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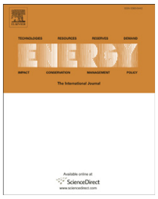

Quantification of electricity flexibility in demand response: Office building case study

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ABSTRACT

Electric demand flexibility in buildings has been deemed to be a promising demand response resource, particularly for large commercial buildings, and it can provide grid-responsive support. A building with a higher electricity flexibility potential has a higher degree of involvement with the grid response. If the electricity flexibility potential of a building is known, building operators can properly alleviate peak loads and maximize economic benefits through precise control in demand response programs. Previously, there was no standard way to quantify electricity flexibility, and it was difficult to evaluate a given building without experiments and tests. Thus, a systematic approach is proposed to quantify building electricity flexibility. The flexibility contributions include building thermal mass; lights; heating, ventilation, and air conditioning (HVAC) systems, and occupant behaviors. This proposed model has been validated by the instantiation of an office building case on the Dymola platform. For a typical office building, the results show that the electricity flexibility resource not only comes from the HVAC system, but also thermal mass and occupant behavior to a large degree, and buildings with energy flexibility can cut down much of their load during peak load time without compromising on the occupant's comfort.

1. Introduction

The use of renewable energy, such as solar and wind energy, has been developing rapidly worldwide to reduce dependence on fossil fuels. However, a discrepancy between supply and demand occurs when these intermittent energies pour into the power grid. To alleviate this problem, various grid-interactive building technologies have been proposed recently [1]. These technologies, such as building demand response, enable the grid operator, building owner, and electrical facilities to connect with each other for better energy management.

There are many measures for turning a grid-interactive building off-load during an extremely high peak load and up-load during the grid's peak—valley time to balance the grid [2]. To reduce the electrical load of heating, ventilation, and air conditioning (HVAC) systems, precooling/preheating and zone temperature reset are two common passive methods [3, 4]. Escriva-Escivá et al. [3] minimized the HVAC systems' energy consumption by using different efficient control strategies which can be used to improve building energy flexibility as well. Xu et al. [4] presented an experimental study of the precooling strategy for a commercial building. They demonstrated that peak load can be reduced by 80% during a normal peak period from 2:00 p.m. to 5:00 p.m. without complaints about comfort from the occupants in heavy-mass buildings. Within the comfort temperature range, the occupants could reset the room temperature to change the building's electrical demand. Only for the zone temperature reset method, cooling/heating loads can be reduced when the room temperature setpoint is a few degrees higher/lower during the peak load period. In the cooling case, a maximum load reduction of 25% and a continuous-time of 20 min can be achieved by resetting 2 °C higher than the normal thermostat setting [5]. These two aforementioned passive methods used to reduce HVAC load can be also found in other works [6, 7]. However, energy flexibility can only be evaluated with experimental testing in these papers. It's hard to generalize this method when the energy system is different.

To balance the power grid, however, the energy flexibility

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Nomenclature

A	the surface area of thermal mass(m^2)
Bi	Biot number of thermal mass
COP_{AC}	air conditioning COP
C_p	specific heat capacity($kJ \cdot kg^{-1} \cdot {}^\circ C^{-1}$)
d	equivalent diameter(m)
F	electricity flexibility (W)
Fo	Fourier number of thermal mass
k_0	lights closed ratio($0 \le k_0 \le 1$)
L_f	furniture size dimension(m)
m_f	furniture weight(kg)
$\dot{m}$	the mass flow rate of air(kg/s)
P	power(W)
t_d	response span time(s)
U_A	overall heat transfer coefficient of the exterior wall [$W/(m^2 \cdot {}^\circ C)$]
V	volume(m^3)
α	heat release ratio
ρ	density(kg/m^3)
Subscript	
AC	air conditioning
extra	higher temperature setting by occupant's behavior
f	furniture
r	room
range	recommended comfort temperature range
w	water
a	air

potential of the building itself is the decisive factor. Thus, how to quantify a building's electricity demand flexibility has become an important topic in this field. The electricity flexibility of a building can be formed by different energy systems. Fig. 1 shows the formation and conversion process of these different flexibility resources in a building. According to the literature study, the common way to calculate the flexibility is by establishing a specific energy system and testing it [8, 9]. Some studies have aimed to evaluate the flexibility of a specific energy system. For example, for HVAC systems, Nuytten et al. [9] proposed a model for the flexibility assessment of a heat and power system with a thermal energy storage system, and flexibility profiles were proposed to quantify the energy flexibility of combined heat and power systems with thermal storage tanks. These profiles are characterized by the minimum and maximum of the state of the charge. From different points of view, Heussen et al. [10] and Reynders et al. [11]

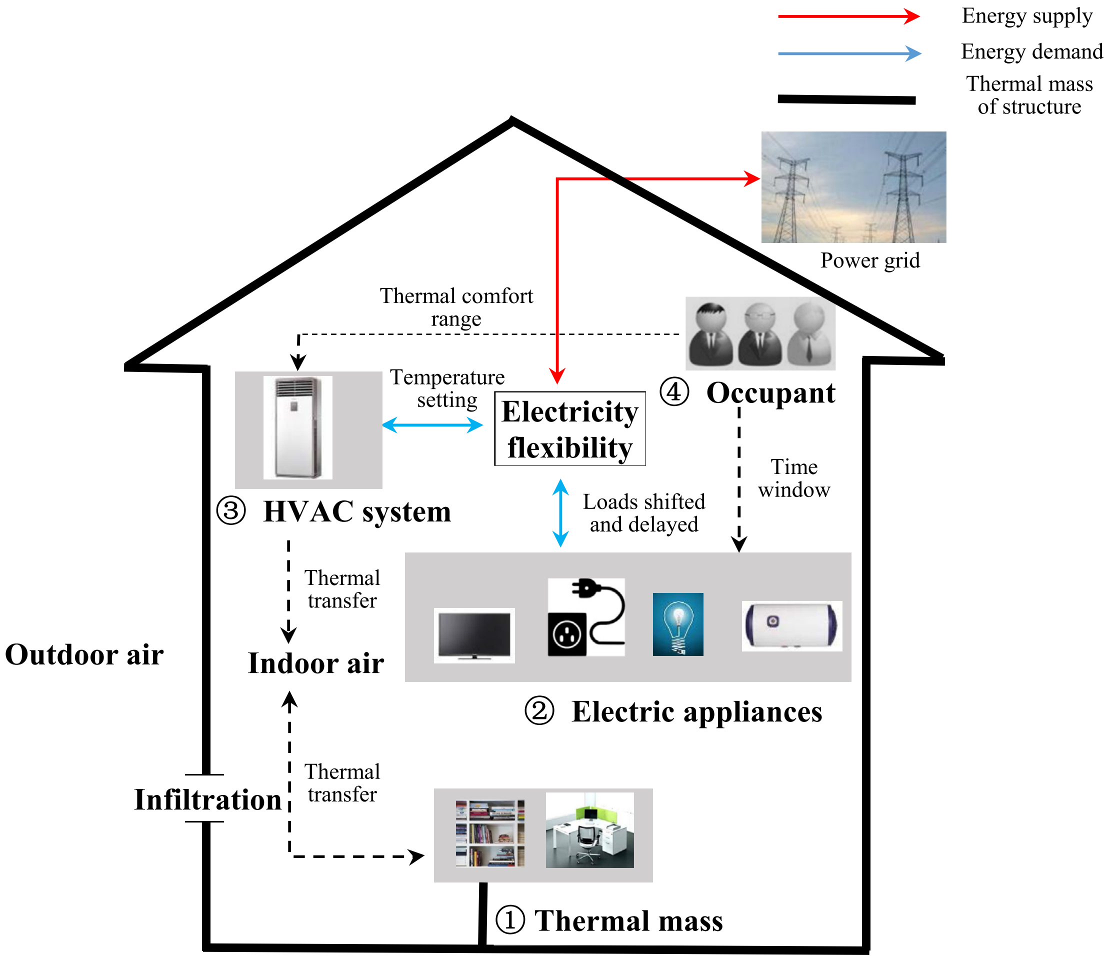


Fig. 1. Different electricity flexibility sources of building.

characterized the energy flexibility using three indicators: the available storage capacity, the storage efficiency, and the power shifting capability. Zhang et al. presented upward and downward flexibility for a heat pump system of residential buildings, then different metrics were used to quantify the impact of energy deployment for different stakeholders [12]. In addition, Stinner et al. [13] proposed a concept of temporal flexibility time that includes forced and delayed operation time and also power flexibility and energy flexibility analysis at a city-district level. The results show that each proposed method mentioned above accurately to quantify the energy flexibility, while the method hardly generalizes to other energy systems.

In addition to the literature focusing on HVAC systems, studies also have demonstrated that the flexibility potential can be achieved by using the heat inertia of the building thermal mass. The use of thermal mass for potential flexibility has been identified as a promising and cost-effective solution [14, 15]. Le Dreau and Heiselberg [16] have assessed the heat storage and conservation of two residential buildings, and they concluded that flexibility potential highly depends on the level of thermal insulation and air-tightness of the envelope. Furthermore, furniture also has thermal inertia that stores or releases heat when the surrounding temperature changes. A few studies have considered the furniture mass to quantify this flexibility contribution. Li et al. [17] proposed a new method dubbed “effective area” to calculate the thermal surface of the irregular internal mass, such as furniture in buildings; thus, the furniture side can be considered together in the envelope side when assessing the flexibility potential of thermal mass. In their studies, no formula was created to quantify the thermal mass flexibility potential of a common building, and people do not know how much flexibility comes from different flexibility resources such as thermal mass, human behavior and so on. This current situation limits the building flexibility's improvement and utilization.

For electric appliances, some studies have shown that electric appliances' loads can be easily shifted for flexibility purposes. For example, D'hulst et al. [18] proposed the concept of a time window (see Fig. 2) for home smart appliances to shift loads when necessary, and the same concept can be seen in other studies [19]. A novel tool for demand response assessment and evaluation in the industrial sector was introduced in Ref. [20], and the flexibility of interruptible loads was evaluated at each time step. Using a day-ahead planning energy management framework, Mohseni et al. [21] concluded that energy costs and peak loads can be reduced efficiently. The appliances were sorted into different types for analysis. Tulabing et al. [19] categorized the flexible loads as thermostatically controlled loads (TCLs), non-TCLs, and battery-based loads, and they established equations to quantify these different loads. Although the flexibility definition in their study has a simple form, the real-time temperature of the thermal zone is not reachable for all participants. Similarly, the quantification of a TCL's flexibility has been described by Yin et al. [22]. In their studies, the power of a reference case and demand response (DR) case were used to calculate the DR potential afterward. A reference case used in the flexibility quantification has also been introduced in many other studies [13, 23, 24], although it might be difficult and confusing for the building operators to obtain.

Furthermore, occupants' behaviors play a vital role in energy flexibility [25]. Different groups of people have different thresholds of thermal comforts, such as tolerance of room temperature. This aspect has seldom been studied. Occupant behavior can be affected by age group, economic status, energy price, building type, climate, and so on. In this regard, it is quite difficult to evaluate the energy flexibility from occupant behavior accurately. In previous research, the occupant behavior flexibility was usually considered together with the energy system, while the flexibility contribution owes to the energy system all. There have been few studies investigating the relation between energy flexibility and occupant's flexibility as well as the relation between energy flexibility and the thermal environment itself.

Energy-flexible buildings are a promising demand response resource, capable of providing grid-interactive support. Buildings' electricity flexibility could be made up of many contributions such as the load changes of the HVAC system and electric appliances. Even though quantified methods have been proposed, there is no commonly accepted definition, and the calculation process is too complex for design engineers and building operators. Furthermore, the electricity flexibility sources from buildings are not clear according to the literature, let alone the entire flexibility evaluation methodology. For example, many of the flexibility studies on HVAC systems have also involved the heat inertia from building thermal mass, but the actual flexibility contribution from thermal mass and other factors individually, particularly the HVAC system with a storage tank, is not known. The installation of a storage tank increases the flexible use of energy of the HVAC system; thermal characteristics and the mass of walls and furniture represent the thermal mass's flexibility contribution. Thus, thermal mass and the other sides' flexibility should be separated to better investigate the flexibility sources in different types of building, which can be sorted by building vintage, building function, and so on.

The electricity flexibility potential in buildings can act as an allocable energy resource among the participants, such as building engineers, owners, energy managers, aggregators, and governments. However, most of the aforementioned methodologies require input parameters that are not easy for the participants to obtain. If it is a building in design, without testing, it is impossible to obtain a baseline load. Building energy managers and other participants often do not know the actual flexibility potential. Based on the aforementioned deficiencies, we believe that these

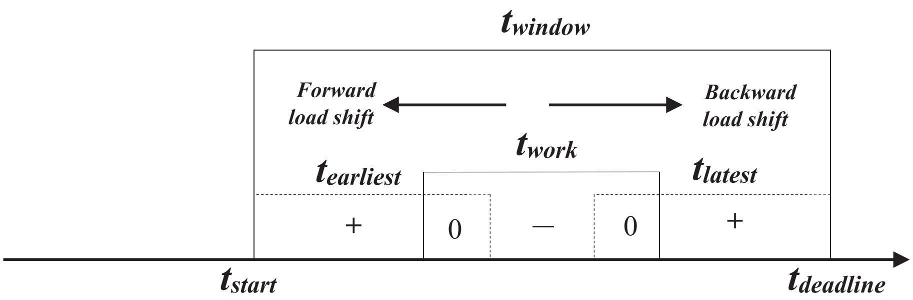


Fig. 2. Schematic of appliance flexibility in the time window.

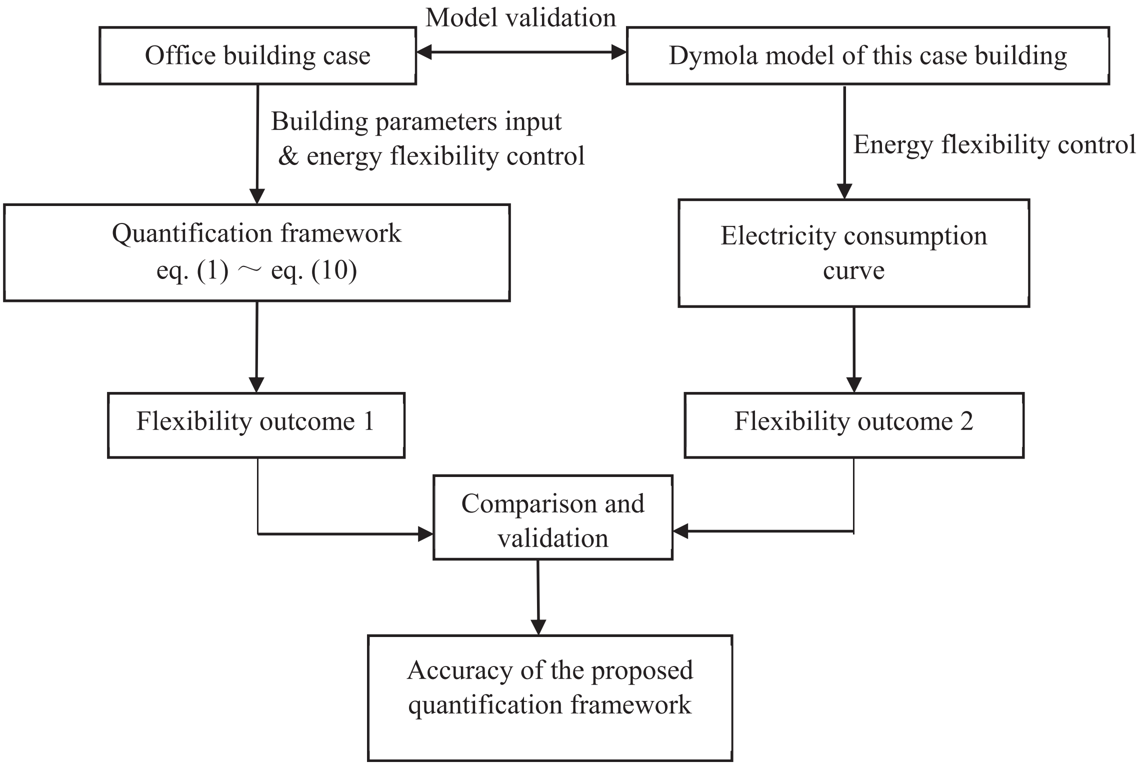


Fig. 3. Flow diagram of the flexibility evaluation framework validation method.

three new ideas in our paper will be an interest to the related readers. Firstly, we built a generalized approach to quantify building's electricity flexibility comparing the previous study that usually focuses on a specific energy system. Secondly, the approach we proposed does not need a load baseline which is normally used to calculate the energy flexibility referring to the literature review. This baseline is hard to predict especially for a design phase building. Lastly, only some basic parameters (e.g. thermophysical parameter of building structure) are required in this approach and all of them are easy to obtain regardless of design phase buildings or existing buildings. With these merits, this quantification framework can be easily integrated into energy management systems so that we can fast calculate energy flexibility before any energy management service (e.g. demand response) for better managing.

In addition, the energy flexibility of a building is an important factor for building performance, even though it has been ignored in past building evaluation norms. Currently, building evaluation standards are more focused on energy efficiency. The energy efficiency is not enough to evaluate one building overall under the development of renewable energy, and energy flexibility ability becomes increasingly important to the grid-integrated building. Thus, energy flexibility should be another evaluation index included in future building evaluation standards, and a generic flexibility quantification method that only requires some easily obtainable parameters from buildings is essential to evaluate a building's degrees of grid interactivity. The objective of this study is to establish an innovative quantification method to evaluate electricity flexibility in buildings. The content of this work are as follows: (i) propose a methodology to analyze and formulate the electricity flexibility contributed from different sources in a building (Section 2); (ii) use an office building case to explain the framework (Sections 3 and 4); and (iii) present and discuss the flexibility results of different contributions (Section 5). The overall goal is to establish a general framework of electricity flexibility and key formulas to quantify electricity flexibility.

2. Electricity flexibility quantification methodology

Energy flexibility is defined as the ability to balance energy supply and demand cost-effectively and continuously, while simultaneously maintaining acceptable service quality to connected loads [26]. The unit of energy flexibility can be watts, kilowatt-hours, or kilojoules. The flexibility in kilowatt-hours was used to investigate the total delayed and forced operation flexibility in previous research [9]. To coincide with the demand response's requirement, where people focus on real-time load reduction more than total energy reduction, in this study, the electricity flexibility in watts is described, and the formulas apply to any forms of energy flexibility. The electricity flexibility in the demand response field is analyzed so that all the energy flexibility forms, such as heating and cooling loads, are converted to electricity. Buildings' electricity flexibility could result from a building's thermal mass, HVAC and storage systems, electric appliances, and occupants' behavior. In this section, the mathematical equations are built as a systematic quantification framework to quantify a building's electricity flexibility from these four different parts. This methodology not only can be applied to existing buildings but also new design buildings.

2.1. Flexibility from thermal mass

Building thermal mass includes furniture and the building envelope, which can function not only as a heat insulator but also as a thermal storage medium, called "heat inertia." The heat can be absorbed or released from the thermal mass of a building. The building thermal mass level and the glazing ratio of buildings have been shown to affect the different peak load reductions and energy consumptions [27, 28]. However, it is not clear how to assess the

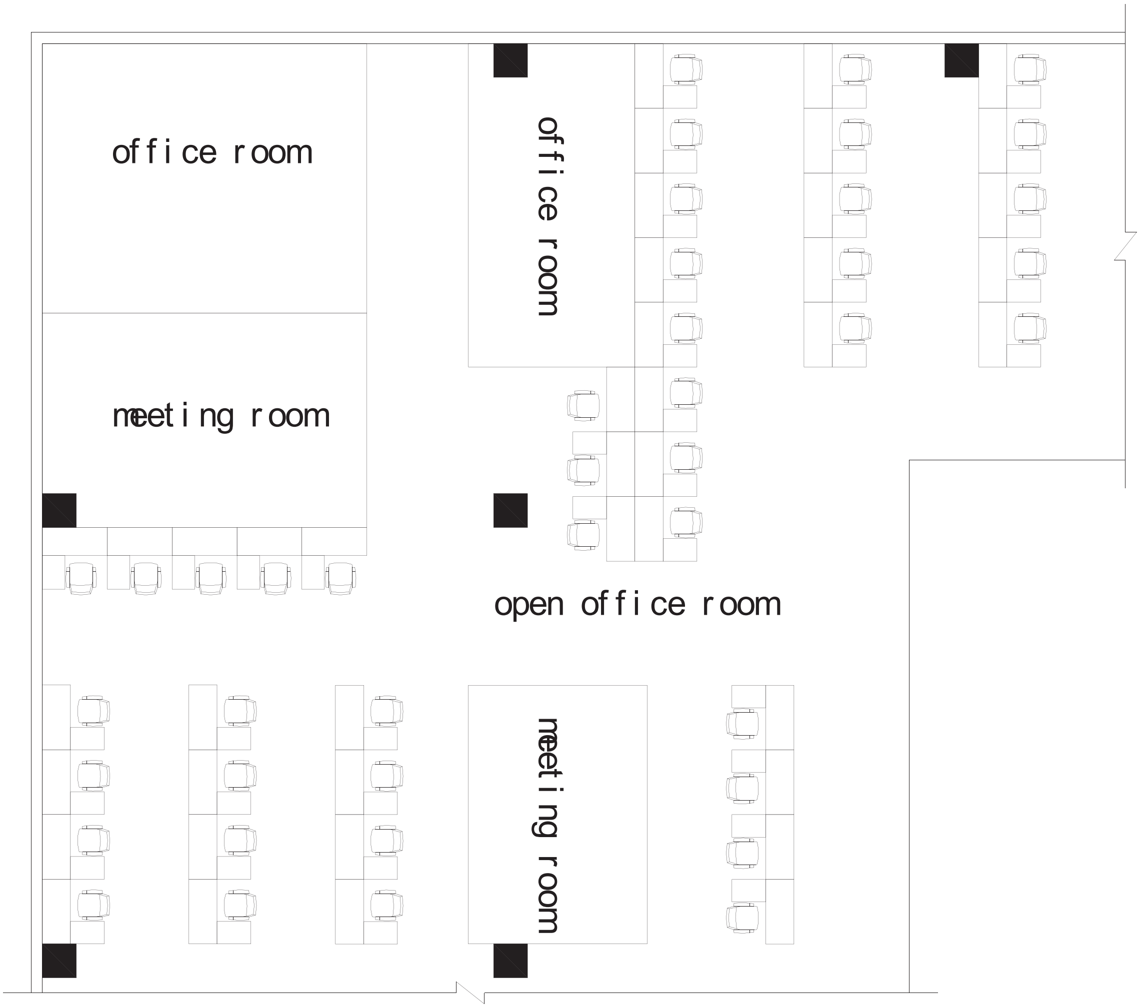


Fig. 4. Floor plan of the office zone.

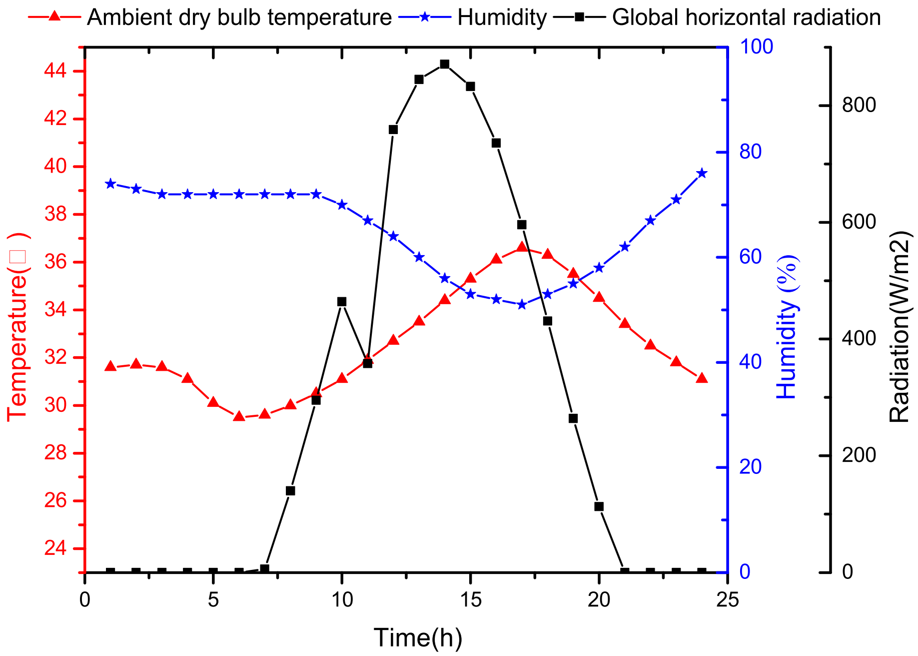


Fig. 5. Main meteorological data of the summer design day (July 21).

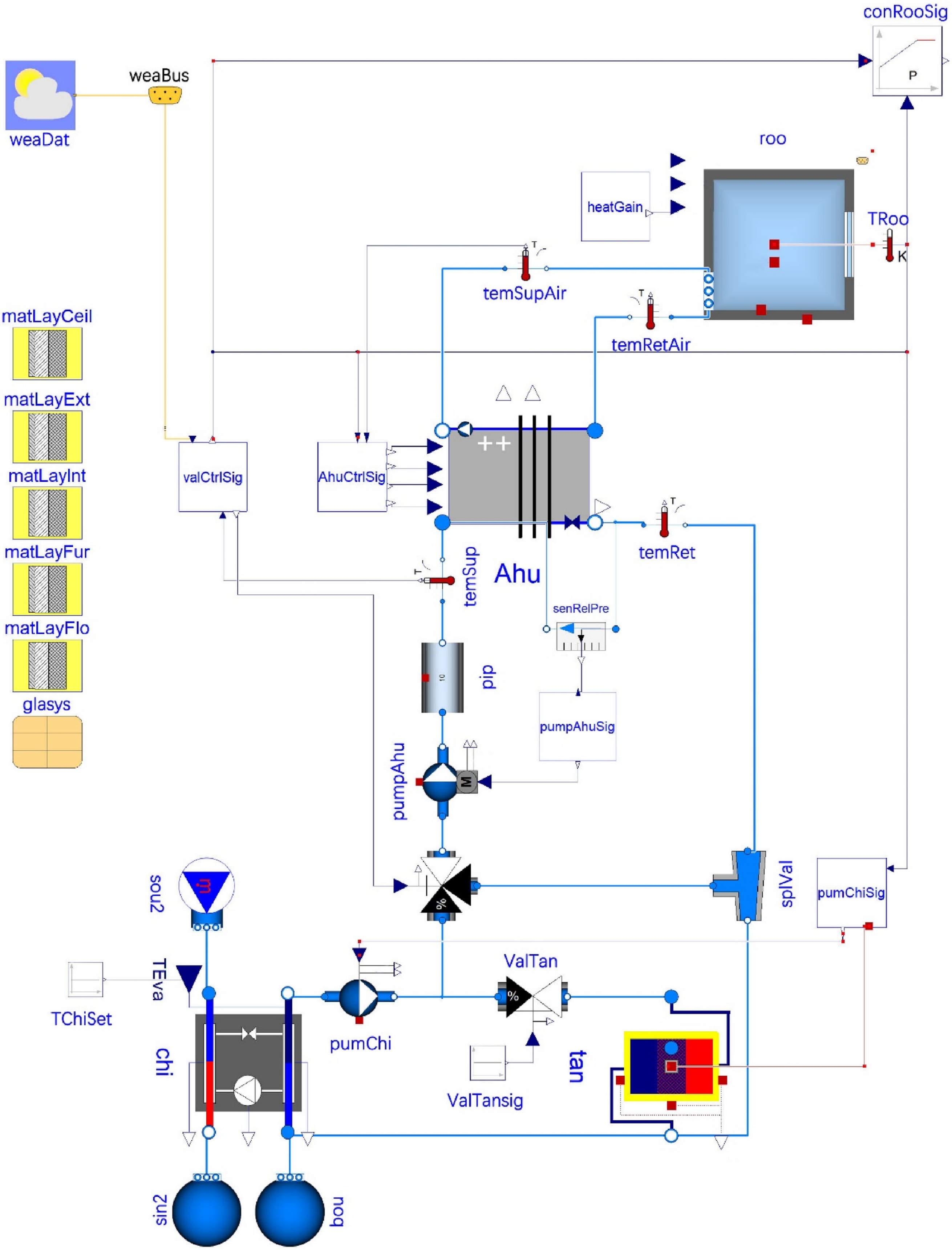


Fig. 6. Schematic layout of the energy system in Dymola.

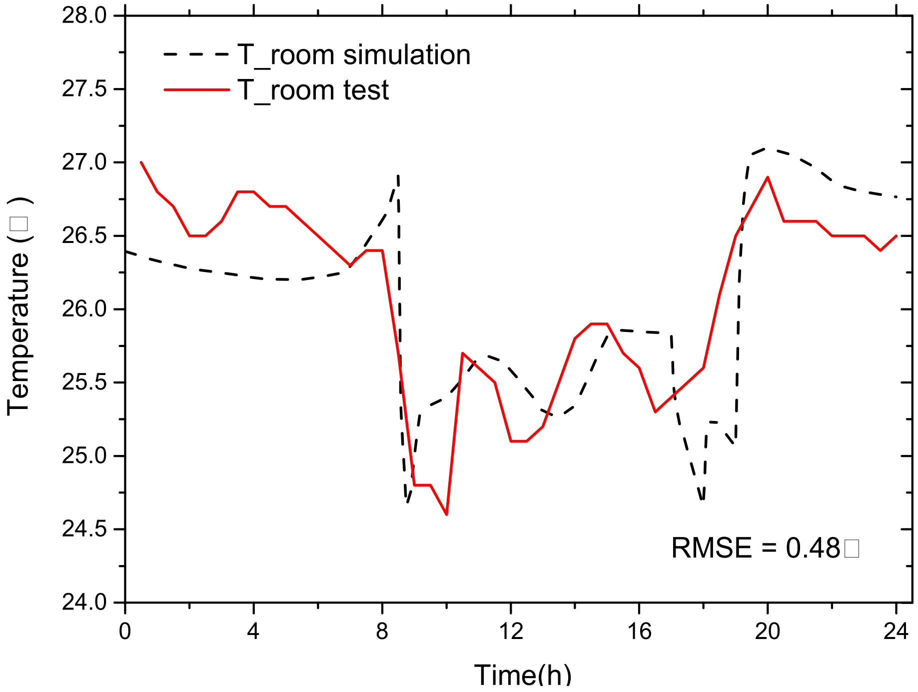


Fig. 7. Room temperature comparison of on-site test and Dymola model simulation.

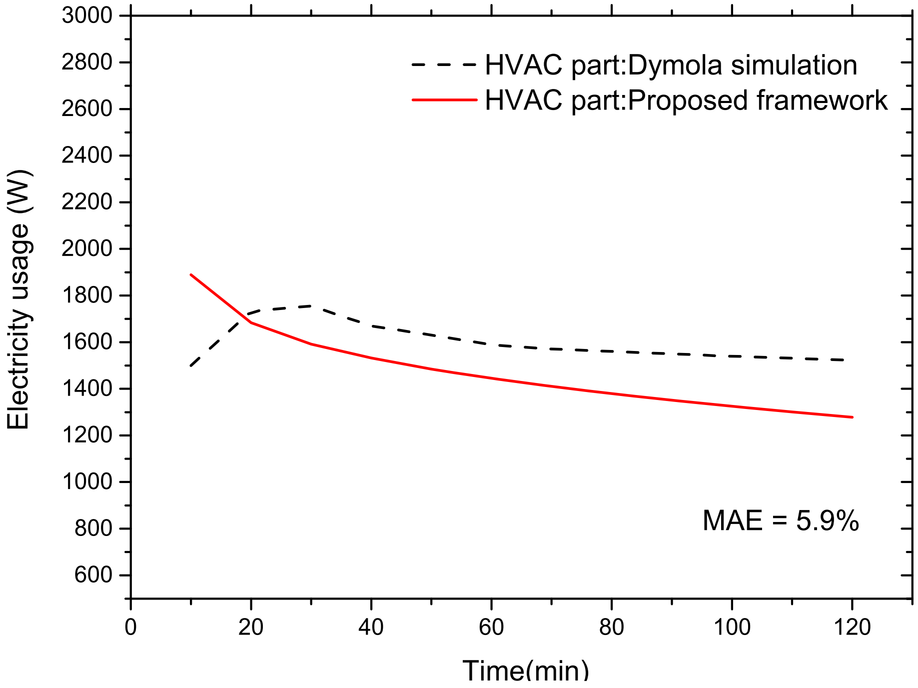


Fig. 8. HVAC flexibility results of the proposed framework and the Dymola simulation.

flexibility capacity of thermal mass, particularly irregular internal masses, such as furniture. By considering an easy approach to quantify the electricity flexibility in design and operation, models are proposed that only require some basic obtainable building parameters. The definition of a building thermal mass's electricity flexibility F_1(W) is expressed by Eq. (1).

$$F_1 = \sum_{i=1}^{n} \alpha_i C_i T_{range} \Big/ (t_d COP_{AC}) \tag{1}$$

$$C_i = c_i \rho_i A_i d_i \tag{2}$$

$$\alpha_i = \frac{Q_t}{Q_0} = 1 - \left[a_1 + b_1\left(1 - e^{-c_1 Bi}\right)\right. \times \left.\right] \cdot \left(\frac{a_2 + c_2 Bi}{1 + b_2 Bi}\right) \cdot \exp\left[-Fo \cdot \left(a_3 + \frac{b_3}{Bi}\right)^{-1}\right] \quad (3)$$

where, T_{range} is the comfort temperature range, the recommended values are various for different building types and climate regions. In literature [29], for the office and residential buildings, T_{range} equals to 2 °C, i.e. from 26 °C to 28 °C in the summer. However, this recommend value is from 22.2 °C to 26.7 °C referring to ASHRAE guidelines, thus the T_{range} can be larger in this case;

t_d is the response span for flexibility evaluation period or demand response period, which can be long or short referring to the DR event. In this paper, 2 h was used as an example, which coincides with common DR event;

C_i is the total heat capacity of building thermal mass which can be defined as Eq. (2), and the envelope include interior walls, floor and ceiling;

A_i, ρ_i , d_i, λ_i are the area, density, equivalent diameter and heat conductivity coefficient of the thermal mass, respectively; COP_{AC} is the coefficient of performance of the air conditioning system, a constant average COP during time t_d for different systems can be used instead;

α_i is the heat release ratio of thermal mass, which denotes the ratio of the released heat (Q_t) at time t and total releasable heat (Q_0) when thermal mass reaches to steady-state. The fitting formula of the heat release ratio can be defined as Eq. (3), where the value of a_i, b_i, c_i are shown in Table 1, Bi is the Biot number and Fo is the Fourier number. The release factor α_i represents the degree of heat released from thermal mass during the time t_d. When $\alpha_i = 1$ means that all the effective stored heat is released to act as flexibility potential; when $\alpha_i = 0$ means that the thermal mass does not have any energy flexibility.

To calculate the area of irregular internal mass, such as furniture, a novel method (i.e., the effective-area method) for calculating the thermal effects of the thermal mass in buildings was presented in previous research [17]. With this method, the furniture calculation area A_f is defined as a function of the furniture's mass m_f, comprising ρ_f and L_f, and is calculated using Eq. (4).

$$A_f = \frac{m_f}{\rho_f \cdot L_f} \quad (4)$$

where ρ_f is the density of the furniture and L_f is the size dimension, which is calculated as half of the thickness of the main material.

2.2. Flexibility from lights and appliances

When peak load happens in daylight, generally, the illumination of the room can be partially reduced. Through turning off some lights or reducing the brightness of lights, the building electricity load can be cut down directly, and the heat gain load to the HVAC system reduces as well. The lights' flexibility is defined as Eq. (5).

$$F_{2,1} = k_0 P_{lights} \quad (5)$$

where P_{lights} is the lights' load, $k_0 (0 \le k_0 \le 1)$ is the lights' dimming rate; $k_0 = 1$ means that the lights can be turned off totally and $k_0 = 0$ means that all the lights should be turned on.

In addition, the electric appliances' load can be easily rearranged if the time window is larger than the work time. An illustration of the window and work time can be seen in Fig. 2. There is no flexibility in the case in which the time window is equal to the work time, while a larger time window is better for the flexibility improvement of the appliances because there is more space for appliances to move and shift its load. Eq. (6) is used to calculate the appliances' flexibility.

$$F_{2,2} = \sum_{i=1}^{n} P_i(t) \cdot k_i(t) \quad (6)$$

$$k(t) = \begin{cases} 0 & t \in (t_{work} \cap t_{earliest}) + (t_{work} \cap t_{latest}) \\ 1 & t \in t_{window} - t_{work} \\ -1 & t \in t_{work} - (t_{earliest} \cup t_{latest}) \end{cases} \quad (7)$$

where t_{work} is the work time and t_{window} is the time window; furthermore, t_{work}, can be freely moved inside the time window; $t_{earliest}$ and t_{latest} are the earliest and latest working windows, respectively, $P_i(t)$ is the appliances' power, and $k_i(t)$ is the flexibility state, which can be defined as Eq. (7).

2.3. Flexibility from HVAC system

When the thermal zone setting temperature changes, the HVAC system's load is influenced. The HVAC system electricity flexibility is coupled with the parts of thermal mass (F_1), heat gain reduction from lights ($k_0 P_{lights}$), room air heat inertia ($\frac{\rho_a V_r c_a}{t_d} \Delta T$), fresh air processing ($\dot{m} c_a \Delta T$), and heat transferred from exterior walls ($U_A \Delta T$). The electricity flexibility of the HVAC system is defined as Eq. (8).

$$F_3 = F_1 + \left[k_0 P_{lights} + \left(\frac{\rho_a V_r c_a}{t_d} + U_A + \dot{m} c_a\right) T_{range}\right] \Big/ COP_{AC} \quad (8)$$

$$F_4 = \frac{c_w \cdot \rho_w \cdot V_{tank} \cdot (T_{tank,\, t_0} - T_{tank,\, t_d})}{t_d} \Big/ COP_{AC} \quad (9)$$

where ρ_a is the density of air, c_a is the heat capacity of air, V_r is the thermal zone volume, U_A is the overall heat transfer coefficient, $\dot{m}$ is the mass flow of fresh air, c_w is the heat capacity of water, ρ_w is the density of water, V_{tank} is the volume of tank, and $T_{tank,\, t_0}$ and $T_{tank,\, t_d}$ are the initial tank temperature and tank temperature after time span t_d, respectively.

Furthermore, the storage tank can be charged by chillers during the night or low-electricity-price time and can discharge stored heating/cooling load during peak electric load time or high-electricity-price time. With the storage tank, the HVAC system can provide a higher flexibility potential and longer flexibility response span. The electricity flexibility of the storage tank is defined as Eq. (9).

2.4. Flexibility from occupant behavior

Occupants' behavior in room temperature settings are quite

Table 1
Recommended value [30] of constants in Eq. (3)

Constants	a_1	b_1	c_1	a_2	b_2	c_2	a_3	b_3
Recommended value	1.0101	0.2575	0.4271	1.0063	0.5475	0.3483	0.4022	0.9188

different. Occupants' behaviors also vary from one individual to another with respect to different ages, genders, and incomes. This behavior highly depends on different individuals and is influenced by economic incentive and benefit consideration. The behavior of occupants, such as different room temperature tolerance settings, can be a significant flexibility source. For example, the zone temperature can swing by as much as 5 °C around a recommended fixed set-point. Because of this, high-temperature tolerance can increase a building's flexibility capacity by regulating the loads of the HVAC system. The electricity flexibility of behaviors is defined as Eq. (10).

$$F_5 = \Delta T_{extra}\left(\sum_{i=1}^{n}\frac{\alpha_i C_i}{t_d}+\frac{\rho_a V_r c_a}{t_d}+U_A+\dot{m}c_a\right)\bigg/ COP_{AC} \tag{10}$$

where ΔT_{extra} is the temperature difference between the upper limit of the recommended temperature range and highest temperature resetting that the occupants are willing to accept. The other symbols in here are the same as in Eq. (1) and Eq. (8).

Therefore, the electricity flexibility of different contributions can be quantified systematically. Table 2 lists the flexibilities of different contributions and the required basic parameters from a building. With this quantification framework and the basic physical parameters from buildings, the building electricity flexibilities can be assessed. In addition, the electricity flexibility ratio (flexibility capacity/total building loads) of a building can be known, which is important for the building owners to assess the DR ability and building flexibility performance. In this case, the total building load P is required. In a previous study [31], the support vector regression model was used to predict the load with historical electricity data. The time span of flexibility is different for DR events and districts; 2 h was used in this study referring to Fig. 9.

3. Case study

To validate the proposed framework to estimate a building's electricity flexibility, an office building case is illustrated here. Fig. 3 shows the flow diagram of the case study and validation. The building's flexibility can be quantified in two ways, one is by the theoretical equations we proposed in Section 2, the other is by dynamic simulation on the Dymola platform. Then, these two quantification outcomes were used to compare and validate. The same office zone model was built on the Dymola platform, which is described in Section 4 in detail, for validating the proposed flexibility quantification framework. This case building is an office building with 21 floors located in Shanghai. One typical office zone was employed to study, and its floor plan is shown in Fig. 4. The office zone has one open office room, two private office rooms, and two meeting rooms having cooling requirements. The total cooling area of this office zone is 224 m^2, and the cooling supply comes from a central air-conditioning system in this office building. In addition, the total internal heat gain is 40 W/m^2, the lights' load density is 11 W/m^2, and the equipment load density is 13 W/m^2. The detailed parameters of this office zone are listed in Table 3.

4. Validation modeling in Dymola

4.1. Modeling tool and climate condition

The simulation tool of this validation study is the commercial modeling software Dymola (Version 2017-04-10) which is based on the Modelica language. The building's model was developed using the Modelica buildings library [32, 33]. This buildings library is a free open-source library with dynamic simulation models for building and control systems, which is applicable to overall building systems and is quite useful for developing models for complex building energy control systems. In this study, the electricity flexibility of an office building in cooling demand is shown; thus, the selection of location is based on the consideration of a cooling-dominated climate region. The weather data of Shanghai is provided by Dymola standard. mos files, which are interpolated over 60 min time steps. According to this weather file, the annual average ambient dry bulb temperature is 16.7 °C, and the annual global horizontal radiation is 1271 kW h/m^2. One typical summer day (July 21) was selected as the meteorological condition in the following research, and the hourly dry bulb temperature, air humidity, and global horizontal solar radiation are shown in Fig. 5.

4.2. Dymola modeling

Besides the theoretical flexibility quantification models described in Section 2, the Dymola model was used to calculate the flexibility directly from the electricity load change of chiller. The office building in Section 3 has an HVAC system, which has two chillers, pumps, an air handle unit (AHU), a tank, pipes, and valves. Because the concern is the electricity flexibility performance at the peak time, the COP of HVAC system is required. The chiller model has a real-time average coefficient of performance (COP) of 4.5 to calculate the electricity consumption, and the control input is the set point of the leaving temperature of the evaporator. The pump model uses performance curves that compute pressure rise as a function of the volume flow rate and speed. The AHU model represents a typical air handler with a cooling coil, a variable-speed fan, and a waterside valve, and this valve can be controlled to meet the required air outlet temperature setting. The water storage tank is a stratified type of model so that the volume of the tank can

Table 2
Quantification framework of building electricity flexibilities.

Flexibility types	Flexibility/W	The flexibility ratio (flexibility capacity/total building load, %)	Parameters required
Thermal mass	F_1 (Eq. (1))	$\frac{F_1}{P_{total,t_d}} \times 100\%$	Wall area (m^2) and thickness (m); furniture area (m^2) and thickness (m); thermal mass heat capacity (kJ/K) and density (kg/m^3); air conditioning COP; response span (s).
Appliances	F_2 (Eqs. (5) and (6))	$\frac{F_2}{P_{total,t_d}} \times 100\%$	Appliances power (W); Closed rate.
HVAC system	F_3(Eq. (8))	$\frac{F_3}{P_{total,t_d}} \times 100\%$	Volume of zone room (m^3); ventilation rate; the same as F_1 and F_2.
Storage tank	F_4(Eq. (9))	$\frac{F_4}{P_{total,t_d}} \times 100\%$	Water volume of tank (m^3), water supply setting temperature of chiller (°C), maximum temperature setting of tank (°C).
Occupants behavior	F_5(Eq. (10))	$\frac{F_5}{P_{total,t_d}} \times 100\%$	Highest zone temperature tolerance; the same as F_3.
Total	$\sum_{i=1}^{5} F_i$	$\sum_{i=2}^{5} F_i/P_{total,t_d} \times 100\%$	

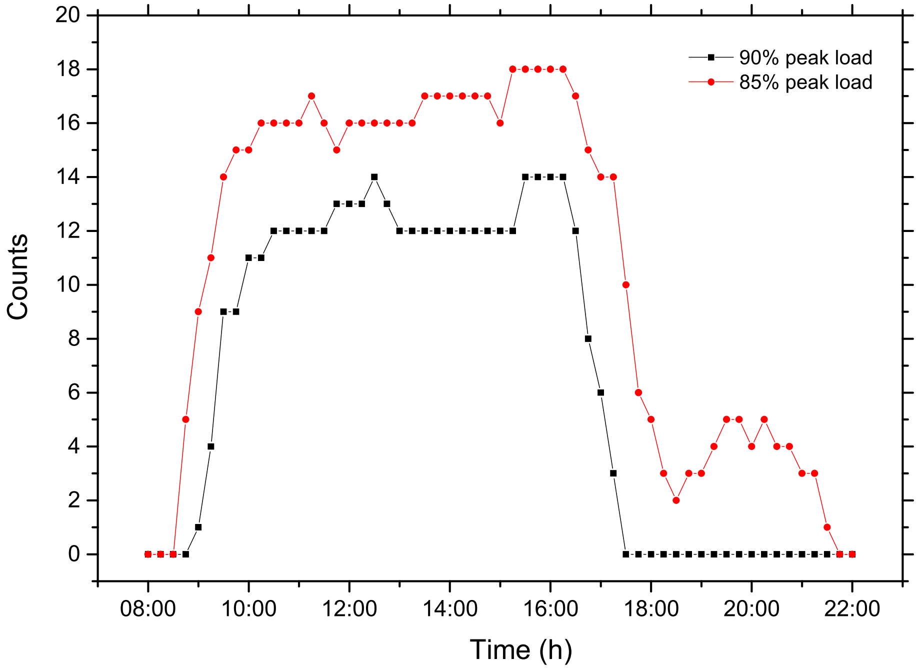


Fig. 9. Electricity peak load occurrence distribution in Shanghai in 2014.

Table 3
Parameters of the typical office zone.

Components	Geometric parameters		Property parameters			
	Area (m^2)	Thickness (m)	Material	Density (kg/m^3)	Heat conduction coefficient (W/(m•K))	Specific capacity (kJ/(kg•K))
External wall	88.0	0.22	Insulation board + Concrete	1490	0.95	0.94
Partition wall	71.0	0.18	Brick	930	0.42	0.93
External window	43.0	0.01	Glass	2500	0.76	0.84
Ceiling/floor	224.0	0.20	Gypsum board	2080	1.33	0.97
Furniture	254.0	0.03	Plywood + Paper	490	0.14	2.26

be separated into specific segments vertically. The room model is a thermal zone that assumes the air to be completely mixed and contains models for heat transfer through the building envelope and HVAC system. Noticing that furniture has similar thermal transfer characteristics to those of the interior wall, furniture was considered as an interior wall in the Dymola model while using the effective-area method.

The schematic layout of the case building system in Dymola can be seen in Fig. 6. The needed input parameters in this Dymola building model are numerous. Firstly, building physical characteristics as one of the important flexibility resources are needed including thermal mass's thickness, area, thermodynamic property and so on, and all of these parameters are shown in Table 3. Subsequently, the design parameters of HVAC systems must be provided including chiller's power, COP, chiller water temperature, the tank and pipe size, and so on. The main parameters' setting in Dymola are listed in Table 4.

4.3. Validation of dymola model

To validate this Dymola model, a real office building (the case study building) with an HVAC system was instantiated. The chiller was open from 8:00 a.m. to 6:00 p.m., and other input parameters can be seen in Table 3. The thermal characteristics of the office building model were investigated and validated. Fig. 7 shows the room temperature of the on-site test and simulation on Dymola. The results show that the room temperature of the simulation case corresponds to the test case generally, and the root mean square error (RMSE) is 0.48 °C. This shows that the Dymola model can represent the thermal characteristics of the office building case closely.

Fig. 8 shows the HVAC electricity flexibility results of the proposed theoretical model and dynamic simulation case. The flexibility of the proposed model is slightly lower than that in the simulation scenario. The mean absolute error (MAE) of the proposed model and the simulation case is 5.9%.

5. Results and discussion

5.1. Electricity flexibility of different resources

The time span of the flexibility response is an important element for characterizing energy flexibility [34, 35]. Fig. 9 shows the yearly electricity peak load occurrence distribution in Shanghai in 2014. The fact that the peak electricity load occurs frequently from 14:00 to 16:00 in Shanghai was considered, so the 2 h time span between 14:00 and 16:00 was used in the following analysis. This also coincides with the span of a common demand response event. In this study, the office zone is analyzed, and the room temperature is reset to 26 °C from 24 °C at 14:00 to investigate the electricity flexibility during the next 2 h.

Table 4
Main parameter settings in Dymola.

Model	Model based on	Main parameters setting
Chiller	Buildings.Fluid.Chillers.Carnot_TEva	Nominal mass flow rate of evaporator = 0.93 kg/s, evaporator leaving water temperature = 10 °C, evaporator heat flow rate = 19.5 kW
Room	Buildings.ThermalZones.Detailed.MixedAir	Based on Table 3, occupancy schedule 8:00–20:00, total internal heat gain = 40W/m^2, lights load density = 11 W/m^2, equipment load density = 13 W/m^2
AHU	Buildings.Applications.DataCenters.ChillerCooled. Equipment. CoolingCoilHumidifyingHeating	Nominal mass flow rate of air = 2.43 kg/s
Tank	Buildings.Fluid.Storage.Stratified	Tank volume = 1.24 m^3, Tank height = 2 m, Volume segments = 5
Pipe	Buildings.Fluid.FixedResistances.Pipe	Pipe length = 10 m, pipe diameter = 0.09 m
weaBus	Buildings.BoundaryConditions.WeatherData.ReaderTMY3	Weather data from Shanghai

5.1.1. *Flexibility: thermal mass*

Building thermal mass contributes to the flexibility through four means (i.e., interior walls, furniture, floor, and ceiling). The electricity flexibility of these four are shown in Fig. 10(a). The furniture has the largest flexibility capacity compared with the others, and its heat release ratio (note that in this paper is heat absorption) is greater as well owing to its lower thickness. Although the floor and interior walls have a large mass heat capacity, to release all the releasable heat from its bulk is a time-consuming process that could take even an entire day. The released-heat ratios of the total releasable heat are approximately 23.9% and 10.8% during 2 h for the interior walls and floor, respectively, while they are approximately 73.2% for furniture. This means that there is still a large portion of heat kept inside the interior wall and floor's bulk, which cannot act as effective electricity flexibility during the peak load time and demand response event.

For this office building case, the percentages of the flexibility of different mass types are shown in Fig. 10(b). The furniture has the largest contribution of 41.24%, while the interior wall contributes the least, 8.49%. With the heat inertia of thermal mass and a 2 °C (from 24 °C to 26 °C) room temperature range, electricity flexibility can be calculated with the real-time average air-conditioning COP of 4.5. The averages of the equivalent electricity flexibilities are 104.5, 507.5, 325.5, and 293.0 W for the interior wall, furniture, ceiling, and floor, respectively. However, with a precooling strategy, such as setting the room air temperature to 22 °C or even lower several hours ahead of the peak load, more electricity flexibility can be achieved [4, 6].

5.1.2. *Flexibility: lights*

In this study, the electricity flexibility from lights was investigated. The loads of lights can be regulated through dimming rate control and this expands the electricity flexibility. Sehar et al. [36] concluded that, in their example office buildings, the dimming rate of lights reaches 0.8 at peak load time at 4:10 p.m., and its daily average is 0.2. Thus, here, a lights dimming rate of 0.4 is assumed to be a reasonable value during the peak load time from 2:00 p.m. to 4:00 p.m. The electricity flexibility is 985.5 W, and it keeps constant because lights shed the load directly. In addition, the internal heat gain reduction can provide additional flexibility that contributes to the HVAC system indirectly. Other appliances can be analyzed (see Eq. (6)) in a similar way.

5.1.3. *Flexibility: HVAC system with and without storage*

The electricity flexibility of the HVAC system is defined by Eq. (8), which contains the flexibility aggregation of the internal mass and other parts. The flexibility includes heat transfer reduction of the exterior walls, the heat demand reduction of fresh air processing, the heat gain reduction when brightness reduces, and room air heat inertia when the room air temperature is reset to the upper limit of the recommended temperature range (i.e., from 24 °C to 26 °C in this study). The results show that the thermal mass has the largest contribution of 72.74%, and a heat gain reduction from lights of 12.95% should be included (see Fig. 11).

The electricity flexibility can be enlarged enormously when the air-conditioning system is integrated with the water storage tank. The water tank volume is 1.24 m^3 in this HVAC system. The chiller is shut down when the tank is discharging to supply the cooling load, while the room temperature goes up along with the stored cold water getting warm. The flexibility results of this tank are shown in Fig. 12. In this situation, the chiller is shut down so that the room temperature reaches 28 °C after 92 min. In fact, the electricity flexibility equals the HVAC system's load after it is shut down. The average electricity flexibility of this storage tank is 1807 W during 2 h.

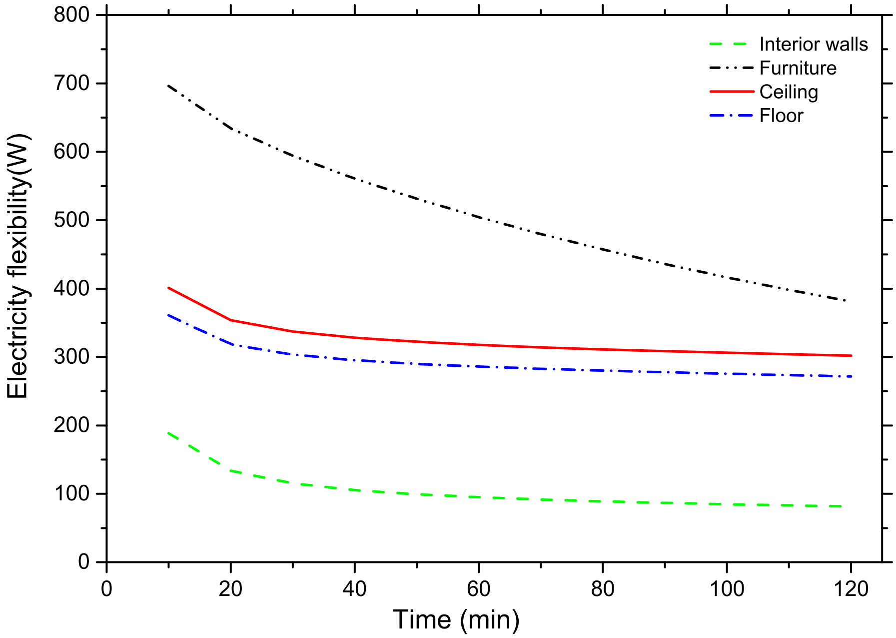
5.1.4. *Flexibility: occupants' behavior*

The occupants' behaviors are quite different because individuals have various comfort requirements as well as considerations of economic benefits, such as setting the room temperature a little higher than the normal value for the sake of economic incentive or avoiding the high price of electricity. Two cases of the room air temperatures are set to 27 °C and 28 °C, respectively; likewise, any other degree of setting temperature can be analyzed in the same way. For the behavior flexibility, the flexibility contribution from the norm recommended temperature range's energy flexibility is not considered, and this means that the flexibility only comes from the extra room temperature increase that the occupants are willing to accept. Fig. 13 shows the electricity flexibility of these two hypothetical acceptable room air temperature settings. A wider acceptable room air temperature setting provides more electricity flexibility.

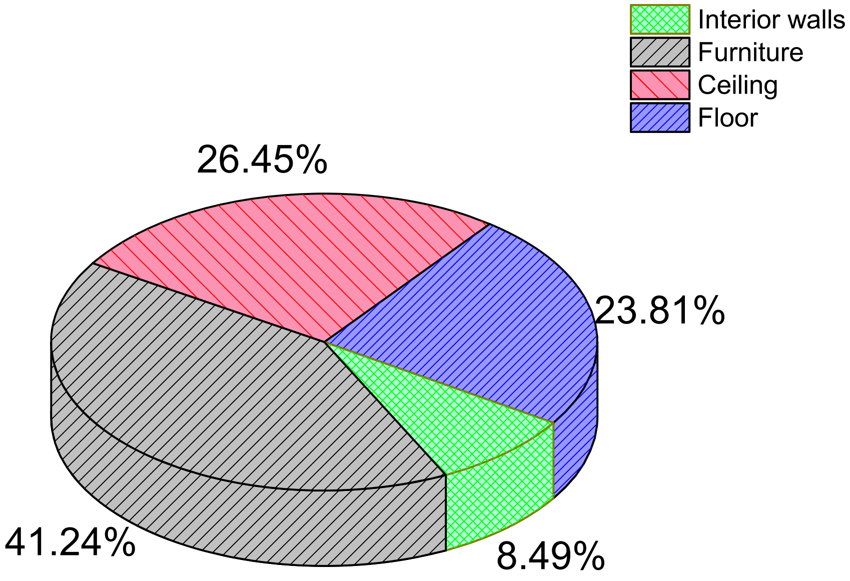
6. Discussion

Through the flexibility contribution analysis, the percentages of different parts can be seen in Fig. 14. The results show that the tank, thermal mass, and behavior sides contribute most of the flexibility. When the storage tank is integrated into the air-conditioning system, this specific storage tank can contribute 31.5% of the flexibility. For the building's air-conditioning system, the maximum flexibility capacity equals the HVAC system's electricity load, even though the theoretical calculation flexibility capacity can be more than the HVAC system's electricity consumption sometimes. In some cases, the chiller can be shut down while a desirable room air temperature can be maintained also. This situation happened in the case of *basic + behavior 28°C* and *basic + tank*. There is another situation in which the chiller can be shut down when the flexibility is higher than the chiller's total electricity load. This situation can be seen in the case of *basic + behavior 28°C* in Fig. 15 for approximately 2 h.

The ratio of electricity flexibility and total building electricity consumption might be more important for the building operators



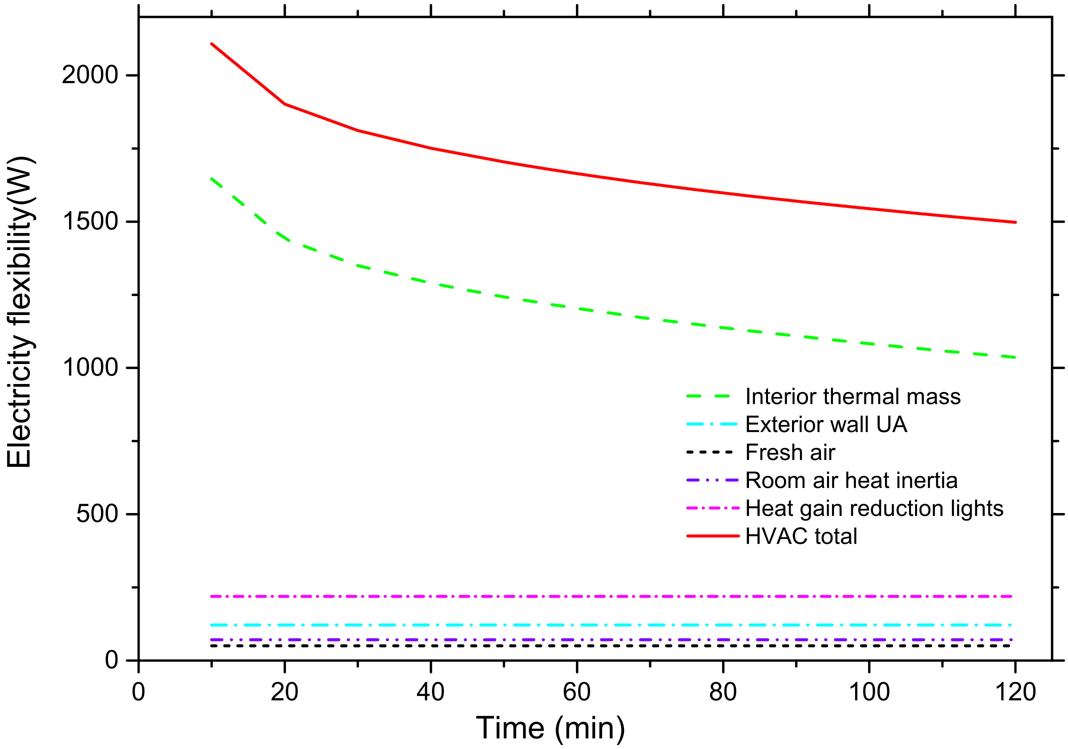
(a) Electricity flexibility profiles of different internal mass resources during 2 h



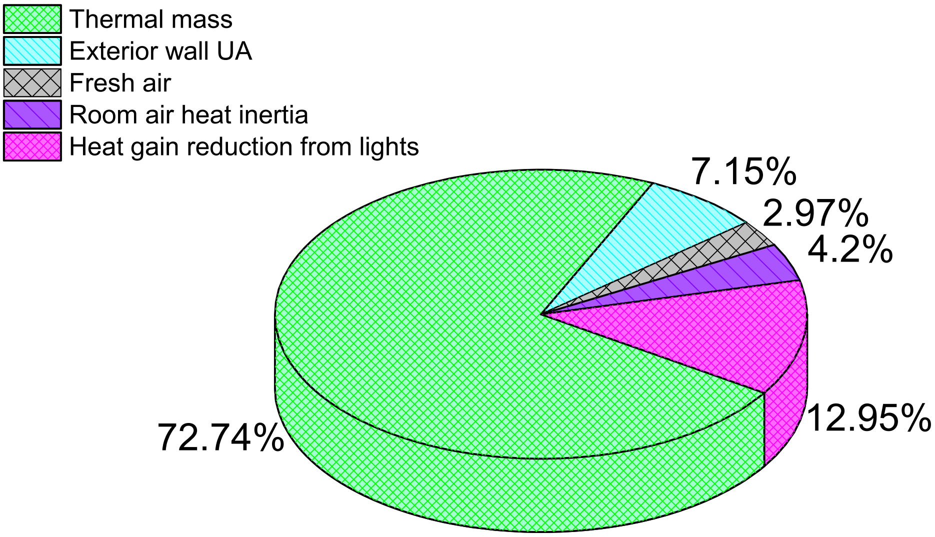
(b) Flexibility percentage of different parts of internal mass

Fig. 10. Electricity flexibility results of thermal mass part (incl. interior walls, furniture, ceiling and floor).

and energy manager. The HVAC system consumes approximately 42% of the buildings total electricity load. Fig. 16 shows this ratio when the HVAC system is integrated with and without the tank. The basic electricity flexibility of the building itself can achieve 18.2% of total flexible electricity use, whereas, considering the occupants' behavior in terms of a higher room air temperature setting, the proportions are 26.8% and 34.1%, corresponding to the case of behaviors for 27 °C and 28 °C. One can conclude that the occupants' behavior upgrades the flexibility capacity significantly. Furthermore, the water storage tank is also an important resource for improving flexibility, although additional investment is generally needed. In the case of an HVAC system with a tank, the abovementioned corresponding proportions are raised to 37.7%, 46.3%, and 53.6%, respectively. The HVAC system can be shut down when electricity flexibility is higher than the HVAC system's total electricity demand. All the flexibility ratios of different



(a) Electricity flexibility profiles of different parts for HVAC system



(b) Flexibility percentage of different parts of the HVAC system

Fig. 11. Electricity flexibility of HVAC system without a water storage tank.

contributions can be seen in Table 5.

In addition to the flexibility from the heating- and cooling-related facilities, there are some other plug-in facilities, such as cell phones, laptops, and battery chargers in office buildings and washing machines, tumble dryers, and dishwashers in residential buildings, which can also be flexibility resources. All these types of flexibility can be quantified by using this proposed methodology. A higher electricity flexibility potential for a building means that it has a higher degree of involvement with the grid response to balance the power grid, and more-flexible strategies can be applied to

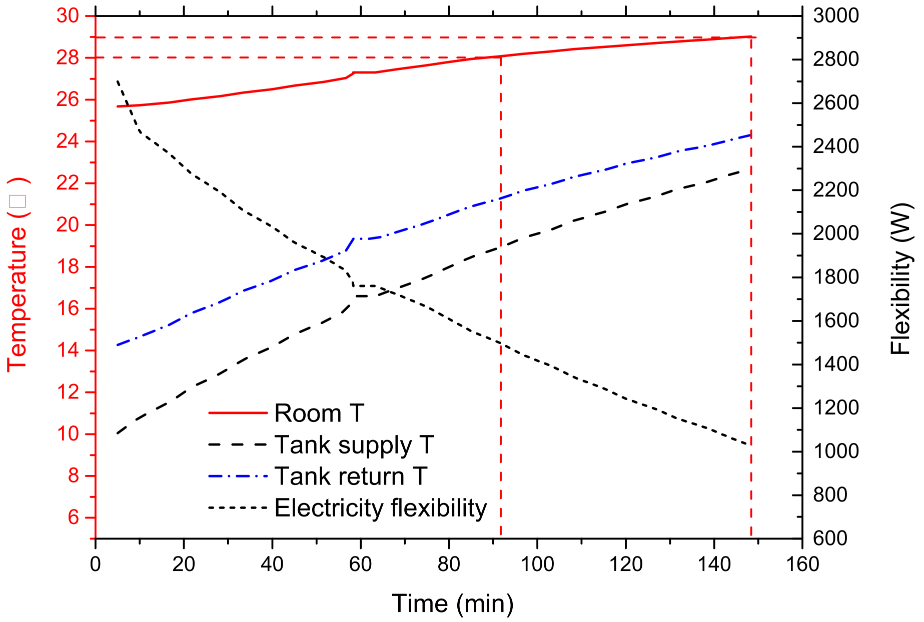


Fig. 12. Electricity flexibility of water storage tank.

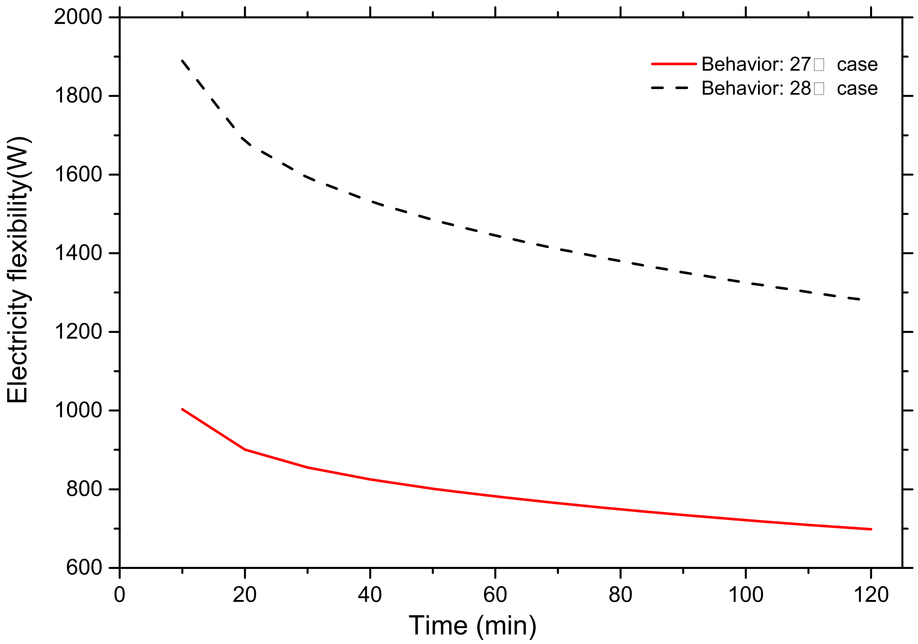


Fig. 13. Electricity flexibility of occupants' willingness to raise the room temperature setting (The 27 °C case denotes that the room temperature is allowed to reach to 27 °C from 26 °C, and the 28 °C case implies that the room temperature is allowed to reach to 28 °C from 26 °C).

achieve economic benefits and improve energy efficiency. In the future, the energy flexibility performance of buildings will be an important index, such as a building's energy efficiency, to be written into building energy standards, such as ASHRAE 90.1.

7. Conclusions

In the field of building demand response and grid integration, it is important to describe accurately a building's energy demand flexibility potential when reducing the electricity demand. An HVAC system's performance and electricity consumption during these peak shedding hours could be largely influenced by the building thermal mass and occupants' behaviors. Therefore, a model was provided to quantify the building's electricity flexibility from overall flexibility resources, which makes it possible to quantify the real energy flexibility capacity of a building before optimal control strategies are made. This model considers the energy flexibility resources, including thermal mass, appliances, HVAC system, water tank, and occupants' behavior. Only some easily available parameters from buildings are needed, and these parameters can be obtained in the design and operation phases. The main conclusions of this research are as follows.

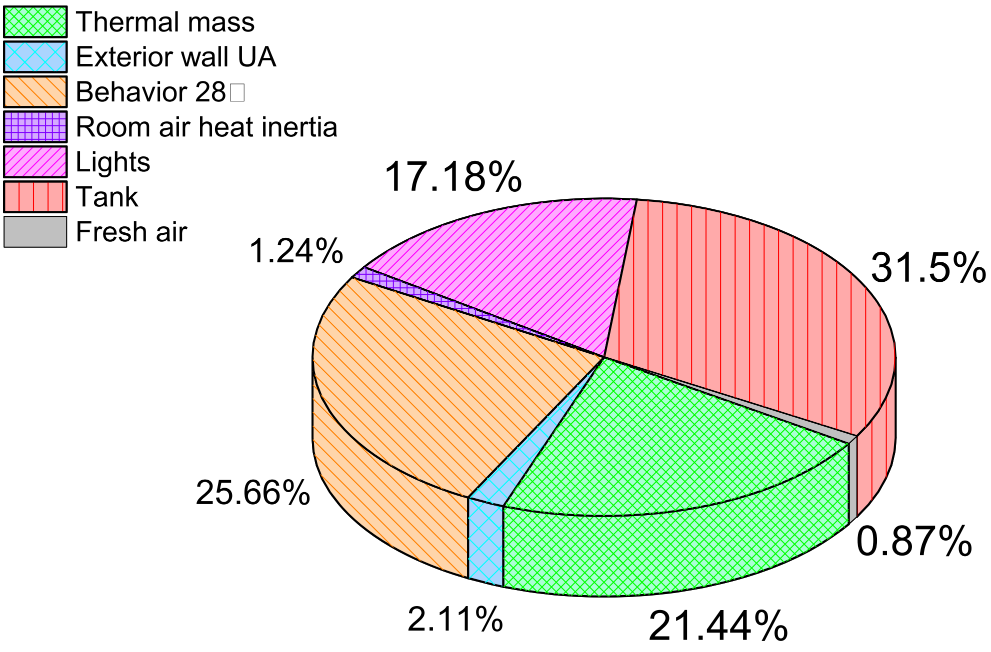


Fig. 14. Electricity flexibility percentage of different contributions in the office zone case.

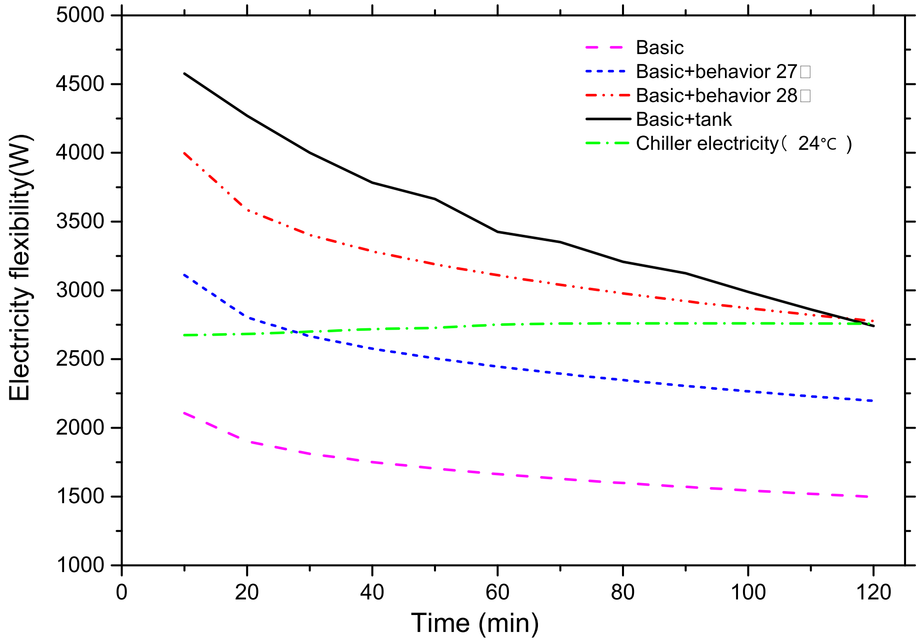
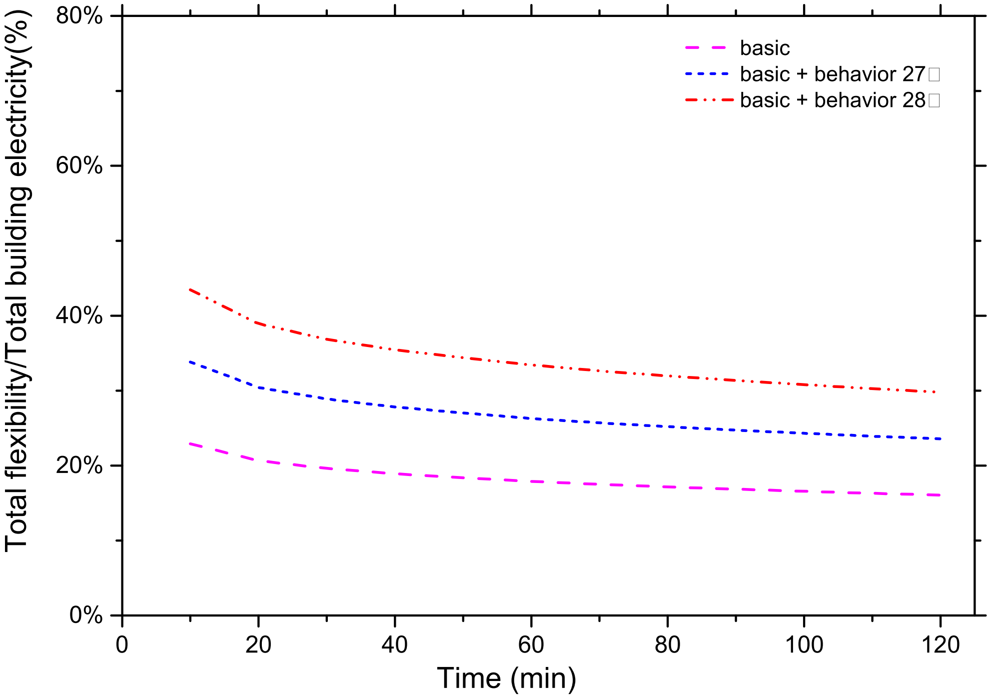
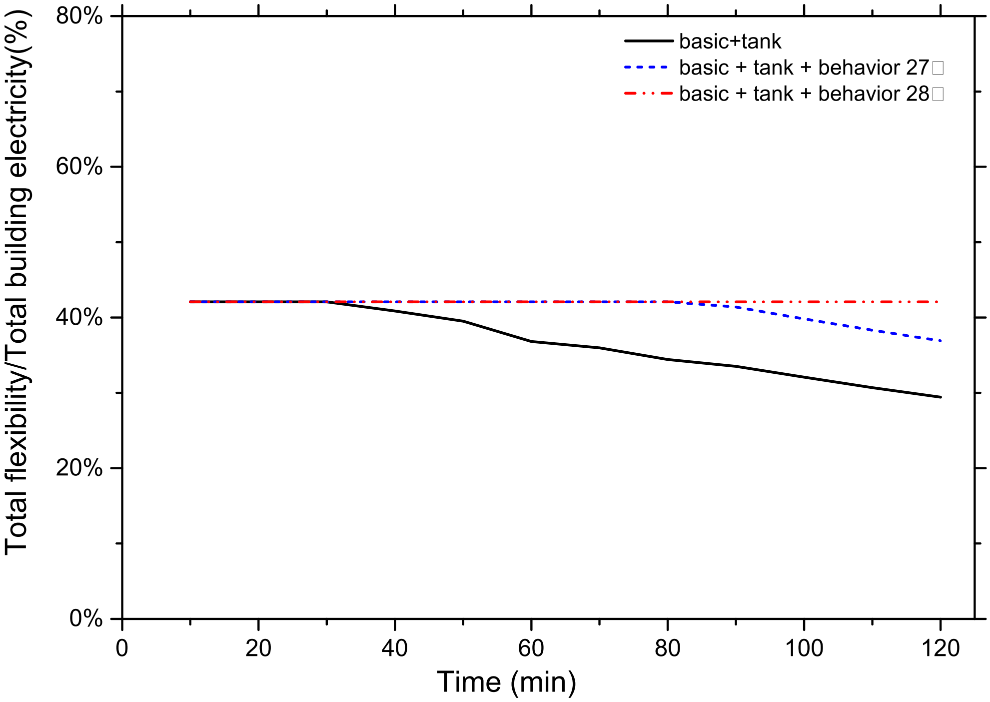


Fig. 15. Total electricity flexibility of different scenarios (*Basic case*: includes the thermal mass, heat gain reduction from lights, fresh air processing and room air heat inertia, and air temperature setting inside the recommended temperature range, i.e., from 24 °C to 26 °C; *Basic + behavior 27°C case*: includes the basic case, and the air temperature setting is 27 °C; *Basic + behavior 28°C case*: includes the basic case, while the air temperature is set to 28 °C; *Basic + tank case*: includes the basic case and a water tank with a volume of 1.24 m^3).

- The proposed flexibility framework and models are reasonably accurate. The electricity flexibility results of the theoretical models show good agreement with the simulation results. The mean absolute error is 5.9%.
- Thinner thermal mass, such as furniture, can react faster to contribute electricity flexibility during peak load times, because of its higher heat-released ratio, while much of heat stored in relatively thick thermal mass cannot be released during a short time, such as a DR event. The heat-released ratio highly depends on the thickness and thermal characteristics of the thermal mass.
- Occupants' behavior is a vital element that should be taken into consideration to improve a building's electricity flexibility. In buildings, the internal thermal mass and occupants' behavior could provide a high electricity flexibility contribution.
- The different flexibility contributions interact with each other, such as thermal mass and the HVAC system; lights and HVAC



(a) HVAC system without the tank



(b) HVAC system with tank

Fig. 16. Total electricity flexibility of different contributions.

Table 5
Flexibility ratios of different resources in the case of an office zone.

Time (min)	thermal mass	lights	HVAC without storage tank	HVAC with storage tank	behavior 27 °C	behavior 28 °C
10	17.90%	10.72%	22.92%	49.76%	10.91%	20.54%
20	15.65%	10.70%	20.66%	46.38%	9.78%	18.28%
30	14.62%	10.68%	19.62%	43.34%	9.26%	17.25%
40	13.93%	10.65%	18.91%	40.86%	8.91%	16.55%
50	13.40%	10.63%	18.38%	39.51%	8.64%	16.01%
60	12.93%	10.59%	17.89%	36.81%	8.40%	15.53%
70	12.54%	10.58%	17.49%	35.96%	8.20%	15.14%
80	12.20%	10.58%	17.15%	34.42%	8.03%	14.80%
90	11.90%	10.58%	16.85%	33.52%	7.88%	14.50%
100	11.62%	10.58%	16.57%	32.07%	7.74%	14.22%
110	11.36%	10.58%	16.31%	30.70%	7.61%	13.96%
120	11.12%	10.58%	16.07%	29.41%	7.49%	13.72%

system. The proposed framework splits these up and presents different sources of electricity flexibility in a building.

The quantification framework of electricity flexibility is a crucial step for electricity markets that require flexible consumption. In future electricity markets, the building's electricity flexibility data will be sent to the power-grid section for optimal power dispatch. Therefore, future energy strategies will not only consider energy efficiency, but also the energy flexibility in the objective function. For example, when the power grid is unbalanced because of renewable energy fluctuation, a building energy system can respond to increase or decrease power consumption for the sake of power-grid safety and the optimal control strategies of the building energy system. To do that, an energy flexibility evaluation mechanism of buildings should be established in future energy markets.

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References

[1] Xue X, Wang S, Sun Y, Xiao F. An interactive building power demand management strategy for facilitating smart grid optimization. Appl Energy 2014;116:297–310.

[2] Chen Y, Desai A, Schmidt F, Xu P. Electricity demand flexibility performance of a sorption-assisted water storage on building heating. Appl Therm Eng 2019;156:640–52.

[3] Escriva-Escriva G, Segura-Heras I, Alcazar-Ortega M. Application of an energy management and control system to assess the potential of different control strategies in HVAC systems. Energy Build 2010;42:2258–67.

[4] Xu P, Haves P, Piette MA, James B. Peak demand reduction from pre-cooling with zone temperature reset in an office building. Lawrence Berkeley Natl. Lab. 2006;14:83–9.

[5] Aduda KO, Labeodan T, Zeiler W, Boxem G, Zhao Y. Demand side flexibility: potentials and building performance implications. Sustain Cities Soc 2016;22:146–63.

[6] Turner WJN, Walker IS, Roux J. Peak load reductions: electric load shifting with mechanical pre-cooling of residential buildings with low thermal mass. Energy 2015;82:1057–67.

[7] Keeney K, Braun J. Application of building precooling to reduce peak cooling requirements. ASHRAE Transact 1997:463–9.

[8] Razmara M, Bharati GR, Hanover D, Shahbakhti M, Paudyal S, Robinett RDI. Building-to-grid predictive power flow control for demand response and demand flexibility programs. Appl Energy 2017;203:128–41.

[9] Nuytten T, Claessens B, Paredis K, Van Bael J, Six D. Flexibility of a combined heat and power system with thermal energy storage for district heating. Appl Energy 2013;104:583–91.

[10] Heussen K, Koch S, Ulbig A, Andersson G. Energy storage in power system operation: the power nodes modeling framework. In: IEEE PES Innovative Smart Grid Technologies Conference Europe, Gothenberg, 11–13; 2010. October.

[11] Reynders G, Diriken J, Saelens D. Generic characterization method for energy flexibility: applied to structural thermal storage in residential buildings. Appl Energy 2017;198:192–202.

[12] Zhang L, Good N, Mancarella P. Building-to-grid flexibility: modelling and assessment metrics for residential demand response from heat pump aggregations. Appl Energy 2019;233:709–23.

[13] Stinner S, Huchtemann K, Mueller D. Quantifying the operational flexibility of building energy systems with thermal energy storages. Appl Energy 2016;181:140–54.

[14] Arteconi A, Hewitt NJ, Polonara F. State of the art of thermal storage for demand-side management. Appl Energy 2012;93:371–89.

[15] Hedegaard K, Mathiesen BV, Lund H, Heiselberg P. Wind power integration using individual heat pumps – analysis of different heat storage options. Energy 2012;47:284–93.

[16] Le Dréau J, Heiselberg P. Energy flexibility of residential buildings using short term heat storage in the thermal mass. Energy 2016;111:991–1002.

[17] Li W, Xu P, Wang H, Lu X. A new method for calculating the thermal effects of irregular internal mass in buildings under demand response. Energy Build 2016;130:761–72.

[18] D Hulst R, Labeeuw W, Beusen B, Claessens S, Deconinck G, Vanthournout K. Demand response flexibility and flexibility potential of residential smart appliances: experiences from large pilot test in Belgium. Appl Energy 2015;155:79–90.

[19] Tulabing R, Yin RX, DeForest N, Li YP, Wang K, Yong TY, et al. Modeling study on flexible load's demand response potentials for providing ancillary services at the substation level. Electr Power Syst Res 2016;140:240–52.

[20] Rodriguez-Garcia J, Alvarez-Bel C, Carbonell-Carretero J, Alcazar-Ortega M, Penalvo-Lopez E. A novel tool for the evaluation and assessment of demand response activities in the industrial sector. Energy 2016;113:1136–46.

[21] Mohseni A, Mortazavi SS, Ghasemi A, Nahavandi A, Abdi MT. The application of household appliances' flexibility by set of sequential uninterruptible energy phases model in the day-ahead planning of a residential microgrid. Energy 2017;139:315–28.

[22] Yin RX, Kara EC, Li YP, DeForest N, Wang K, Yong TY, et al. Quantifying flexibility of commercial and residential loads for demand response using setpoint changes. Appl Energy 2016;177:149–64.

[23] Reynders G, Lopes RA, Marszal-Pomianowska A, Aelenei D, Martins J, Saelens D. Energy flexible buildings: an evaluation of definitions and quantification methodologies applied to thermal storage. Energy Build 2018:372–90.

[24] De Coninck R, Helsen L. Quantification of flexibility in buildings by cost curves - methodology and application. Appl Energy 2016;162:653–65.

[25] Allison J, Bell K, Clarke J, Cowie A, Elsayed A, Flett G, et al. Assessing domestic heat storage requirements for energy flexibility over varying timescales. Appl Therm Eng 2018;136:602–16.

[26] Ulbig A, Andersson GR. Analyzing operational flexibility of electric power systems. Int J Elec Power 2015;72:155–64.

[27] Xu P. Demand shifting with thermal mass in light and heavy mass commercial buildings. In: 2009 ASHRAE annual conference. Louisville, Kentucky; June,2009. p. 20–4.

[28] Hu M, Xiao F, John B, Li R. Price-responsive model predictive control of floor heating systems for demand response using building thermal mass. Appl Therm Eng 2019;153:316–29.

[29] Lu Y, Ma Z, Zou P. Heating, ventilation and air conditioning (language: Chinese). China Building Industry Press; 2014.

[30] Yang S, Tao W. Heat transfer theory (the fourth edition, language: Chinese). Beijing Higher Education Press; 2006.

[31] Chen Y, Xu P, Chu Y, Li W, Wu Y, Ni L, et al. Short-term electrical load forecasting using the Support Vector Regression (SVR) model to calculate the demand response baseline for office buildings. Appl Energy 2017;195:659–70.

[32] Open source library for building energy and control systems. Lawrence Berkeley National Laboratory.

[33] Wetter M, Zuo W, Nouidui TS. Modelica of heat transfer in rooms in the Modelica “Buildings” library. In: 12th conference of international building performance simulation association; November, 2011. p. 14–6. Sydney.

[34] Junker RG, Azar AG, Lopes RA, Lindberg KB, Reynders G, Relan R, et al.

Characterizing the energy flexibility of buildings and districts. Appl Energy 2018;225:175–82.

[35] Madsen H, Holst J. Estimation of continuous-time models for the heat dynamics of a building. Energy Build 1995;22:67–79.

[36] Sehar F, Pipattanasomporn M, Rahman S. An energy management model to study energy and peak power savings from PV and storage in demand responsive buildings. Appl Energy 2016;173:406–17.