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Energy Flexibility Quantification of Grid-Responsive Buildings: Energy Flexibility Index and Assessment of Their Effectiveness for Applications

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Abstract

The demand side is increasingly expected to provide energy flexibility for power grid economy and reliability. Buildings have various flexibility sources that can be effectively utilized for such purposes. According to different requirements of demand responses to power grid on response duration, response direction and response speed (within seconds, minutes, or even longer timescales), building energy flexibility is categorized as fast regulation, moderate regulation, load shedding, load shifting and load covering. In this paper, a comprehensive method is proposed to quantify building energy flexibility based on these categories. Two sets of flexibility indexes (flexibility capacities and flexibility ratios) for the above five energy flexibilities are proposed. An implementation case study is conducted to illustrate the use of these indexes and to validate the effectiveness of using them in flexibility performance assessment of buildings in particular. The impacts of different system design and control parameters on flexibility performance are also investigated quantitatively. The potential economic benefits of utilizing those energy flexibilities are analyzed in a real electricity market with an optimized use of different flexibility sources. Results show that electricity costs can be reduced by up to 21% if the market is available for such grid-responsive buildings.

Keywords:

Energy-flexible building, grid-responsive building, flexibility index, building demand response, smart grid.

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Abbreviations and Nomenclature

cv	Load covering	$G(t)$	Power generation at time t
sf	Load shifting	$P_{load}(t)$	Power demand at time t
sd	Load shedding	ε	Storage efficiency
mr	Moderate regulation	T_{pre}	Pre-cooling/heating temperature
fr	Fast regulation	τ_{pre}	Pre-cooling/heating time
act	Active storage	γ_L	turned off or shedding rate
ps	Passive thermal storage		of the lighting system
pa	Postponable appliances	α	the available adjustment rate of
AC	Air-conditioner		variable frequency drives
stb	Stationary battery	β_L	Dimming rate of the lighting
EV	Electrical vehicle		system
bat	Battery (incl. stationary battery and	E_{rated}	Rated energy capacity
	EV battery)	P_{rated}	Rated power capacity
VFD	Variable frequency drive	E_{min}	Minimum energy limit
COP	Coefficient of Performance	E_{max}	Maximum energy limit
tw	Time-window of the appliances	SOC	State of charge of the battery
wh	Working hour of the appliances	SOC_0	Initial State of charge
lw	Light-weighted building	SOC_{exp}	Expected State of charge
mw	Medium-weighted building	P_t^E	Power consumption at time t
hw	Heavy-weighted building		
cha	Charging of the storage		
dis	Discharging of storage		
thresh	Threshold		
Rg	Frequency regulation		
Rs	Spinning reserve		

1. Introduction

The penetration of renewable energy resources (RES) as alternatives to the fossil fuel resources is growing rapidly in the modern energy system [1]. The integration of more RES generation of intermittent nature has put increasing challenges in the planning, design and the real-time operation of power grids. The enhancement of power system flexibility is necessary to maintain the grid economy, balance and reliability. Multiple demand side measures have been considered to improve the power system flexibility, in contrast to traditional supply side measures. The load management of demand side as the flexibility provider has gained increasing attention, particularly with the development of smart grids.

The building sector, which consumes more than 70% of total electricity in the United States and 90% in Hong Kong [2-4], has great energy flexibility potential for the power system. Unlike the industry and transportation sector, building sector may bring about less inconvenience and productivity decrease. Various building energy systems can be utilized in different means for demand response. The utilization of responsive building loads can alleviate the power imbalance and improve the reliability as well as the operational efficiency of entire power grids. The architecture of the electricity market and miscellaneous demand response programs reflect different flexibility requirements of power grids. Lu et.al [5] summarized the roles and the implementation of demand response in the electricity markets which shows the significance of the flexible resource aggregators. Where, the managed resources are categorized based on the direction of flexibility. In [6], different demand response services are described as “shape”, “shift”, “shed” and “shimmy” of loads according to their effects on power grid dispatch over a range of timescales. Based on the analysis of grid services in electricity markets and the control characteristics of building service systems, this study categorizes the energy flexibility of buildings into *fast regulation*, *moderate regulation*, *load shedding*, *load shifting*, *load covering* in terms of *response speed, duration, and direction*, as shown in Table1.

Table 1. Building energy flexibility categories and requirements [7]

Market-based service	**Response speed**	**Response duration**	**Response direction**	**Flexibility type**
Frequency regulation (Ancillary service) [8, 9]	Seconds	Continuous	Up/down load regulation	Fast regulation (kW)
5/15-minute RTP [10, 11]	5-minute/15-minute	Continuous	Up/down load regulation	Moderate regulation (kWh)
Contingency reserve (Ancillary service); Conventional incentive-based DR [8, 9]	≤ Minutes	Minutes ~ hours	Load reduction	Load shedding (kW)

Day-ahead hourly price; TOU; CPP [12]	Hour	Continuous	Up/down load regulation	Load shifting (kWh)
Grid independence support [13]	-	Long-term	Load reduction	Load covering (kWh)

However, the benefits of utilizing building energy flexibility are overlooked in the existing assessment criteria for building energy performance. The available indicators (e.g., energy use intensity (EUI) and energy efficiency (EE) [14, 15]) are insufficient to identify this new value of the smart buildings. For the design, construction, and commissioning of smart and grid-responsive buildings, the effective assessment method is required to evaluate building energy flexibility performance.

Over the last decades, the potential “responsiveness” of buildings at multiple timescales have been investigated and validated by different researchers using simulation [10, 16-18] as well as field experiments [19, 20]. However, most studies concerning the quantification and assessment of building energy flexibility usually focus on one specific purpose. For example, Chen et al. [21] defined the building energy flexibility as the peak load reduction capacity. They analyzed energy flexibility from different resources and validated their proposed quantification model through the simulation. Arteconi et al.[22] also defined flexibility as the load reduction potential, and proposed an indicator to rate the flexibility performance of different buildings. They integrated the response time of load reduction, committed power, comfort recovery time, and energy efficiency into one performance indicator with the given weight factors. Fischer et al. [23] proposed a model-based assessment methodology to evaluate the shifting flexibility of the residential heat pump pool. They introduced five parameters (i.e. maximum power, shiftable energy, duration, regeneration time, and mean power) to characterize the energy flexibility. Wang et.al [24] proposed a method to quantify demand response (DR) capacity during the DR event at the load aggregators level which mainly focuses on the peak load shifting flexibility. The bidirectional fast regulation potential was also investigated by other researchers. Hao et.al [25] found that up to 15% of a building's fan power can be offered for frequency regulation (i.e. fast regulation flexibility). The quantification results of Wang et al. [8] showed that the flexibility by fast regulating the fan power in HVAC systems of commercial buildings can contribute up to 50% of the required frequency regulation capacity in Hong Kong. Lack of studies investigate the flexibility quantification method considering the flexibility at multiple timescales which can be utilized in different means for multiple purposes. Thus, a comprehensive quantification framework concerning different energy flexibilities of buildings are essentially needed.

Both commercial and residential buildings can implement different DR strategies and control methods in HVAC systems, lighting systems, onsite generations, and other building service systems. However, after categorizing the building energy flexibilities, it is found that the capacity of each category of flexibility provided by the same technology is different, and each flexibility performance may influence each other. For example, in a building with integrated battery storage, when more available battery capacity is prearranged for providing load shedding flexibility, there will be less capacity for fast regulation at the same time. Hence, the quantification method for each category of energy flexibility and the optimization for their use are both important. Meanwhile, for future development of energy-flexible and grid-responsive buildings, the assessment criteria of building energy performance concerning flexibility performance is also needed for design optimization and operation/control decisions.

The main motivation of this study is to develop a systematic framework to quantify the energy flexibility of buildings when interacting with smart power grids considering the multiple potential services. The main original contributions of this study include:

1). A comprehensive quantification framework and systematic performance index are proposed for the energy flexibility of buildings, including absolute flexibilities (capacities) and relative flexibilities (ratios), in providing different potential services in terms of response speed, duration and direction. To our best knowledge, no study has yet investigated the energy flexibility of buildings at multiple timescales systematically.

2). An implementation case study is conducted to assess the capabilities and effectiveness of the proposed flexibility quantification framework and indexes. A parametric analysis is conducted to investigate the impacts of major system design and control parameters on the building energy flexibilities at multiple timescales.

3). The allocation of building energy flexibilities for different potential grid services is optimized to validate the potential economic benefits of utilizing building energy flexibility in a real electricity market.

2. A comprehensive quantification framework and building energy flexibility index

This section presents and elaborates the quantification method of energy flexibility for grid-responsive buildings. Two sets of indexes, flexibility capacity and flexibility ratio, are proposed to quantify the flexibility of a building corresponding to different response speeds based on the flexibility categories.

2.1 Outline of the framework and indexes

Making use of flexibility to respond effectively to the needs of the connected power grid is an important “smartness” of buildings today and will be particularly important in the future. During the interaction process between the power grid and the responsive buildings, the “grid operator” needs to identify the particular contributions from buildings collectively. The performance index is also required to evaluate the “responsiveness degree” or “smartness degree” of buildings effectively and conveniently. Thus, flexibility capacity and ratio are proposed.

According to the nature of services or the contribution of responses and market trading rules, the units used to measure the flexibility capacities are different, which can be kilowatt (kW) or kilowatt-hour (kWh). The flexibility capacities include five absolute values, which reflect the maximum contribution that a building can make to the power grids. The flexibility ratios include five corresponding relative values which are presented as the ratio of a flexibility capacity to its corresponding power demand or total energy demand. This set of relative indexes forms a five-dimension flexibility performance map of a building. The functions to quantify the flexibility capacity and ratio for these five flexibilities are listed in Table 2. It is notable that the storage capacity not only refers to the active thermal and electrical storage, but also to the passive thermal storage (i.e. building thermal mass) which depends on the building envelope design.

Since the energy flexibility is defined as the ability to reshape consumption patterns when interacting with the power grid, the consumption baseline of the building needs to be determined first. *In order to assess potential energy flexibility performance in a generic way for buildings with different system designs, the suitable and unified operation condition needs to be defined or assumed.* For the quantification of each flexibility concerned in an application or a standard, the operation condition has a significant impact on the quantification indexes, particularly the relative indexes. The following five subsections present the detailed information about the quantification methods of five flexibility capacities and ratios.

Table 2. Quantification formulations for each flexibility and their influencing factors

Flexibility type	**Flexibility capacity**	**Flexibility ratio**	**Main influencing factors**
Load covering	L_{cv} (kWh)	$F_{cv} = \frac{L_{cv}}{\int P_{load}(t)dt}$	Generation capacity, shiftable loads
Load shifting	L_{sf} (kWh)	$F_{sf} = \frac{L_{sf}}{\int P_{load}(t)dt}$	Postponable loads, storage capacity

Load shedding	L_{sd} (kW)	$F_{sd} = \frac{L_{sd}}{P_{load}}$	Storage capacity
Moderate regulation	L_{mr} (kWh)	$F_{mr} = \frac{L_{mr}}{\int P_{load}(t)dt}$	Storage capacity, power-
Fast regulation	L_{fr} (kW)	$F_{fr} = ave\left(\frac{L_{fr}(t)}{P_{laod}(t)}\right)$	Storage capacity, VFD rated power, diming rate

2.2 Load covering capacity and ratio

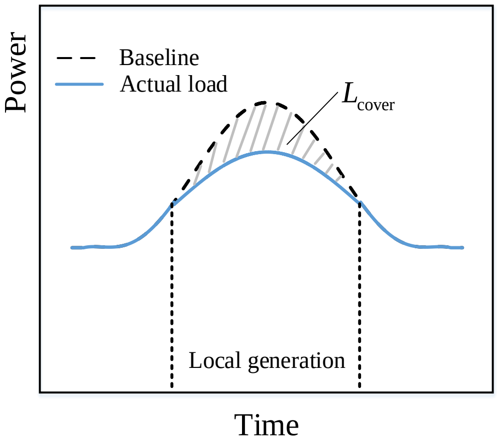


Fig.1. A typical pattern of load covering flexibility

As shown in Fig.1, load covering flexibility refers to the self-generation capability as a long-term load reduction of the energy systems in a building, which is able to satisfy part of the building load. Making use of the on-site power generations reduces building net load and increases the grid independence degree of the building. Here, the load covering flexibility of the building is the function of the onsite generated power and the building power demand, as shown in Eq. (1). Different durations of time can be chosen for different applications. In this study, a 24-hour duration is chosen as the response span. The load covering ratio is the proportion of the energy demand which can be satisfied by the self-energy generation, as shown in Eq. (2).

$$L_{cv} = \max\left(\int \min\big(G(t), P_{load}(t)\big)\, dt\right) \quad (kWh) \tag{1}$$

$$F_{cv} = \frac{L_{cv}}{\int P_{load}(t)dt} \tag{2}$$

The power demand of the building (P_{load}, kW) over a duration can be changed by the load shifting flexibility sources. When there is surplus energy generated by the on-site generation units over the "normal building demand", some loads can be shifted to this time interval to achieve higher energy efficiency. Thus, the shiftable load needs to be scheduled in an optimal manner when quantifying the maximum load covering flexibility capacity, as load shifting affects the time-varying power demand.

2.3 Load shifting capacity and ratio

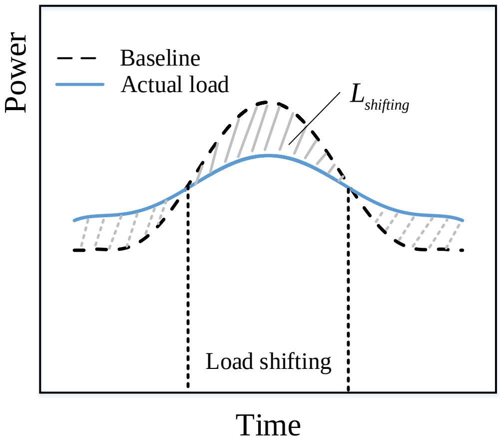


Fig.2. A typical pattern of load shifting flexibility

As shown in Fig.2, load shifting flexibility as the hourly load regulation can be utilized to reshape the daily load profile of a building by smartly controlling the postponable loads and energy storage systems. For example, by responding to dynamic energy pricing with a time interval of one-hour, economic benefits can be achieved by proper use of the load shifting flexibility. The load shifting flexibility capacity (L_{sf}) with a response duration is the collective capability of the active storage capacity (e.g., batteries, thermal energy storage systems, $L_{sf,act}$), passive building thermal storage capacity ($L_{sf,ps}$), and the load of postponable electrical appliances ($L_{sf,pa}$), as a function shown in Eq. (3). Therefore, the load shifting ratio is calculated as the proportion of the shiftable energy demand to total energy demand, as shown in Eq. (4).

$$L_{sf} = L_{sf,act} + L_{sf,ps} + L_{sf,pa} \quad (kWh) \tag{3}$$

$$F_{sf} = \frac{L_{sf}}{\int P_{load}(t)dt} \tag{4}$$

Integrating the active storage systems in a building can store and release the energy through optimal control. Here, $L_{sf,act}$ is the maximum shiftable load of the active storage system, which is a function of the storage efficiencies (ε_{act}), the available storage capacity ($P_{cha,act}$, kW), the charging period ($\Delta\tau_{cha}$) and the times (n) of the charging/discharging cycle, as shown in Eq.(5). ε_{act} represents the fraction of the stored energy that can be used for load shifting. The energy loss of the active electrical storage systems and the well-insulated thermal storage systems might sometimes be negligible (ε_{act}=1).

$$L_{sf,act} = \varepsilon_{act} \cdot P_{cha,act} \cdot \Delta\tau_{cha} \cdot n \tag{5}$$

It is notable that the shifting flexibility provided by the thermal storage system is actually the electricity load change of the HVAC system. The shiftable thermal load ($\Delta Q_{pre,HVAC}$) needs to be converted into electricity load considering the overall coefficient of performance (COP) of HVAC systems. The shifting flexibility provided by passive storage (i.e. building thermal mass) is shown in Eq. (6). It is mainly determined by the building envelope, weather conditions, and control. When utilizing passive building thermal mass in pre-cooling/pre-heating control to shift thermal load, the total energy demand increase obviously (ε_{ps}<1). In order to have an equal basis for comparison when quantifying the maximum shifting flexibility of different buildings, the operation conditions (weather conditions and control strategies) should be assumed to be the same. In this study, pre-cooling/pre-heating the building during the unoccupied period with fixed temperature and fixed time is adopted.

$$L_{sf,ps} = \varepsilon_{ps} \cdot \frac{\Delta Q_{pre,HVAC}}{COP} = \varepsilon_{ps} \cdot \frac{f(T_{pre}, \tau_{pre})}{COP} \tag{6}$$

The shifting flexibility capacity of postponable appliances is the function of their power input, working hours, and the flexible time-window, as shown in Eq. (7). Utilization of postponable appliances (e.g., washing machines, tumble dryers) for load shifting would not affect the building total energy demand. The flexible time-window [26] is composed of a preferred starting time and a deadline set by users. If the time-window (*tw*) equals the working hours (*wh*) meaning that the time-window is inflexible, the shifting flexibility is zero. If the time-window is longer than double the working hours, the load shifting flexibility is maximal which means that the total energy use of these appliances can be shifted.

$$L_{sf,pa} = P_{pa} \cdot \Delta t \qquad \Delta t = \begin{cases} 0 & wh = tw \\ tw - wh & wh < tw < 2wh \\ wh & tw \geq 2wh \end{cases} \tag{7}$$

2.4 Load shedding capacity and ratio

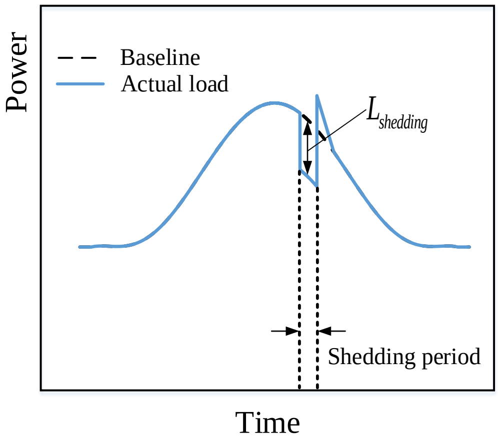


Fig.3. A typical pattern of load shedding flexibility

As shown in Fig.3, load shedding refers to the fast load curtailment within minutes of a building and lasts for a limited duration following a sudden request which mostly occurs as a contingency event in grid operation. Load shedding flexibility can be utilized as the reserve capacity in ancillary service or shedding capacity in conventional demand response programs. In this way, power system reliability can be guaranteed when unexpected problems lead to the supply shortage. The peak hour is chosen as the shedding duration in this quantification framework as it is the most critical condition where the flexibility ratio is concerned. The load shedding capacity is a function of the shedding capacity of active storage ($L_{sd,act}$), passive building thermal mass storage ($L_{sd,ps}$), and the load shedding of lighting ($L_{sd,lig}$), as shown in Eq (8). The load shedding period is short and normally limited within one hour. The shedding capacity is quantified using the unit of kW. The load shedding flexibility ratio is the shedding capacity to the corresponding power demand (P_{load}, kW) of the building, as shown in Eq.(9).

$$L_{sd} = L_{sd,act} + L_{sd,ps} + L_{sd,lig} \quad (kW) \tag{8}$$

$$F_{sd} = \frac{L_{sd}}{P_{load}} \tag{9}$$

The shedding capacity of the active storage system is defined as the maximum average value of its discharging rate for the shedding duration ($\Delta\tau_{sd}$), shown in Eq.(10).

$$L_{sd,act} = \frac{\max\left(\int P_{dis}(t)dt\right)}{\Delta\tau_{sd}} \tag{10}$$

When quantifying the load shedding capacity provided by building thermal mass, one actually calculates the reduction of power consumption of HVAC systems as defined in Eq.(11). For different buildings, the reduction of the cooling load ($\Delta Q_{sd,HVAC}$) is mainly determined by the building envelope, weather conditions, and control (i.e. acceptable temperature increase during the shedding period).

$$L_{sd,ps} = \frac{\int \frac{\Delta Q_{sd,HVAC}(t)}{COP} dt}{\Delta \tau_{sd}} \tag{11}$$

The illumination of rooms can be partially reduced for the shedding duration within the occupants' acceptance. Through on/off or dimming control of some lights, the load of the lighting system can be directly cut down. It can also reduce the heat gain of the HVAC system which furthers the reduction of building thermal load ($\Delta Q_{sd,HVAC}$). The direct shedding flexibility from the lights is shown in Eq.(12). γ_L represents the percentage of lights turned off or the shedding rate of the lighting system corresponding to the occupants' acceptance.

$$L_{sd,lig} = \gamma_L P_{lig} \tag{12}$$

2.5 Moderate regulation capacity and ratio

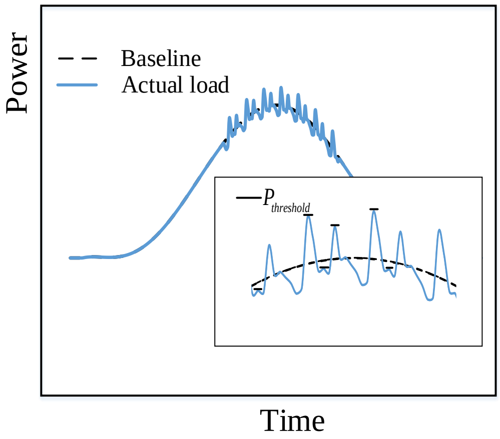


Fig.4. A typical pattern of load moderate regulation flexibility

As shown in Fig.4, moderate regulation refers to load regulation in the speed of minutes. It is a promising tool in the application scenarios of existing electricity pricing which is settled typically within a timescale interval of minutes, such as 5-minute or 15-minute real-time price (RTP). A price-to-power threshold model needs to be formulated in this demand response control scheme. The typical contributors to moderate regulation flexibility can be active battery storages and domestic air conditioning, and the flexibility capacity can be then quantified by Eq.(13). The moderate regulation flexibility ratio is shown as Eq.(14).

$$L_{mr} = \Delta t \cdot \left(P_{dis,bat} + \frac{Q_{actual,AC} - Q_{thresh,AC}}{COP}\right) \ (kWh) \tag{13}$$

$$F_{mr} = \frac{L_{mr}}{\int P_{load}(t) dt} \tag{14}$$

However, the signal of 5-minute or 15-minute RTP actually reflects the deviation in short-term energy balance. It is proposed to quantify the moderate regulation capacity under the condition when a high-price signal is followed by a low-price signal, since the maximum capacity of moderate regulation flexibility is obtained concerning the recovery of both electrical and thermal storages. For example, under this assumption, the flexibility capacity of a battery is its maximum accumulated discharging energy demand over a 24-hour duration. As for domestic air-conditioners, by making use of building thermal mass storage, a cooling supply threshold ($Q_{thresh,AC}$) is adopted to limit the maximum power use during the period of high RTP (Δt).

2.6 Fast regulation capacity and ratio

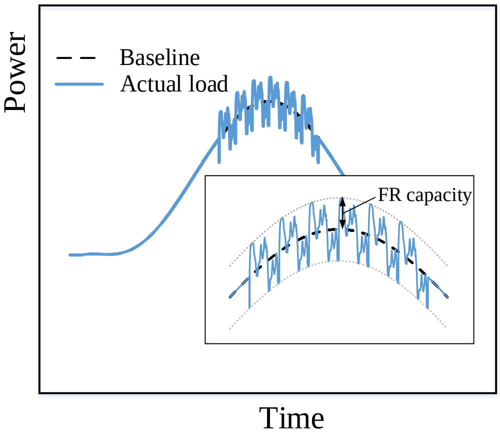


Fig.5. A typical pattern of load fast regulation flexibility

As shown in Fig.5, fast regulation (FR) refers to the bidirectional load regulation of buildings responding to the request of its power grid at the timescale of seconds. FR signals are assumed to change every few seconds, and their impact on energy consumption is assumed to be neutral over a relatively long period of time (i.e. typically 1-hour interval). This FR flexibility of buildings can be utilized to provide frequency regulation service in response to Automatic Generation Control (AGC) signal which is normally at very short intervals [8] (e.g., 2-second in Pennsylvania–New Jersey–Maryland market). The main FR flexibility sources can be electrical batteries, variable frequency drives (VFD), and dimmable lighting systems. The fast regulation capacity (e.g., frequency regulation capacity) needs to be calculated every hour, as shown in Eq.(15). Since the power demand of a building changes every hour, the fast regulation ratio is defined as an average value over a 24-hour cycle, as shown in Eq.(16).

$$L_{fr} = P_{dis,bat} + \alpha P_{rated,VFD} + \beta_L P_{lig} \quad (kW) \tag{15}$$

$$F_{fr} = ave\left(\frac{L_{fr}(t)}{P_{load}(t)}\right) \tag{16}$$

where, $P_{dis,bat}$ is the maximum discharging rate of the batteries. α is the available adjustment rate of VFD (variable frequency drives). $P_{rated,VFD}$ is the rated power of variable frequency drives. β_L is the dimming rate of the lighting system for fast regulation.

3. Flexibility quantification and the implementation of flexibility index in a building

In this section, a case study is conducted in an office building to illustrate and validate the proposed framework for assessing building energy flexibility performance. A few key design and control parameters of building envelope and energy systems are selected to study their effects on building flexibility performance and to verify the effectiveness of the flexibility indexes. Fig. 3 shows the flexibility quantification process of this case study and a typical schedule optimization (discussed in Section 4).

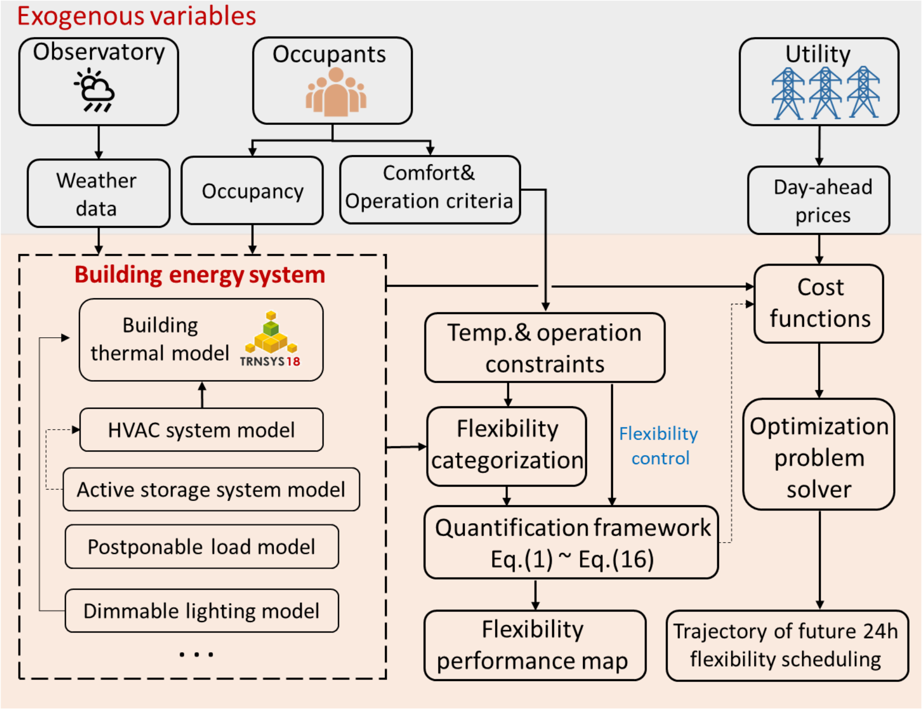


Fig.6. Flow chart of flexibility quantification and schedule optimization

3.1 Overview of the building information and the flexibility sources

This case study involves a ten-story office building located in Hong Kong. The ceiling height is 3 meters and the area of each floor is 1000 m^2 (25m×40m). The window-to-wall ratio of external walls is assumed to be 0.3 (South) and 0.4 (other directions). The lighting load density is 15 W/m^2 and the equipment load density is 25 W/m^2. The occupancy capacity is assumed to be 10 m^2/person and the heat load is assumed to be 150W/person. The key information about the flexible sources of the building is listed in Table 3. The main parameters of this medium-weighted building envelope are presented in Table 4. Due to the increasing penetration of the electrical vehicles, large commercial and public buildings are encouraged to implement charging stations for the occupants' convenience. In this case, 50 electrical vehicles (E_{rated}=30 kWh, P_{rated}=6 kW) are assumed to have charging requirements in the underground carpark from the initial state (SOC_0=0.2) to the expected state (SOC_{exp}=0.8) during the whole occupied period (i.e. time-window). To avoid over-charging/discharging the batteries which may accelerate the battery degradation, both EV and the stationary battery should be restricted by minimum and maximum energy limits (E_{min} and E_{max}).

Table 3. Information about the office building and the flexibility sources

Building information		
Infiltration Air Change Rate	-	0.2 h^{-1}
Fresh air Ventilation	-	30 $m^3/h \cdot person^{-1}$
PV panel	Area	890 m^2
Stationary battery	Rated energy and power	140 kWh (50 kW)
Electrical vehicles	Rated energy and power	30 kWh (6 kW)
VFD fan	Rated power	2*37 kW
Dimmable lighting	Lighting density	15 W/m^2
Chiller	Cooling capacity	2*700 kW
Cooling conditions	Temperature and relative humidity	24℃, 60% RH
Occupied period	-	8:00-18:00

Table 4. Information about the building envelope (medium-weighted)

Construction type	Layers	Thickness (mm)	U-value ($W/m^2 \cdot K^{-1}$)
External walls	Finish+ insulation+ concrete+ plaster	240	0.95
Internal walls	Gypsum+ brick+ gypsum	230	1.86
Floor/ceilings	Floor+ stone+ silence+ concrete	345	0.83
External windows	Double glazing	12	1.10

3.2 Quantification results: demand baseline and the quantified five energy flexibilities

3.2.1 Simulation and results of demand baseline

The power demand baseline is the power demand of the building under normal operation without activating any energy flexibility sources. It is the basic information (baseline pattern) when quantifying the relative energy flexibility (i.e. flexibility ratio) of the building. Fig.6 shows the outdoor temperature and the power demand baseline (hourly average) of the building. Here, building energy performance simulation is conducted in TRNSYS [27], at the simulation time interval of five minutes, to obtain the demand baseline using the building model (Type 56) provided. The baseline simulation is conducted on a typical summer day under the indoor setting of 24℃ and 60% RH during the occupied period. The charging load of the electrical vehicles is evenly distributed to each occupied hour. The overall coefficient of performance (COP) of the HVAC system is assumed to be 4 as a constant in this study. The total daily energy consumption is 7,336 kWh on the selected test day. In this study, the peak hour of the power grid is assumed to be between 14:00 and 15:00 in summer. It is found that the power demand in this peak hour is 684 kW. It is worth noting that a representative test day with relatively high demand is selected referring to the available Hong Kong TMY data. When accessing and comparing the energy flexibility performance of different buildings, the selected reference day should be the same and representative. The peak hour should be selected according to the frequently occurred peak time of the power grid in a day.

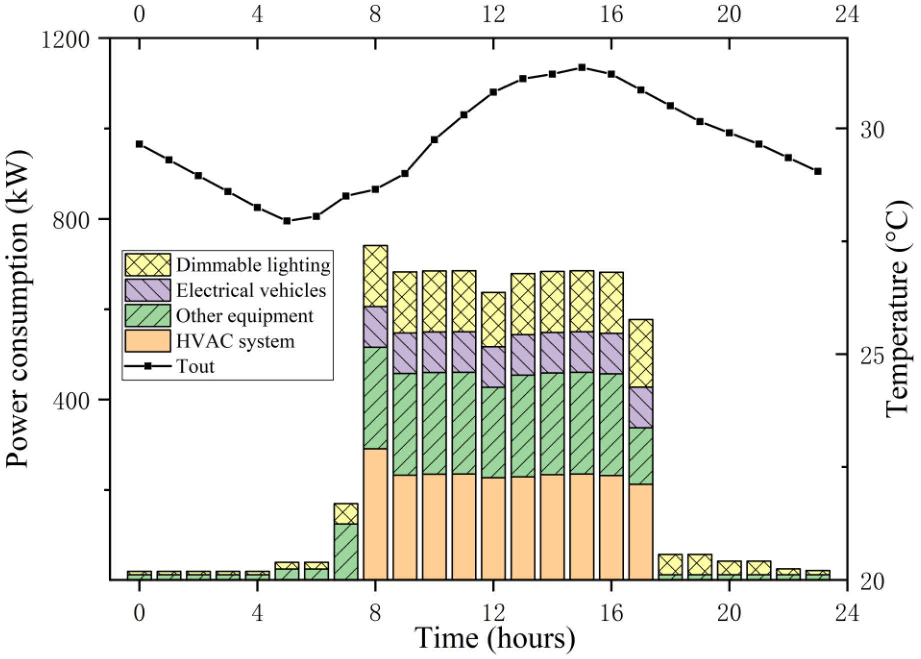


Fig.7. Outdoor temperature and the power demand baseline of the building

3.2.2 Quantification results of five energy flexibilities

According to the proposed flexibility indexes, five flexibility capacities and five flexibility ratios can be quantified under the corresponding control strategies, which are listed in Table 5. The quantification results are presented in Table 6.

Table 5. Description of control strategies for flexibility quantification

Flexibility type	Flexibility sources	Control strategies
Load covering	PV panel area: 890m2 Stationary battery: 140kWh (50kW) Electrical vehicles: 30kWh (6kW)*50 Building thermal storage: medium-weighted	Self-consumption is optimized with load shifting.
Load shifting	Stationary battery: 140kWh (50kW) Electrical vehicles: 30kWh (6kW)*50 Building thermal storage: medium-weighted	The discharging/ charging rates of the storages are optimized ($P_{cha,act}$ and $\Delta Q_{pre,HVAC}$). Mechanical pre-cooling (24℃) for 1 hour.
Load shedding	Stationary battery: 140kWh (50kW) Electrical vehicles: 30kWh (6kW)*50 Building thermal storage: medium-weighted Dimmable lighting: 20% for shedding	The discharging/ charging rates of the storages are optimized ($P_{dis,act}$ and $\Delta Q_{sd,HVAC}$). Allowing 2K increase during the shedding period. Dimming control of the lighting system.
Moderate regulation	Stationary battery: 140kWh (50kW) Electrical vehicles: 30kWh (6kW)*50	The discharging/ charging rate of the storage is optimized ($P_{dis,act}$).
Fast regulation	Stationary battery: 140kWh (50kW) Electrical vehicles: 30kWh (6kW)*50 Dimmable lighting: 8% for fast regulation VFD fans: 15% for fast regulation	The discharging/ charging rate of the storages is optimized ($P_{dis,act}$). Dimming control of the lighting system. Direct frequency control of the fans;

Table 6. Quantification results of the flexibility capacities and flexibility ratios

Flexibility type	Total flexibility capacity	Baseline	Flexibility ratio
Load covering	612 (kWh)	7336 (kWh)	0.08
Load shifting	2507 (kWh)	7336 (kWh)	0.34
Load shedding	457 (kW)	684 (kW)	0.67
Moderate regulation	1650 (kWh)	7336 (kWh)	0.22
Fast regulation	20 - 371.9 (kW)	20 - 741 (kW)	0.72

Load covering flexibility

In this building, PV panels are the contributor to load covering flexibility through self-generation. Based on the outputs of the above building performance simulation, the PV generation and the net power demand (to the power grid) on the test day are obtained as presented in Fig.7. The total PV generation is 612 kWh. The load covering flexibility capacity and ratio are 612 kWh and 0.08, calculated using Eq.(1) and Eq.(2) respectively. It can be seen that load covering flexibility is rather low as indicated by both absolute capacity and relative ratio. It is also worth noticing that there is no potential to enhance the load covering flexibility by utilizing load shifting measures, since no surplus generation is available.

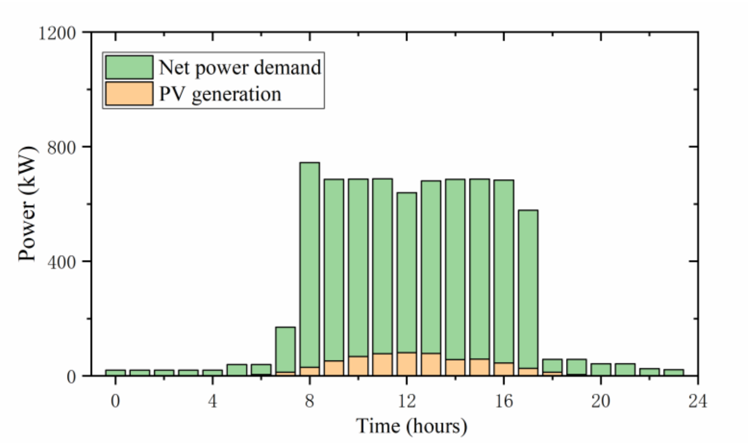


Fig.8. The power generation of PV panels and the net load of the building

Load shifting flexibility

Load shifting flexibility is typically contributed by electrical vehicles (EVs), stationary batteries and passive building thermal mass. Based on the optimized charging/discharging schedule of the batteries and outputs of the building performance simulation, the load shifting flexibility capacity and ratio are 2,507 kWh and 0.34, calculated using Eq. (3) and Eq. (4). The quantification of flexibility capacities from three contributors is described in detail below.

EVs can be seen as both the postponable appliances and the active storages. Thus, both the expected charging load (from SOC_0 to SOC_{exp}) and the available energy storage capacity of EVs are considered. The total load shifting flexibility from EVs is 1,800 kWh, calculated using Eq. (5) and Eq. (7). Fig.8 shows the time-window for EVs (8:00-18:00), as well as the earliest and latest charging window (3 hours). Fig.9 shows the operation mode when the maximum load shifting flexibility of EVs is achieved. In this operation mode, EVs are fully charged during the latest charging window, and their remaining electricity storages are used for shifting other loads before the latest charging window (i.e. 15:00-18:00). The storage efficiency of electrical storages is assumed to be 100%.

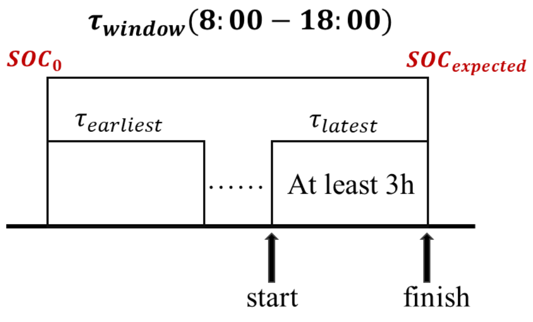


Fig.9. The time-window of the electrical vehicles

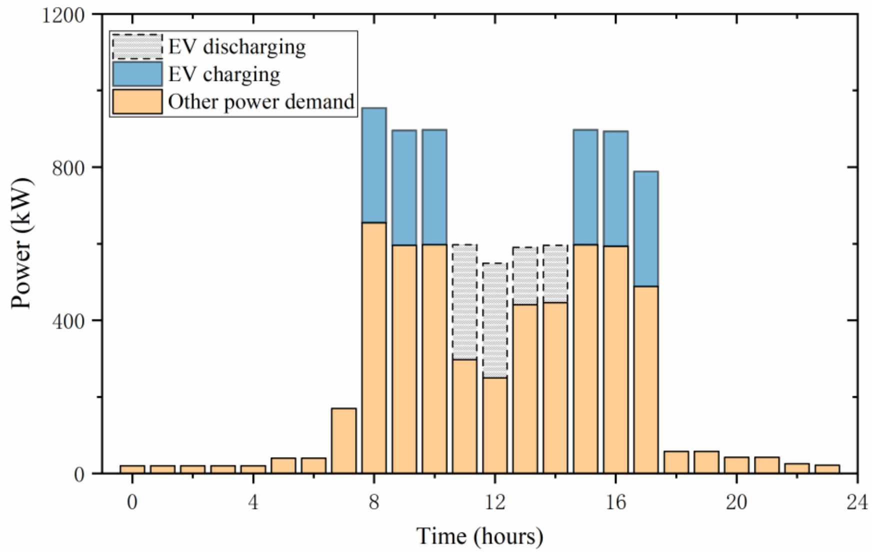


Fig.10. The operation mode of EVs to achieve the maximum load shifting flexibility

The maximum load shifting capacity of the stationary batteries is 600 kWh, as calculated using Eq. (7). In the quantification, the initial state of stationary batteries is assumed to equal their final state within the load shifting duration. The charging/discharging power for the batteries is limited by the physical constraints ($|P_{stb}| \leqslant P_{rated,stb}$).

The load shifting flexibility from building thermal mass is 107 kWh, which is obtained by comparing the baseline operation mode with the pre-cooling mode of the HVAC system, based on outputs of the building performance simulation. Fig.10 shows the cooling load (hourly average) of the building under the baseline operation mode and pre-cooling mode.

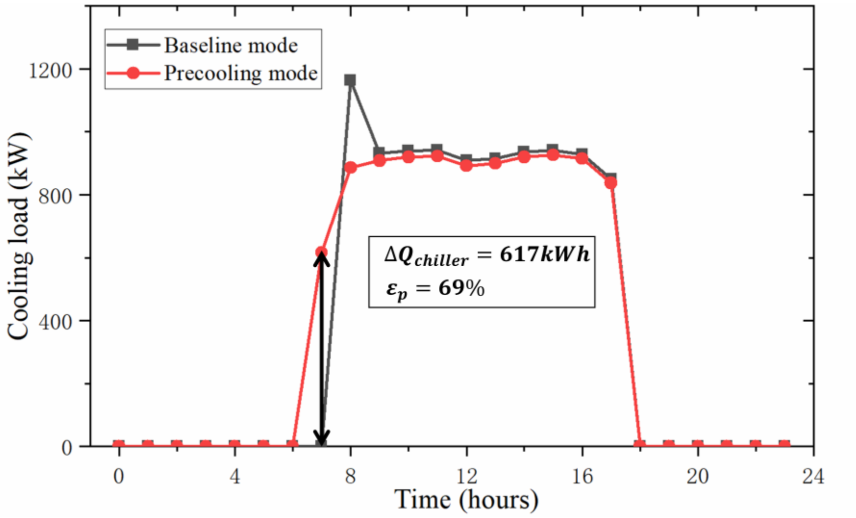


Fig.11. The cooling load of the building under the two operation modes

Load shedding flexibility

The load shedding period is between 14:00 and 15:00 as this period is assumed to be the peak hour of the power grid (mentioned in Section 3.2.1). Load shedding flexibility is contributed by EVs, stationary batteries, dimmable lighting system, and passive building thermal mass (i.e. the HVAC system). The load shedding flexibility capacity and ratio are 457 kW and 0.67, which are calculated using Eq. (8) and Eq. (9) respectively. Fig.11 shows the proportion of load shedding flexibility contributed by different sources.

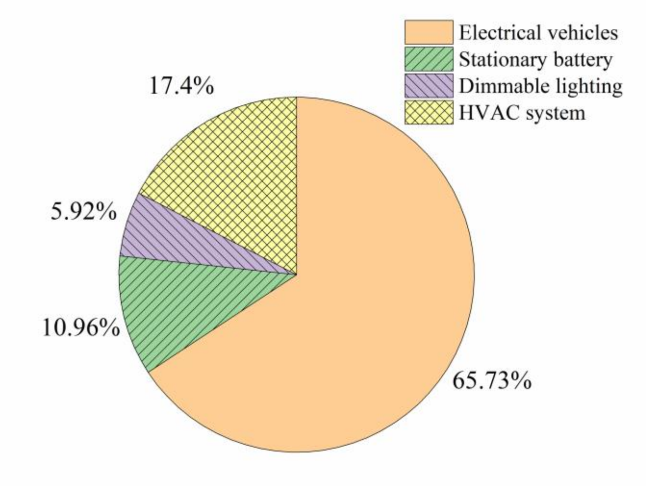


Fig.12. The percentages of the load shedding flexibility from different sources

The load shedding capacities of the stationary battery and EVs are 50 kW and 300 kW respectively as they can be discharged continuously at their maximum discharge rate during this period. The load shedding flexibility of the lights is 27 kW, which is calculated using Eq. (12). The loads of lights can be adjusted through dimming rate control. A dimming rate of 0.2 is chosen during the shedding period. Based on the outputs of the building performance simulation, the power consumption of the HVAC system can decrease from 235 kW to 156 kW during this load shedding period. This is because the building thermal mass is discharged by allowing 2 K increase of the indoor temperature and the heat gain from the lighting system is reduced.

Moderate regulation flexibility

In this case, the moderate regulation flexibility is contributed by EVs and stationary batteries. The flexibility capacity and ratio are 1,650 kWh and 0.22, which are calculated using Eq. (13) and Eq. (14) respectively. The flexibility capacity from the active storages is the maximum accumulated storage capacity during their available regulation periods (i.e. 24-hour for stationary battery, 7-hour for EVs).

Fast regulation flexibility

The fast regulation (FR) flexibility is contributed by EVs, the stationary battery, VFD fans (variable-frequency drive), and the dimmable lighting in this case. Over the 24-hour duration, the total hourly FR flexibility capacity ranges from 20 kW to 371.9 kW, and the average ratio is 0.72, which are calculated using Eq. (15) and Eq. (16). Fig.12 shows the hourly FR flexibility capacity of the building. Note, FR flexibility capacity varies by different time of a day, depending on the working condition of the system/devices (e.g., the number of available electrical vehicles).

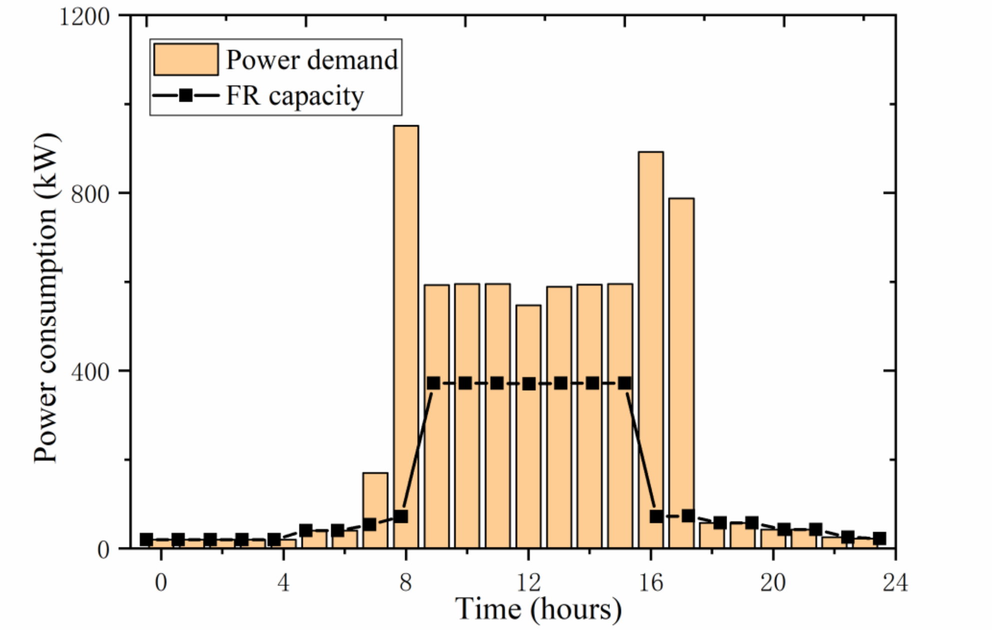


Fig.13. The total hourly FR flexibility capacity over the 24-hour duration

The fast regulation flexibility capacity of the stationary battery is 50 kW at each hour, since the battery can be continuously regulated from zero power output to full capacity (i.e. rated power) within every few seconds [28]. When providing the maximum FR flexibility, the available energy storage capacity (E_t) of the stationary battery is constrained by its maximum and minimum energy limit and the maximum accumulated regulation up/down capacity.

It is also worth noticing that the maximum FR flexibility capacity of EVs essentially depends on the operation mode. Fig. 13 shows the hourly FR capacity of two typical operation modes of EVs. Mode 1 is the operation mode used in the baseline simulation (also see Section 3.2.1). Mode 2 is the operation mode which can achieve the maximum FR flexibility. In fact, constrained by the SOC_0 and SOC_{exp}, EVs have no FR flexibility in the first and the last hour during the EV time-window. The FR flexibility is constrained by the rated power and the charging rate (i.e. $L_{EV}^{fr} \leq P_{rated} - P_{EV}^{cha/dis}$).

According to the experiment results in [25], it is assumed that 15% of the fan rated power (α_{fan}=15%) is used for providing FR flexibility in this case. As long as the variation of fan power is fast and small, this variation would not affect the power consumption of chillers. For the dimmable lighting system, 8% of the lighting power consumption (β_L = 8%) is assumed to provide FR flexibility, based on the results given in [29]. Each light ballast is assumed to operate at above 80% light levels.

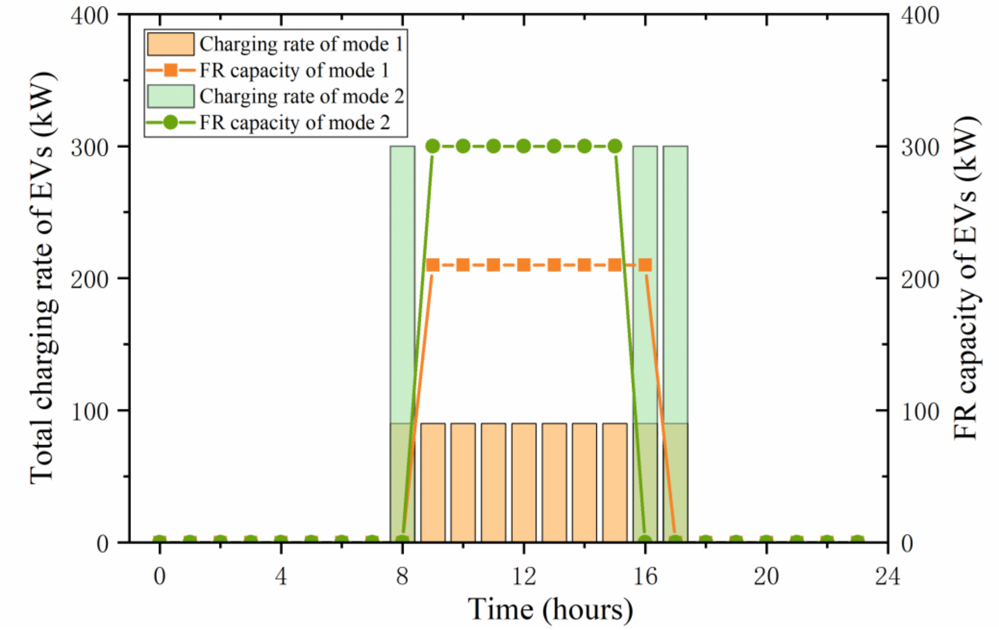


Fig.14. Hourly charging rate and FR capacity of two different operation modes for EVs

3.3 Impacts of building envelope and system parameters on energy flexibilities

The quantitative impacts of the design and control parameters associated with the building envelope and other flexibility sources on the flexibility performance are the essential information for the design and control of energy-flexible and grid-response buildings. A parametric study is therefore conducted to investigate such quantitative impacts and further verify the effectiveness of the proposed quantification indexes. In this parametric study, all of the indexes are obtained by varying the parameters of the flexibility sources within selected ranges (in total ten more scenarios), as listed in Table 7. The parameters concerned belong to five categories: self-generation capacity, building envelope design (weight type), active storage capacity, flexible window setting, and the dimming rate setting of the lighting system. Flexibility capacities and ratios are listed in Table 8 and Table 9 respectively, under these ten modified scenarios and the benchmark scenario (Scenario 1). In each of these ten modified scenarios, one parameter changes and the other parameters remain unchanged (i.e. are the same as in Scenario 1). To present the flexibility performance of all five dimensions graphically, the "flexibility radar chart" is proposed. Fig.15 presents the flexibility radar charts of the building when varying the parameters of five flexibility sources. Fig.14 presents a comparison between the flexibility performance of two cases: this office building (under benchmark scenario) and that of a residential building which consists of a rooftop PV with a 10kWh battery, postponable household appliances and a variable speed air-conditioner. It can be seen that the flexibility ratios of the residential building are larger than that of the office building in this specific case.

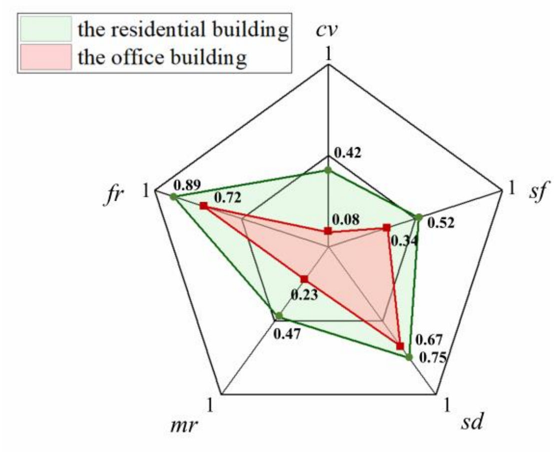


Fig.15. Flexibility radar chart of the office building and residential building (*cv*: load covering, *sf*: load shifting, *sd*: load shedding, *mr*: moderate regulation, *fr*: fast regulation)

Table 7. Parameters of flexibility sources concerned in parametric study

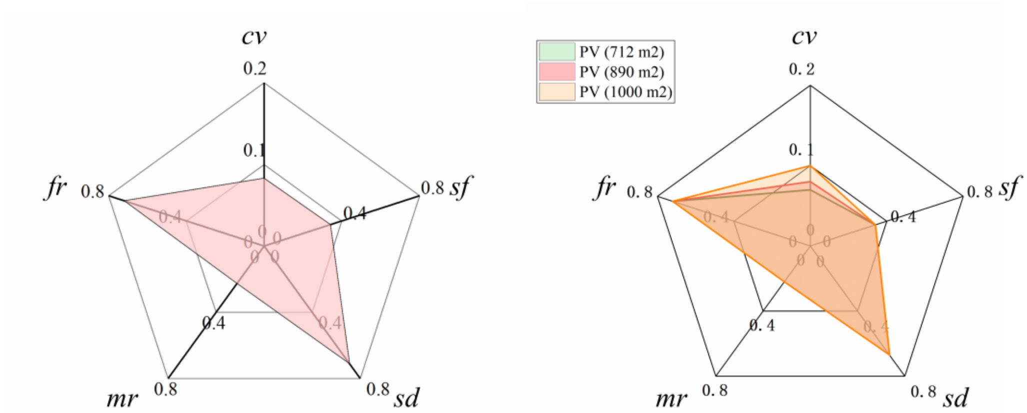
Technologies	Parameters change	Range	Scenario No.
PV panel	Area	712	2
		890	1
		1000	3
Stationary battery	Storage capacity	70kWh (25kW);	4
		140kWh (50kW);	1
		210kWh (75kW);	5
Electrical vehicle	Flexible window	8:00-12:00 (inflexible);	6
		8:00-18:00 (flexible);	1
		8:00-12:00 (40%), 8:00-18:00(60%) (adjustable);	7
Dimmable lighting	Available dimming rate	10% for shedding;	8
		20% for shedding;	1
		30% for shedding;	9
Available building thermal storage	Weight type	Light weighted;	10
		Medium weighted ;	1
		Heavy weighted;	11

Table 8. Flexibility capacities under different scenarios

Flexibility capacity		PV area (m^2)		Stationary battery (kWh)		EV flexible window		Dimming rate of lighting		Building weight type	
		712	1000	70	210	Inflexible	Adjustable	10%	30%	Light weighted	Heavy weighted
Scenario No.	1	2	3	4	5	6	7	8	9	10	11
Load covering (kWh)	612	489	918	612	612	612	612	612	612	612	612
Load shifting (kWh)	2507	2507	2507	2207	2807	1007	1907	2507	2507	2524	2490
Load shedding (kW)	457	457	457	432	482	157	317	440	477	440	472
Moderate regulation (kWh)	1650	1650	1650	1350	1950	750	1290	1650	1650	1650	1650
Fast regulation (kW)	20-371.9	20-371.9	20-371.9	20-347	20-396.9	20-371.9	20-371.9	20-371.9	20-371.9	20-371.9	20-371.9

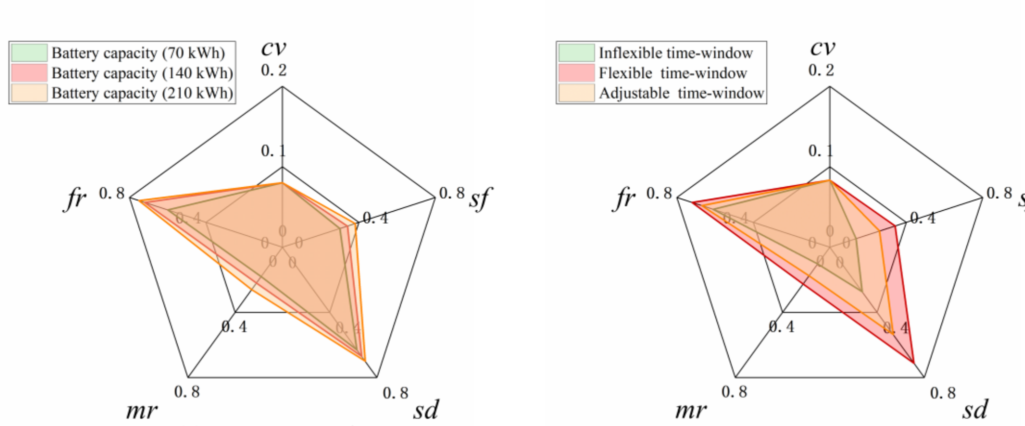
Table 9. Flexibility ratios under different scenarios

Flexibility capacity		PV area (m^2)		Stationary battery (kWh)		EV flexible window		Dimming rate of lighting		Building weight type	
		712	1000	70	210	Inflexible	Adjustable	10%	30%	Light weighted	Heavy weighted
Scenario No.	1	2	3	4	5	6	7	8	9	10	11
Load covering	0.08	0.07	0.10	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.09
Load shifting	0.34	0.34	0.34	0.30	0.38	0.14	0.26	0.34	0.34	0.34	0.35
Load shedding	0.67	0.67	0.67	0.63	0.70	0.23	0.46	0.64	0.70	0.64	0.71
Moderate regulation	0.22	0.22	0. 22	0.18	0.26	0.10	0.18	0.22	0.22	0.21	0.23
Fast regulation	0.72	0.72	0.72	0.60	0.75	0.61	0.67	0.72	0.72	0.72	0.72



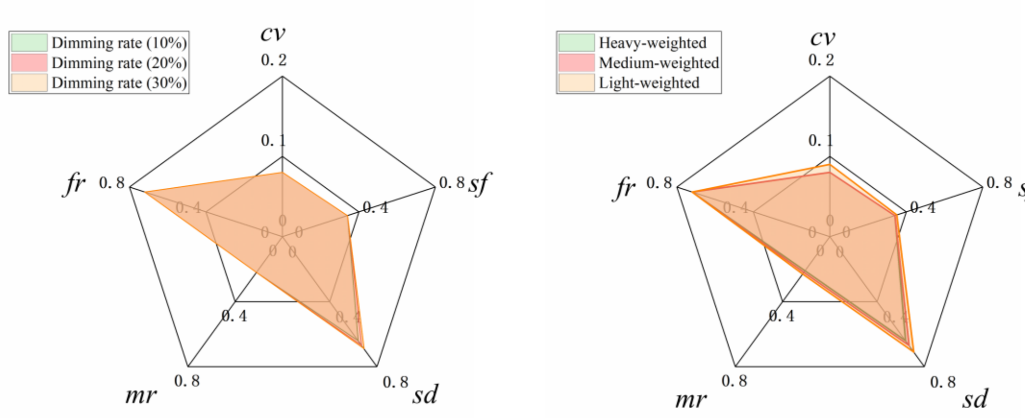
(a) Scenario 1

(b) PV area



(c) Battery capacity

(d) EV time window



(e) Lighting dimming rate

(f) Building weight type

Fig.16. flexibility performance radar chart of different scenarios

Regarding the design aspect of building systems, varying the capacity of PV generations does not significantly affect the load covering ratio (i.e. 0.07 - 0.1) in this case, as shown in Fig. 15(b). It is because the PV generation is very small compared to total building energy consumption, due to the limited available area for PV installation. However, the enhanced load covering flexibility can provide great economic benefit, as it results in a greater reduction of net load for the building (i.e. load reduction is increased by 430 kWh). In contrast, in other cases with surplus power generation (e.g., in residential buildings), the load covering flexibility ratio would be larger due to the relatively small baseline demand and the contribution of the energy storage system to the enhancement of the load covering flexibility.

The results also show that varying the stationary battery capacity affects four of the five flexibilities, as shown in Fig. 15(c). The impacts on fast regulation and moderate regulation ratio are the most obvious, since the stationary battery is the main contributor to these flexibilities. In recent years, the cost of lithium-ion (Li-ion) battery which can be implemented as the electrical storage system in the building has decreased rapidly due to the development of battery technology [30]. This will make their implementation more attractive in buildings for their contributions to multiple flexibilities.

Regarding the design aspect of the building envelope, it can be observed that, the flexibilities vary with the building weight types. Here, three buildings with different concrete thicknesses (100 mm, 200 mm, 400 mm) and different densities (900 kg/m^3, 900 kg/m^3, 1800 kg/m^3) are compared. The results of building performance simulation show that heavy weighted building consumes less energy which can be used to explain the increase of load covering/moderate regulation ratios. The heavy weighted building has better performance on load shedding flexibility due to its larger thermal energy storage capacity. However, in the pre-cooling operation mode, the load shifting flexibility capacity and the storage efficiency of the heavy-weighted building are smaller than the light-weighted building (i.e. $\varepsilon_{p,lw} = 0.74$, $\varepsilon_{p,mw} = 0.69$, $\varepsilon_{p,hw} = 0.67$). But the shifting ratio is less influenced.

Regarding the control aspect, a more flexible time-window setting of EVs can achieve better flexibility performance. Three window settings are compared, including an inflexible time-window (i.e. completing the charging of EVs before 12:00), a flexible time-window (i.e. a 10-hour available charging period) and an adjustable time-window (i.e. assuming that 40% of EVs with an inflexible time-window and 60% with flexible time-window). The differences in their flexibilities are obvious as shown in Fig. 15(d). The load shifting, load shedding and moderate regulation flexibility of the flexible time-window are all twice as large as those of the inflexible time-window. Thus, implementing a sufficient number of charging stations in the carparks and adopting strategies to encourage EV owners to set a more flexible time-window can be an effective way to improve the flexibility performance of the building.

In addition, the results also show that varying the dimming rate of lighting systems affects the load shedding flexibility. An increase of 10% of the dimming rate has almost the same impacts on the load shedding ratio as increasing half of the battery storage (from 0.67 to 0.70). It is beneficial to implement dimming control and set a reasonable dimming rate for lighting systems.

3.4 Discussion on benefits and costs associated with flexibility enhancement

From the perspective of power grids, demand side resources of larger available flexibility capacity are preferred. The time-varying energy prices and other service revenues are increasingly offered in electricity markets in order to stimulate the enhancement of energy flexibility in the demand side. The proposed flexibility quantification method could be useful to multiple stakeholders. For market participants from the demand side, their energy flexibility at different timescales can be quantified, which means that they can play a more important role in power systems and earn revenues by providing multiple grid services. Also, the flexibility index can be utilized in the assessment of energy performance for different types of buildings. It can accelerate the development of smart energy-flexible buildings and smart grids. Meanwhile, in the system operation, this new approach can guide system operators to manage and utilize the demand side flexibility more effectively. Benefits can be obtained by avoiding generation modes that have higher marginal cost and by reducing investments in power-grid infrastructure and reinforcement. For policymakers, the sustainable development goal of introducing more renewable energy can be achieved as the grid reliability could be guaranteed by utilizing demand side flexibility. The market power can be reduced because more demand side users can participate in the electricity market as the flexibility service providers. However, from the perspective of buildings at the demand side, enhancing energy flexibility will naturally bring about increased investments and might bring about comfort or building service quality sacrifice.

Therefore, there is a trade-off at the design stage when the life cycle cost or environmental impact are considered. The trade-off also exists at the system operation stage when allocating the flexibility for different grid services to maximize the benefits of demand response. Optimizing these trade-offs during design and control is essential. At the implementation stage, forecasting the PV generation output and the load baseline consumption [31, 32] is basic but critical when utilizing the demand side flexibility. Several literatures provide effective methods to improve the prediction accuracy [33, 34], which can be adopted in the future work on optimal control process of the energy flexible building. The proposed flexibility indexes would provide a convenient means to estimate the benefits and costs of flexibility sources and grid services.

Thus, it is interesting and important to further investigate how these indexes can be used to develop effective optimization methods for the design and control processes of buildings and their energy systems in the future.

4. Application case study on optimization flexibility allocation in operation

Following the proposed categorization and quantification methods, this section presents the investigation on the economic benefits of building energy flexibilities. However, when considering the market participation of those flexibility types, they can be coupled if multiple incentive programs are provided in a power grid (or market) at the same time. In such a situation, the flexibility allocation needs to be optimized to maximize the benefits of using these flexibilities collectively. A case study is conducted based on the California electricity market (CAISO). Although it is unavailable to directly trade flexibility in the existing electricity markets, buildings can obtain economic benefits, acting as flexibility providers, from various market services by responding to the grid signals at multiple timescales.

4.1 Participation in the joint electricity markets

In this case, the optimization of building energy systems based on the day-ahead market is considered. Table 10 shows the timescale-product mapping of the CAISO market. The electricity products include energy and ancillary services which require building responses at different timescales. In the real-time market, price information is updated every few minutes according to the real-time operation of the power system. In the day-ahead market, the hourly price information of different products can be obtained one day ahead. It has less variability and uncertainty and can be easily applied in decision-making during building energy system operation.

Table 10. Timescale-product mapping for CAISO market [35]

	Day-ahead market	Real-time market	
Electricity Products	Integrated Forward Market (IFM)	Fifteen Minute Market (FMM)	Real-Time Dispatch (RTD)
	1 h	15 min	5 min
Energy(kWh)	√	√	√
Ancillary Services(kW)			
Regulation up (seconds)	√	√	-
Regulation down (seconds)	√	√	-
Spinning Reserves (minutes)	√	√	-
Non-spin. Reserves (minutes)	√	√	-

In the day-ahead market, two main product categories with the price of 1-h interval are provided: the energy product and ancillary service products. The energy product (kWh) is sold for the energy consumption of end-users, while the ancillary service products offer revenues to end-users. Based on the categorization and quantification of the building energy flexibility, utilizing fast regulation flexibility and load shedding flexibility can earn revenue by providing regulation and spinning reserve capacity respectively, as ancillary service products. Load shifting flexibility can shift the energy demand from high-price hours to low-price hours. Load covering can reduce the total energy demand (cost). If the resource failed to meet scheduled energy production/consumption due to unanticipated reasons, the deviation would be settled in the real-time dispatch (RTD) market. In the optimization process of the building system operation, this deviation is ignored.

4.2 Optimization of the building energy system operation considering the flexibility performance

The formulation of the optimization objective for the control of the building energy system is presented as Eq. (17), where the trading involves energy, reserve and regulation products. The total cost is minimized by manipulating the load covering, load shifting, load shedding, and fast regulation flexibility (i.e. the amount of purchased energy and offered ancillary service capacity), subject to the constraints of Eq. (18) – Eq. (27). According to the proposed assessment criteria of building flexibility, it is assumed that the hourly regulation capacity (kW) is symmetrical in up and down directions. The impacts of fast regulation flexibility on the energy consumption (kWh) is ideally neutral. The load shedding flexibility from storages and the dimmable lighting will be activated only once in the peak hour. The impacts of storage recovery on energy consumption which may increase the energy cost after the shedding period is considered. The revenue from regulation mileage [36] and the payment related to the called reserve capacity [37] are not considered in the optimization process. The SOC of the batteries (i.e. stationary battery and EV battery) is constrained by their upper/lower limits considering the total power reserved for ancillary service provision [38]. The utilization of load covering and load shifting flexibility can reduce the total energy cost. In this study, the optimization target is a nonlinear programming problem which is solved based on the Genetic Algorithm (GA) method by using MATLAB on a computer with Intel Core i7 CPU including eight cores. [39].

$$min \sum_{t\in T}(\pi_t^E P_t^E - \pi_t^{Rs} P_t^{Rs} - \pi_t^{Rg,up} P_t^{Rg,up} - \pi_t^{Rg,d} P_t^{Rg,d}) \tag{17}$$

Subject to:

$$P_t^{Rg} = L_{fan,t}^{fr} + L_{lig,t}^{fr} + P_{EV,t}^{fr} + P_{stb,t}^{fr} \tag{18}$$

$$P_t^{Rs} = L_{ps,t}^{sd} + L_{lig,t}^{sd} + P_{EV,t}^{sd} + P_{stb,t}^{sd} \tag{19}$$

$$\sum_{t\in T} P_t^{E} = \sum_{t\in T}(P_{base,t}^{E} - L_{PV,t}^{cv}) \tag{20}$$

$$P_{bat,t}^{E} + P_{bat,t}^{Rg} \le P_{bat,rated} \tag{21}$$

$$P_{bat,t}^{E} - P_{bat,t}^{Rs} - P_{bat,t}^{Rg} \ge -P_{bat,rated} \tag{22}$$

$$SOC_{EV,t} = SOC_{EV,0} + (\textstyle\sum_{i=9}^{t} P_{EV,i}^{E} h)/E_{EV,rated} \qquad t \in [8,18] \tag{23}$$

$$SOC_{stb,t} = SOC_{stb,0} + (\textstyle\sum_{i=1}^{t} P_{stb,i}^{E} h)/E_{stb,rated} \qquad t \in [0,24] \tag{24}$$

$$\frac{E_{min} + P_{bat,t}^{Rg} h/2 + P_{bat,t}^{Rs} h}{E_{rated}} \le SOC_{bat,t} \le \frac{E_{max} - P_{bat,t}^{Rg} h/2}{E_{rated}} \tag{25}$$

$$SOC_{EV,8} = 0.2\,, SOC_{EV,18} = 0.8 \tag{26}$$

$$SOC_{stb,0} = SOC_{stb,24} \tag{27}$$

where, P_t^E is the total purchased energy in the day-ahead energy market at the hour *t*. P_t^{Rg} is the offered regulation capacity in ancillary service at the hour *t*. $P_t^{Rg,up}$ and $P_t^{Rg,d}$ are the same in this case. P_t^{Rs} is the offered spinning reserve capacity at the hour *t*. $L_{fan,t}^{fr}$ and $L_{lig,t}^{fr}$ are the fast regulation capacity of fans and the lighting system, respectively. $\pi_t^E, \pi_t^{Rs}, \pi_t^{Rg,up}, \pi_t^{Rg,d}$ are the price of energy and ancillary service products at the hour *t*. h refers to the time period of one hour.

4.3 Results and analysis

Fig.16 shows the time-varying prices of different electricity products (grid services) on a summer day [40]. Using the optimization method based on the objective function described above, the optimal schedules of the building energy system for different services are obtained, as shown in Fig.17.

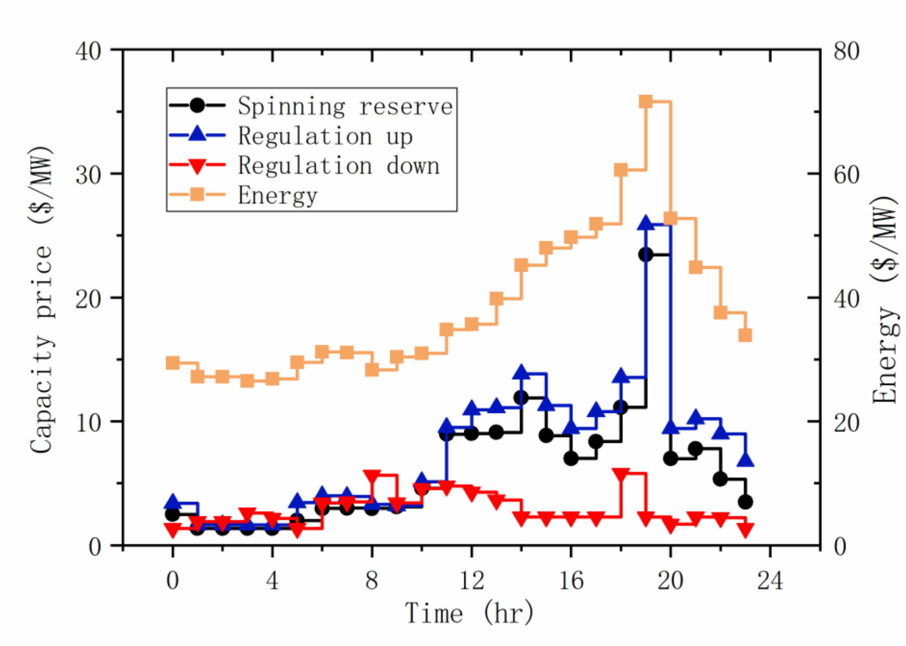
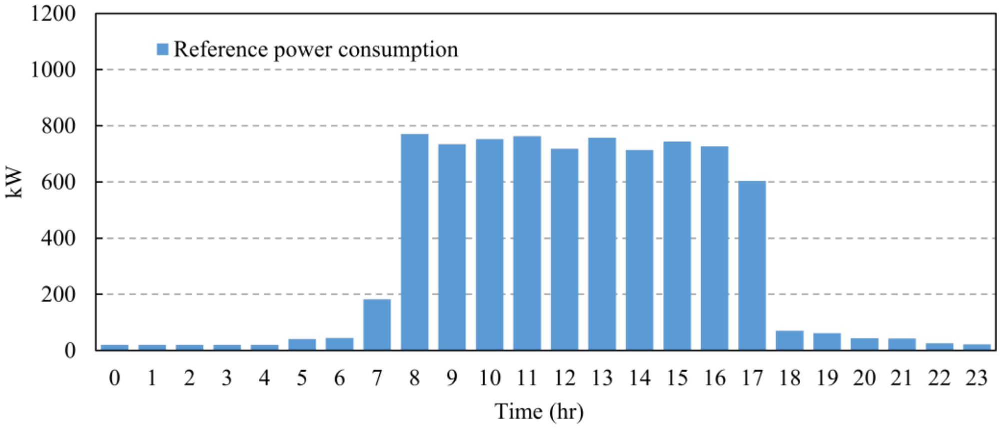
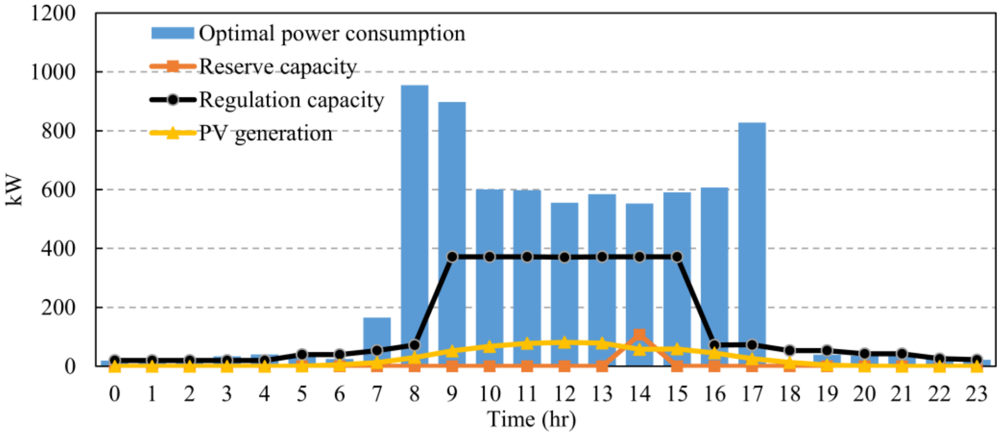


Fig.17. Hourly energy prices and ancillary service revenues from CAISO for July 14, 2017



(a) Reference power consumption in the baseline simulation



(b) The optimal schedules from different services

Fig.18. Hourly power consumption and offered service capacity in the electricity market

Compared with the reference power consumption in the baseline simulation, the final electricity cost of the optimal schedule simulation is reduced from 311 to 243USD, achieving a cost-saving of 21%. 720 kWh of load is shifted according to the time-varying energy prices and 612 kWh (8%) of load reduction is achieved by the load covering flexibility, which reduces the energy cost by 28USD. Since the energy price is lower in the early time of the day, pre-cooling the building thermal mass which is usually used to shift the peak demand in the morning is not economic. The main contributor of load shifting flexibility is the electrical vehicles which are only available during the working hours (8:00- 18:00) in this case. The lighting load is reduced by about 27 kW during 14:00-15:00, due to the highest spinning reserve revenue in this period. It also results in a further reduction of the HVAC system consumption. The building thermal mass as the passive storage is also activated to provide load shedding flexibility. The total contribution of the HVAC system is nearly 80 kW in the same period. It can be observed that the available capacity of the active storage is all allocated to provide FR flexibility instead of load shedding in the ancillary service market. This is mainly because the regulation revenue is higher than the reserve revenue during this shedding period. The optimized power consumption is higher during 17:00-18:00 than in reference, because the revenues stimulate the electrical vehicles to provide reserve capacity for ancillary service before 17:00.

5. Conclusion

This paper proposes a comprehensive quantification framework for building energy flexibility that is grouped into five categories according to grid requirements. The capabilities and efficiencies of proposed flexibility indexes are verified through an implementation case study. The analysis of potential economic benefits from providing different flexibilities to a power grid is also investigated in a real day-ahead electricity market. The main conclusions can be summarized as follows:

- Based on an analysis of various services in electricity markets, the building energy flexibility can be categorized as load covering, load shifting, moderate regulation, load shedding and fast regulation according to the demand response speeds, response duration and response direction to power grids. Two sets of indexes are then proposed to effectively quantify the building energy flexibility at different timescales. Five absolute flexibility capacities indicate the maximum contributions of a building that can be made to the power grid. Five relative flexibilities (i.e., flexibility ratios) indicate flexibility or responsiveness degree of a building that can be used as performance indicators to assess future smart and energy-flexible buildings.

- By increasing power generation and storage capacity, the energy flexibility can be obviously enhanced. Making use of building thermal mass through the control of the HVAC system also has a great contribution to different flexibilities.
- Comparing the optimal scenario with the flexible control and the scenario of the baseline simulation without activating the flexibility sources, the flexibility contributions of sources to different grid services are optimized according to the market prices of the corresponding products. The optimization results show that the costs of the building concerned on the test summer day could be reduced by 21%.

The roles and contribution mechanism of energy-flexible and grid-responsive buildings to smart power grids are demonstrated. In the modern context of smart grids, it is essential to improve the energy flexibility of buildings for the purpose of enhancing the economy and reliability of the entire grid-buildings ecosystem.

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