but the flexibility capacity of pre-cooling strategy varied from city to city.

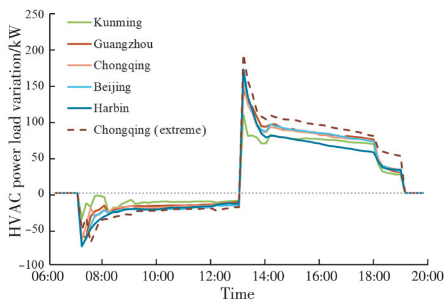


Fig. 10 Average HVAC power load difference between pre-cooling and the baseline case for the six conditions

Based on Equations (1)-(3), the results of three energy flexibility indicators (peak load reduction rate, energy consumption reduction rate, and the ratio difference of peak load during the on-peak period) are shown in Table 4. The Pre-cooling strategy largely reduced the peak load during the on-peak period without adversely increasing HVAC energy consumption. Additionally, the pre-cooling strategy's average peak load reduction was 15% to 23%, which was lower when the outdoor climate was warmer. With lower outdoor temperatures during the cooling season, the pre-cooling strategy in Kunming and Harbin cities showed higher energy flexibility with better load shedding capacity, though they also had higher energy consumption. Although the HVAC power load of Chongqing in the extreme condition was higher than that of the typical conditions, the average daily power load reduction rate and the energy consumption reduction rate showed no significant difference.

Table 4　Flexibility indicators for the pre-cooling strategy during the cooling season

City	F_E	F_P	F_R/%
Kunming	−1.45%(±1.36%)	22.99%(±1.70%)	100
Guangzhou	−0.91%(±0.69%)	16.22%(±2.21%)	100
Chongqing	−0.71%(±1.18%)	15.41%(±1.92%)	100
Beijing	−1.00%(±0.90%)	15.99%(±1.69%)	100
Harbin	−1.41%(±1.44%)	19.81%(±2.75 %)	100
Chongqing (extreme)	−0.90%(±1.20%)	16.06%(±1.27%)	100

Note: The number in the parentheses is the standard deviation.

Although the pre-cooling strategy effectively reduced and shifted the peak load, the proportion of indoor PMV in the comfortable range ($-0.5 < PMV < 0.5$) dropped significantly due to the cooler outdoor climate (Fig. 11), Kunming experienced an increased proportion of PMV being lower than −0.5, but an increased proportion (about 40%) of "slightly warm" sensations were observed in other conditions. However, an increase in the possibility of an unacceptable thermal environment was observed in the Chongqing extreme condition that was 12% higher than that of the typical condition.

3.2　The flexibility of the zone temperature reset strategy

The zone temperature reset strategy reset the indoor temperature setpoint in occupied areas from 26 ℃ to 28 ℃ for 5 hours from 13:00 on workdays. Fig. 12 shows the seasonal average HVAC power load difference between the zone-temperature reset and baseline cases in the six climate conditions. We can see that the power load decreased after 13:00 when the zone temperature was reset to 28 ℃.

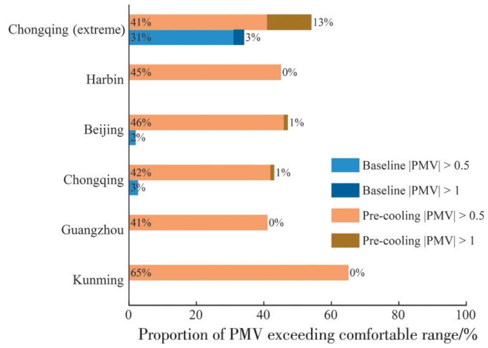


Fig. 11　The proportion of PMV exceeding the comfortable range in different city conditions for the pre-cooling strategy

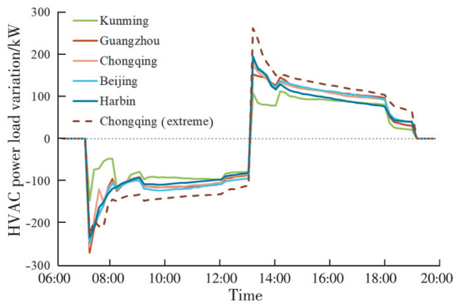


Fig. 12　HVAC power loads in zone temperature reset case (solid line) and baseline case (dash line) of five cities

Unlike the pre-cooling strategy, the zone temperature reset strategy was able to provide energy savings alongside peak power load-shedding capacity.

Similarly, although the zone temperature reset strategy presented a higher energy conservation potential, it had a lower peak load reduction rate. The average energy consumption reduction rate and peak load reduction rate of the zone temperature reset strategy were about 4.46% and 12.13% of the baseline energy consumption and peak load. Compared to the Chongqing typical condition case, the energy saving potential in the extreme condition was slightly lower but slightly higher in terms of peak load reduction rate.

The three energy flexibility indicators for the zone temperature reset strategy are shown in Table 5. The zone temperature reset strategy reduced peak load by 11% to 19% and reduced peak load during the on-peak period by about 70% to 96%. The reduction rate of peak load during the on-peak period was generally positively related to the outdoor climate conditions and cooling degree days (CDD), except for Kunming, which had a cooler climate. For this reason, the highest reduction rate in energy and peak load was found in Kunming. The zone temperature reset strategy also showed higher energy conservation potential with its warmer indoor temperatures (28 ℃). Again, the warmer the outdoor climate condition, the less potential for load shifting and shedding.

Table 5 Flexibility indicators for the zone temperature reset strategy during the cooling season

City	F_E	F_P	F_R/%
Kunming	9.20%(±1.16%)	19.25%(±1.39%)	70
Guangzhou	4.69%(±0.58%)	11.88%(±1.39%)	77
Chongqing	4.53%(±0.86%)	11.81%(±1.28%)	88
Beijing	4.40%(±0.93%)	12.05%(±1.35%)	91
Harbin	4.88%(±1.07%)	14.12%(±1.72%)	96
Chongqing (extreme)	4.46%(±0.89%)	12.13%(±1.02%)	100

Note: The number in the parentheses is the standard deviation.

The zone temperature reset strategy kept the occupied zone's thermal environment mostly within the acceptable PMV range (−1<PMV<1), as shown in Fig. 13. However, PMV beyond the acceptable range was observed in Chongqing and Beijing, especially in the Chongqing extreme condition, indicating that the effectiveness of the zone temperature reset strategy might be sensitive to the outdoor climate conditions in the hot summer regions.

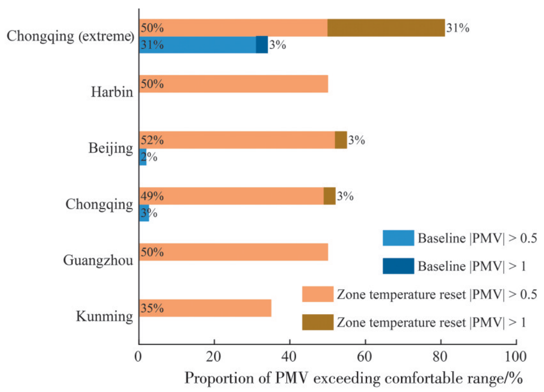


Fig. 13 The proportion of PMV exceeding the comfortable range in different city conditions for the zone temperature reset strategy

3.3 The flexibility of the partial shutdown strategy

The partial shutdown strategy partially closed some occupied building zones to compensate for an emergency power shortage. In particular, we investigated the load shifting and shedding potential of HVAC systems by shutting down the occupied zones facing west (zones 7 and 8 in Fig. 2). Fig. 14 presents the seasonal average HVAC power load difference between the partial shutdown and baseline cases in the six climate conditions.

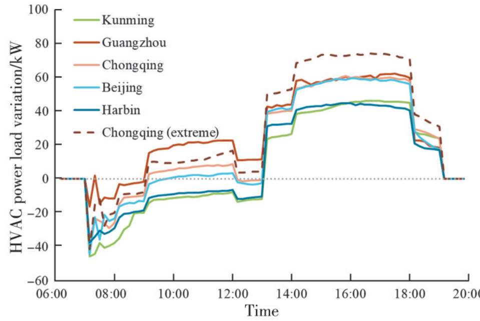


Fig. 14 HVAC power loads in partially shutting down strategy case (solid line) and baseline case (dash line) of five cities

The power load of HVAC systems was reduced after 13:00 when the partial shutdown started. The average amount of power load reduction was generally higher in Guangzhou, Chongqing, Beijing, and Chongqing extreme condition due to their warmer climate conditions.

The three energy flexibility indicators for the partial shutdown case are shown in Table 6. As a local control strategy only, the peak load shedding and load shifting ability were lower than in the other two strategies. The average peak load reduction rate for the six conditions was around 10%, and the reduction rates of peak load occurring during the on-peak period were around 50% for Guangzhou, Chongqing and Beijing.

Table 6 Flexibility indicators for the partially shutting down strategy during the cooling season

City	F_E	F_P	F_R/%
Kunming	2.95%(±1.31%)	12.31%(±1.74%)	30
Guangzhou	4.64%(±0.75%)	8.66%(±1.09%)	43
Chongqing	3.52%(±1.37%)	8.72%(±1.58%)	42
Beijing	3.27%(±0.88%)	8.62%(±0.98%)	58
Harbin	2.15%(±1.59%)	8.44%(±1.93 %)	82
Chongqing (extreme)	4.18%(±1.07%)	9.06%(±1.12%)	94

Note: The number in the parentheses is the standard deviation.

The indoor thermal environment in the occupied areas remained nearly unchanged under the partial shutdown case, benefiting from the unchanged indoor temperature setpoint in the occupied areas during the on-peak period. As shown in Fig. 15, the PMV value was within the comfortable range (−0.5 < PMV <0.5) over 90% of working hours in the five typical climate zones, and around 60% in the Chongqing extreme condition due to the continuous warm days.

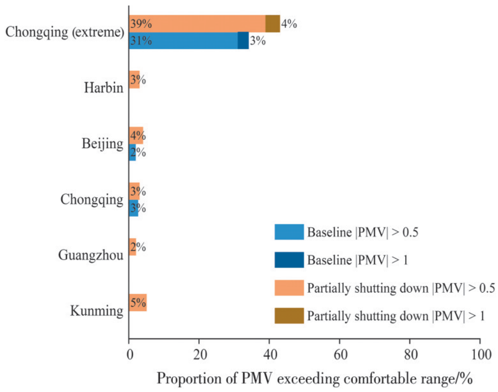


Fig. 15　The proportion of PMV exceeding the comfortable range in different city conditions for the partial shutdown strategy

4　Discussion

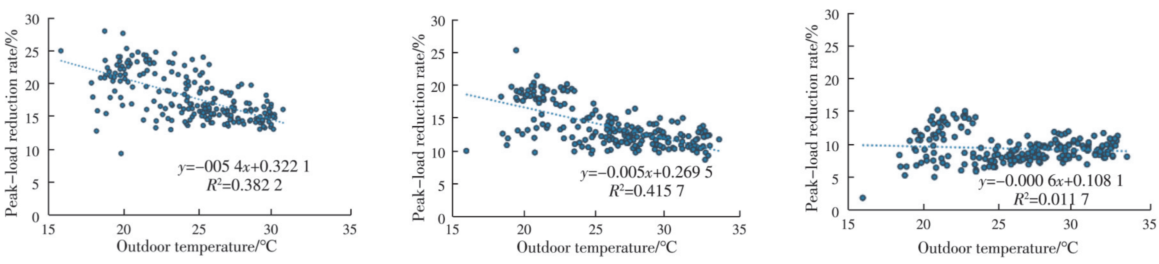
Building energy flexibility is important for regional power managers to balance the power load supply and demand during the on-peak period of the cooling season. As the major energy consumers and power load sources during this time, HVAC systems in office buildings have been recognized for their positive impact on load shifting and shedding potential under various flexibility management strategies. However, the flexibility and effectiveness of HVAC systems can be influenced by the outdoor climate. For this reason, in this study we used typical weather data for five climates in China and extreme weather data for one of them to simulate the energy flexibility of an office building under three short-term HVAC management strategies in order to evaluate them with respect to these various different climates specifically.

4.1　Load flexibility capacity and climate conditions

For the typical climate conditions, although the cooling demand (determined by CDD) varied from city to city, all three short-term HVAC management strategies were effective to some degree in all climate conditions. Taking advantage of a building's thermal mass, the pre-cooling strategy had the highest peak-load reduction and shifting potential. However, due to a lower temperature setpoint during the off-peak period, the pre-cooling strategy can lead to increased overall energy consumption during the occupied period in all climate conditions. The zone temperature reset and partial shutdown strategies had higher energy-saving potential but slightly lower peak-load reduction rates. The lowest load-shifting was found in the partial shutdown strategy.

Generally, the peak-load reduction rate was found to be highest in Kunming, which had cooler outdoor conditions and lower in Guangzhou, Chongqing, and Beijing, which had warmer conditions. Fig. 16 shows the relationship between outdoor dry-bulb temperature and the peak-load reduction rate in five typical climate conditions. Although variation was observed in the correlation, the peak load reduction rate of the pre-cooling and zone temperature reset strategies generally presented a negative linear relationship with outdoor temperature. Interestingly, more variations in the peak-load reduction rate were observed in the cooler outdoor environment, whereas the peak load reduction capacity was more convergent in warmer conditions. The peak-load shedding potential of the partial shutdown strategy was less correlated with the outdoor temperature, but it also presented a larger variation in the cooler climate condition compared to the warmer conditions.

Based on the analysis in section 3.3, the daily peak load time in the extreme condition was found to be earlier than that of the typical conditions. The average peak-load time and median peak-load time were 12:52 and 12:00 in the extreme condition, which was about 2 hours and 4 hours earlier than the



(a) Pre-cooling　　(b) Zone temperature reset　　(c) Partially shutting down

Fig. 16　The correlation between outdoor dry-bulb temperature and peak-load reduction rate in typical conditions

typical climate condition. This early peak-load time resulted in a considerably higher peak load reduction rate during the on-peak period for all three flexibility management strategies (Table 4 and 5). Fig. 17 shows the correlation between outdoor dry-bulb temperature and peak-load reduction rate for the three flexibility management strategies in the extreme condition. Since the outdoor temperature in the extreme condition was mostly between 30 ℃ to 38 ℃, the peak-load reduction potential showed relatively less variation. One of the reasons could be the higher solar radiation and less cloud cover in the Chongqing extreme condition dramatically increasing the solar heat gain. This may indicate a difference in the effectiveness of building energy flexibility management strategies under extreme and normal weather conditions, which emphasizes the importance of using real weekly and monthly weather forecast data (not only the outdoor temperature but also solar radiation) into consideration when assessing energy flexibility.

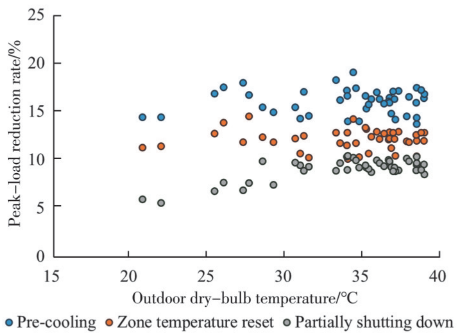


Fig. 17 The correlation between outdoor dry-bulb temperature and peak-load reduction rate in the extreme condition

4.2 Indoor thermal comfort under flexibility management

The primary aim of HVAC systems is to provide occupants with a comfortable, or at least acceptable indoor thermal environment. As a handy approach to managing building flexibility, typical flexibility management strategies often integrate HVAC control with a building's passive thermal storage capacity (building envelope and indoor furniture) in order to adjust the indoor temperature setpoints to the upper limit of the acceptable temperature during the on-peak period. However, this could potentially result in an unpleasant indoor thermal environment.

This study evaluated indoor thermal comfort by simulating the hourly PMV value under three flexibility management strategies. In typical climate conditions, applying pre-cooling and zone temperature reset strategies kept the indoor thermal environment within the acceptable range, increasing the possibility of feeling "warm" in the occupied zones by 30%-40%. With the occupied zones being barely influenced, the partial shutdown strategy performed better in keeping the occupied zone comfortable, especially in the extreme condition.

In the extreme condition, although the pre-cooling and zone temperature reset strategies presented better potential for peak load and overall energy reduction, a large risk was observed in creating an uncomfortable indoor environment (Fig. 11 and 13). Again, the main reason could be the strong solar radiation, which led to the setpoint setback (28 ℃) barely being able to stabilize the indoor environment within the expected range. However, taking advantage of not influencing the HVAC operation in the occupied zones, the partial shutdown strategy simultaneously provided a reasonable peak-load shifting and shedding capacity and sacrificed less thermal comfort in the occupied zone, which might be a useful flexibility management approach for buildings in the extremely hot areas.

As a result, the indoor temperature setpoint was often set to be the upper limit to decrease building cooling demand and boost energy flexibility, especially on the hot summer days when regional power demand was higher. As reported by this study, the peak-load reduction capacity was about 10%-25% in different climate conditions, but this reduction rate would become lower if we considered thermal comfort, especially in extreme conditions in which building energy flexibility management is in high demand. Therefore, although load shifting and shedding capacity were regarded as the main indicators to assess building energy flexibility, it is important to include a specific indicator or assessment on indoor thermal comfort to figure out actual usable load flexibility.

4.3 Limitations and recommendations for future work

This study has several limitations. First, the building modeling data was obtained from a real office building property, so we recommend that future work compare simulated peak load flexibility with actual measurement data to validate our results the reported results. Second, since the indoor thermal comfort was beyond the acceptable range under passive management strategies in extreme weather conditions, we recommend that future work focus on developing comfort-determined building flexibility management strategies.

5 Conclusion

To evaluate the energy flexibility of three typical short-term HVAC flexibility management strategies (pre-cooling, zone temperature reset, and partial shutdown) in different climate conditions of China, this study simulated the HVAC power load shifting and shedding potential during the cooling season (July and August) of an actual prototype office building in five major climate conditions and one extreme climate condition. Three building energy flexibility indicators were used to assess the peak-load shifting/shedding capacity and overall energy performance. Indoor thermal comfort was also evaluated for each flexibility management strategy under different climate conditions. The main conclusions are as follows.

The building peak load flexibility and overall energy performance of the three short-term HVAC flexibility management strategies were impacted by outdoor climate conditions. The peak-load reduction rate was found to be highest in Kunming, which had the coolest outdoor conditions and lower in Guangzhou, Chongqing, and Beijing, which had warmer outdoor conditions.

All three short-term HVAC management strategies were effective to some degree in all climate conditions. The pre-cooling presented strategy the best peak-load shifting and shedding capacity of between 15% and 30%, but there was a risk of more energy consumption. The partial shutdown strategy had the lowest load shifting and shedding ability, which was between 8% and 13%, but it was able to maintain a comfortable thermal environment in the occupied zones.

The peak load reduction rate of pre-cooling and zone temperature reset strategies generally declined linearly with increases in outdoor temperature but were more convergent in warmer conditions.

In the extreme summer condition, the daily peak load time was found to be over two hours earlier than that of the typical conditions. The correlation between peak load reduction and outdoor temperature was weak in the extreme condition as well, which may have resulted from intensive solar radiation.

The short-term HVAC flexibility management strategies that integrate temperature setpoint adjustment with passive thermal storage may lead to a risk of maintaining a comfortable indoor thermal environment, especially in the extreme summer condition with intensive solar heat gain, in which the possibility of uncomfortable thermal environments could be up to 81%.

This study demonstrated the effectiveness of short-term HVAC flexibility management strategies under different climate conditions, and future work could focus on developing comfort-determined building flexibility management strategies and validating load shifting/shedding capacity against measured building operation data.

References

[1] CURTIN J, MCINERNEY C, GALLACHÓIR BÓ, et al. Quantifying stranding risk for fossil fuel assets and implications for renewable energy investment: A review of the literature [J]. Renewable and Sustainable Energy Reviews, 2019, 116: 109402.

[2] Race to zero campaign [EB/OL]. [2023-03-20]. https://www.climatechampions.net/campaigns/race-to-zero/.

[3] JENSEN S Ø, MARSZAL-POMIANOWSKA A, LOLLINI R, et al. IEA EBC annex 67 energy flexible buildings [J]. Energy and Buildings, 2017, 155: 25-34.

[4] KEENEY K R, BRAUN J E. Application of building precooling to reduce peak cooling requirements [C]// American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Winter Meeting, Philadelphia, PA (United States), 24-28 Feb., 1997.

[5] NUYTTEN T, CLAESSENS B, PAREDIS K, et al. Flexibility of a combined heat and power system with thermal energy storage for district heating [J]. Applied Energy, 2013, 104: 583-591.

[6] LUND P D, LINDGREN J, MIKKOLA J, et al. Review of energy system flexibility measures to enable high levels of variable renewable electricity [J]. Renewable

and Sustainable Energy Reviews, 2015, 45: 785-807.

[7] AMASYALI K, EL-GOHARY N M. A review of data-driven building energy consumption prediction studies [J]. Renewable and Sustainable Energy Reviews, 2018, 81: 1192-1205.

[8] LU F, YU Z Y, ZOU Y, et al. Energy flexibility assessment of a zero-energy office building with building thermal mass in short-term demand-side management [J]. Journal of Building Engineering, 2022, 50: 104214.

[9] SHAN K, WANG S W, YAN C C, et al. Building demand response and control methods for smart grids: A review [J]. Science and Technology for the Built Environment, 2016, 22(6): 692-704.

[10] ADUDA K O, LABEODAN T, ZEILER W, et al. Demand side flexibility coordination in office buildings: A framework and case study application [J]. Sustainable Cities and Society, 2017, 29: 139-158.

[11] WANG L P, MATHEW P, PANG X F. Uncertainties in energy consumption introduced by building operations and weather for a medium-size office building [J]. Energy and Buildings, 2012, 53: 152-158.

[12] CHEN Y B, CHEN Z, XU P, et al. Quantification of electricity flexibility in demand response: Office building case study [J]. Energy, 2019, 188: 116054.

[13] MALIK A, HAGHDADI N, MACGILL I, et al. Appliance level data analysis of summer demand reduction potential from residential air conditioner control [J]. Applied Energy, 2019, 235: 776-785.

[14] BODE J. Measuring short-term air conditioner demand reductions for operations and settlement [R/OL]. [2023-03-23]. https://escholarship.org/uc/item/50v9d6xc.

[15] WANG S W, TANG R. Supply-based feedback control strategy of air-conditioning systems for direct load control of buildings responding to urgent requests of smart grids [J]. Applied Energy, 2017, 201: 419-432.

[16] OLIVIERI S J, HENZE G P, CORBIN C D, et al. Evaluation of commercial building demand response potential using optimal short-term curtailment of heating, ventilation, and air-conditioning loads [J]. Journal of Building Performance Simulation, 2014, 7(2): 100-118.

[17] WANG H L, WANG S W, TANG R. Development of grid-responsive buildings: Opportunities, challenges, capabilities and applications of HVAC systems in non-residential buildings in providing ancillary services by fast demand responses to smart grids [J]. Applied Energy, 2019, 250: 697-712.

[18] YIN R X, KARA E C, LI Y P, et al. Quantifying flexibility of commercial and residential loads for demand response using setpoint changes [J]. Applied Energy, 2016, 177: 149-164.

[19] KISHORE R A, BIANCHI M V A, BOOTEN C, et al. Modulating thermal load through lightweight residential building walls using thermal energy storage and controlled precooling strategy [J]. Applied Thermal Engineering, 2020, 180: 115870.

[20] XU P, HAVES P, PIETTE M A, et al. Peak demand reduction from pre-cooling with zone temperature reset in an office building [C]// 2004 ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA (US), 23-27 August, 2004.

[21] JIANG Z H, RISBECK M J, RAMAMURTI V, et al. Building HVAC control with reinforcement learning for reduction of energy cost and demand charge [J]. Energy and Buildings, 2021, 239: 110833.

[22] HU M M, XIAO F, WANG L S. Investigation of demand response potentials of residential air conditioners in smart grids using grey-box room thermal model [J]. Applied Energy, 2017, 207: 324-335.

[23] STOPPS H, TOUCHIE M F. Load shifting and energy conservation using smart thermostats in contemporary high-rise residential buildings: Estimation of runtime changes using field data [J]. Energy and Buildings, 2022, 255: 111644.

[24] TURNER W J N, WALKER I S, ROUX J. Peak load reductions: Electric load shifting with mechanical pre-cooling of residential buildings with low thermal mass [J]. Energy, 2015, 82: 1057-1067.

[25] UMMENHOFER C C, MEEHL G A. Extreme weather and climate events with ecological relevance: A review [J]. Philosophical Transactions of the Royal Society B: Biological Sciences, 2017, 372(1723): 20160135.

[26] STOTT P. How climate change affects extreme weather events [J]. Science, 2016, 352(6293): 1517-1518.

[27] DAI L K, LI Z Q, CHEN X Y, et al. Usage behavior characteristics of household air-conditioners during the extremely hot summer: A case study of Chongqing [J]. Building and Environment, 2023, 234: 110160.

[28] MAJDALANI N, AELENEI D, LOPES R A, et al. The potential of energy flexibility of space heating and cooling in Portugal [J]. Utilities Policy, 2020, 66: 101086.

[29] JUNKER R G, AZAR A G, LOPES R A, et al. Characterizing the energy flexibility of buildings and districts [J]. Applied Energy, 2018, 225: 175-182.

[30] LIU M Z, HEISELBERG P. Energy flexibility of a nearly zero-energy building with weather predictive control on a convective building energy system and evaluated with different metrics [J]. Applied Energy, 2019, 233/234: 764-775.

[31] VANHOUDT D, GEYSEN D, CLAESSENS B, et al. An actively controlled residential heat pump: potential

on peak shaving and maximization of self-consumption of renewable energy [J]. Renewable Energy, 2014, 63: 531-543.

[32] CUI Y, YAN D, HONG T Z, et al. Comparison of typical year and multiyear building simulations using a 55-year actual weather data set from China [J]. Applied Energy, 2017, 195: 890-904.

[33] THOMPSON R, HORNIGOLD R, PAGE L, et al. Associations between high ambient temperatures and heat waves with mental health outcomes: A systematic review [J]. Public Health, 2018, 161: 171-191.

[34] General code for energy efficiency and renewable energy application in buildings: GB 55015—2021 [S]. Beijing: China Architecture & Building Press, 2021.

[35] TANG H, WANG S W, LI H X. Flexibility categorization, sources, capabilities and technologies for energy-flexible and grid-responsive buildings: State-of-the-art and future perspective [J]. Energy, 2021, 219: 119598.

（编辑　胡英奎）