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Flexibility Categorization, Sources, Capabilities and Technologies for Energy-Flexible and Grid-Responsive Buildings: State-of-The-Art and Future Perspective

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Abstract

The rapid development of remote telemetry, control and communication technologies in smart grids enables the demand side to provide energy flexibility for power grid economy and reliability. The building sector, as a consumer of large amounts of electricity, has various flexible loads that can be effectively utilized for such purposes if buildings and their energy systems are under proper design and control. In this paper, a systematic methodology is proposed for categorizing the building energy flexibility according to different power grid requirements. Considering the requirements of response duration, response direction and response speed (within seconds, minutes, or even longer timescale), the flexibility can be categorized as fast regulation, moderate regulation, load shedding, load shifting and load covering. A comprehensive review is presented to summarize and compare various flexibility sources, their characteristics and capabilities in buildings for providing those five different types of energy flexibility. The analysis of available information technologies and business development indicate great capability and potential of buildings to participate in energy flexibility markets as a practical demand side management instrument. Three major limitations in existing research and energy markets are identified as the major challenges for the future development of energy flexible buildings.

Keywords:

Demand side flexibility, building demand response, energy-flexible building, grid-responsive building, smart grid.

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1. Introduction

1.1 Challenges of power systems and solutions

Global electricity consumption has increased in line with the increasing demand for the improvement of living standards. Electrical power systems are faced with increasing challenges, such as high costs of generation and grid reinforcement, inefficient operation, and balancing and reliability problems [1, 2]. Addressing these challenges will require large investments in deploying more power generation plants and reinforcing transmission and distribution systems [1]. Since demand and supply need to be matched at multiple timescales, the high inertia of conventional generators and the high peak-to-average demand ratio in large interconnected systems makes system operation inefficient and less secure [3, 4]. Although the problem of generation and load mismatch can be managed by the use of load-following reserves, the existing fluctuation in system load during different periods is already creating significant pressure on power grids.

The increasing use of renewable energy has stimulated the transition of the energy consumption structure to a cleaner, more sustainable, and low-carbon state. According to the long-term technology roadmap of the International Energy Agency, renewable energy could represent at least 31% of global electricity production by 2050 [5, 6]. However, the challenges described above are heightened by the growing penetration into the power grid of variable renewable energy (VRE), such as that produced by solar and wind systems. Since these sources of energy are inherently intermittent and uncontrollable, they exacerbate the fluctuation in the net system load (i.e., system load minus renewable generation) [7]. This means that although the installed generation capacity of solar photovoltaic (PV) and wind power plants has grown rapidly [8], their curtailment rates in applications have become another challenge [9].

The approach used to ease these challenges and integrate more VRE into power grids is to enhance the flexibility of the participants in power grids [4]. Here, flexibility is defined as the ability to schedule and leverage resources to satisfy the net system load, while assuming that the other part of the load is served by VRE [10]. Fig. 1 summarizes the multiple sources of energy flexibility and their functions and costs across an entire power system [11, 12]. Where, "+" represents the power regulation up flexibility, including the increase of net power generation from the supply side or the reduction of net load from the demand side. "-" represents the power regulation down flexibility.

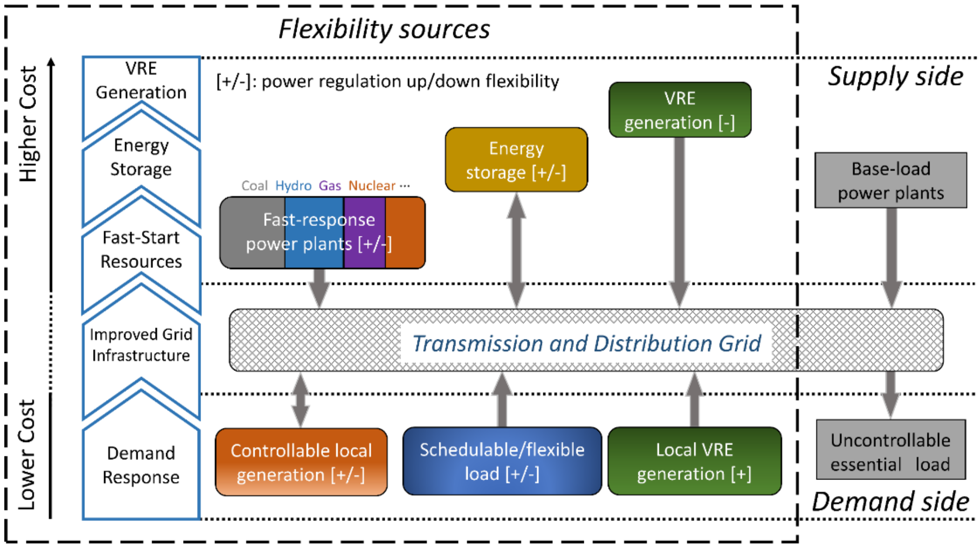


Fig.1. Functions and costs of various flexibility sources in an entire power system

Measures to provide power system flexibility are typically derived from the supply side, exemplified by the responses of various . The roles of power-plant responses include providing back-up capacity and load-following plants [4]. Grid-scale energy storage provides a valuable means to enhance flexibility by shifting the energy generation from times of surplus to times of peak load or by enabling rapid charge/discharge to provide power balancing services. Various energy storage technologies have been developed for this purpose [13], such as hydro pumping, compressed air, flywheels, hydrogen, batteries, and supercapacitors, due to the aim of increasing VRE penetration. As attempts are made to increase the VRE penetration, the curtailment of VRE generation from the supply side is the most inefficient means of increasing flexibility. Moreover, as shown in Fig. 1, the costs of flexible sources vary significantly; energy storage is the most expensive option, and the cost of fast-responding power plants is also high compared with demand responses (DR) [12]. In fact, in recent years, competitive markets, including the wholesale sector and retail sector [14], have been provided for different participants to involve those from both the supply side and demand side. The rapid development of the remote telemetry, and control and communication technologies in smart grids enable the demand side to provide energy flexibility for power grid economics and reliability. Benefits can be obtained by avoiding generation modes that have higher marginal cost and by reducing investments in power-grid infrastructure and reinforcement [15]. Well managed demand side flexibility derived from the schedulable/flexible loads [16] and controllable local generation can improve the coordination and energy management of power grids.

However, most of existing studies related to demand side flexibility focus on overcoming the technical hurdles to achieve this capability, and often ignore a systematical evaluation and the practical utilization of the demand side resources, connecting the full-scale possibilities at demand side with the needs at power grid side. Thus, this paper not only analyze the response characteristics and compare different control methods of various demand side resources (mainly in building energy field) when providing energy flexibility to power grids, but also investigate further challenges for the proliferation and utilization of demand side flexibility.

1.2 Energy flexibility of grid-responsive building

"Demand response" was defined by the Federal Energy Regulatory Commission (FERC) as "changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized" in 2006 [17]. The demand response programs currently available in electricity markets can be grouped into two categories: incentive-based programs and price-based programs [18]. These programs, in which the demand-side is offered some incentives or economic benefits, encourage end-users on the demand side to exploit their flexibility potential.

As the supply and demand sides are required to be matched at multiple timescales during power grid operation, the demand response programs are based on the multiscale market hierarchies. In [19], 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. In this report, the costs and functions of various types of demand response services were compared, and their potential application to the entire CAISO (California Independent System Operator) market was evaluated.

Buildings are one of the largest sectors in terms of power usage and consume more than 70% of total electricity in the United States and 90% in Hong Kong [20-22]. There is thus great potential for the building sector to provide energy flexibility for power grids. Notably, the building sector has more flexible loads that can be used effectively for power grid operation, if the buildings and their energy systems are under proper design and control. This is in contrast to the industry and transportation sector, in which the reduction of loads will unavoidably lead to inconvenience and productivity decline. The variety and performance characteristics of available technologies in buildings means that smartly managing the electricity usage of buildings can achieve demand responses with different response speeds, durations, and directions. Thus, the potential flexibility of buildings warrant exploration for enhancing power grid balance and reliability.

Annex 67 is a joint research programme of IEA focused on building energy flexibility, in which building energy flexibility is defined as “the ability to manage building demand and generation according to local climate conditions, user needs, and energy network requirements (electrical, district heating and gas grids)” [23]. This program has certainly stimulated numerous research programs focused on: *i*) the development of flexibility performance indicators or evaluation for buildings relevant to district heating networks and power grids [24-28]; *ii)* methods for quantification of building energy flexibility [29-34]; *iii)* methods for rating the flexibility performance of buildings [35]. Most proposed control strategies in the literature are tailored to investigate the flexibility potential of buildings considering the building thermal mass or other thermal storages in heating conditions.

If energy flexibility is to be used as an indicator to assess building energy performance, the benefits of energy flexibility at different timescales must be considered. While most existing quantification methods are proposed for only one specific demand response action (e.g., short-term load shedding, load shifting under dynamic power prices).To address this issue, the co-author of this paper has proposed a new concept of a “grid-responsive building,” which emphasizes the importance of considering the building response to multiple needs and requests of smart grids. This enables the effective development of buildings’ contributions to the power grid balance, thus enhancing the reliability of power grids and optimizing the overall efficiency of the grid-building ecosystem [36, 37]. Following this concept, Shan and Wang [38] summarized four types of strategies that could be adopted in the building sector for demand response including demand limiting, demand shedding, demand shifting and on-site generation. Xue and Wang [39] proposed a demand management strategy for commercial buildings that highlighted the significant benefits obtained from the interaction of buildings with smart power grids, if building power characteristics are properly identified and used. “Grid-responsive building” focuses on the effects of building energy flexibility on power grids at multiple timescales. Where, building energy flexibility is defined as the ability to reshape the normal building consumption pattern under various requests from a power grid. In this way, the quality and value of different demand response actions with different response speeds are considered in reference to electricity markets.

However, to our best knowledge, there are still no papers that systematically investigate building energy flexibility with respect to demand response potentials across multiple timescales, and little is known considering both fast and slow interaction between buildings and the smart power grid. Therefore, the main motivation of this research is to categorize the building energy flexibility by conducting a systematic study on the flexibility sources, capabilities and technologies for grid-responsive buildings. This paper also investigate the main information technologies and business development for the practical utilization of building energy flexibility, in order to identify the major challenges for the future development of energy flexibility of buildings.

The rest of the paper is organized as follows. Section 2 presents a comprehensive analysis of the programs and services in the existing electricity markets to determine the typical needs of power grids at different timescales, and five building energy flexibility types are then categorized. In Section 3, the characteristics and control strategies of various flexibility sources in the buildings, their potential contribution to different types of energy flexibility are also summarized. In Section 4, the advanced information technologies and potential business models for utilizing the building energy flexibility are investigated.

2. Needs and requirements of power system on demand side flexibility and categorization of building energy flexibility

"Power system flexibility" is defined as the largest variation that a power system can accommodate. Assessment of power system flexibility commonly considers a set of metrics based on three elements: power ramp-rate capacity (MW/min), power capacity (MW), and energy capacity (MWh) [40]. Taking both operational and economic criteria into consideration, these metrics are affected by the capacity of the responding generation units and the robustness of the electricity markets [12]. Driven by various electricity products or demand response programs in electricity markets, end-users are becoming responsive to pricing and incentives and are beginning to manipulate their loads. The demand side flexibility that is reliant on the operational characteristics of loads is becoming important.

2.1 Overview of the needs of demand side flexibility in existing electricity markets

Fig. 2 summarizes two categories of technologies and programs that can be adopted in demand side management to provide flexibility for power grids: "grid independence support" and "demand response". According to the characteristics of the consumption pattern change required in each category or demand response program, it can be found that their requirements of response speed and response direction are different. For example, some require fast response (with speed of seconds or a few minutes), whereas others require slow response. Some only require load reduction, whereas others require bidirectional load regulation.

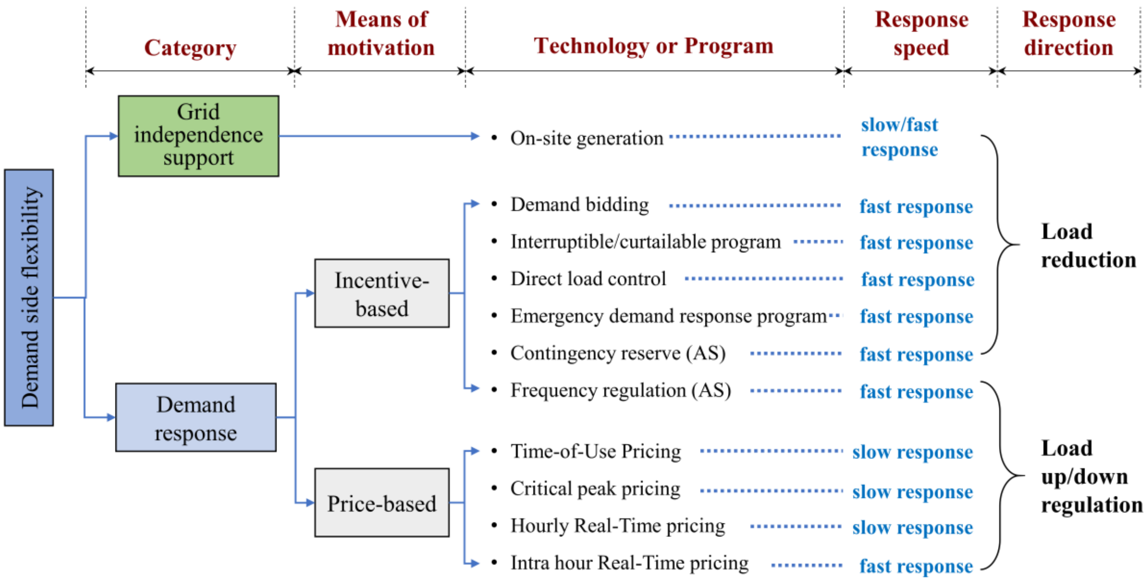


Fig. 2. Overview of demand side flexibility

The prerequisite of "grid independence support" is the power end-users involved in on-site generation, who prefer a higher degree of control over both energy consumption and on-site production [41]. Regardless of whether the form of the system is standalone or semi-standalone, the self-consumption capability of the demand side users reduces their dependence on the power grid and can thus be considered as one type of load reduction flexibility.

"Demand response capability" is more complicated. Since a power grid should be balanced all the time through scheduling energy (kWh) and capacity (kW), various energy products and capacity products (or ancillary services) are introduced as the major electricity commodities in modern electricity markets [42, 43]. During operation, energy scheduling is the primary method used in most situations to ensure economic efficiency. Capacity scheduling, as exemplified by ancillary services (AS), is focused on the use of short-term dispatch to maintain the reliability of a power grid [42]. These operation and dispatch principles of power grids introduce two categories of demand response programs that are currently offered to commercial and residential consumers: price-based and incentive-based programs.

In the price-based programs, customers are encouraged to change their normal demand profiles considering the electricity pricing variation during a 1-day period typically [18]. Different types of pricing require different speeds of demand responses. In the time-of-use (TOU) program, electricity pricing is specified during each time interval, which is usually at least one hour. Critical Peak Pricing (CPP) is similar to TOU but with much higher critical peak prices. The price schedules in these two pricing programs do not change frequently where the slow response of demand side can make contribution, and thus customers can easily determine how to shift their power consumption from the peak price hour to a lower price hour to lower their electricity costs [44]. However, in real-time pricing (RTP) programs, the price continually changes because it is determined by the real-time operation of power grids. In "hourly RTP" programs, the electricity price of each hour might be settled one day or a few hours in advance. In "intra-hour RTP" programs, the interval of the electricity price is much shorter (e.g., less than 1 hour) and might be settled a much shorter time in advance. For example, the high-granularity intra-hour RTP at 5-minute and 15-minute intervals are commonly used in many North American markets (such as Pennsylvania, New Jersey, and Maryland [PJM] [45], the California Independent System Operator [CAISO] [46], and the Electric Reliability Council of Texas [ERCOT] [47]). In this situation, customers must engage in real-time and intensive interactions with the power grid and manipulate demands with fast response speed to follow the instantaneous price signal from the market. The participation of the demand side in these price-based programs is reflected in the form of load regulation up and down.

In incentive-based programs, customers usually receive incentives from electricity utilities for their effective participation in the market [18]. Most of these programs are activated as the reserve capacity in contingency situations to prevent generation or grid failures [48]. Detailed information on each program can be found in [18, 38], such as "how they sign contracts with electricity utilities, whether the load curtailment is voluntary or mandatory, whether the customers will be punished if they do not curtail load". Conventional incentive-based programs, such as "Demand bidding", "Interruptible/curtailable programs", "Emergency programs", "Direct load control" are commonly adopted in demand side management. While, the responsive demand participating in ancillary service is still rarely considered in building energy field [37]. Notably, most incentive-based programs rely on requests for short-term load reduction and response within a few minutes, except for "frequency regulation". Frequency regulation requires bidirectional load regulation at intervals of seconds to avoid short-term unbalancing or frequency deviation of power grids. Qualification rules for contingency reserves and frequency regulation for demand response are well established in some electricity markets [49]. Since the time interval of frequency regulation signal might be seconds [37], utilizing the flexible loads to provide this service in the market is of the highest requirements concerning the response speed.

2.2 Flexibility requirements and classification in building demand management

As discussed in Section 2.1, miscellaneous demand response programs in different electricity markets indicate that the flexibility requirements of power grids on demand side can be reflected in different timescales fundamentally. A comprehensive analysis of the buildings and various building energy systems including their characteristics in operation reveals that building energy flexibility can be categorized into five types, based on *response speed, duration, and direction* for typical application scenarios and programs in electricity markets, as shown in Table 1. The demand baseline of a building is the fundamental information (i.e., normal demand pattern in the absence of flexibility measures) as the reference when quantifying the flexibility provided by the building side. Considering the response speed and the response duration from seconds, minutes, or even longer time scale, the flexibility can be categorized as *fast regulation, moderate regulation, load shedding, load shifting, load covering*.

Fig. 3 presents an overall comparison of the baseline and the load pattern of each flexibility type. The market-based services provide opportunities for buildings to reduce energy costs or earn revenues by smartly managing their flexible demands or changing their power use patterns. Although not all of these flexibilities can currently be directly used by power grids, they could be used in near-future markets by building-system operators or grid operators to provide flexibility services. The mechanisms of the five energy flexibilities listed above are elaborated as follows.

Table 1. Building energy flexibility categories and requirements

Market-based service	**Response speed**	**Response duration**	**Response direction**	**Flexibility type**
Frequency regulation (AS)	Seconds (fast)	Continuous	Up/down load regulation	Fast regulation (kW)
5/15-minute RTP	5-minute/15-minute (fast)	Continuous	Up/down load regulation	Moderate regulation (kWh)
Contingency reserve (AS); Conventional incentive-based DR	≤ Minutes (fast)	Minutes ~ hours	Load reduction	Load shedding (kW)
Day-ahead hourly price; TOU; CPP	Hour (slow)	Continuous	Up/down load regulation	Load shifting (kWh)

Grid independence support	-	Continuous	Load reduction	Load covering (kWh)

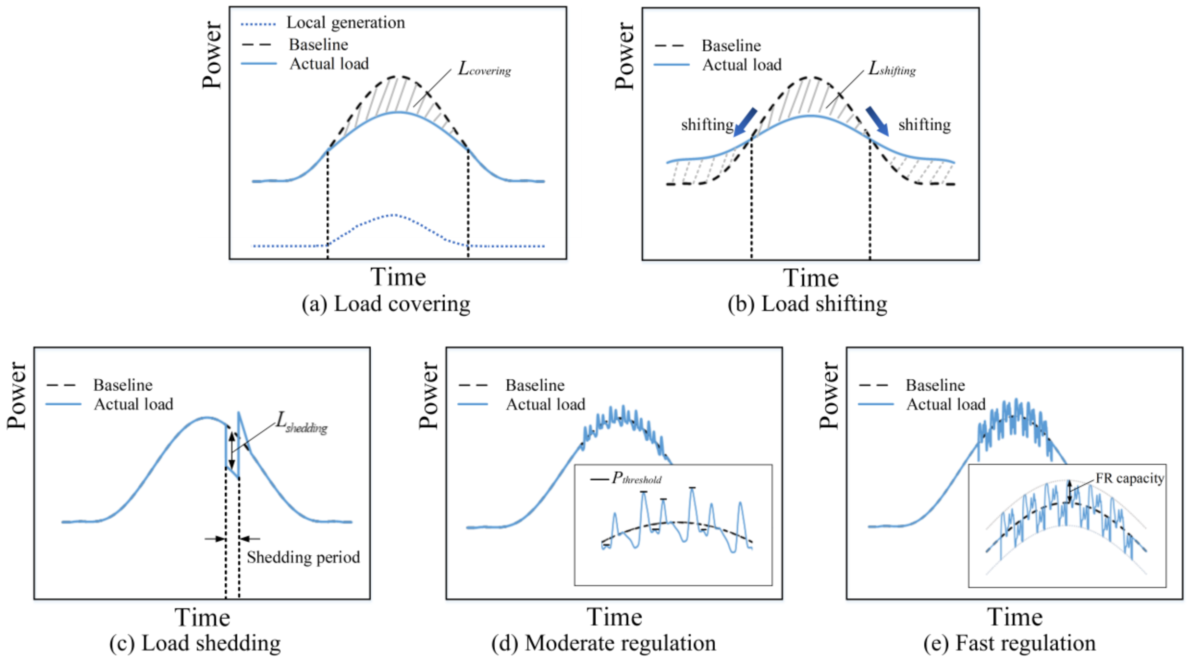


Fig. 3. Comparison of load patterns between baseline and each flexibility type

"Fast regulation" refers to the bidirectional load regulation of buildings within seconds in response to power grids. The flexible loads of buildings qualified for such service have the potentials to provide frequency regulation capacity in ancillary service market considered as the fastest responsive flexibility.

"Moderate regulation" refers to load regulation within minutes which is a little slower than fast regulation. It is a promising tool in the application scenarios of existing electricity pricing settled within a timescale interval of minutes, such as 5-minute or 15-minute RTP. This means that load regulation at the timescale of minutes is valuable for power grid economy and reliability.

"Load shedding" refers to the fast load curtailment of buildings during a limited and a short period of time in response to an urgent request from a power grid, usually in the context of a contingency event. This type of flexibility can be utilized in conventional incentive-based DR or utilized as reserve capacity in ancillary service. In this way, the power system reliability can be guaranteed even if there is a sudden supply shortage.

"Load shifting" refers to the flexibility type that shifts the loads of building from peak time to valley time over hours, in the form of dispatchable resources. The peak and valley time are determined by referring to the price signal (e.g., TOU, CPP, and hourly RTP) that reflects the

daily flexibility requirements of power grids). This flexibility reshapes the daily load profile of a building by smartly controlling the deferrable loads and energy storage systems in the context of cost-optimal control or other optimization objectives.

"Load covering" is also considered as a type of energy flexibility, although it is not a true or classical flexibility that contributes to the grid power balance. It concerns the long-term load reduction, also considered as a type of building flexibility performance. It refers to the on-site generation capability of a building, which can satisfy part of the building load. The deployment of on-site generations makes the building act as a "prosumer" (producer and consumer) in the connected power grid. The resulting reduction of the total net electricity imported from the grid can alleviate the transmission congestion, improve the reliability of the power system, and minimize extra investment costs for grid reinforcement by supporting grid independence.

3. Sources, characteristics and capabilities for building energy flexibility

A great number of sources or measures can be deployed and utilized to improve the building energy flexibility for the requirements of the power grid at multiple timescales. The feasibility and benefits of grid economic and frequency stabilization can be achieved through the energy flexibility control. Building energy flexibility can come from managing the direct electricity net loads and the thermal loads. When the direct electrical energy is concerned, the flexibility comes from managing the on-site generation, directly changing the schedule of electricity usage or charging/discharging the electrical energy storage. When the thermal energy is concerned, the flexibility comes from the use of passive thermal storage capacity of building structure or charging/discharging active thermal storage.

This section summarizes the sources of building energy flexibility and their characteristics and contributions to five flexibility types under different control strategies. The information technologies for effective communication between buildings and smart power grids are also discussed. As shown in Fig. 4, the sources to improve the flexibility include building on-site generations, the electrical storage, the thermal storage, on/off and dimming control of lighting systems, on/off and variable frequency control of the components in heating, ventilation and air-conditioning (HVAC) systems (e.g., chillers, fans and pumps), and postponable appliances (e.g., washing machines, dishwashers, electrical vehicles). Table 2 presents the main contributing sources to five flexibility types. The details regarding the contributions of these technologies to multiple flexibility types under various control strategies are described as follows.

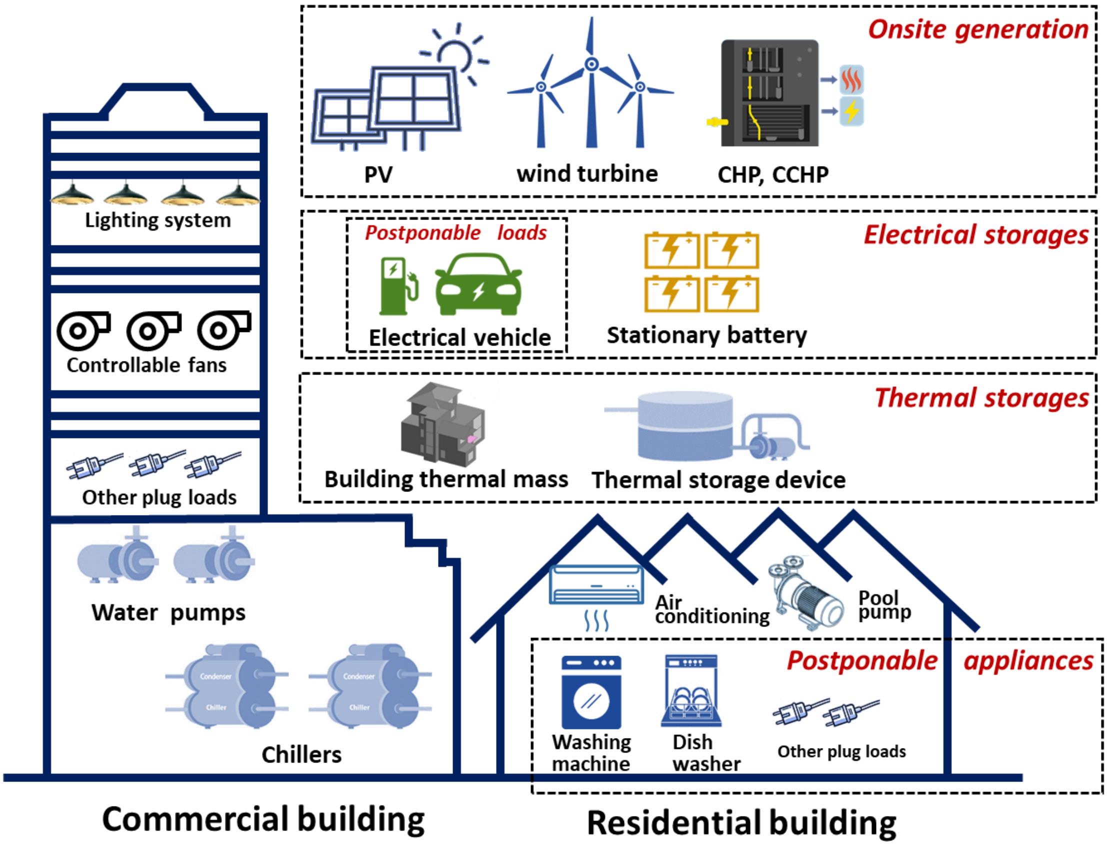


Fig.4. Flexibility sources in commercial and residential buildings

Table 2. Technologies for providing each type of flexibility

Flexibility types	**Response speed**	**Response direction**	**Technology (Flexibility sources)**
Fast regulation	Seconds (fast)	Up/down load regulation	CHP/ CCHP, battery, electrical vehicle, variable frequency driver, dimmable control of lighting systems
Moderate regulation	5-minute/15-minute (fast)	Up/down load regulation	CHP/ CCHP, battery, electrical vehicle, on/off and frequency control of residential air-conditioning
Load shedding	≤ Minutes (fast)	Load reduction	CHP/CCHP, HVAC system (thermal storage), battery, electrical vehicle, on/off and dimmable control of the lighting systems
Load shifting	Hour (slow)	Up/down load regulation	Battery, electrical vehicle, HVAC system (thermal storage), postponable appliances
Load covering	-	Load reduction	CHP/ CCHP, renewable on-site generation

3.1 Building on-site generations

Renewable generations (e.g., solar PV, wind turbine) and small-scale controllable generation plants (e.g., combined heating and power [CHP] and combined cooling heating and power

[CCHP]) are the two major categories of technologies, which are popularly adopted for applications in the building sector [50, 51]. Regardless of whether the on-site generations deliver electricity only (solar PV, wind turbine) or both electricity and thermal energy (CHP, CCHP), building loads can be covered partially or even fully by self-generated energy which greatly reduces the building net demand imported from the power grid and facilitates the building with load covering flexibility. These technologies can reduce the energy losses of the power transmission and distribution grid [52], and can also enhance the reliability and reduce the emission of micro-grids. The contributions of these technologies to different energy flexibilities are summarized and elaborated as follows.

3.1.1 Buildings integrated renewable generations

Implementing renewable generations such as PV and wind turbines at the building scale has great benefits in the sustainable development of environment and net load reduction of buildings. Micro wind turbines are often installed on building rooftops, and PV panels can be installed on the building envelopes (e.g., roof, façade, and glazing). The application of these technologies has grown rapidly in recent years.

Many indicators have been proposed for assessing and quantifying the load covering performance of building integrated on-site renewable generations, among which, "*Load match index*" [53, 54], "*Self-coverage*" [55], "*Self-consumption factor*" [56, 57], "*Solar fraction*" [58] are defined as the ratio of the matched (or provided) load to the overall load of the building. As solar and wind generations are intermittent and heavily dependent on the weather condition, many studies have been conducted focusing on the improvement of load covering flexibility of buildings by managing the shiftable loads [56], thermal storage [59], and electrical storage [60]. Also for building clusters, by optimizing the electrical storage and the PV energy sharing, Huang et al. [61] developed a coordinated control for improving the load covering performance of a building cluster. Load shifting can effectively improve the load covering performance of the building in some cases.

3.1.2 Buildings integrated CHP/CCHP

Unlike on-site renewable generations which are dependent on the weather condition, the generation of CHP/CCHP can be better controlled. CHP/CCHP can provide the electrical flexibility at short timescale through the real-time operation adjustment in response to changes in heat and electricity demands. This is achieved by adjusting the pressure regulators (reduction valves) of the turbine steam bypass to rapidly change heat and power generation within seconds or minutes [62, 63]. In this context, CHP/CCHP not only provides load covering flexibility but also enables short-term adjustment (i.e., fast regulation of electricity generation) can also act as the flexibility sources of load shedding, moderate regulation and fast regulation when the constraints of heat demand are loose.

Numerous studies have been conducted to investigate the operational flexibility of CHP/CCHP with different response speeds in electricity markets. With a focus on hourly response, Wang et al. [64] proposed a two-stage optimal dispatch model for CHP that considers the day-ahead hourly electricity price and the hourly power deviation between real-time net demand and forecasted net demand. With a temporal resolution of fifteen minutes, Dietmar et al. [65] examined the potential of an on-site CHP system in both residential buildings and non-residential buildings to provide the balancing power for the connected power grids and to participate in the minutes reserve market. They also found that the balancing power market would involve shorter time slices, shorter announcement terms or smaller minimum bids to enhance the operational flexibility of CHP especially when the heating demand is quite low. Considering the potential energy flexibility of the CHP system in the context of various demand response programs, Mattia et al. [66] indicated that adjusting the output of CHP generation can substitute for fast curtailing the direct loads of the building during the demand response period. Thus, load shedding flexibility can be provided by a CHP system, because the electric power demand imported from the power grid can be reduced rapidly. Mattia et al. also analyzed the economic benefits of a CHP system in an RTP program through a case study of a commercial building.

3.2 Electrical energy storage systems

Electrical energy storage (EES) systems are integrated into different levels of all modern power systems to realize various economic and environmental benefits [67]. These technologies convert the electricity into a storable form and store it temporarily for later use. The increasing market-share of plug-in electrical vehicles and the application of stationary battery systems in buildings bring about far-reaching effects on building demand and building energy flexibility [68]. Both technologies can substantially enhance the demand flexibility with multiple attractive functions as demand shifting, peak load shaving, energy management and system reliability [69]. The following three subsections present a comprehensive review of the technical potentials, economic benefits and controllability of electrical storage systems contributing to five flexibilities (i.e., load covering, load shifting, load shedding, moderate regulation and fast regulation).

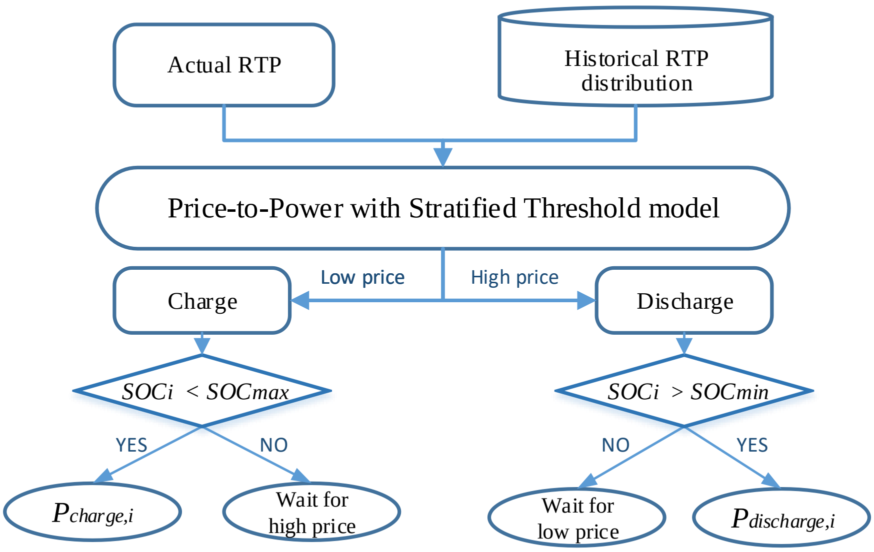
3.2.1 Enhancement of load covering and load shifting flexibility

When on-site small-scale renewable generations are installed in buildings, EESs can be used to avoid wasting surplus renewable energy, and to reduce diurnal demand fluctuation [70]. From the perspectives of building operators and grid operators, building electrical storage leads to greater use of the energy infrastructure and provides greater flexibility for the management of intermittent renewable generations [71]. Several statistical and economic analyses of the effects of battery systems on self-consumption (i.e., load covering) enhancement have been conducted [57, 72-78]. Luthander et al. [57] showed that the relative self-consumption rate can be increased by 13% to 24% with a battery storage capacity of 0.5 to 1 kWh per kWp of installed PV panel. An example reported by Kempener and Borden [77] showed that the installation of a 4-kWh battery with a 5-kWp PV panel can increase a building's self-consumption from 30% to 60%. Munkhammar et al. [79] investigated the coincidence between household load with respect to electrical vehicle (EV) charging and PV generation at the individual level and the aggregate household level. Their results showed that EV can effectively increase buildings' self-consumption, with efficiency being highly dependent on the coincidence between EV charging and PV generation. Thus, as batteries can store surplus renewable energy for later use, they can improve buildings' load covering performance.

Besides the load covering, optimizing the discharging/charging process of electrical storage can substantially smooth load fluctuations and effectively achieve economic benefits through load shifting, as reported by Han et al. [80] and López et al. [81]. Phan et al. [82] also proposed an economically optimized schedule for battery use over a 24-hour period considering variable building load and intermittent renewable energy and found that an average daily cost savings of 28% to 31% could be achieved by using battery to shift the loads. A novel model predictive control (MPC) method was developed by Wei et al. [83] to optimize coordination of EV charging, battery usage and other loads to shift demand from peak to off-peak hours. Their experimental analysis revealed that a significant reduction in electricity cost could be achieved while maintaining the occupancy comfort. Wu et al. [84] defined three operation modes of EV (i.e., vehicle-to-grid, vehicle-to-home, and grid-to-vehicle) by considering the time-varying building power demand and hourly electricity price, and showed that economic benefits can be achieved by shifting the charging load of EVs to off-peak period. As community energy storages for demand shifting becomes an attractive research topic, Parra et al. [85] conducted a study based on the simulation of a 100-home community integrated with batteries considering equivalent full cycles and round-trip efficiency of batteries. They also quantified the economic benefits from demand shifting under two different pricings. The results of their study showed that pricing plays an important role in capacity optimization and technology selection of batteries.

3.2.2 Contribution to moderate regulation flexibility

Electrical storage can also enable the buildings to participate in RTP (Real-Time Pricing) markets due to their ability to rapidly regulate the electricity usage. Although the flexibility control (i.e., energy dispatch) of a battery in response to 5-min/15-min RTP, and how this enables moderate regulation flexibility, has yet to be examined, it is obvious that the batteries' response speed will allow them to be applied for this purpose. Fig. 5 illustrates the mechanism by which batteries provide moderate regulation for a utility grid. The distribution of RTP generated by the historical RTP database is used as the reference scenario to estimate the price level of the actual RTP received by buildings. In this control scheme, a price-to-power threshold model must be formulated. When the actual RTP is high, a low threshold will be used for the building power use, meaning that the battery system might be in the discharging state if $SOC_i > SOC_{min}$. Otherwise, the battery system needs to wait another low RTP signal for being charged.



* SOC_i: state of charge of the battery at time *i*.

Fig.5. Flowchart of real-time operation of battery storage with response to RTP

3.2.3 Contribution to load shedding and fast regulation flexibility

Batteries can perform even better compared with conventional generators in providing energy flexibility with fast response speed. The building demand power imported from the grid can be fast reduced by discharging batteries continuously during the period when load shedding is required in buildings. Reserve capacity (kW) can be provided by activating the unused capacity of batteries as the "active power" of a grid within a short timescale for a specified period of time. Batteries can also provide frequency regulation (kW) services by regulated the discharging/charging rate to follow automatic generation control (AGC) signals [86, 87]. This can be considered as the fast regulation flexibility of buildings if integrated with batteries.

Numerous studies have investigated the potential economic benefits of the stationary batteries concerning different flexibilities of slow and fast response speeds. At the grid-scale, Dowling et al. [88] evaluated the revenue potential of the batteries in a joint market, including energy products (load shifting), spinning reserve service (load shedding) and frequency regulation service (fast regulation). They investigated the market opportunities of batteries as flexibility providers under real-time operation. At the building-scale, Mariaud et al. [73] investigated the revenue potential of a battery system in a commercial building to provide frequency response (i.e., fast regulation capacity), given the small state-of-charge fluctuation of state-of-charge of batteries. A real-time operation model was proposed by He et al. [89], who used it to simulate the dynamics of a battery system coupled with wind generation under an optimal bidding strategy in joint energy and regulation markets. Their simulation results showed that the revenue of battery systems from fast regulation flexibility could reach 12% of the total income. By considering the capacity, efficiency and degradation of batteries, Liu et al. [90] conducted a case study to verify the economic potential of coordinated operation of distributed batteries, based on the performance-based regulation (PBR) mechanism in the PJM regulation market. The results showed that the profit of batteries would decrease by 25% without PBR mechanism.

Electrical vehicle (EV) technology has been a hot topic in recent years. Sarabi et al. [91] assessed the potential use of EV technology to provide a fast response. They modeled the availability uncertainty of electrical vehicles and considered localization limitation in the electricity market. Shi et al. [92] proposed a novel trading model to optimize the reserve capacity of EVs and supply side generation in an electricity market. They considered both risk cost and purchase cost and found that EVs can substitute for the reserve capacity from supply side if the price and reliability conditions are the same. Many studies have also been conducted to examine the technical issues of control and economic potential of EVs in electricity markets [93-95]. Tan et al.[96] conducted a comprehensive review of EV technology from the perspective of grid service, challenges and optimization techniques.

As both stationary batteries and EVs can provide all the five energy flexibilities to electricity markets, the management of their discharging and charging schedule is an important and complicated problem that affects the value of these services. Consequently, optimization techniques are essential for the integration of buildings with electrical storage.

3.3 Heating, ventilation and air conditioning (HVAC) systems

HVAC systems, as the largest energy consumer in the building, can achieve great environmental and economic benefits through different control strategies in demand side management [97, 98]. As the building thermal mass (BTM) (i.e., passive thermal storage) can be considered as a natural source of flexibility and the active thermal energy storage (ATES) systems are often implemented in buildings, smart controls of HVAC systems can effectively provide energy flexibility [32]. In the following four subsections, a comprehensive summary is given of the potential uses and associated controls of HVAC systems, in terms of their technical controllability and the economic benefits derived from their contribution to the five flexibilities mentioned above.

3.3.1 Enhancement of load covering and load shifting flexibility

Both passive and active thermal storage systems can be used to store thermal energy in buildings for later use. Due to the power-to-heat mechanism and system dynamics of HVAC systems, charging/discharging the thermal storage systems can indirectly shift the electricity demand in response to the power grid. The potential load shifting flexibility of HVAC systems can also enhance the load covering flexibility of the buildings integrated with on-site energy generation. Table 3 presents a list of the studies on load shifting potential and load covering enhancement of the HVAC systems. System configurations, storage techniques, and control strategies are listed. The associated flexibility performance and main results are also summarized.

Table 3. Load covering enhancement and load shifting flexibility provided by HVAC system

Flexibility performance	System configurations and storage techniques	Method of study	Control variables concerned	Main results
Load covering enhancement and load shifting	PV system, HVAC units and BTM	Simulation	Indoor temperature set-point [99]; Indoor temperature set-point, fan speed[100]	The annual load covering factor was improved by 1.7%- 4.4% [99]. The total improvement score (considering energy cost and thermal comfort) was 27%-36% [100].
	PV system, heat pump and ATES	Simulation	ATES tank set-point [97, 101, 102]	Improved performance of self-consumption (i.e., load covering); Electricity cost reduction
	CHP system, heat pump and ATES	simulation	ATES tank set-point [32]	The use of TES flexibility can increase the self-supply (i.e., load covering) of a building.

Load shifting	HVAC units and BTM	Simulation	Pre-cooling: indoor temperature set-point [103-107]; Pre-heating [108]	Minimal effect on indoor thermal comfort; peak load shifted to off-peak times
	Chiller and BTM	Simulation and experiment	Pre-cooling: indoor temperature set-point [109-112]	Pre-cooling strategies effectively reduced the peak demand; simulation data and field data matched well.
	Heat pumps and BTM	Simulation	Indoor temperature set-point (±2 K) [113]	The electricity bill can be reduced by 3%-10% under different scenarios of energy shifting.
	HVAC units and ATES	Simulation	ATES tank set-point [114, 115]	Peak load shifting and cost-saving are achieved under dynamic electricity pricing
	Chiller, ATES and BTM	Simulation	Simultaneously control the ATES tank set-point and indoor temperature set-point [116]	Electricity cost-saving of up 5% achieved by shifting the peak load.

The pre-cooling/heating of buildings by making use of their passive storage is commonly adopted, which can be used to provide the load shifting flexibility. Fig.6 shows a typical pre-cooling control strategy [117]. When charging cooling in building thermal mass, the temperature set-point during the unoccupied period can be slightly lower than the occupied period. In some Nordic countries, pre-heating is commonly adopted. In this context, Nyholm et al. [108] investigated the load shifting potential of electrical space-heating systems by optimizing the pre-heating time and duration of the system operation. Their results showed that peak-load shifting of 5.5 GW could be achieved in Sweden, based on current Swedish electricity prices.

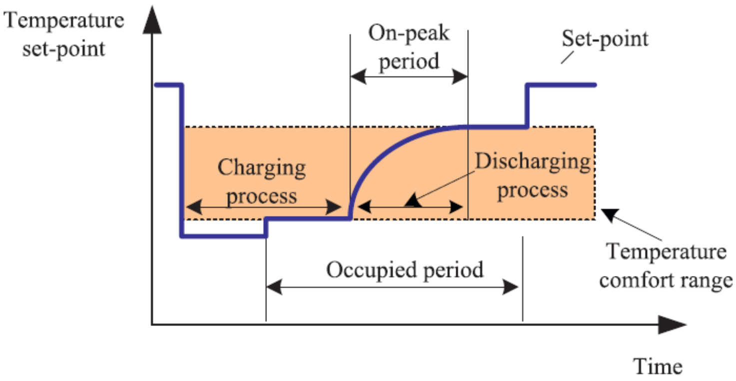


Fig.6. Typical pre-cooling strategy using building thermal mass

Optimizing the time and discharging/charging rate of ATES is essential in providing load shifting flexibility. By shifting the cooling/heating load from on-peak periods to off-peak periods, buildings can benefit from dynamic electricity pricing (e.g., TOU, hourly RTP) [117]. Several studies have been carried out on load shifting flexibility of ATES under hourly dynamic electricity pricing or peak demand shifting control. Arteconi et al. [114] reported that the indoor temperature can still be in good control and the electricity bill can be reduced in TOU pricing, by switching off the heat pump and discharging the ATES during peak hours. Alimohammadisagvand et al. [115] analyzed the performance of load shifting flexibility for a heat pump coupled with a stratified storage tank considering different temperature set-points and tank sizes, and reported that, by adopting optimization, the maximum annual cost saving can be achieved to 10%.

3.3.2 Contribution to load shedding flexibility

Discharging thermal energy storage to maintain an acceptable indoor temperature during a fast demand response (urgent load reduction) period is also an effective means of load shedding, since a certain proportion of the power demand of HVAC systems can be fast curtailed. Table 4 presents the control methods for HVAC systems, available in literature, to achieve the load shedding flexibility with fast response speed.

Table 4. Overview of studies on load shedding flexibility provided by HVAC systems

System configuration and storage technique	Method and focus	Control variables concerned	Main results
Chillers and BTM	Experiment Response speed	Shutting down/cycling the chillers	22% to 37% of a total building load can be shed within 12 to 60s between the shedding signal (the switching off) and the final load curtailment [118]; Compressors can respond within 60s and reach full shedding capacity within 6min [119].
Chillers and BTM	Simulation Response speed	Zone air dry-bulb temperature, Supply air temperature, Chilled water temperature, Duct static pressure.	Each of these methods performed well in 10-minute load shedding scenarios [120].
Chillers and BTM	Simulation Disorder problems	Shutting down the chillers, Chilled water flow, Airflow for each zone.	Avoid uneven cooling distribution, excessive speeding of fans and pumps during the shedding period [121].
Chillers and BTM	Simulation Shedding potential	Zone air dry-bulb temperature, Supply air temperature, Chilled water temperature, Condenser water temperature.	23%-47% of the cooling demand can be reduced depending on the desired limit of occupant comfort [122].
HVAC units and BTM	Simulation Shedding potential	Indoor air temperature setpoint (+2K)	Hourly load shedding potential of HVAC system was obtained using the developed regression building thermal model [104].
Chiller and BTM	Simulation Shedding potential	Indoor air temperature setpoint (+1K, +2K, +3K)	All HVAC systems can provide 68.7% to 82.4% of the total reserve capacity for Hong Kong grid during urgent events [37].
Chiller and ATES	Simulation Indoor comfort	Chiller power demand, Cooling discharging rate of the storage	Proposed model predictive control strategy can achieve the expected load shedding capacity and guarantee the indoor thermal comfort [123].

The simplest and most common control method for load shedding is to directly shut down some operating equipment (e.g., chillers, air-conditioning units). As reported by Kirby et al. [118], directly switching off air-conditioners has a time lag of 12 to 60 s between the shedding signal (the switching off) and the final load curtailment. Bode et al. [119] also conducted a series of demonstration studies and found that both shutting down or cycling compressors can respond within 60 seconds and reach full capacity within 6 minutes after receiving the load shedding signal. To solve the disorder problems (e.g., uneven cooling distribution, excessive speeding of fans and pumps) that may occur by simply shutting down the chillers, Wang and Tang [121] proposed a supply-based feedback control strategy based on an adaptive utility function that resetting the chilled water flow and airflow for each individual zone with the use of global and local cooling distributors. They also proposed a model predictive control strategy for HVAC system integrated with an active cooling storage system to provide fast load shedding capacity [123]. Other control strategies have also been proposed, such as the adjustment of zone air dry-bulb temperature, duct static pressure, supply air temperature, and chilled water temperature in the HVAC system. The simulation results of Blum and Norford [120] showed that each of these methods performed well in 10-minute load shedding scenarios. A few studies have been performed on the quantification methods of load shedding capacity provided by HVAC systems of buildings, which can be labeled as short-term curtailment [122], peak load shed [104], spinning reserve [37].

3.3.3 Contribution to moderate regulation flexibility

Variable-speed air conditioning devices can provide moderate regulation flexibility by effectively responding to the high-granularity RTP (real-time pricing) signals. Yoon et al. [124] developed a dynamic demand response controller that considered both indoor thermal comfort and the 15-min RTP. The results showed that by resetting the controlled thermostat within 1 K of the temperature change based on the preset price threshold, the thermal load reduction/increase of air conditioning systems can be quantified, and the demand response potential can be estimated. However, the change of indoor air temperature is too slow to track the change request of the power use according to higher granularity RTPs. Thus, Hu et al. [125] developed a frequency-based control method for a variable-speed air-conditioner in response to 5-minute RTP. A proportional–integral–derivative (PID) controller was used to modulate the compressor speed which is adjusted according to the difference between real-time and historical electricity prices. Direct frequency control of air-conditioning devices thus enables moderate regulation flexibility.

3.3.4 Contribution to fast regulation flexibility

Many devices in HVAC systems are capable of variable speeds and of high-quality frequency regulation that enhances the fast regulation flexibility of buildings for power grids. The thermal energy supply variation caused by the fast regulation of these variable speed devices in HVAC systems can be compensated by using building thermal mass, which is a natural source of flexibility.

Table 5. Overview of studies on fast regulation flexibility provided by HVAC system

Method	Controlled components	Control variables concerned	Main results
Simulation	Variable speed fan + pump + chiller	Static pressure of supply duct, Indoor air temperature.	The fast regulation response of the whole HVAC system is accurate and on time which can meet the electricity market requirement [126].
	Variable speed fan + chiller	Indoor air temperature	A three-layer control scheme was proposed and tested to maximize the electrical flexibility of a full HVAC system [127].
		Static pressure of supply duct, Indoor temperature setpoint, Discharge air temperature, Outside air fraction.	HVAC system could provide fast regulation capacity with high performance similar to the tested batteries and flywheels [128].
	Variable speed fan	Frequency of the fan	15% of the total fan power can be used for fast regulation [129].
	Variable speed water pump	Frequency of the pump	Variable speed pump can provide fast regulation flexibility without impacting the thermal comfort [130].
Experiment	Variable speed fan	Static pressure of supply duct	Variable speed fans can provide at least 4GW fast regulation flexibility capacity in the US [131].
		Fan speed	HVAC fan can provide fast regulation flexibility without impacting the thermal comfort [132].
			Fan speed control for fast regulation is accurate and reliable and a hierarchical control is proper for day-ahead regulation capacity bid in the market [133, 134].
	Variable speed heat pump (VSHP)	Supply water temperature	A direct load control enabled VSHP based on a data-driven dynamic model can actively and fast regulate the power consumption [135].
	Variable speed supply fan+ compressor + condenser fan	Discharge air temperature	A pseudo-optimization was used to maximize the hourly fast regulation capacity of for a rooftop unit [136].
	Variable speed water pump	Frequency of the pump	Variable speed pumps can rapidly follow the regulation signal with satisfactory quality [137].

Various control methods shown in Table 5 have been proposed to achieve fast regulation flexibility, such as resetting the static pressure of supply fans/supply ducts [126, 131], resetting the indoor air temperature [126, 127], resetting discharge air temperature and controlling the outside air fraction [128], resetting the supply water temperature [135] to modulate the power consumption of the whole HVAC system (including fans, pumps and chillers). Cai and Braun [136] proposed a regulation capacity reset strategy for a rooftop unit with a variable speed supply fan, a variable speed compressor, and a variable speed condenser fan. The results of the simulation and laboratory validation showed that providing frequency regulation service (i.e., fast regulation flexibility) in the electricity market can have significant economic benefits (12% to 26% cost reductions for buildings).

In some complicated commercial HVAC systems, it is critical to use the above-mentioned means to achieve fast regulation as expected, due to large time constant resulted from the feedback control mechanism of the systems. Such indirect frequency control of variable speed chillers and other variable speed devices might not achieve great regulation capability and acceptable performance score due to the counteraction effects and delay of a dynamic system with feedback control. For example, Kim et al. [135] proposed a method to reset the supply water temperature of a variable-speed heat pump to provide frequency regulation service, but the reported composite performance scores only meet the minimum requirement in PJM market.

Instead of indirect control, direct frequency control of variable speed fans [129, 132, 134, 138] and pumps [130, 137] can effectively provide fast regulation flexibility with much smaller time constants (typically in seconds). These methods can more accurately track and respond to the regulation signal in the order of seconds by directly controlling the frequency. Hao et al. [129] reported that 15% of the rated power of an HVAC fan can be utilized to provide frequency regulation service (i.e., fast regulation flexibility) with a negligible influence on the indoor thermal comfort. Wang et al. [37] developed a method by using practical operation data to quantify the potential frequency regulation capacity of HVAC fans for non-residential building in Hong Kong, and reported that half of the required frequency regulation capacity of the power grid can be provided by HVAC fans in non-residential buildings.

3.4 Postponable electrical appliances

As residential electrical appliances can be scheduled automatically and coordinated with a smart home energy management system, the flexible usage patterns of some postponable appliances such as washing machines, dishwashers, tumble dryers can be utilized to provide load shifting flexibility by postponing and scheduling the starting time. When residential buildings involve on-site generations such as PV panels, load covering flexibility can also be enhanced.

D'hulst et al. [139] first proposed the concept of *"flexibility window"* for postponable residential electrical appliances. In a smart configuration, occupants can set the earliest starting time and a deadline for the use of electrical appliances which compose the flexible time-window via a home energy management system. 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 the maximum, meaning that the total energy use of these appliances can be shifted. The shifting flexibility capacity ($L_{sf,pa}$) of postponable appliances can be defined as the function of their power input (P_{pa}), working hours, and the flexible time-window, shown in Eq.(1).

$$L_{sf,pa} = P_{pa} \cdot \Delta t \qquad \Delta t = \begin{cases} 0 & wh = tw \\ tw - wh & wh < tw < 2wh \\ wh & tw \geq 2wh \end{cases} \tag{1}$$

There are also some field experiments conducted by D'hulst et al. [139] and Klaassen et al. [140] which quantify the maximum power change and the time required to maintain the demand response flexibility of these postponable appliances in residential buildings. Setlhaolo et al. [141] developed a mixed-integer nonlinear optimization model to optimize the schedule of the postponable residential appliances. Their results show that the load shifting potential of these appliances could reduce the electricity cost by more than 25%. In other words, the postponable appliances are capable to provide load shifting flexibility since their starting time can be postponed according to the flexibility window set by the occupants.

3.5 Dimmable lighting system

Dimmable lighting systems are increasingly adopted in modern buildings in the last two decades which can properly adjust the lighting intensity to improve visual comfort, efficiency, and economics [142] according to the needs or preferences of occupants and the change of natural light condition. These systems are controlled by building automation systems. Both open-loop and closed-loop control can be adopted in lighting systems and occupant preferences can be adopted as the control variables [143]. Whether the occupants can accept the temporarily lower light level can be examined and used to improve the control. In some cases, reducing the indoor illumination level can partially ramp down the load from the dimmable lighting systems and also reduce the cooling loads of HVAC systems. Unlike other building service devices, lighting outputs and power inputs of fluorescent ballasts using both analog and digital controls can be altered within seconds to any reasonable intensity [144]. Thus, the smart control of dimmable lighting systems can enhance the load shedding flexibility and fast regulation flexibility for building.

Chen et al. [33] defined the load reduction of lighting systems as one source of energy flexibility and assumed 0.4 as the dimming rate to quantify the power flexibility during the load shedding period. Rubinstein et al. [144] also reported that a 25% power reduction of the dimmable lighting in the large buildings of California can provide 2.5 GW reserve capacity. In addition, Rubinstein et al. [144] assumed that decreasing or increasing the ballast output by 8% from its nominal operating light level is unnoticeable to buildings' occupants. Fig.7 shows the relationship between the light power input and relative light output for a modern two-lamp dimming ballast (2*32-watt T-8 fluorescent lamps). Rubinstein et al. [144] found out that when the dimming ballast is operating at nearly 80% light level (i.e., power input is 50W), it can be adjusted by ±8% relative to its operating light output without annoying the occupants. Thus, it can provide 4-W capacity for fast regulation.

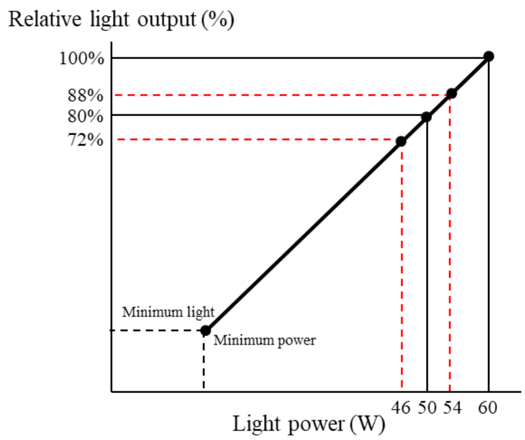


Fig.7. Power and light characteristic for a modern fluorescent dimming ballast [144]

4. Information technologies and potential business models for facilitating grid-responsive buildings

The actual achievement of flexibility contributions of buildings to smart power grids relies on the advanced communication infrastructure which supports timely, reliable and secure information transfer between various entities including information management and control centers and demand-side participants such as buildings. The growing information technologies also stimulate novel business models suitable for both the smart grid and energy flexibility providers. In this section, advanced information technologies, microgrid technologies and potential business models are discussed.

4.1 Advanced information and microgrid technologies for energy flexibility of buildings

In the context of smart grid, the technological advances which facilitate the utilization of demand side resources include grid-device bilateral communication, intelligent local and centralized controllers, IoT-based coordination and negotiation architecture, controlled and communicated smart appliances/ energy resources [41, 145]. Its main advance on conventional power grids is the establishment of two-way communication. The typical solution today is to equip smart meters at every customer location. Smart meters can then collect real time crucial information and establish a two-way communication for operation [146]. Many wireless and wired communication technologies are envisioned and adopted for smart grid applications [147, 148] to provide two-way communication between power grids and demand-side participants. However, the global penetration rate of smart meters has just passed 41% in 2019, and the expansion speed is constrained by significant barriers including challenges in finance, system regulation and consumers' push-back [149].

In buildings, the existing building automation systems, which perform the operation and performance monitoring and real-time control of building energy systems, can play a major role to communicate the power grid requests to energy flexibility systems/components in buildings and control them in response to power grids, when interfaced with the grid communication infrastructure such as smart power meters [150]. In recent years, the emerging IoT technologies have received increasing attention for applications in facilitating the demand control of energy flexibility systems/components in buildings in response to power grids. The means of adopting IoT technologies could be grouped into two categories, including development of Building Energy Management System (BEMS) [151] and Home Energy Management System (HEMS) [152, 153] for non-residential buildings and residential buildings respectively, and engagement of IoT-embedded flexibility systems/components into smart grids directly [154]. A flexible smart energy management system was proposed by Pawar and Vittal K [151], which is integrated with IoT framework in smart grid environment, to control the partial load shedding in the case of power outage in a region. A self-learning algorithm was developed by Zhang et. al [155] for coordinated control of multiple rooftop units that can be used with the emerging IoT-based building energy management system (BEMS), to facilitate rapid demand response implementation in commercial buildings. An algorithm was developed by Adhikari et. al [154] for the optimal management of aggregated power demand of a group of HVAC units, by leveraging widespread availability of smart IoT-based thermostats, allowing the direct participation of residential buildings to contribute to smart grids without additional IT infrastructure changes.

Micro-grid is another emerging concept and technology, which can enhance the energy flexibility contribution of individual buildings or a number of buildings by integrating different flexibility sources, such as energy generations, energy storages, HVAC systems and other energy consumers. It could not only better manage the power generations and use in the buildings, but also provide an effective platform for grid-connected buildings, in particular, to organize themselves in order to reduce the stress on power grids and provide energy flexibility to power grids. Hu et al. [145] summarized various “coordination and negotiation" behaviors of multiple flexibility entities in residential microgrids. Compared with the conventional buildings, a building micro-grid, integrating and coordinating different flexibility sources in a building or a number of buildings, could provide greater benefits for buildings and also greater energy flexibility for the power grid [156]. Increasing studies have been conducted to develop demand response control strategies for building micro-grids to minimize the operation cost of buildings and increase the energy flexibility contributions to the power grids [157]. For instance, an operation optimization strategy was proposed by Zhao et al. [157] for a microgrid involving a micro-gas turbine, wind turbines, electrical storages and electric appliances considering demand response to participate in the day-ahead electrical market. Wang et al. [158] proposed a demand response control strategy for a grid-connected commercial building micro-grid to minimize its operation cost by utilizing its solar generation, stationary energy storages and mobile electric vehicle storages as much as possible considering day-ahead energy price. Nguyen and Le [159] developed a demand response control framework for a building micro-grid to ensure efficient utilization of renewable energy considering day-ahead energy price. The zero energy building energy systems, as a typical building micro-grid, have also been studied by many researchers. An optimal scheduling strategy was developed by Lu et al. [160] for a grid-connected zero energy building micro-grid considering dynamic electricity pricing. Liu and Heiselberg [25] investigated the impacts of different control strategies on the energy flexibility of a nearly zero energy building micro-grid.

4.2 Business development and models for exploiting energy flexibility of buildings

The integrated building energy systems become energy flexible hubs involving various coordination and negotiation behaviors and various electricity market stakeholders. Several studies have identified the opportunities and barriers in business development for energy flexible buildings. Behrangrad et al. [41] summarized various demand response business models related to different market stakeholders (including system operator, generation, transmission and distribution, retailer and load segment) systematically, which listed numerous market opportunities for demand side management. Mlecnik et al. [161] identified the main obstacles in business development for energy flexibility of buildings. By investigating several examples from European countries, they indicated that there is a need for the improvement of policy, more flexible energy tariffs, supporting incentives, as well as raising awareness in business development of the energy flexible buildings as the active demand-side management instruments.

Four potential business models for energy flexible buildings are summarized by Ma et al. [162] in which the direct market participants can be building with large consumption, energy retailers, independent aggregators or the virtual power plants aggregators. Buildings can provide energy flexibility as the option to the retailers when optimizing the energy procurement planning, while buildings can receive incentives or cost less in return. The independent aggregator is another business development which is specialized with expertise knowledge as well as mechanism and automation engineering compared with the energy retailers [145]. In independent aggregators, the energy flexibility providers are usually the small electricity consumers which can not directly participate in the wholesale electricity market but can provide a coordinated response. Some studies investigated the optimization models [163-165] and other studies showed the business success of multiple buildings in providing energy flexibility in the electricity market via independent aggregators [166-169]. Virtual power plant is another concept which is considered as the efficient framework to manage and schedule the distributed energy resources (including local generation and distributed flexible loads) for optimally participating in the wholesale electricity market [170]. As virtual power plant is facilitated with smart metering and advanced information technologies, it can also be an effective option of business model for buildings to provide energy flexibility in the market. For instance, Wei et al. proposed a bi-level scheduling model for virtual power plant to manage the flexible cooling loads of buildings and the distributed renewable energy generations [171]. Wang et al. [170] conducted the technical and economic analysis of their proposed business case for virtual power plant considering the flexible cooling loads of buildings, battery storage and distributed generations. Results show that annual operational saving of electricity bills could reach 34% if the utilization of the energy flexibility in multiple electricity markets is optimized.

5. Conclusion

The enhancement of power system flexibility is increasingly important to address the economic and global sustainability issues. To fully explore the energy flexibility of buildings at multiple timescales, this paper presents a comprehensive review of the existing research and categorizes the flexibility according to their functionality and potential contributions of building response technologies. Various flexible sources and associated control strategies in building energy systems are summarized and discussed in terms of their ability to provide demand side flexibility for power grids. An in-depth investigation on the information technologies for grid-buildings communication and potential business models for flexibility trading is also conducted, which highlights the increasing interest, opportunities and existing obstacles for the utilization of building energy flexibility from the future perspective. By analyzing these technologies and the existing studies, the main conclusions are as follows:

- Although the direct economic trading of energy flexibility services is currently lacking, the demand response programs that exist in electricity markets have clear requirements for response speed, duration, and direction. Thus, building energy flexibility can be categorized as fast regulation, moderate regulation, load shedding, load shifting, and load covering.
- Various building technologies and systems can contribute to multiple flexibility types under different control strategies, and each type of flexibility may affect another. For example, if the entire available capacity of a battery is used to provide fast regulation, it has no capacity to provide load shedding flexibility.
- The inherent thermal mass of a building can be used as a natural source of energy flexibility. By making use of this passive and natural thermal energy storage, HVAC systems can provide various energy flexibilities across multiple timescales under various control strategies.

Based on current limitations, three major challenges are identified for the future development of energy flexible buildings:

- A holistic framework and methods for quantification of energy flexibilities based on the categorization is required for assessing the performance of building energy flexibility comprehensively.
- The deployment rate of advanced metering infrastructure needs to expand to remove the barrier of asymmetrical information between power grids and end-users in demand side.
- More business models with encouraging policy, flexible tariffs and incentives are needed to stimulate the utilization of energy flexible buildings as a practical demand side management instrument.

To support the development of energy-flexible and grid-responsive buildings, a systematical and comprehensive quantification method, together with the flexibility index are proposed in another follow-up paper [172]. Within the future context of smart buildings, building energy flexibility should be considered as a new key performance indicator in building design and operation.

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