Carbon Neutrality

ORIGINAL ARTICLE Open Access

Flexible resource endowment of urban buildings considering climate diversity in China

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Abstract

Decarbonizing power systems necessitates both integrating substantial renewable energy and exploring flexible resources to accommodate their inherent intermittency and variability. Building Heating, Ventilation, and Air Conditioning (HVAC) systems are emerging as valuable dispatchable resources, offering flexibility for power systems through demand response (DR) programs. As HVAC operation and occupant comfort are highly dependent on temperature and humidity (T&H), their flexibility potential exhibits significant regional disparities across China's diverse climate. This research systematically investigates the flexibility across 5 representative city clusters (15 cities), to characterize these regional attributes and inform effective guidelines for harnessing this flexibility. We find that under 3 distinct weather conditions (sunny, cloudy, and rainy), the Maximum inter-regional flexibility exceeds the minimum by 61%, 113%, and 134%, respectively. Notably, intra-regional differences are also Substantial, reaching up to 51%, 89%, and 104% for the same weather conditions. Extending this analysis to a national scale, we evaluate the average flexibility per HVAC to be 45.1kW under extremely hot conditions and 16.1kW under hot-humid conditions. This research identifies regional patterns: northern cities exhibit significant diurnal flexibility variations, eastern regions demonstrate pronounced weather sensitivity, central areas show consistent weather response, western regions present distinct city-specific characteristics, and southern cities possess stable and high flexibility. These findings underscore the importance of considering such regional heterogeneity to prioritize efforts in leveraging urban HVAC systems, as well as help power systems optimize the development of renewable energy in China based on complementary HVAC flexibility.

Keywords Decarbonization, Energy flexibility, Climate diversity, Urban buildings, Power systems

1 Introduction

Developing renewable energy sources (RES) is a crucial pathway to achieving carbon neutrality [1]. In 2021, the Chinese government committed to installing over 1.2TW of RES capacity by 2030 [2]. However, replacing conventional thermal power plants with substantial RES introduces significant output uncertainties into power systems while simultaneously reducing their dispatchable regulation capacity [3]. These effects together complicate the maintenance of the strict real-time supply–demand balance required in power systems. Under these circumstances, power systems need to supplement regulation capacities by leveraging demand-side resources [4], a practice known as demand response (DR) [5]. Urban buildings, which consume more than 40% of the global energy [6], can serve not only as energy consumers but also as valuable sources of flexibility. Among various building loads, Heating, Ventilation, and Air Conditioning (HVAC) systems are regarded as the most representative resource due to their substantial energy consumption and inherent thermal inertia of buildings, which naturally buffers temperature changes during DR events.

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Research interest in HVAC flexibility has grown substantially [7–9], with studies exploring its application for various grid services, including peak shaving [10, 11], operating reserves [12, 13], frequency regulation [14, 15], and other ancillary services [16]. This interest aligns with policy directions: the China National Energy Administration has stipulated that typical areas should develop DR capacities equivalent to 5% of their peak load to establish the normalized DR resource pool by 2027 [17]. While HVAC systems are competitive candidates for meeting this target, their effectiveness has not been sufficiently addressed as HVAC flexibility varies significantly with local climate conditions. Some studies have examined how weather affects cooling demand [18] and developed climate-specific HVAC control strategies such as in the subtropical climate [19], and the comparative analysis was conducted among 4 cities in humid climate zones [5]. However, the comprehensive inter- and intra-regional disparities in flexibility remain underexplored. This knowledge gap is particularly problematic for the national-scale development of HVAC flexibility, where climate diversity could significantly impact implementation strategies and expected outcomes.

The fundamental challenge in evaluating HVAC flexibility lies in quantifying the maximum adjustable capacity while maintaining occupant comfort [20]. While the impacts of climate on HVAC operation and occupant comfort are widely recognized, traditional methods for evaluating flexibility have primarily considered temperature impact alone [21–23]. Typically, these methods define flexibility as the reduction in power consumption achievable while keeping the indoor temperature within tolerable ranges, using model analytic methods [24], data-driven methods [25], or software simulations [26]. As these studies mainly focus on high ambient temperatures where HVAC systems contribute to peak load events, the impact of humidity is not remarkable. However, this narrow focus and the potential for evaluation inaccuracies severely hinder their application for investigating large-scale flexibility endowments.

Humidity affects HVAC operation and occupant comfort in ways that cannot be ignored in comprehensive flexibility evaluations. The total cooling load comprises sensible load and latent load [27], which are directly influenced by T&H, respectively. Besides, high humidity also results in discomfort even at moderate temperatures [28]. Although some researchers have noticed these issues [29] and developed models to predict indoor T&H [30], thus optimizing and controlling the HVAC systems with the aim of energy savings [31]. The complex coupled relationship between T&H often necessitates building energy simulation software like EnergyPlus [32], whose parameter-intensive nature limits scalability for large-scale applications.

While these studies provided insightful points regarding the flexibility evaluation of HVAC systems, several critical issues remain unaddressed. Primarily, a national investigation necessitates analytical models that can accurately and efficiently capture the T&H dynamics driven by DR events. Secondly, incorporating humidity extends the flexibility evaluation from a 1-dimensional temperature problem to a 2-dimensional T&H challenge, necessitating methods to identify which factor (temperature or humidity) is the dominant constraint. Thirdly, the HVAC systems are highly sensitive to environmental factors (e.g., outdoor T&H and solar radiation), leading to dramatic variability in flexibility across different regions.

This study provides a comprehensive evaluation of building HVAC flexibility potential across China's diverse climate regions. We present first hierarchical evaluation of the temporal and spatial flexibility of HVAC systems, focusing on how climate diversity influences the T&H dynamics, flexibility potential, and resource availability, as shown in Fig. 1. We have made three novel contributions. First, we develop comprehensive analytical models of HVAC systems to separately depict the T&H variations triggered by DR events, coupled with a "cask effect" principle that identifies the more constraining factor (temperature or humidity) determining the actual flexibility potential. Second, we concentrate on 15 cities from 5 representative city clusters with significant geographical and climatic differences, systematically investigating how weather influences HVAC operation, the dominant factor, and resulting varying flexibility. Third, we scale up the evaluation to all of China, to explore the impacts of climate diversity on flexible resource endowment, focusing on extremely hot and hot-humid scenarios to assess the feasibility and economics of leveraging HVAC flexibility in different regions.

The ongoing expansion of distributed RES (e.g., rooftop photovoltaics and building-integrated photovoltaics) ties buildings and power systems more closely in cities. Given the significant regional difference in both RES and flexibility exhibited, our research offers timely insights for power system planners and operators, enabling them to assess the feasibility of facilitating HVAC systems to enhance flexibility. It also describes the sensitivity of HVAC flexibility to varying weather conditions, thus realizing the synergism between HVAC exploration and RES development.

2 Methods for evaluating HVAC flexibility

Accurate evaluation of HVAC flexibility requires simultaneous consideration of T&H constraints, as either parameter May Limit system adjustability. This section

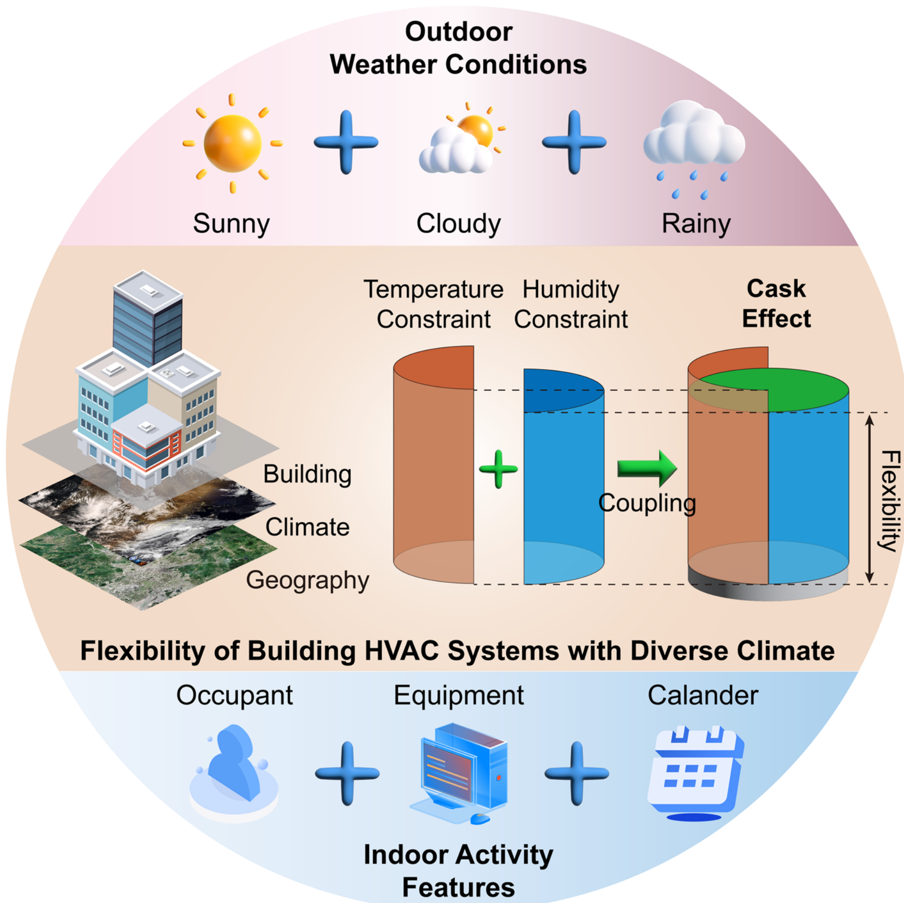

Fig. 1 Flexibility evaluation of building HVAC considering climate and geography diversity. Flexibility evaluations for HVAC systems need to account for both T&H, which often result in different flexibility values. To guarantee occupant comfort, the lower of these two values determines the actual flexibility. This principle is similar to the cask effect, where the shortest plank determines the cask capacity. Both outdoor climates and indoor activities influence the T&H constraints, thereby demonstrating the regional flexibility endowments

presents our comprehensive methods, including 1) models of indoor temperature and humidity dynamics, 2) models of HVAC system operations, 3) identification of the dominant comfort constraint, and 4) flexibility evaluation considering T&H constraints.

2.1 Model of indoor temperature and humidity dynamics

In the cooling zone, both indoor T&H maintain dynamic balances affected by multiple factors, including outdoor weather, indoor occupant activities, and supply air provided by HVAC systems. The real-time indoor temperature T_z^t and humidity W_z^t can be calculated according to the following heat and moisture balance equations:

$$\rho_{air} V_b C_{air} \frac{dT_z^t}{dt} = m_{sa}^t C_{air} (T_{sa}^t - T_z^t) + K_{env} A_{sf} (T_{oa}^t - T_z^t) + Q_{solar}^t + N_{occ}^t (Q_{occ} + Q_{eqpt}) \tag{1}$$

$$\rho_{air} V_b \frac{dW_z^t}{dt} = m_{sa}^t (W_{sa}^t - W_z^t) + N_{occ}^t (\dot{m}_{occ} + \dot{m}_{eqpt}) \tag{2}$$

where ρ_{air} is the density of air; V_b is the volume of the building; C_{air} is the specific heat of air; m_{sa}^t is the mass flow rate of supply air; T_{sa}^t is the temperature of supply air; K_{env} is the thermal conductivity of building envelope;A_{sf} is the surface area of the building; Q_{solar}^t heat gains derived from solar radiation; N_{occ}^t is the number of occupants; Q_{occ} and Q_{eqpt} are the average heat generations derived from occupants and equipment, respectively; W_{sa}^t is the humidity of supply air; $\dot{m}_{occ}$ and $\dot{m}_{eqpt}$

are the average water vapor generations derived from occupants and equipment, respectively.

2.2 Model of HVAC systems

The indoor T&H dynamics described above are driven by HVAC systems, which deliver cooled and dehumidified supply air. The specific T&H of supply air are crucial for calculating the indoor T&H dynamics. The energy exchange process between the supply air and HVAC systems is described using the principle of enthalpy conservation. The enthalpy of moist air h_a with temperature T_a and humidity ratio W_a can be expressed as follows:

$$h_a = C_{air} T_a + W_a (C_{wv} T_a + h_{fg}) \quad (3)$$

where C_{wv} is the specific heat of water vapor; h_{fg} is the latent heat of vaporization.

The mixed air (a combination of indoor return air and outdoor air) is processed by HVAC systems to produce the supply air. The enthalpy of supply air h_{sa}^t can be calculated according to the enthalpy of mixed air h_{ma}^t and the total cooling capacity of HVAC systems Q_{ac}^t:

$$h_{sa}^t = h_{ma}^t - Q_{ac}^t / m_{sa}^t \quad (4)$$

However, determining the specific T&H of supply air from its enthalpy value alone is mathematically underconstrained, as a single enthalpy value corresponds to multiple T&H combinations. To resolve this, a simplifying assumption based on engineering experience is introduced. The supply air is assumed to have a relative humidity (RH) of about 90%, a state typical for air leaving the cooling coil saturated with water vapor. Otherwise, if dehumidification is not required, the humidity ratio remains constant. Therefore, the solved humidity of the supply air must satisfy the following constraints, and more solution details are provided in supplementary information (S1.1).

$$\begin{cases} W_{sa}^t / W_{sa,s}^t (T_{sa}^t) = 0.9 & W_{sa}^t < W_{ma}^t \\ W_{sa}^t = W_{ma}^t & W_{sa}^t \geq W_{ma}^t \end{cases} \quad (5)$$

where $W_{sa,s}^t(T_{sa}^t)$ is the saturation humidity ratio at the supply air temperature T_{sa}^t, this dependency of T&H complicates the solution process; W_{ma}^t is the humidity of mixed air.

After determining the T&H of supply air, the total cooling load can be decomposed into its sensible and latent components.

$$Q_{ac,s}^t = m_{sa}^t C_{air} (T_z^t - T_{sa}^t) \quad (6)$$

$$Q_{ac,l}^t = Q_{ac}^t - Q_{ac,s}^t \quad (7)$$

where Q_{ac}^t is the total cooling load of HVAC systems; $Q_{ac,s}^t$ and $Q_{ac,l}^t$ are the sensible and latent loads, respectively. The relationships between cooling capacity and electricity consumption are provided in S1.2.

2.3 Identification of the dominant comfort constraint

Beyond its impact on cooling load, humidity is also a critical factor of occupant comfort. Hence, we design a two-dimensional T&H comfort area, as shown in Fig. S1, where the acceptable humidity threshold decreases as the temperature grows. This prevents conditions from becoming uncomfortably muggy, even if the temperature itself is within an acceptable range.

When HVAC power is reduced during DR deployment, both indoor T&H will rise. Flexibility is limited by whichever parameter first reaches its comfort boundary. As shown in Fig. 2, T&H dynamics are classified into 2 types according to the dominant factor: temperature-sensitive and humidity-sensitive. The key challenge is to efficiently identify this dominant factor. Otherwise, evaluating flexibility typically requires a computationally expensive iterative simulation: increase the power reduction continuously to calculate the equilibrium states until the temperature or humidity ratio first reaches its boundary, and the current power reduction is the flexibility of HVAC systems.

To overcome this challenge, we propose a criterion to identify the dominant factor first based on calculating a hypothetical critical state for the supply air, which would cause the indoor T&H to reach their respective boundaries simultaneously. These critical states can be expressed as follows, and specific derivations are provided in S2.

$$T_{sa}^{cri} = T_z^{max} - \frac{K_{env} A_{sf} (T_{oa}^t - T_z^{max}) + Q_{solar}^t + N_{occ}^t (Q_{occ} + Q_{eqpt})}{m_{sa}^t C_{air}} \quad (8)$$

$$W_{sa}^{cri} = W_z^{max} - \frac{N_{occ}^t (\dot{m}_{occ} + \dot{m}_{eqpt})}{m_{sa}^t} \quad (9)$$

where T_{sa}^{cri} and W_{sa}^{cri} are the critical states of the temperature and humidity ratio of supply air, respectively; T_z^{max} and W_z^{max} are the acceptable maximum temperature and humidity ratio, respectively.

Next, we can calculate the RH corresponding to this critical air state. By comparing its RH to the system's realistic operational limit (about 90% RH), we can identify the dominant constraint:

If the RH value is higher than 90%, the T&H dynamic belongs to the temperature-sensitive type. HVAC systems are capable of providing the necessary dehumidification to satisfy the humidity constraint. Thus, the

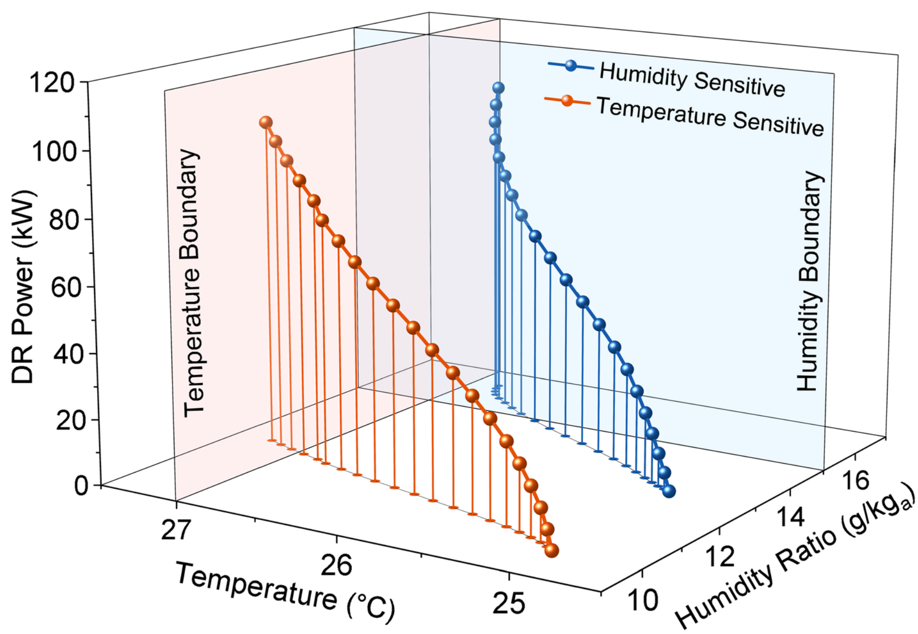

Fig. 2 Specific T&H dynamics of temperature-sensitive and humidity-sensitive types as the growth of DR power

temperature will reach its boundary first, becoming the dominant factor.

If the RH value is lower than 90%, the T&H dynamic belongs to the humidity-sensitive type. Reaching both T&H boundaries simultaneously would require more dehumidification than the system can physically achieve, meaning that humidity will rise faster and violate its comfort boundary first.

This criterion, illustrated in Fig. S2, allows for the direct identification of the dominant factor without complex simulations, significantly reducing computational requirements for large-scale flexibility evaluations.

2.4 Flexibility evaluation considering T&H constraints

Based on the identified dominant factor, the flexibility of HVAC systems can be efficiently evaluated. Firstly, we calculate the equilibrium indoor conditions during DR events, ensuring that either the temperature or the humidity reaches its comfort boundary.

$$T_z^{DR} = \frac{m_{sa}^t C_{air} T_{sa}^{cri} + K_{env} A_{sf} T_{oa}^t + Q_{solar}^t + N_{occ}^t (Q_{occ} + Q_{eqpt})}{m_{sa}^t C_{air} + K_{env} A_{sf}} \tag{10}$$

$$W_z^{DR} = W_{sa}^{cri} + N_{occ}^t (\dot{m}_{occ} + \dot{m}_{eqpt}) / m_{sa}^t \tag{11}$$

where T_z^{DR} and W_z^{DR} represent the actual T&H of indoor air during DR events, respectively.

Then, we can substitute the indoor T&H into the operating model of HVAC systems, so as to obtain the minimum required cooling capacity, thus calculating the minimum power consumption of HVAC systems. Flexibility is the difference between baseline power and minimum power.

$$Q_{ac}^{DR} = m_{sa}^t (h_{ma}^{DR} - h_{sa}^{DR}) \tag{12}$$

$$\Delta P_{ac}^{flex} = \frac{Q_{ac}^{DR} - Q_{ac}^{steady}}{\eta_{cop}^t} + \frac{Q_{ac}^{DR} - Q_{ac}^{steady}}{\eta_{pump}^{wtf}} + \frac{Q_{ac}^{DR} - Q_{ac}^{steady}}{\eta_{tower}^{wtf}} \tag{13}$$

where h_{ma}^{DR} and h_{sa}^{DR} are the enthalpies of mixed air and supply air, respectively; Q_{ac}^{DR} is the minimum cooling load of HVAC systems during DR events; ΔP_{ac}^{flex} indicates the flexibility of HVAC systems; Q_{ac}^{steady} represents the steady cooling capacity of HVAC systems. η_{cop}^t is the COP of chillers; η_{pump}^{wtf} and η_{tower}^{wtf} are the water transfer factors of pumps and the cooling tower, respectively.

3 Case study design

3.1 Geographical scope and climatic scenarios

The flexibility of HVAC systems is highly dependent on local climate and weather conditions. Given China's vast and diverse geography, a targeted investigation of representative cities is both necessary and practical for deeper analysis. Therefore, our study design focuses not only on the broad climatic diversity across China, but also on the more Subtle variations among Major city clusters. Accordingly, 5 prioritized urban agglomerations (Beijing-Tianjin-Hebei, Yangtze River Delta, Middle Reaches of

Yangtze River, Chengdu-Chongqing, and Greater Bay Area regions) are selected for this study. These clusters represent five major geographic regions of China (north, east, center, west, and south), as shown in Fig. S3. Within these agglomerations, 15 provincial capital cities and municipalities are chosen for a detailed analysis. The specific climate and geography information can be found in Table 1 [33–36].

Summer typically experiences the highest electrical loads, and the need for HVAC flexibility often coincides with peak load conditions. Understanding the potential HVAC flexibility during these peak demand periods is of particular importance for DR programs, thereby our research is conducted during the Summer months. Furthermore, to account for the impact of multiple weather conditions in addition to regional climate, we analyzed 3 typical weather conditions (sunny, cloudy, and rainy), using data from July to August in 2023. Relevant outdoor temperature, humidity, and global horizontal irradiance (GHI) are introduced in the operation of HVAC systems. These data are obtained from the National Solar Radiation Database provided by the National Renewable Energy Laboratory (NREL) [37].

Moreover, the national evaluation is conducted to better reveal the national flexibility endowment. Extreme hot and hot-humid scenarios are designed to evaluate the potential flexibility of HVAC systems. The climate data for these scenarios were observed by 402 weather stations in China in 2023, provided by the National Centers for Environmental Information [38].

3.2 Building model, HVAC systems, and control parameters

In accordance with China's technical specifications outlined in GB 50736–2012, a parametric reference building model representative of a typical commercial office was developed for cross-regional simulation studies. This method specifically employs standardized architectural parameters, thereby establishing a consistent baseline for comparative analysis of climate impacts across different geographical locations. The primary control strategy aims to Maintain occupant comfort within defined Limits. The neutral temperature setpoint is 25°C, with an acceptable temperature range of 23 °C to 27°C. A Proportional-Integral-Derivative (PID) controller is simulated to adjust the total cooling capacity provided by HVAC systems, thereby eliminating the deviations between the actual temperature and the setpoint. Temperatures outside the range result in thermal discomfort, as occupants feel either hot or cold. Similarly, an acceptable humidity range is defined, which requires the indoor humidity ratio should be Maintained between 4.7g/kg_a and 15.1g/kg_a. The parameter configurations adhere to the thermal comfort criteria prescribed in ASHRAE Standard 55–2023. The flexibility of HVAC systems is evaluated across a 24-h cycle with a 15-min time resolution. Detailed parameters for the building model and HVAC systems are provided in Table S1, and the occupancy patterns are shown in Fig. S4.

4 Results and analysis

This section presents a comprehensive analysis of HVAC flexibility potential in urban buildings across China's diverse climate regions. The results are presented in

Table 1 Information on 5 typical city clusters with 15 cities

City clusters	Cities	Location	Average temperature (July)	Average RH (July)
Beijing-Tianjin-Hebei Urban Agglomeration	Beijing (BJ)	39°54′N 116°23′E	23–34°C	75%
	Tianjin (TJ)	39°08′N 117°12′E	24–34°C	75%
	Shijiazhuang (SJZ)	37°87′N 114°25′E	23–34°C	74%
Yangtze River Delta Urban Agglomeration	Nanjing (NJ)	32°30′N 118°47′E	26–34°C	69%
	Hangzhou (HZ)	30°14′N 120°12′E	26–36°C	71%
	Shanghai (SH)	31°15′N 121°23′E	27–35°C	71%
	Hefei (HF)	31°86′N 117°28′E	25–33°C	79%
Middle Reaches of the Yangtze River Urban Agglomeration	Wuhan (WH)	30°35′N 114°19′E	26–34°C	78%
	Changsha (CS)	28°13′N 112°56′E	26–36°C	77%
	Nanchang (NC)	28°40′N 115°51′E	27–35°C	69%
Chongqing-Chengdu City Group	Chongqing (CQ)	29°33′N 106°32′E	26–35°C	58%
	Chengdu (CD)	30°40′N 104°04′E	23–32°C	78%
Guangdong-Hong Kong-Macao Greater Bay Area	Guangzhou (GZ)	23°80′N 113°17′E	26–35°C	78%
	Hong Kong (HK)	22°21′N 113°91′E	26–32°C	81%
	Macao (MO)	22°08′N 113°34′E	27–32°C	83%

a structured manner to offer a clear understanding of how HVAC flexibility is characterized and influenced by climatic factors. Firstly, we analyze the indoor T&H without DR events, which affect the subsequent T&H dynamics. Secondly, we identify the T&H dynamics and investigate the impacts of regional climate diversity and local weather conditions. On this basis, the flexibility of HVAC systems is evaluated according to the identified T&H dynamics. Moreover, the cumulative duration of flexibility is analyzed to reveal the availability across different regions under different weather conditions. To investigate the influencing mechanisms of outdoor climatic parameters, we compare the indoor humidity ratio, T&H dynamics, and flexibility between varying outdoor T&H and solar radiation. Finally, the evaluation is scaled up all over China, and we further explore the flexibility endowments of building HVAC systems considering climate diversity.

4.1 Baseline indoor T&H profiles

Figure 3 (a)-(f) illustrates the baseline indoor T&H profiles for 15 cities under 3 distinct weather conditions during normal operations. These profiles are crucial for subsequent dominant factor identification and flexibility evaluation.

Indoor temperature is actively controlled by HVAC systems, which adjust the cooling load to eliminate the temperature deviations from the neutral setpoints (25°C). Therefore, temperature generally remains at the setpoint throughout the day, with only a few exceptions. To be specific, if the outdoor temperatures fall below the setpoint, the HVAC systems will be turned off. In such cases, the indoor temperature gradually decreases driven by outdoor temperature rather than the HVAC systems, leading to lower temperatures from neutral setpoints during nighttime hours (e.g., BJ, TJ, and SJZ).

In contrast, the indoor humidity shows significant fluctuations due to passive control mechanisms. Humidity levels tend to be lower during the daytime but show considerable increases during nighttime hours, often exceeding acceptable Limits. Average day-night differences can be as high as 2.76 g/kg$_a$. Additionally, indoor humidity levels in most cities are sensitive to weather conditions, displaying a notable growth from sunny to rainy days.

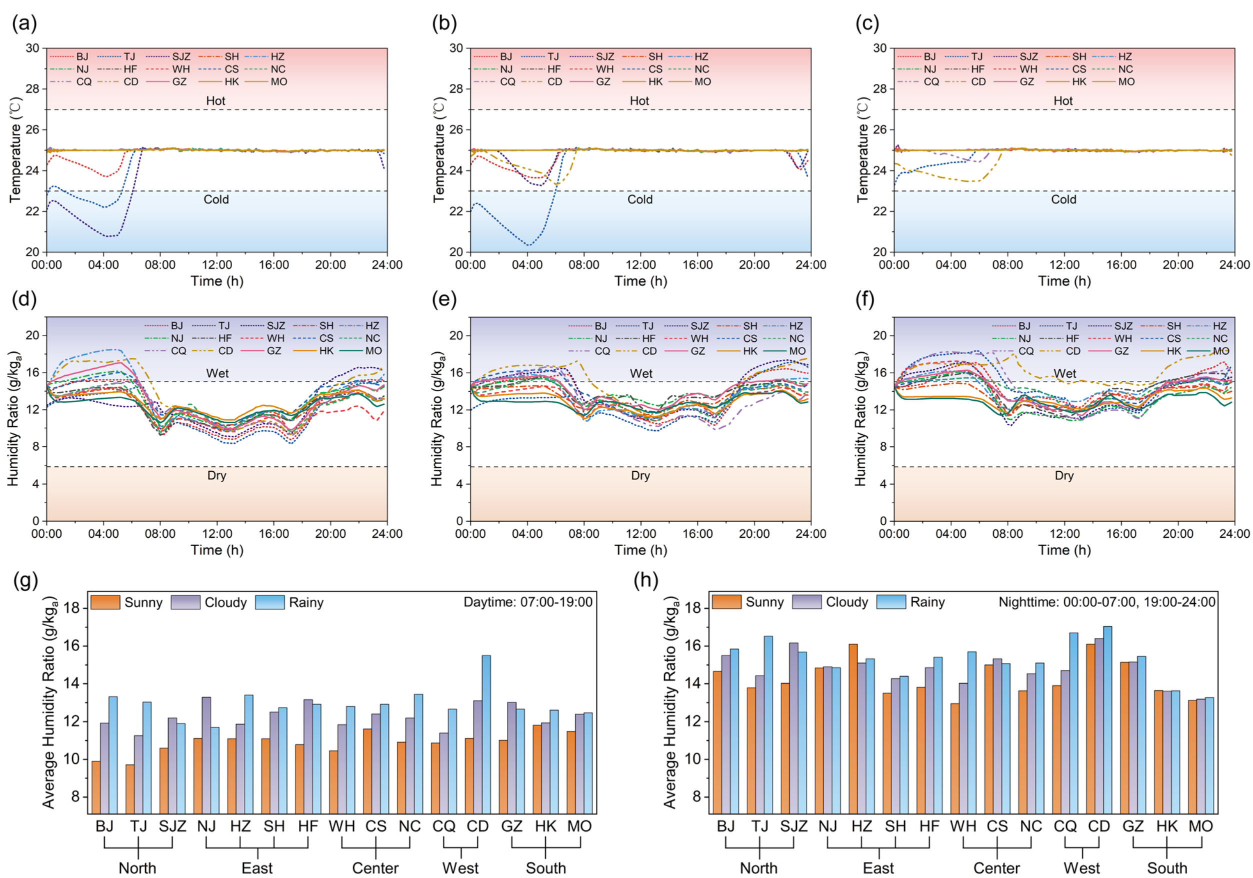

Fig. 3 Indoor T&H profiles of 15 cities. **a**-**c** Temperature profiles under sunny, cloudy, and rainy conditions; **d**-**f** Humidity profiles under sunny, cloudy, and rainy conditions; **g**-**h** Average humidity ratios in the daytime and nighttime

These phenomena can be attributed to a reduction in sensible load, which is primarily influenced by outdoor temperature and GHI. As these factors decrease at night or on rainy days, the cooling capacity required for a sensible load decreases. This reduction in sensible load often leads to decreased dehumidification capacity, thus resulting in higher indoor humidity. These results highlight a tight coupling between sensible and latent loads, underscoring the necessity to decouple them for a more accurate description of T&H dynamics during DR events.

Given that the temperature is consistently maintained at its neutral setpoint, humidity levels emerge as crucial factors influencing T&H dynamics. Specifically, when the initial indoor humidity approaches the boundary of the acceptable range, the T&H dynamics become increasingly sensitive to humidity. Overall, northern and central cities generally exhibit lower daytime humidity levels compared to other regions. However, during the nighttime, cities with lower humidity levels are predominantly found in the southern and central regions. These differences may contribute to distinct flexibility potentials among cities.

4.2 Climatic influence on T&H dynamics

According to the indoor T&H profiles, the specific T&H dynamics at different time instants are identified, as illustrated in Fig. 4. These results provide a crucial foundation for the subsequent evaluation of HVAC system flexibility.

The T&H dynamics demonstrate notable spatial–temporal characteristics. Typically, the temperature-sensitive type mainly occurs during the daytime (07:00–19:00). This observation aligns with the T&H profiles, indicating lower daytime humidity levels. Conversely, humidity-sensitive dynamics are prevalent during nighttime, regardless of weather conditions. In general, the occurrence of temperature-sensitive type declines from sunny to cloudy to rainy weather conditions, corresponding with rising outdoor humidity. More importantly, the analyzed city clusters also exhibit unique spatial patterns in the T&H dynamics, encompassing both intra- and inter-regional differences.

1) Beijing-Tianjin-Hebei Urban Agglomeration: This agglomeration, characterized by a temperature monsoon climate, exhibits the highest frequency (31%) of temperature-sensitive type, attributable to its lower average annual humidity compared to other regions. Besides, nighttime outdoor temperatures here are lower than in other city clusters, Making the HVAC systems inactive 21.8% of the time. This suggests that exploiting the flexibility of HVAC systems during nighttime in this area is nearly infeasible, despite the growing demand for regulation capacities (e.g., accommodation of offshore wind power). Moreover, some differences are observed among the 3 cities. For instance, regarding the distribution of temperature-sensitive type, SJZ shows less sensitivity to weather variations, whereas BJ is highly affected.
2) Yangtze River Delta Urban Agglomeration: Situated in a subtropical monsoon climate zone and bordering the temperate monsoon climate area, this region displays a combination of northern and southern climatic characteristics. Specifically, while temperature-sensitive dynamics are dominant during daytime on Sunny days, humidity-sensitive dynamics completely prevail on cloudy and rainy days. However, the 4 cities demonstrate divergent behaviors without a consistently discernible pattern. For instance, the percentage of temperature-sensitive type can remain high even on cloudy and rainy days, Such as 37.5% on cloudy days in HZ and 33.3% on rainy days in NJ.
3) Middle Reaches of the Yangtze River Urban Agglomeration: Also situated in a subtropical monsoon climate zone, this region is distinguished by its central location. Temperature-sensitive dynamics achieve the highest prevalence (48.6%) on Sunny days and exhibit a consistent decrease from Sunny to rainy conditions. This Suggests that, compared to the Yangtze River Delta Urban Area, distance from the ocean is a key factor of T&H dynamics. Among the 3 cities, WH is the most temperature-sensitive, with this dynamic reaching up to 62.5% on sunny days. In comparison, CS exhibits lower temperature sensitivity, potentially influenced by its more southerly and westerly position.
4) Chongqing-Chengdu City Group: These representative western cities also demonstrate distinct responses to weather changes. Notably, the 2 cities exhibit the most distinct intra-cluster differences among all city clusters, primarily due to their significant outdoor temperature differences. CQ with a hotter climate shows minimal variation in its T&H dynamics across the 3 weather conditions, with similar distributions of temperature-sensitive periods. On the contrary, CD not only exhibits clear distinctions in its response to weather differences but also experiences lower nighttime temperatures, often leading to HVAC systems deactivation.
5) Guangdong-Hong Kong-Macao Greater Bay Area: This region is located near the boundary between Subtropical and tropical monsoon climates, characterized by prolonged hot and humid conditions. Under Such circumstances, the humidity-sensitive type consistently dominates across all kinds of weather conditions, accounting for approximately

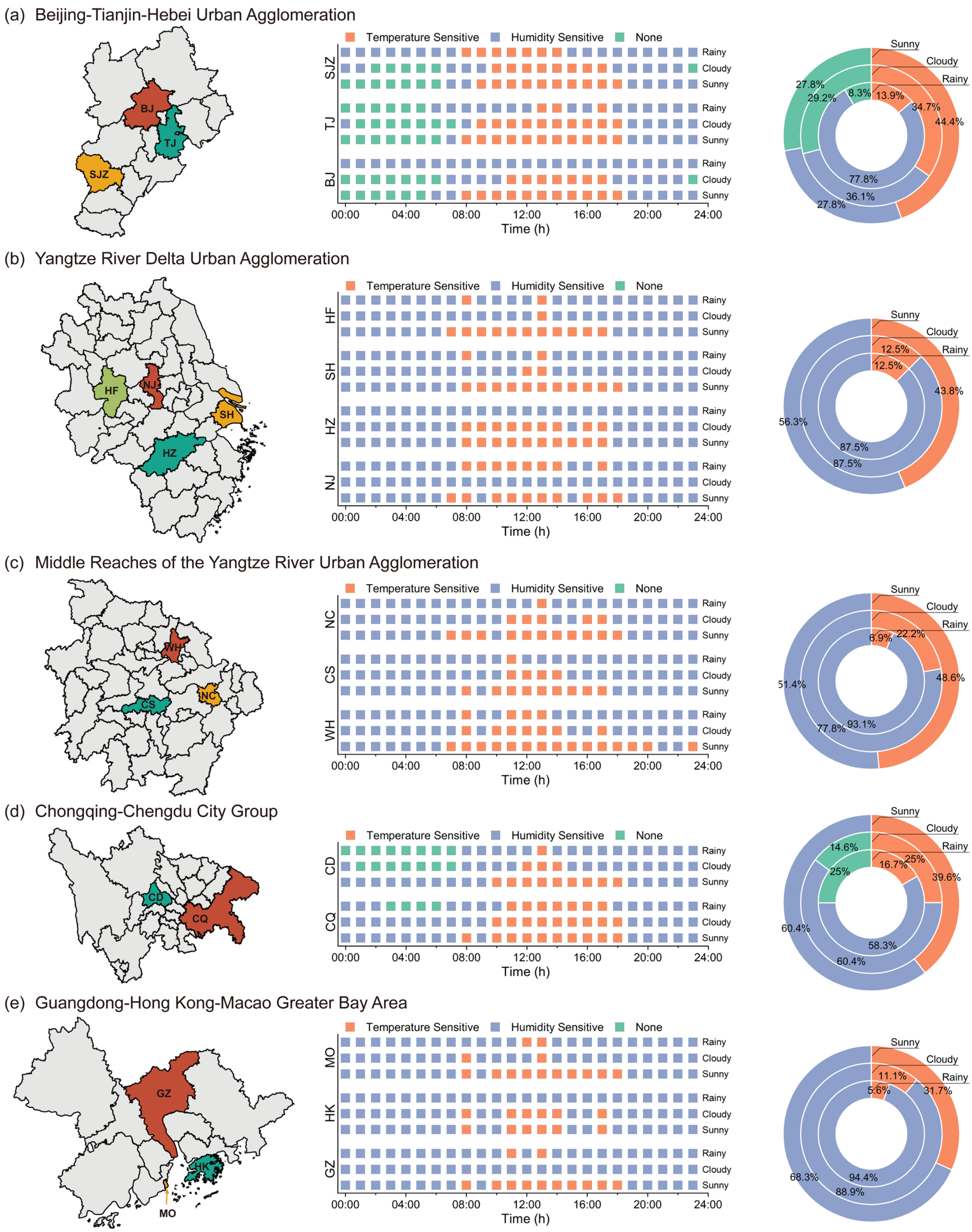

Fig. 4 The identified T&H dynamics of 15 cities under 3 weather conditions. **a** Beijing-Tianjin-Hebei Urban Agglomeration; **b** Yangtze River Delta Urban Agglomeration; **c** Middle Reaches of the Yangtze River Urban Agglomeration; **d** Chongqing-Chengdu City Group; **e** Guangdong-Hong Kong-Macao Greater Bay Area

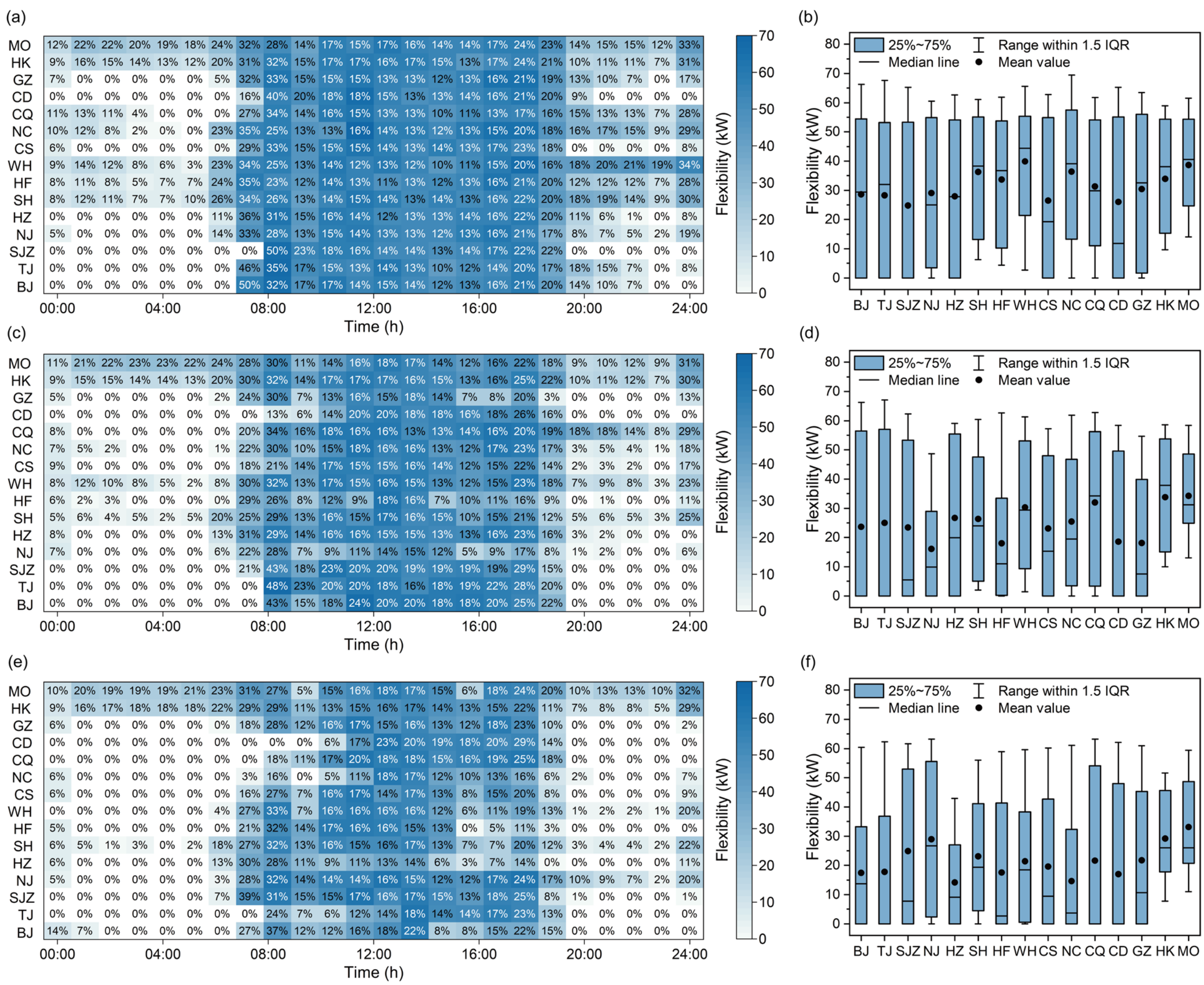

Fig. 5 Flexibility profiles and distributions of HVAC systems in 15 cities under 3 weather conditions. **a**-**b** Sunny; **c**-**d** Cloudy; **e**–**f** Rainy

84% of the time. Overall, this southern region also displays a decreasing trend in the occurrence of temperature-sensitive types from Sunny to rainy days. However, this pattern is less obvious when examining individual cities. For instance, T&H dynamics in GZ are completely humidity-sensitive on cloudy days. In contrast, 2 h exhibit humidity-sensitive features on rainy days, illustrating the less consistent patterns in coastal cities.

4.3 Characterizing the HVAC flexibility endowment

Following the identification of T&H dynamics, the flexibility of HVAC systems is further evaluated as depicted in Fig. 5. It should be noted that flexibility is also related to the baseline power of HVAC systems, which can be found in Fig. S4. Therefore, the flexibility rate also serves as a critical index to reflect the potential flexibility. For example, while the nighttime flexibility in southern cities is considerably lower than daytime flexibility, the corresponding flexibility rates remain Substantial at 15%–20%. Overall, both flexibility and the associated flexibility rate decrease from sunny to rainy conditions, aligning with initial expectations.

Besides, the availability of flexibility is also an important criterion that indicates how long the flexibility is available throughout the day. While HK and MO provide all-weather flexibility, several other cities (e.g., SH, HF, WH, NC, and CQ) can also provide extended flexibility on sunny days. But on cloudy and rainy days, this availability diminishes sharply.

1) Beijing-Tianjin-Hebei Urban Agglomeration: The flexibility evaluation results reveal a prominent feature: minimal regulation potential during non-working hours, consistent with the T&H dynamic identifi-

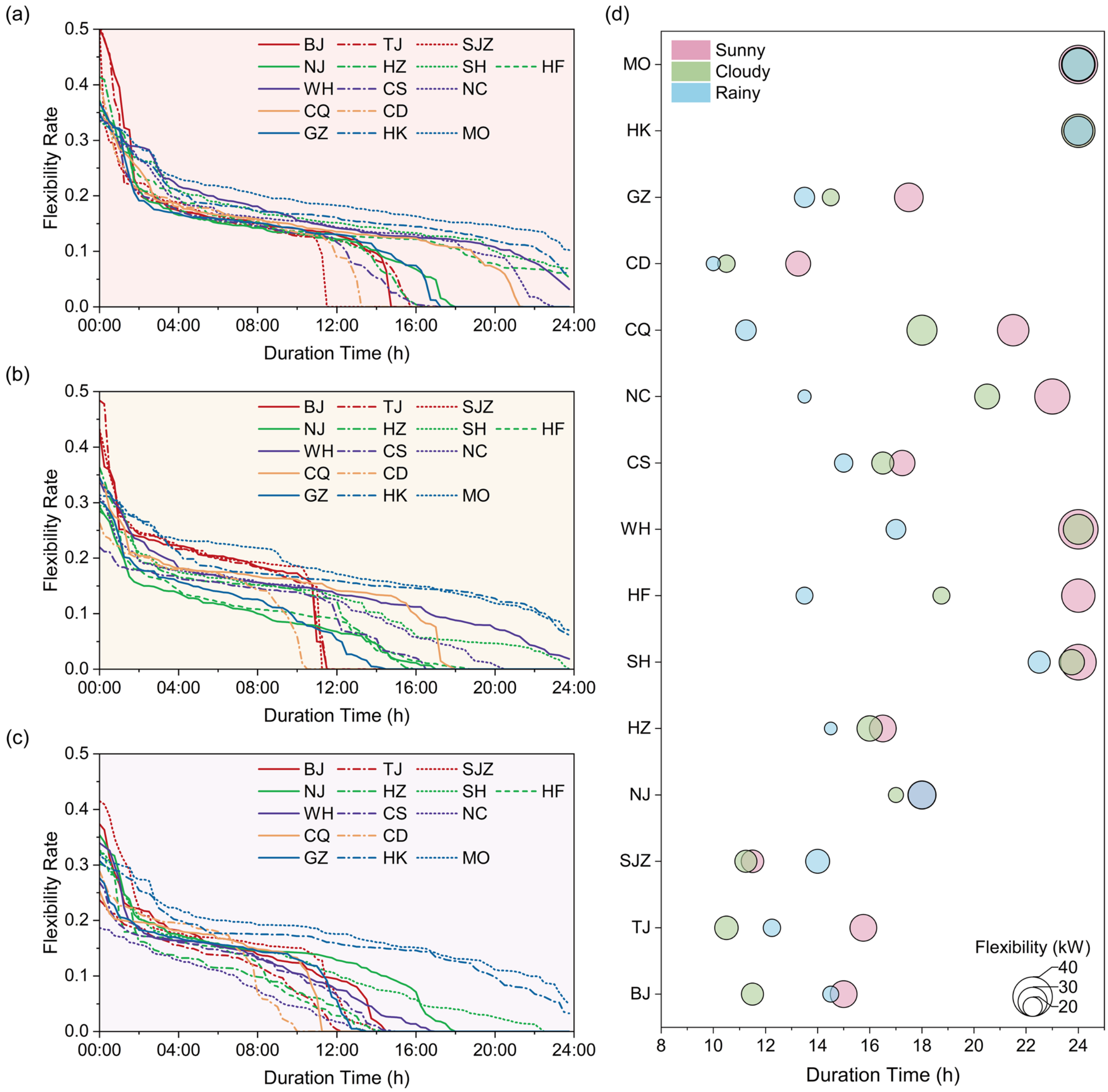

Fig. 6 The flexibility availability across 15 cities: **a**-**c** Duration curves of flexibility rate under sunny, cloudy, and rainy days; **d** Distribution of flexibility and duration time

cation. Despite this limitation, Substantial flexibility is observed during working hours, with median values reaching about 30kW, 25kW, and 20kW on sunny, rainy, and rainy days, respectively. Moreover, significant variations in flexibility within this region can be indicated by large interquartile ranges (IQR) and cannot be ignored. This highlights the need to consider temporal characteristics. In general, these 3 cities exhibit similar performance in flexibility, with SJZ performing marginally better than BJ and TJ.

2) Yangtze River Delta Urban Agglomeration: Differences in flexibility are more pronounced in this region. SH is unique in exhibiting relatively stable flexibility across the 3 weather conditions. The performance of the other 3 cities varies, sometimes exceeding that of northern cities and at other times falling short. Taking HZ as an example, its mean flexibility is approximately 28kW on cloudy days, but this decreases by nearly 50% on rainy days. A posi-

tive aspect is that these cities demonstrate smaller intraday flexibility fluctuations and longer availability periods compared to northern cities. As a result, cities in this agglomeration should focus on the intra-regional disparities and their own unique response to weather variations.

3) Middle Reaches of the Yangtze River Urban Agglomeration: Flexibility in the 3 cities aligns with their T&H dynamics, showing a distinct decreasing trend from sunny (mean ~ 35kW) to rainy (mean ~ 19kW) conditions. Overall flexibility and availability are comparable to the average across the five city clusters. Notably, WH demonstrates strong comparative performance, ranking first in mean flexibility on sunny days and fourth on cloudy days. Despite this, the intra-region differences are not markedly distinct. This suggests that insights derived from geographically proximate cities within this agglomeration may be more relevant than comparisons with distant coastal cities.
4) Chongqing-Chengdu City Group: As Suggested by the T&H dynamics, differences in flexibility between the 2 cities are indeed very distinct. CQ exceeds the average level while CD falls below it. For example, the mean flexibility in CQ is nearly double that in CD on cloudy days. These findings highlight the significance of accounting for intra-regional differences in regions with distinct geographical features, such as western China.
5) Guangdong-Hong Kong-Macao Greater Bay Area: A prominent advantage in southern cities is their reduced sensitivity to weather variations. Although flexibility in GZ is lower than in HK or MO, their own values remain relatively consistent across 3 weather conditions. Furthermore, HK and MO can offer 24-h flexibility availability. Crucially, in these cities, the nighttime flexibility rates can exceed daytime values, which is beneficial for integrating substantial offshore wind power. These unique characteristics emphasize the potential for prioritizing the exploration of HVAC system flexibility in southern cities, where utilization rates are notably higher than in other regions.

4.4 Weather-dependent characteristics of HVAC flexibility

Ensuring the availability of flexibility is essential for power systems with a high penetration of RES. Accordingly, we examine both the Magnitude and duration of flexibility that HVAC systems can provide under 3 weather conditions. The flexibility rate is defined as the flexibility expressed by the proportion of the baseline power. To facilitate a consistent comparison across scenarios, the duration curves of the flexibility rate are plotted in the order of decreasing magnitude, as illustrated in Fig. 6 (a)-(c). The sensitivity to weather variations is illustrated in Fig. 6 (d).

1) Sunny conditions: Primary distinctions among city clusters Mainly Lie in the duration time, as flexibility is usually the highest among 3 weather conditions. While the Magnitudes of flexibility vary significantly, their flexibility rates are broadly comparable as shown by the middle portions of the duration curves. SH, HF, WH, HK, and MO exhibit the longest duration at 24 h, whereas SJZ shows the shortest at 11 h. Excluding the sharp variations at the beginning and end of the curves, the flexibility rates on Sunny days remain relatively stable. This Suggests that most cities can provide at least 10% of their baseline power as flexibility for the majority of the available period.
2) Cloudy conditions: The differences in flexibility characteristics among city clusters become more pronounced. BJ, TJ, and SJZ maintain a very short duration (less than 12 h). Although their flexibility rates are still high, the magnitude of flexibility is limited. Remarkable intra-regional variations are observed in the Yangtze River Delta. For instance, SH's duration can reach up to 24 h, whereas HZ's duration is Limited to 16 h. A similar disparity also exists in central China, where WH (24h) and CS (17h) represent the longest and shortest durations, respectively. In the west, CD demonstrates both the shortest duration and the lowest average flexibility, remarkably underperforming CQ. In contrast, HK and MO maintain both high flexibility rates and long durations, while GZ shows a marked reduction in flexibility.
3) Rainy conditions: The variability in flexibility potential becomes even more pronounced, reflected by greater divergence in the duration curves. Meanwhile, the flexibility durations in rainy conditions are usually the shortest among the 3 weather conditions. Counterintuitively, the flexibility duration for BJ, TJ, and SJZ has increased compared to their performance on cloudy days. HK and MO again exhibit their high resilience, Maintaining 24-h flexibility availability. Conversely, most other cities experience varying degrees of decline, with SH being the least affected.

In Summary, the sensitivity of HVAC flexibility to weather conditions varies across different regions in China. For applications requiring consistent and all-weather flexibility, cities Such as MO, HK, SH, HZ, and CS represent the most promising candidates for large-scale deployment. On the contrary, CQ, NC, and HF display high variability across 3 weather conditions, which could introduce uncertainty into grid regulations that rely on their flexibility. Notably, geographical proximity does not guarantee similar performance in flexibility, a trend particularly evident in coastal regions. The intra-regional disparities observed in the Yangtze River Delta and the Greater Bay Area provide strong evidence for this conclusion. These findings emphasize the significance of accounting for climate diversity when evaluating the integration of flexible resources into power systems.

4.5 Mechanisms underlying the impact of climate diversity on flexibility

In order to investigate the mechanisms of climate diversity and how it affects flexibility, this section analyzes the interplay between outdoor climate variables (temperature, RH, and GHI), indoor conditions (humidity ratio, T&H dynamics), and the resulting flexibility potential, as illustrated in Fig. 7.

The increase in outdoor temperature or GHI leads to a higher cooling load, which in turn enhances the HVAC's dehumidification effect and reduces the indoor humidity ratio. On the contrary, a higher outdoor RH increases the moisture content of the injected fresh air, thereby increasing the indoor humidity ratio. These relationships,

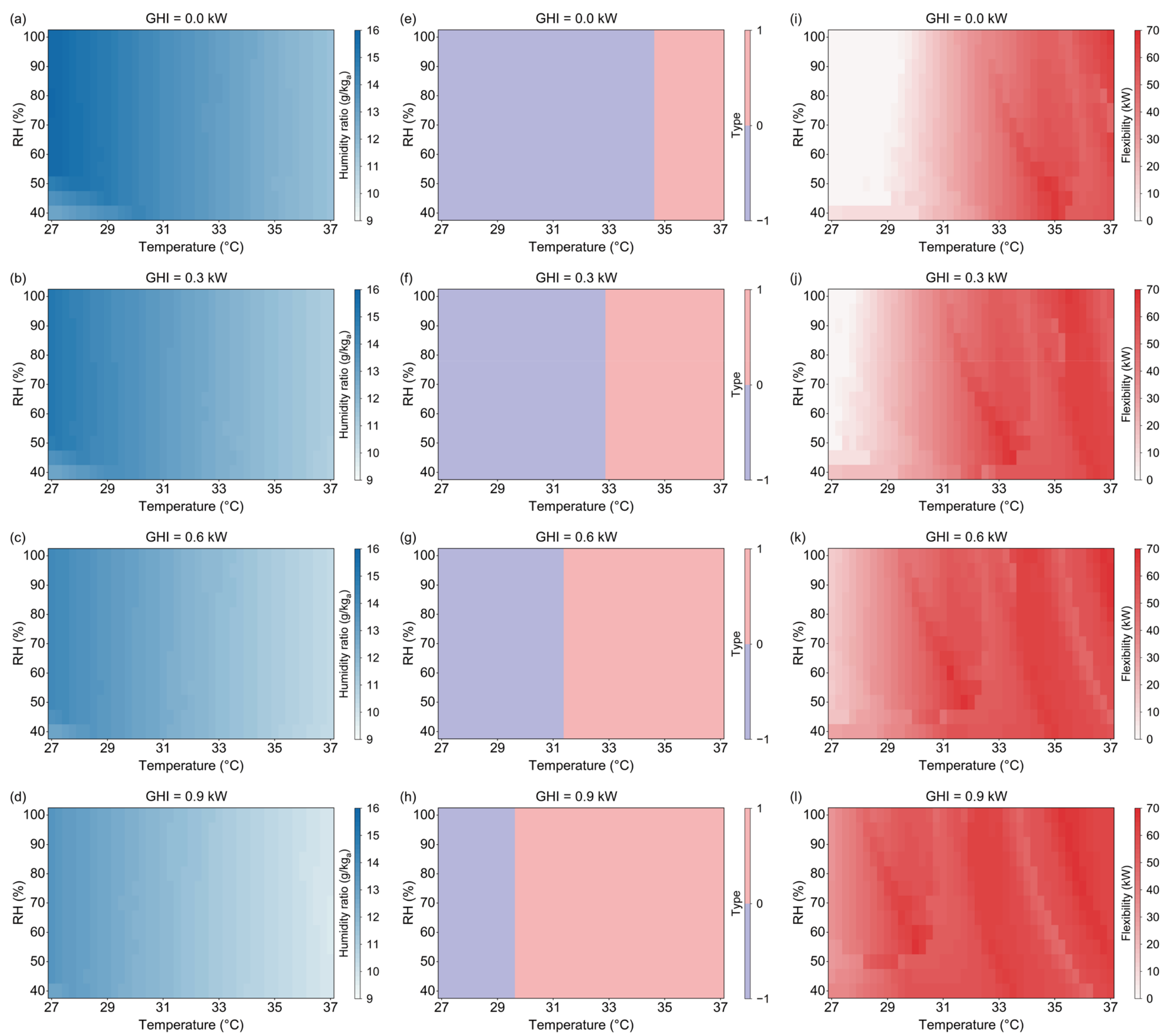

Fig. 7 The impacts of outdoor temperature, RH, GHI on indoor humidity ratio, T&H dynamic, and flexibility: **a**-**d** humidity ratio; **e**–**h** T&H dynamics; **i**-**l** flexibility

depicted in Fig. 7 (a)-(d), explain the observations that indoor humidity levels are typically lower during the day than at night.

Higher indoor humidity levels lead to the T&H dynamics being more sensitive to humidity. As shown in Fig. 7 (e)-(h), distinct thresholds separate 2 operational areas, a temperature-sensitive area (indicated in purple) and a humidity-sensitive area (indicated in pink), respectively. GHI serves as a proxy for weather conditions, with high values corresponding to sunny days and low values to cloudy or rainy days. Critically, the temperature threshold at which the T&H dynamic from humidity-sensitive to temperature-sensitive dynamics decreases as GHI increases. This indicates that temperature-sensitive dynamics, which are more favorable for flexibility provision, are prevalent on sunny days.

While higher GHI (i.e., sunny weather) generally correlates with greater available flexibility, it also drives a simultaneous increase in cooling loads. This creates a complex trade-off: the conditions that generate the most flexibility also coincide with periods of high electricity demand, which is often when that flexibility is most needed by the power system. Furthermore, the influence of outdoor T&H on flexibility is less clear compared to the humidity ratio and T&H dynamics. Humidity-sensitive dynamics, in particular, severely constrain potential flexibility. For instance, under low GHI conditions (e.g., 0 and 0.3 kW/m^2), available flexibility is nearly zero at low outdoor temperatures. However, as GHI increases (e.g., to 0.6 or 0.9 kW/m^2), the relationship becomes highly non-linear, with significant flexibility emerging across a wide range of conditions. Consequently, predicting flexibility potential from outdoor weather variables alone is challenging.

In summary, while the causal links between outdoor weather and indoor T&H dynamics are relatively straightforward, their combined effect on system flexibility is complex and non-linear. This complexity underscores the necessity of performing detailed, model-based evaluations to accurately quantify the available flexibility from HVAC systems before their large-scale integration into power grids.

4.6 Flexibility endowments under extremely hot and hot-humid conditions

The above mechanism analysis highlights the complexity of flexibility evaluation. While the flexibility evaluation is conducted in representative developed cities, it limits the guiding significance to other regions. To this end, we further analyze the T&H dynamics and investigate the flexibility endowments in China under extreme weather conditions, when power systems face not only a surge in total load but also a shortage in flexible regulation capacities. Under such circumstances, power systems tend to seek additional flexibility to enhance their own resilience, and these results can provide valuable information on whether it is feasible to explore flexibility in building HVAC systems.

In this subsection, we concentrate on the specific instant when the dry-bulb or wet-bulb temperature is the highest across all weather stations. The highest dry-bulb temperature scenario always indicates sunny weather and the largest baseline cooling load, as shown in Fig. 8 (a). The scenario of maximum wet-bulb temperature, which is contributed by both T&H, is more complicated than the dry-bulb temperature, as depicted in Fig. 8 (b). For instance, its corresponding weather can be cloudy or rainy, even Sunny days, which further formulates different T&H dynamics. Flexibility, evaluated under the 2 scenarios, is represented by the maximum capacity and shown in Fig. 8 (c) and (d). The fundamental calculation of DR capacity is consistent with the HVAC flexibility evaluation methodology described in Sect. 2, which involves determining the maximum power reduction achievable by HVAC systems while rigorously maintaining indoor temperature and humidity within predefined comfort ranges. More details are provided in S3.

China's vast geographic diversity leads to significant regional variations in Maximum temperatures. In some regions, e.g., BJ, the Maximum temperature exceeds 38°C. However, in cooler regions, e.g., Tibet, the value is even lower than 25°C. In these cooler regions, there is little cooling demand, and thus, no flexibility can be provided by HVAC systems during summer. Obviously, there is no need to exploit flexibility from HVAC systems in these regions.

In eastern hot regions, the temperature completely dominates T&H dynamics. Interestingly, higher DR capacities always occur in regions where Maximum temperatures are lower than 35°C, like the northeast region. The findings are consistent with the above results that flexibility does not increase proportionally with rising outdoor temperatures. In most regions of eastern China, the Maximum capacities range between 35-44kW, there are few differences in the flexibility, indicating that power systems can facilitate HVAC systems to enhance regulation capabilities under extreme hot weather.

The scenario with the highest wet-bulb temperature, which typically corresponds to hot and humid conditions, shows district differences compared to the dry-bulb temperature scenario. On the one hand, the values of wet-bulb temperature are lower than those of dry-bulb temperature. On the other hand, the distributions of wet-bulb temperatures are a Little different, i.e., the whole western regions are below 24.1°C, and the maximum

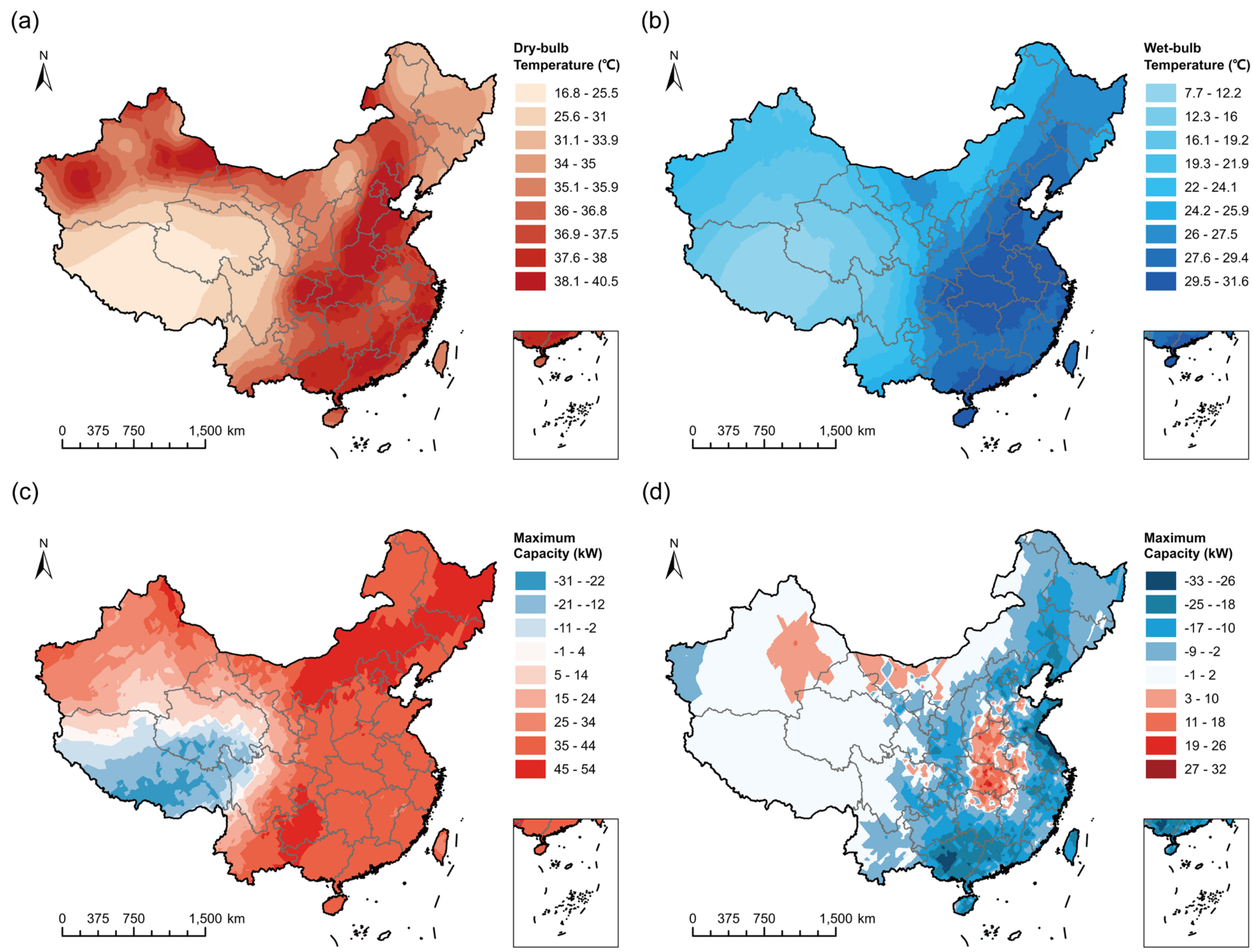

Fig. 8 Spatial distribution of meteorological conditions and corresponding DR capacities across China. **a** Maximum dry-bulb temperature distribution indicating the extremely hot scenario; **b** Maximum wet-bulb temperature distribution indicating the hot-humid scenario; **c** Maximum DR capacities under extremely hot scenario; **d** Maximum DR capacities under hot-humid scenario. The red areas with positive values indicate the temperature-sensitive type, and the blue areas with negative values denote the humidity-sensitive type. It should be noted that the positive and negative signs are only used to indicate the types of T&H dynamics, while the absolute values represent actual flexibility

values mainly concentrate on the central regions. Therefore, we can see the maximum capacities in the western regions delineated above are almost between −1-2kW, meaning that the flexibility of HVAC systems is hard to explore on cloudy and rainy days. Given that the northwest regions exhibit partial DR potential on hot days, they should carefully consider the economics of utilizing HVAC systems. For those cities with dominant sunny weather, the HVAC systems can be considered as a feasible supplementation.

In eastern China, humidity dominates the T&H dynamics in most regions, except in the central regions. Central regions are neither coastal nor cool, their dry-bulb temperature mainly contributes to high temperature rather than humidity. As a result, humidity has a smaller impact on HVAC systems, and their T&H dynamics still belong to the temperature-sensitive type. Under Such circumstances, the central regions also exhibit great DR potential, with Maximum capacities reaching as high as 32kW. Then, in terms of regions classified as humidity-sensitive type, flexibility increases as proximity to the sea decreases, so most coastal regions possess higher DR capacities. However, northeastern regions exhibit significant decreases from the dry-bulb temperature scenario to the wet-bulb temperature scenario, indicating there are distinct flexibility fluctuations with weather changes. Most importantly, the maximum capacity demonstrates very significant variations in neighboring regions, even though the wet-bulb temperatures are similar. This underscores the necessity of incorporating humidity and accounting for regional differences.

Overall, the maximum capacities in the wet-bulb temperature scenario are much lower than in the dry-bulb temperature scenario. However, the former can even reveal more flexibility characteristics. On the one hand, RES like photovoltaics tend to fluctuate more frequently due to the weather conditions, the power systems may still face challenges on regulation capacity insufficiency, and need to pay attention to the DR potential on cloudy or rainy days. On the other hand, the wet-bulb temperature scenario can provide a more comprehensive reference to evaluate the feasibility and economics of exploiting HVAC flexibility, as their flexibility performance in the dry-bulb temperature scenario is very similar.

5 Discussion and conclusion

This research develops and applies a comprehensive framework for evaluating the flexibility of urban HVAC systems. By incorporating both T&H impacts, the framework improves evaluation accuracy and is Suitable for national-scale application. We applied this framework to evaluate HVAC flexibility in 15 Major Chinese cities across 3 distinct weather conditions. The results reveal that T&H dynamics vary significantly with climate, which in turn affects the magnitude and duration of flexibility. Further analysis of outdoor climatic parameters demonstrates the complex and climate-dependent nature of HVAC flexibility. Extending this evaluation across China, we map the flexibility endowment of urban buildings as shaped by climate diversity, highlighting the necessity of a comprehensive evaluation that accounts for varying weather conditions.

This framework addresses a critical gap in prior research, which often overlooked the role of humidity in favor of temperature alone. The absence of humidity can lead to inaccurate results and potentially compromise occupant benefits, thus hindering the large-scale utilization of HVAC systems across diverse regions.

Previous studies have also predominantly focused on HVAC performance on Sunny days, where flexibility potential tends to be similar across different locations. Nevertheless, our findings demonstrate that significant inter-regional differences emerge under varying weather conditions. As HVAC systems are among the loads most sensitive to weather, examining their response under diverse weather conditions is critical before large-scale exploration. Our results have identified several cities that exhibit robust and all-weather flexibility, Such as SH, HK, and MO, Making their HVAC systems prime candidates for integration as regular grid regulation resources. On the contrary, cities Like CQ, NC, and HF demonstrate polarized performance, with high flexibility on Sunny days but significantly less on rainy days. This implies that relying on HVAC systems as the dominant flexibility Supplier in these cities May lead to insufficiency during cloudy or rainy periods. Furthermore, although our study examines 3 representative weather conditions, their annual frequency varies by location. For instance, sunny days dominate summer in MO, whereas cloudy days are more prevalent in HZ. Therefore, when exploring city-level flexibility, detailed consideration of local weather patterns is necessary.

In addition to climate, significant performance disparities exist even among geographically proximate cities. In our studied 5 city clusters, only the Beijing-Tianjin-Hebei and Middle Reaches of the Yangtze River clusters exhibit strong intra-regional similarities. This finding further emphasizes the need to consider local characteristics in policy and resource planning [39], as directly transposing strategies from one city to another may be ineffective. Our analysis also indicates that coastal proximity is a key factor. Coastal cities usually display heightened sensitivity to humidity, resulting in distinct flexibility performance. These differences, however, can be advantageous [40]. For example, system frequency support from other provinces is in progress in China Southern Power Grid, which can reduce the overall frequency regulation capacity demand by taking full use of the regional differences.

A broader examination of flexibility endowments across China further emphasizes the regional distinctions during typical summer conditions and peak demand scenarios. By examining performance under extreme dry-bulb and wet-bulb temperatures, we can obtain a preliminary judgment of the feasibility of exploiting HVAC systems. Western regions with low ambient temperatures (such as Tibet and the west of Sichuan) are generally unsuitable. Northeastern and northwestern regions, along with Inner Mongolia, offer flexibility primarily on sunny days, limiting their application scenarios.

Comparatively, most other regions show considerable potential, though both inter- and intra-regional remain significant. Combined with the analysis of 5 typical city clusters, we propose the following region-specific considerations for developing HVAC flexibility:

1) Northern China: Characterized by large diurnal temperature variations, these cities show notable day-night variations in flexibility. They would benefit from integrating complementary flexible resources, such as electric vehicles [41], to compensate for low HVAC flexibility at night and create a more robust grid resource pool.
2) Eastern China: Many cities in this region possess high flexibility potential but also high sensitivity to weather variations, necessitating careful evaluation under different weather conditions to determine the appropriate positioning for HVAC systems. Meanwhile, the DR markets also actively incorporate

weather-adjusted baselines to prevent under- or over-estimations of response capacities.

3) Central China: These continental cities show a consistent decrease in flexibility from sunny to rainy days. Initial policy efforts should be directed toward funding pilot programs. The key task is to quantify specific flexibility and further assess the economic and technical feasibility of exploration.
4) Western China: This region displays the greatest heterogeneity in flexibility, driven by a combination of climate, terrain, and altitude. A case-by-case evaluation for each potential city is essential. Correspondingly, the DR strategies need to be tailored according to the flexibility characteristics, aimed at exploiting more flexibility.
5) Southern China: These cities offer the most stable flexibility, as high ambient humidity levels make them less sensitive to weather and diurnal changes. It is recommended to design more diverse and reliable DR market products to fully utilize their long-duration flexibility from HVAC systems. For cities other than the high-performing examples (HK and MO), their focus should be on examining the gaps in these benchmarks.

Actually, regional differences in resource characteristics are already reflected in the development of supply–demand interactions in China. For example, northern China typically employs virtual power plants (VPPs) [42], integrating resources such as RES, energy storage, and diesel generators. Southern China mainly concentrates on multiple flexible loads, which are classified and aggregated to participate in DR programs [43]. However, the role of flexibility differences has yet to be fully incorporated into these frameworks. As China's electricity market matures, it is vital that new policies and market designs account for the regional characteristics of dominant flexible resources like HVAC systems [44].

The research's main limitations are the availability of detailed climate data and building information. We have found that outdoor T&H has a profound impact on the performance of HVAC systems, yet our weather data lacks granularity. In reality, T&H conditions can vary considerably within the same city. Besides, specific building details and HVAC system parameters are also essential for accurate flexibility evaluation. For finer-grained evaluations, such as those focused on small urban blocks or neighborhoods, more detailed climate and building data would improve accuracy, with some studies even factoring in microclimate effects [45]. Moreover, the research limits the comprehensive evaluation of year-round temporal characteristics by focusing solely on summer data. Multi-seasonal evaluations can provide more holistic information to assess the feasibility and economics of leveraging large-scale HVAC flexibility. Our results illustrate how humidity and climate diversity could affect the flexible resource endowment of building HVAC systems in China. Incorporating humidity in flexibility evaluation not only enhances accuracy but also helps meet occupant comfort requirements during DR events, which is one of the most difficult obstacles to promoting large-scale implementations. Historically, resource endowments, such as water, solar, and wind, were utilized to evaluate the economics of RES development. Our findings emphasize the importance of also accounting for regional differences in HVAC flexibility.

To better match the development of RES, flexible resource endowments like HVAC systems need to be incorporated into future energy roadmaps [46]. For provinces or cities with specific spatial and temporal demands of regulation capacities, the flexibility provided by HVAC systems can be examined for compatibility. For example, the Guangdong-Hong Kong-Macao Greater Bay Area faces challenges accommodating offshore wind power at night, where leveraging HVAC flexibility could be beneficial. Although we recognize that not all countries or regions have such diverse climates as China, our results suggest that the differences in flexibility under different weather conditions are also crucial globally as efforts toward decarbonization continue.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1007/s43979-025-00136-9.

Supplementary Material 1.

Authors' contributions

Conceptualization: Taoyi Qi, Hongun Hui, Yonghua Song. Methodology: Taoyi Qi, Hongun Hui. Investigation: Taoyi Qi, Wei Feng. Visualization: Taoyi Qi, Hongun Hui. Supervision: Yonghua Song. Writing—original draft: Taoyi Qi, Hongun Hui. Writing—review & editing: Wei Feng, Yonghua Song.

Funding

This work was supported by the National Natural Science Foundation of China (524B2100, 52407075), the Guangdong Basic and Applied Basic Research Foundation, China (2025A1515011531), University of Macau (MYRG-GRG2025-00305-IOTSC, CPG2025-00023-IOTSC) and the Science and Technology Development Fund, Macau SAR (001/2024/SKL).

Data availability

The data are available from the corresponding author upon reasonable request.

Declarations

Competing interests

The authors declare they have no competing interests.

Received: 1 April 2025 Revised: 23 June 2025 Accepted: 20 August 2025
Published online: 28 September 2025

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