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Utilizing commercial heating, ventilating, and air conditioning systems to provide grid services: A review

Yangyang Fu [a], Zheng O'Neill [a,*], Jin Wen [b], Amanda Pertzborn [c], Steven T. Bushby [c]

[a] J. Mike Walker '66 Department of Mechanical Engineering, Texas A&M University, College Station, TX, USA
[b] Department of Civil, Architectural and Environmental Engineering, Drexel University, Philadelphia, PA, USA
[c] National Institute of Standards and Technology, Gaithersburg, MD, USA

HIGHLIGHTS

- This paper reviews strategies in commercial buildings for grid service delivery.
- Review and technical papers are searched by Sub-keyword Synonym Searching Method.
- Primary limitations, gaps, and future trends are identified.

ARTICLE INFO

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Grid service
Delivery control strategy
Rule-based control
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Building-to-grid integration

ABSTRACT

The modern power grid faces multiple challenges due to an increase in the adoption of renewable generation, such as dynamically balancing supply and demand at different time scales. Demand side management in buildings plays a vital role in achieving this balance because buildings can provide grid services through a variety of building assets. However, the development of grid-interactive, efficient buildings is still in its infancy, and a systematic and holistic understanding of grid service delivery strategies in terms of energy efficiency, load shifting, load shedding and load modulating is still limited. This paper is a comprehensive review of the development and application of building-level control strategies for utilizing heating, ventilating, and air conditioning systems to provide grid services. These strategies have been investigated through numerical and experimental studies. Control algorithms, such as heuristic rule-based control and model-based control, have been used to enable the automatic control delivery of grid services. The advantages and disadvantages of the strategies are summarized and discussed. Research trends are also identified, which include considering predicted mean vote-based and occupant-based thermal comfort, modeling of occupant behavior, integrating power grid operations with building control, and combining different demand flexibility modes in the control design.

1. Introduction and motivation

The electrical grid is facing multiple challenges: increasing peak electricity demand, high penetration of variable renewable electricity generation, and transmission and distribution infrastructure constraints. These challenges stress the electrical grid by making it more difficult to balance supply and demand at different time scales using existing infrastructure. Balance management services are largely provided by supply-side entities: integrated utilities, grid operators, and generators. However, demand-side entities, such as buildings with flexible electrical loads, can also provide balance management. Buildings have been reported to consume more than 70 % of electricity in the United States (U.S.) [1], and their contributions to balance management services can be as viable as supply-side counterparts. In 2019, the U.S. Department of Energy released a series of reports about grid-interactive efficient buildings (GEBs) that use smart technologies and on-site demand side resources (DSRs) to provide demand flexibility while co-optimizing for energy cost, grid services, and occupant needs and preferences, in a continuous and integrated way [2]. GEBs can provide demand flexibility via five modes: efficiency, shedding, shifting, modulating, and generation as shown in Fig. 1.

The types of grid services include: generation service - reduces generation operations and defers generation capacity investment; ancillary service - provides contingency reserve by reducing demand for short periods of time and supports frequency regulation and ramping by

* Corresponding author.
E-mail address: zoneill@tamu.edu (Z. O'Neill).

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Nomenclature

AHU	Air handling unit
CAV	Constant air volume
CHWSP	Chilled water supply temperature setpoint
CHWST	Chilled water supply temperature
CPP	Critical peak pricing
DP	Differential pressure
DR	Demand response
DSM	Demand side management
DSR	Demand side resources
EE	Energy efficiency
FR	Frequency regulation
GEB	Grid-interactive efficient building
HVAC	Heating, ventilation and air-conditioning
MBC	Model-based control
MPC	Model predictive control
OPF	Optimal power flow
PI	Proportional-integral
PID	Proportional-integral-derivative
PJM	Pennsylvania-Jersey-Maryland
RBC	Rule-based control
RTP	Real time pricing
SAT	Supply air temperature
TOU	Time-of-use
VAV	Variable air volume
VFD	Variable frequency drive

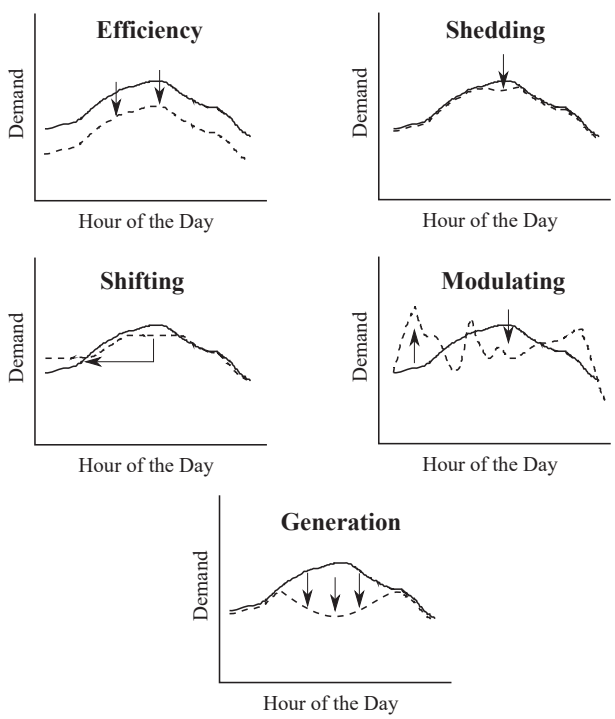

Fig. 1. Modes of demand flexibility. The solid line is the base load and the dashed line is the resulting load [2].

fast response resources; delivery service - defers the need for investments in transmission & distribution infrastructure [2]. The efficiency mode is a generation service, while the shifting, shedding and generation modes are used for generation, ancillary and delivery services. The modulating mode is used mainly for ancillary service.

Demand side management (DSM) can enable the provision of grid services with a variety of DSRs in GEBs. DSM refers to the comprehensive integration of DSRs to provide energy efficiency (EE), demand response (DR) and other advanced services. In this paper, we focus on EE and DR. EE brings long-term reductions in both energy use and peak demand without compromising building functional service, thus playing an important role in supporting decreased carbon emissions and grid reliability. DR, in contrast to EE, reduces peak demand by focusing on the timing of energy use, sometimes with the consequence of increasing overall energy use. There are many DSM programs that promote EE and DR in commercial buildings. For example, programs that provide rebates or financing for customers who use energy efficiency measures are widely available [3]; both price-based (e.g., time-of-use, real-time pricing, etc.) and incentive-based (e.g., demand bidding, ancillary service market, etc.) programs are designed for DR [4]. Long-term planning is typically required for consumers to participate in capacity market programs. For example, the Pennsylvania-Jersey-Maryland (PJM) interconnection in the U.S. allows consumers or aggregators to bid into its capacity market months or a year ahead [5].

The heating, ventilation, and air conditioning (HVAC) system in commercial buildings is widely considered a type of DSR, and thus plays an important role in enabling GEBs. By leveraging the existing building automation system, these HVAC loads can provide controllable and fast DR. In most applications, a building's thermal mass is large enough that occupants will not experience thermal discomfort, despite the frequent short interruptions of HVAC operations that occur with fast DR. In addition, many of the loads in modern and large commercial HVAC systems are controlled via a variable frequency drive (VFD), making the total HVAC load nearly continuously variable within a tolerant operation range. However, utilizing commercial HVAC equipment and systems for GEB applications requires special attention to the selection of control strategies. The challenge stems from the distributed nature of HVAC control and interactions between the mechanical equipment components. Interacting local controllers could create conflicts during DR operations [6]. For example, when short term shedding is required during a cooling day, one approach is to increase the air handling unit (AHU) supply air temperature (SAT) setpoint, which may lead to a reduction of the chiller load and an increase of AHU supply air flowrate to maintain the same zone temperature. Although the chiller may use less power during the shedding, the supply air fan could use more power, which will counteract the intentions of shedding.

Fig. 2 shows a timeline of the development of GEBs. Energy efficiency in buildings has been studied and demonstrated since the 1970s [7] with the emergence of load shifting and load shedding in the 1990′s [8] and the 2000′s [9]. Load modulation using HVAC equipment in buildings [10–19] emerged with the growing penetration of renewable energy techniques such as solar panels in the power grid. Most existing studies using buildings to provide grid services specifically target one of the demand flexibility modes. Starting around the 2010 s, more studies integrate constraint considerations in building control design such as thermal comfort based on predicted mean vote [20], indoor air quality [21], occupant behaviors in buildings [20], grid operation constraints [22], and integrated demand flexibility modes [23] etc..

Although two review papers on the DR control exist (summarized in Table 1), they both have a specific focus with limited coverage. For example, Shan et al. [4] provided a detailed review of building DR control, but with a focus on the available control variables for slow DR such as load shifting and load shedding. Control algorithms to adjust those variables were not reviewed. Wang et al. [24] summarized control strategies for providing fast ancillary service using modulating loads in

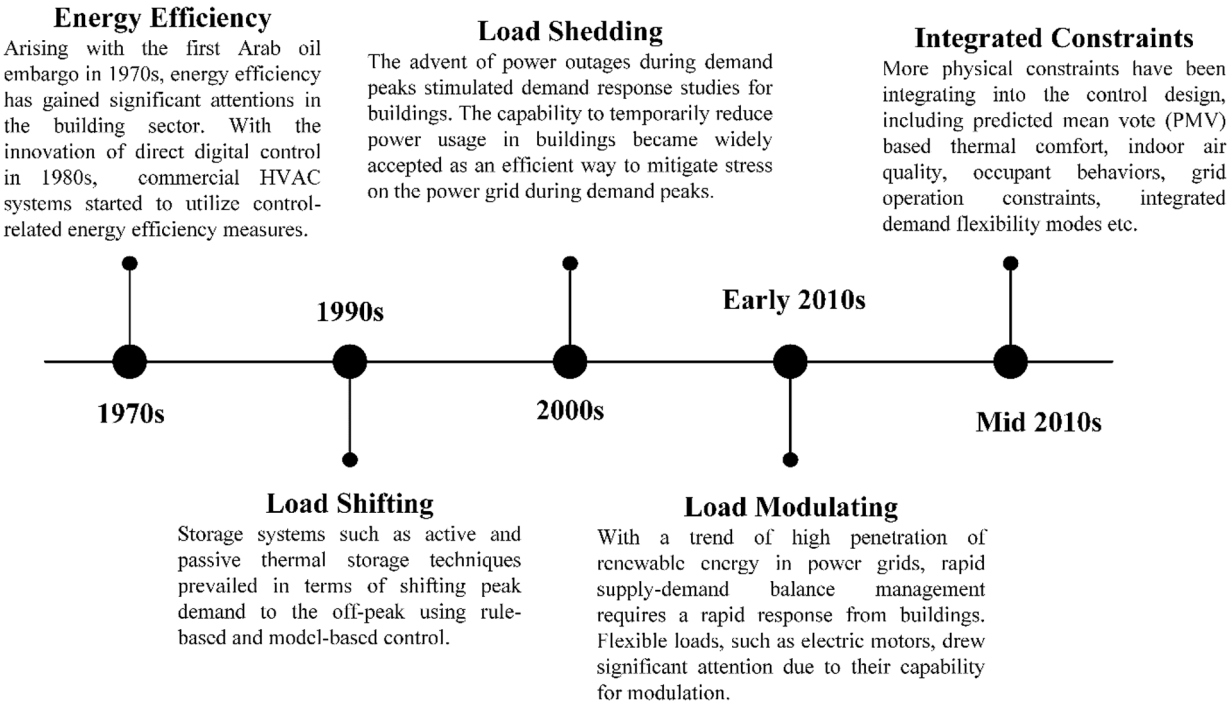

Fig. 2. Timeline for the exploration of demand flexibility modes in GEBs.

Table 1
Summary of the review papers.

NO.	Year	Demand Flexibility Mode	Building Type	Highlights	Ref.
1	2016	Load shifting, Load shedding	Commercial, Residential	• Reviewed commonly-used control variables strategies for load shifting, and load shedding and onsite generation scenarios • Reviewed only DR-related control	[3]
2	2019	Load modulating	Non-residential	• Summarized implementable control strategies for providing ancillary services from non-residential buildings	[24]
3	2021	Energy efficiency, Load shifting, Load shedding, Load modulating	Commercial	• Review comprehensive control strategies in typical commercial building for utilizing all demand flexibility modes • Summarize control strategies for guiding implementation • Provide current and future research trends on integrating physical trends into the control design	This Paper

non-residential buildings. The separation of slow and fast demand response in these two papers fails to provide insights on how to coordinate demand resources with different response times. In addition, the most recent research trends are not well demonstrated. Therefore, a comprehensive review of grid service building-level delivery control strategies is still lacking. This paper provides a holistic overview of grid service building-level delivery control strategies considering both EE and DR in commercial GEBs, with a focus on the flexibility modes of efficiency, shifting, shedding and modulating.

We used a sub-keyword synonym searching method as mentioned in Ref. [25] to find the relevant literature. This method uses a set of synonym sub-keywords to exhaust relevant papers by multiple searches. We used three sets of sub-keywords. The first sub-keyword defines the scope of building energy systems; the full list is: “commercial buildings”, “HVAC”, “cooling” and “heating”. The second sub-keyword defines the grid services; the full list is: “control”, “demand response”, and “demand side management”. The third sub-keyword defines the demand flexibility modes and grid services; the full list is “energy efficiency”, “shifting”, “shedding”, “modulating”, “regulation”, and “ancillary services”. Combinations of the sub-keywords are used as search keywords in Google Scholar. For example, “commercial building electricity demand response” and “HVAC demand regulation” are search keywords. The total number of search keywords is $4*3*6 = 72$. For each keyword, only the first 5 papers with more than 5 citations are considered. We reviewed the 360 papers generated by this search and organized them based on the scope of the paper. We eventually selected about 100 papers by removing papers whose focus was outside the scope of our work; for example, those focusing on residential buildings and district energy systems.

Based on the review results, this paper is organized as shown in Fig. 3. Section 2 describes a typical commercial HVAC system in terms of control. Section 3 summarizes a generalized grid-service building-level delivery control framework based on different power grid signals. Section 4 then details common grid service building-level delivery control strategies using HVAC systems and how they are utilized in the control design for efficiency, shifting, shedding, and modulating. Section 5 provides a discussion about the trending constraints in current and future GEB studies. Section 6 is a summary of this review work.

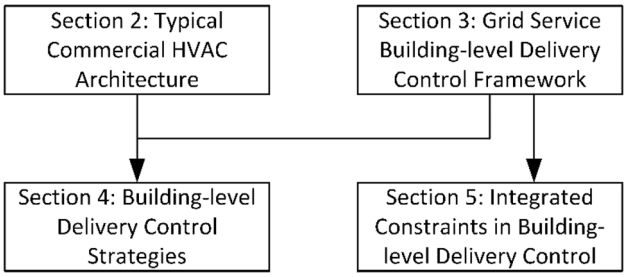

Fig. 3. Outline of the review contents.

2. Typical commercial HVAC architecture

Commercial building HVAC systems come in a variety of architectures, one of which is known as the single duct variable air volume (VAV) system, as illustrated in Fig. 4. For cooling, the HVAC system consists of a central chiller plant that distributes chilled water to cooling coils in several independent AHUs. Each AHU contains a fan that drives the mixed air of circulated return air and outside air through the cooling coils to supply the cold air to the conditioned zones. Typically, one AHU serves multiple thermal zones. The following local proportional-integral (PI) controllers are typically designed for this air loop: 1) VAV terminal box discharge air flow rate controller, where a damper in the VAV terminal box is regulated to meet a discharge air flow rate setpoint for each zone; and 2) AHU supply air fan speed controller, where the AHU fan speed is regulated through a VFD to meet a pressure or a differential pressure setpoint.

The heat removed from the mixed air is absorbed by the chilled water which is circulated back to a chiller plant. The chillers then reject the heat to the ambient environment through cooling towers. The water circulation is achieved by pumps. The primary chilled water pumps and condenser water pumps usually have a constant speed, but the secondary chilled water pumps are equipped with VFDs so that their speed can change over time. There are mainly four local controllers on the chiller plant. First, the cooling coil valve regulates the supply of the chilled water by a PI controller to each cooling coil for controlling the AHU SAT at its setpoint. Second, a built-in controller in the chillers regulates the chilled water supply temperature (CHWST), for example, by modulating the compressor speed. Third, the secondary chilled water pump speed is regulated to maintain the differential pressure setpoint of the chilled water network. Forth, the condenser water supply temperature is maintained at its setpoint by regulating operations of the cooling tower fans (e.g., speeds or stages).

The BAS provides communication and supervisory control for the entire HVAC system. Based on data from a building's sensors and actuators, the BAS determines the operating setpoints, including AHU supply air pressure, AHU SAT, and CHWST, etc. In modern buildings, the BAS updates these setpoints on a time scale of 2–30 min based on control designs.

3. Building-level grid service delivery control framework

Participating in DSM programs eventually requires that the committed resources provide the corresponding services to the grid. The provision can be realized by manual operations or automatic control. This paper will focus on providing grid services via automatic control.

Fig. 5 illustrates a general control flow to implement grid-interactive programs from both the grid and buildings' perspectives. The figure is a summary based on Ref. [26–31]. To participate in grid-interactive programs, there are in general three levels of control to be considered: grid-level, aggregator-level, and building-level. While the grid-level controller generates outputs for both the supply and demand sides to maintain grid-level reliability and economic profits, the aggregator-level and building-level controllers provide a committed service to the grid without downgrading a building's functional service. If a building is large enough, it can provide services to the grid directly rather than as part of an aggregation. In this paper, we focus on building-level control.

Fig. 6 illustrates a general framework of the building-level controller for providing grid services in response to a load signal (Fig. 4(a)) or a price signal (Fig. 4(b)) based on [13,32–33]. The load signal and the price signal are explained in Section 3.2. This framework consists of three parts: a commitment process, a dispatch process, and a delivery process. When responding to price signals, the framework can be simplified as a delivery process only Fig. 4(b). The commitment process

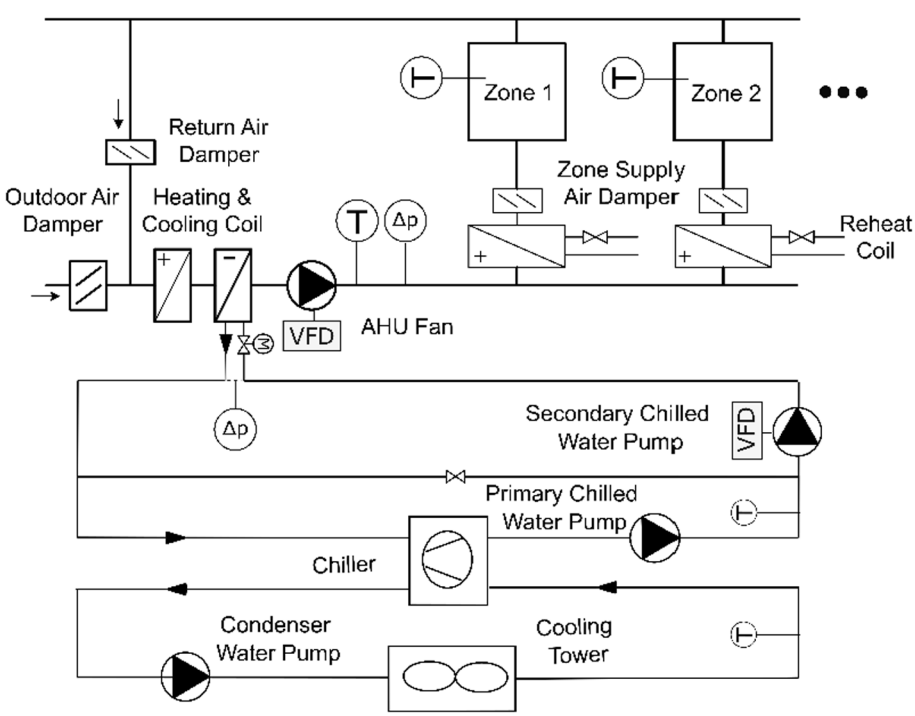

Fig. 4. A typical commercial building HVAC system.

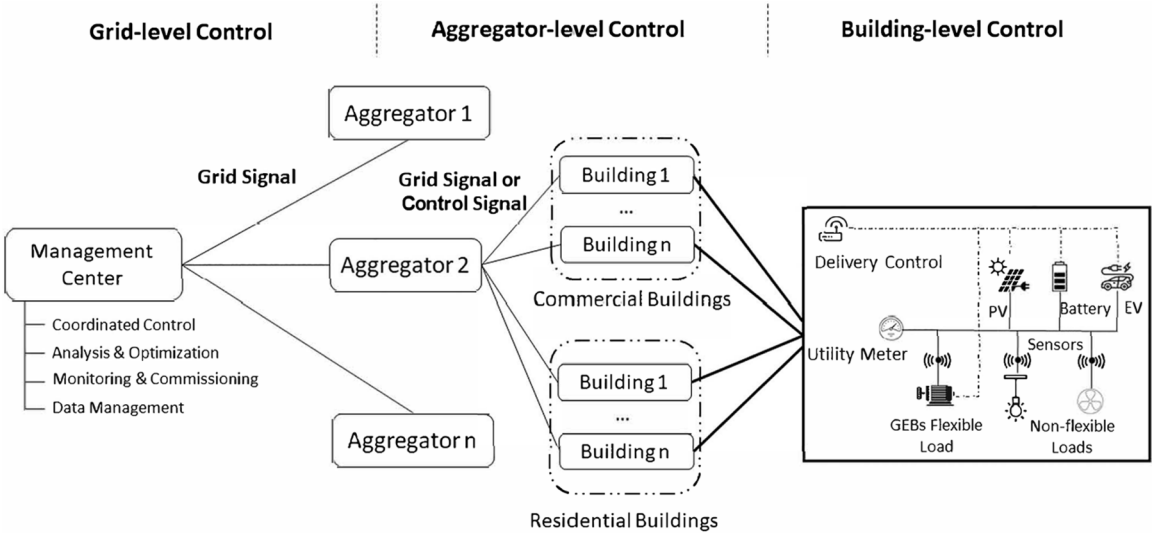

Fig. 5. General process for the provision of grid services by DR.

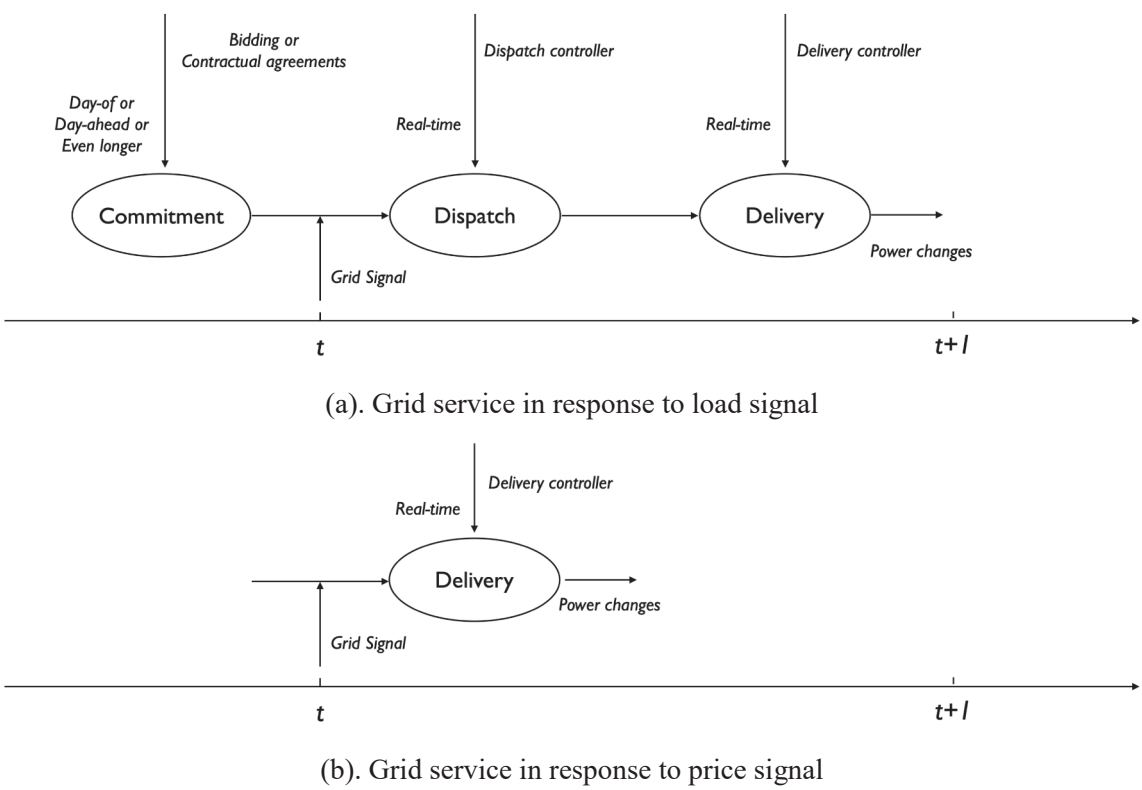

Fig. 6. Generalized grid service control framework for different programs.

addresses the type, level, and cost of the services. This process is usually performed ahead of time by participating in an electric market or signing bilateral contracts with energy providers. Once the resource is committed, the controller needs to solve a real-time dispatching problem that determines which buildings in an aggregator or which devices in a building should be dispatched to deliver the service. Finally, the delivery process decides how a building/device provides the service in real-time, e.g., by adjusting a setpoint temperature. This general framework emphasizes the possible problems that a building-level controller should address. There is existing research that explicitly or implicitly uses a variation of this framework by simplifying one or more the above-mentioned processes. For example, to enable a frequency regulation (FR) service, the authors in [10,15–16,34–35] only consider the delivery process while the authors in [12–13,26,32–33] consider the bidding, dispatching, and delivery processes as a whole.

3.1. Control objectives

A major goal of delivery control in buildings is to provide the committed grid service to reduce operational costs while maintaining normal building services. Therefore, the control objectives on the demand resource side are threefold. The first is to meet the grid operation requirements by delivering the promised grid service, e.g., load reduction, by minimizing the difference between the targeted service and the

delivered service. For example, Kiliccote et al. [36] designed a closed-loop feedback controller to provide a targeted demand shedding level by incrementally decreasing or increasing zone temperature setpoints. For FR service, the difference between the power reference signal for providing FR and the measured power is minimized by a feedback controller [10–13]. The second goal is to minimize the operational costs. The operational costs usually consist of energy costs, demand costs and grid service revenues. Corbin et al. [37] presented a supervisory controller to reset zone temperature with the goal of minimizing energy costs. Ma et al [38] formulated an economic Model Predictive Control (MPC) for a multi-zone commercial building to minimize its daily energy and demand costs by scheduling zone temperatures. Pavlak et al. [23] proposed a supervisory controller to minimize the energy cost, demand costs and FR revenues as a whole. The third one is to maintain the level of desired building services such as thermal comfort during the DR events. This goal is not met separately but comes with the other two.

These control objectives are usually fulfilled by designing a hierarchical controller. Vrettos et al. [12–13] proposed a three-stage controller for FR service, where the top-stage controller performs robust optimization to minimize a certainty-equivalent cost by scheduling day-ahead hourly regulation reserve capacity, the mid-stage controller calculates the supply air flow rate setpoints every 15 min to minimize the energy cost while ensuring occupant comfort under reserve provision, and the bottom-stage controller adjusts the fan speed to track the regulation signal in real-time. Similarly, Fu et al. [39] also designed a three-stage controller, where the top-stage MPC controller schedules an efficient day-ahead power baseline by minimizing the total operational cost including energy and demand costs. The mid-stage control schedules the hourly reserve capacity by minimizing the energy cost, demand cost, and FR revenues. The lowest level controller tracks the regulation signal using rule-based schemes.

3.2. Grid signals

Participation in most DR programs requires that a building as a program customer can receive and respond to the grid signals indicating a need to provide service, while EE programs do not. There are two types of grid signals: load-based signals and price-based signals. These signals serve as either reference signals for a closed-loop control system or disturbance inputs for an open-loop control system. A classification scheme is depicted in Fig. 7.

Customers receive price-based signals if participating in Time-of-Use (TOU), Real-time Pricing (RTP), or Critical Peak Pricing (CPP), and load-based signals if participating in dispatchable programs such as direct load control, etc. Participants of demand bidding programs can receive either type of grid signals depending on the details of the program design. The price-based signal is merely the price information of the service, and it could be the day-ahead/real-time energy market price, or utility-posted prices, etc. The load signal is the dispatch signal from a grid operator or utility, and it may contain information such as load curtailment start time, duration, and quantity. Customers respond to these two types of signals by shifting, shedding, or modulating the loads to maximize their benefits while maintaining functional services of the system.

3.3. Control variables

In this study, we refer to control variables as those that can be manipulated by a controller to change the system outputs. The HVAC system in commercial buildings, including chillers, heat pumps, pumps, and fans, contributes to a variety of DSRs. These DSRs can be controlled to change system power by manipulating equipment inputs or control setpoints. For example, fan power can be changed either by directly changing the frequency of a supply air fan motor through a VFD or changing the differential pressure setpoint. The selection of which variable to control is a design choice made after considering factors such as the controllability and implementation cost. The control variables that are typically manipulated in a commercial building are summarized and discussed in Section 4.

3.4. Control algorithms

How a control variable responds to the grid signal is determined by predefined algorithms in the controller. This review categorizes the algorithms into two types: rule-based control (RBC) and model-based control (MBC). RBC refers to control algorithms that do not require a model of the system, such as closed-loop PI control and some open-loop control with pre-defined rules. MBC refers to control algorithms that utilize mathematical models of the system to make real-time control decisions, such as MPC.

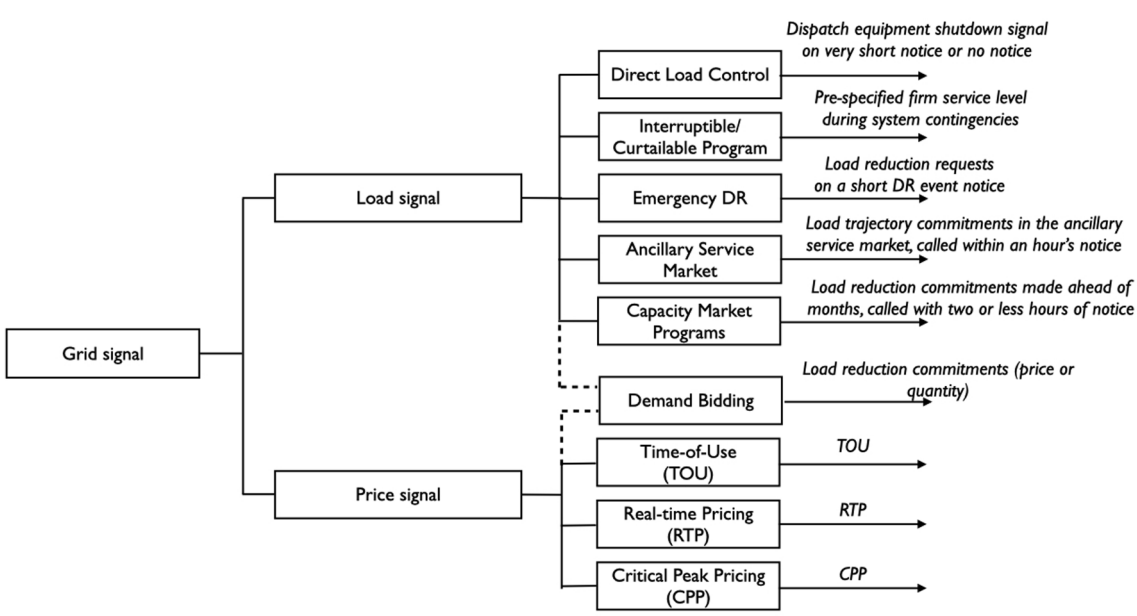

Fig. 7. Grid signal for different demand side programs.

3.4.1. Rule-based control

RBC follows pre-set rules of the form "if initial condition, then action" [40], where the initial conditions are determined from sensors and actuators implement the actions by directly acting on the mechanical equipment. In general, RBC critically depends on correct choices for rules and associated parameters [40].

RBC is suitable for almost all control-related DSM programs. When a DSR voluntarily provides grid services, for example, in an economic demand bidding program, RBC can be designed with predefined rules using an open-loop control scheme. The rules can be predefined by experimentally or numerically studying the relationship between the control output (e.g., load reductions) and control variables (e.g., zone temperature). For example, when using global temperature adjustment as the delivery strategy to respond to load curtailment requests, a simple rule such as "increase temperature by a certain amount (e.g., 1 °C) when a specific amount of reduction (e.g., 10 kW) is required" can be used after the relationships between temperature variations and power variations are studied and established [6]. When the resource is required to provide a specific level of service, for example, in market-based programs, RBC using closed-loop control could be applied. One example is FR in ancillary market programs. The delivery of FR services is typically enabled by a closed-loop control such as PI to realize real-time power tracking. For example, if continuous adjustment of the chilled water temperature setpoint is the FR delivery strategy, a PI controller can be designed to minimize the error between the required power profile and the delivered power profile by resetting the chilled water temperature setpoint [34].

3.4.2. Model-based control

MBC is an approach that uses indirect logic that employs models to simulate building behaviors in order to compare different control policies and choose the best one [41]. MBC is more complex than RBC and can capture complex dynamic interconnections among phenomena that RBC strategies cannot effectively capture. A promising MBC application is MPC, which can generate and analyze multiple possible operating scenarios, identifying optimal settings when supplemented with predictive capabilities.

MPC has been investigated in DSM programs that involve the solution of a scheduling problem, such as DR programs that receive price signals and ancillary service market programs. MPC has been well studied for load shifting in response to different pricing schemes in commercial buildings [40,42–45]. Afram et al. [46] provided a comprehensive review on utilizing MPC for load shifting in buildings.

For load shedding, if the notification time is long enough, MPC might be able to provide maximum load reduction without violating thermal constraints. Cao et al. [43] utilized MPC in a commercial building to charge the thermal storage in the pre-DR period and discharge the storage during the DR period while shutting down all chillers to provide load curtailment. Tang et.al. [47] proposed an MPC with shrunken prediction horizons over the DR period to minimize the chiller power and thus maximize the chiller power reductions. However, this work has several limitations: one is that they did not take advantage of a pre-DR period, which is especially important when thermal storage is also present in the system; the other limitation is they barely took the post-DR period into considerations, which eventually leads to a power rebound at the end of the DR period.

For load modulating, ancillary service programs such as the regulation market require the resources to schedule their baseline power and reserve range. Pavlak et al. utilized MPC as the supervisory controller to schedule the zone temperature to indirectly schedule the reserve range for commercial buildings to provide FR services [23]. The authors in [12–13] and [33] developed and experimentally implemented a multi-stage MPC controller for FR delivery. MPC has been both numerically and experimentally demonstrated for its capability to help buildings harvest benefits by providing ancillary services. The control performance for load modulating is typically evaluated to meet predefined control requirements. For example, in PJM regulation market, the performance of the DSRs is continuously evaluated based on their FR performance score as defined in the following equations.

$$c_{sig,res} = \frac{COV(reg, res)}{\sigma_{reg}\sigma_{res}} \tag{1}$$

$$S_{accuracy} = \max_{\delta=0-5min}\left(c_{reg,res(\delta)}\right) \tag{2}$$

$$S_{delay} = \left|\frac{5\text{min} - \delta^*}{5\text{min}}\right| \tag{3}$$

$$S_{precision} = 1 - \frac{1}{n}\sum\left|\frac{res - reg}{\overline{reg}}\right| \tag{4}$$

$$S_{performance} = \frac{S_{accuracy} + S_{delay} + S_{precision}}{3} \tag{5}$$

In the above equations, *reg* represents the regulation signal the DSRs receive from the electrical markets, and *res* represents the response signal that the DSRs generate after control actions. c , COV and σ are the correlation coefficient, covariance, standard deviation of these two signals, respectively. In PJM, the response signal *res* is recalculated with a time shift δ ranging from 0 to 5 min in an increment of 10 s, which leads to 31 response signals $res(\delta)$. The accuracy score $S_{accuracy}$ is the maximum correlation coefficient c between *reg* and $res(\delta)$. The delay score S_{delay} is calculated based on the delay time δ^* when the maximum accuracy score is obtained using Eq. (3). The precision score $S_{precision}$ is defined as the relative difference between regulation signal and response signal, where n is the number of samples in the hour, and $\overline{reg}$ is the hourly average regulation signal. The final performance score $S_{performance}$ in that hour is calculated as the weighted average of the three individual scores.

Another application of MPC is in solving a multi-market participation problem, where DSM resources can gain benefits from bidding into multiple electrical markets. For example, a large consumer can bid into the day-ahead energy market and the regulation market to minimize operational costs. Lampropoulos et al. [48] proposed an MPC scheme on the operations of the day-ahead wholesale market and the real-time market for operating reserves. MacDougall et al. [49] studied multi-market trading using a model-based predictive controller for aggregated loads. Blum et al. [50] proposed an MPC for a HVAC system to participate in the energy market, regulation market and spinning/non-spinning reserve market.

4. Building-level delivery control strategies

A delivery control strategy refers to the configuration of control variables, control algorithms and control objectives for a building to deliver a specific grid service. This section provides detailed reviews of the delivery strategies for commercial buildings. The reviews are summarized based on 12 different available control variables as shown in Table 2, with regard to targeted devices, response time, research methods, and flexibility modes. More detailed descriptions of how each strategy is implemented and evaluated are found in the literature. We evaluate the pros and cons of each strategy in terms of their applicability in GEB-related control.

4.1. Strategy 1 – Zone air temperature adjustment

This strategy allows the building to change its power profile at the whole building level. It is applicable to all types of commercial buildings with zone-level temperature control. The adjustment of a thermostat's setpoint to provide grid services takes advantage of building thermal mass. This strategy has been valued as the most effective and the least objectionable [51]. It has been widely studied for load shifting

Table 2
Summary of building-level delivery control strategies for proving grid services

NO.	Control Variable	Targeted Device	Response Time	GEB Mode	Reference	Control Algorithm	Research Method
1	Zone temperature setpoint	Whole HVAC System	~minute	Shifting	[23,37–38]	MPC	Simulation
					[52]	MPC	Experiment
					[53]	RBC	Simulation
					[112–114]	RBC	Experiment
				Shedding	[55]	MPC	Simulation
					[56–57]	RBC	Simulation
					[6,36,51,58–60,112]	RBC	Experiment
				Modulating	[61]	RBC	Simulation
					[35]	RBC	Experiment
2	Motor speed	Chiller, Heat Pump, Pump, Fan	~second	Shedding	[51,60]	RBC	Experiment
				Modulating	[11,18]	MPC	Simulation
					[12–13]	MPC	Experiment
					[10,17,19]	RBC	Simulation
					[14–15]	RBC	Experiment
3	Quantity of operating equipment	Chiller, Heat Pump, Pump, Fan, Electric Heater	~second	Efficiency	[64]	MBC	Simulation
				Shedding	[44,47,63,65,69,115]	RBC, MPC	Simulation
					[51]	RBC	Experiment
				Modulating	[32,70]	MBC	Simulation
					[26]	MBC	Experiment
4	Discharging temperature setpoint	Chiller, Heat Pump	~minute	Efficiency	[72–73]	MBC	Simulation
				Shifting	[74]	MPC	Experiment
				Shedding	[55]	MBC	Simulation
					[57]	RBC	Simulation
					[51]	RBC	Experiment
				Modulating	[71]	RBC	Simulation
					[15,34,75]	RBC	Experiment
5	Differential pressure setpoint	Pump, Fan	~second to minute	Efficiency	[64,72–73]	MBC	Simulation
				Shedding	[57]	RBC	Simulation
					[51]	RBC	Experiment
				Modulating	[61]	RBC	Simulation
					[76]	NA	Experiment
6	Water/air flowrate setpoint	Pump, Fan	~ second to minute	Shedding	[116]	MBC	Simulation
				Modulating	[77]	MBC	Simulation
					[78]	MBC	Experiment
7	Power charging rate	Electrical Storage	~second	Shifting	[79,83]	MPC	Simulation
				Shedding	[86]	MPC	Simulation
				Modulating	[18,94]	MPC	Simulation
8	Supply air temperature setpoint	Air Handling Unit, Electric Heater,	~minute	Shedding	[55,57,117]	RBC	Simulation
				Modulating	[61]	RBC	Simulation
					[28]	RBC	Experiment
9	Power level	Electric Heater	~second	Shifting	[87]	MPC	Simulation
				Modulating	[29,33]	MPC	Experiment
10	Thermal heat charging rate	Thermal Energy Storage	~ second to minute	Efficiency	[90]	RBC	Simulation
				Shifting	[43,94,118]	MPC	Simulation
					[119]	RBC	Experiment
				Shedding	[47,94]	MPC	Simulation
				Modulating	[39]	MPC	Simulation
					[96]	RBC	Simulation
11	Valve position	Air Handling Unit	~minute	Shedding	[51]	RBC	Experiment
				Modulating	[61]	RBC	Simulation
12	Optical and thermal properties	Dynamic Window and Insulation	~minute to hour	Efficiency	[120–121]	MBC, MPC	Simulation
					[97,99–100,102,121–122]	RBC	Simulation
				Shifting	[102]	RBC	Simulation
				Shedding	[123]	NA	NA
				Modulating	[123]	NA	NA

[22–23,37–38,45,52–54] and load shedding [6,20,36,55–60], but barely studied for load modulating [61].

Precooling or preheating the zone ahead of on-peak hours by decreasing or increasing zone temperatures, respectively, can shift on-peak HVAC loads to off-peak hours. The thermal mass of the building envelope and furniture absorb additional thermal energy (cooling or heating) during off-peak hours and release the thermal energy to the zone during on-peak hours to reduce the cooling or heating requirements of HVAC systems. Many researchers have numerically or experimentally demonstrated the effectiveness of the approach of resetting zone temperature to achieve load shifting [22–23,54].

Load shifting can be realized by RBC and MBC. The control is usually implemented at a supervisory level. For RBC, simple rules, such as predefining the zone temperature setpoints based on unoccupied and occupied hours, are typical. For example, Braun et al. proposed precooling a commercial office building at a fixed setpoint of 19.4 °C prior to the occupied hours and then maintaining a fixed setpoint of 22.8 °C during occupied hours [53]. This strategy is often integrated with MBC using predictive controllers to maximize the performance. With a predictive controller, the zone temperature can be optimally reset to respond to future disturbances. Both numerical and experimental studies have been widely performed using MPC to provide efficient building controls. Ma et al. formulated an economic MPC for a multi-zone commercial building to minimize its daily electricity costs in response to TOU and demand charges by scheduling zone temperatures [38]. The simulation results demonstrated a substantial cost savings by automatically triggering precooling and shifting the peak demand away from on-peak hours, which was then further confirmed in an onsite

experiment [52]. Corbin et al. presented a MPC framework for building energy systems, and numerically demonstrated that scheduling the zone setpoint in a large office building using MPC can decrease operation costs by 5% [37].

A load shedding strategy increases the zone temperature setpoint when cooling and decreases the setpoint when heating during a DR event with relaxed thermal comfort requirements. The key to using this strategy for load shedding is to find the correlation between the load reduction and zone temperature increase. RBC is the most widely used approach for this scenario, where simple correlations such as a linear relationship between the load reduction and temperature increase are typically established. Goddard et al. [6] related the required power changes to the desired temperature changes for an office building. The specific relation was quantified from onsite experiments as 62.5 KW/°C zone temperature. The duration considered for the power change was 30 min. The relation was then used in an RBC via an open-loop control scheme to regulate the zone temperature by responding to power reduction requests from the grid. Aduda et al. [60] experimentally evaluated the demand flexibility of a cooling system by regulating the cooling setpoint of the zone (adjustment of 2 °C). Results indicated that increasing the cooling setpoint temperature by 2 °C realized a maximum peak power reduction of up to 25 % of the maximum cooling power demand (7 kW) for up to approximately 20 min of continuous operation. Blum et al. numerically investigated the performance of resetting zone temperature to provide 10-min spinning reserve [57]. Kiliccote et al. experimentally tested a closed-loop feedback controller in a government office building to provide a targeted demand shedding level [36] by incrementally decreasing or increasing zone air temperature setpoint within a predefined range.

It is less common for zone temperature adjustment to be used for load modulating. Beil et al. [35] adjusted zone temperature setpoint in an open-loop controller to regulate the supply fan power in order to track the FR signal. The correlation between the zone temperature changes and fan power changes was experimentally evaluated in a 3,000 m^2 test building by exciting zone temperature setpoints and observing fan power changes as in [6]. Their experiments showed that the FR performance score for tracking the testing RegA signal in the PJM market was around 0.5 ~ 0.65, which was lower than the qualification requirement of 0.75. They have identified a few reasons, including time delays and inaccuracies in the open-loop scheme, latency in the Building Automation System (BAS) communication platform, etc. Wang et al. [62] used a group of distributed air-source heat pumps as the primary heating source in the responsive buildings, and as a dispatchable grid-side energy resource, where the aggregated power output can be manipulated through the use of smart thermostats to provide voltage support to the grid.

The advantages of using the strategy of adjusting zone air temperature setpoints are multi-fold. First, it is easy to implement, especially when a building energy management system (BEMS) is available. Local interactive controls between the waterside and airside systems will not counteract the DR benefits. Second, this strategy focuses on system-level power changes, which can provide a significant demand reduction compared with other local-level policies. Third, this strategy is generally suitable for all types of commercial buildings. However, this strategy does need additional attention to avoid a rebound effect during the post-DR period [51].

4.2. Strategy 2 – Direct motor speed adjustment

Equipped with a variable frequency drive (VFD), HVAC equipment such as chillers, pumps, and fans can be controlled to adjust their motor speed to respond to external signals. The motor speed can be controlled directly by changing the frequency via the VFD interface or indirectly by changing other associated variables such as the supply water temperature setpoint in the chiller controller and the supply pressure setpoint in the fan controller. Direct motor speed control of fans or pumps is practical for building operators, while it is generally infeasible or more difficult in chillers and heat pumps due to the proprietary nature of the manufacturer's compressor control system. This strategy is mostly used for load modulating.

For load shedding, the motor is usually controlled to not exceed a pre-defined limit during DR events. The limit should be lower than the speed in the pre-DR mode to achieve the curtailment. Motegi et al. [51] experimentally applied this strategy to supply air fans by limiting the speed to 60 %~70 % of the nominal speed, which produced a 17 %~35 % power reduction compared to the baseline operation with 100 % fan speed. Aduda et al. [60] also limited the supply air fan speed continuously for 120 min to reduce the peak power without compromising indoor air quality.

This strategy has been studied most for load modulating due to its fast response. Researchers have applied this strategy to heat pumps [15–19], pumps [14] and fans [10–13] through closed-loop control schemes. Kim et al. numerically studied the capability to adjust the heat pump compressor speed to provide FR to the grid [15–18]. However, the complexity of their controller design limits its use in a practical experiment, although simulation results demonstrated a minimal influence on occupant thermal comfort. Dallmer-Zerbe et al. [19] numerically investigated the impact of a high penetration of air to water heat pumps and PV plants on the distribution grid. The heat pumps were controlled to support voltage stability by adjusting the compressor speed through a pre-designed rule-based droop controller. Wang et al. [14] experimentally evaluated the performance of water pumps for the provision of FR. A proportional-integral-derivative (PID) controller was designed to adjust the pump frequency to track the desired power trajectory. Hao et al. [10–11] demonstrated a closed-loop feedback RBC algorithm to track the regulation reference signal by adjusting the supply air fan speed, and numerical experiments show that it is feasible to use up to 15 % of the rated fan power for regulation service to the grid, without noticeably impacting the built environment and occupants' thermal comfort.

The internal compressor speed control system in chillers and heat pumps limits the direct use of this strategy for onsite experiments with chillers and heat pumps, but the local controllers for fan and pump speed can be directly manipulated by a BAS to implement GEB control with minimal retrofitting. However, caution is required for a successful implementation. For load shedding, temporarily limiting the speed of fans or pumps may cause problematic fluid distribution among different air-conditioned zones [63], and result in power rebound during post-DR periods when the fans or pumps have to speed up to restore the system to its baseline. Besides other interactive components may also counteract the reduction (e.g., cooling coil valve may open wider if the supply air fan speed is limited to a low value). Therefore, additional assistive strategies are required, such as a fluid distribution controller to address the problematic fluid distribution during DR events [63], a step-wise increase of the fan speed during post-DR periods [51], and locking the cooling coil water valve position when reducing the fan speed [51].

4.3. Strategy 3 – Quantity of operating equipment adjustment

Large commercial HVAC systems may have multiple chillers, pumps, fans, and electric heaters to support the whole building operation. The quantity of these operating equipment could be controlled to provide a temporary power reduction by shutting some online equipment down, or a temporary power surge by bringing offline equipment online (e.g., to balance an overabundance of generation at windy nights). The response of turning on/off additional electrical equipment is very fast. If the electrical HVAC equipment is turned off to shed load using this strategy, then additional passive (e.g., building envelope) or active (e.g., chilled water storage) storage techniques must be leveraged to maintain occupants' thermal comfort. This strategy is widely documented in the literature for energy efficiency through optimal control, load shedding upon request, and limited load modulating when used in an aggregated

manner.

For energy efficiency, research has been conducted to control the number of pieces of operating equipment to reduce energy use by HVAC systems. For example, the optimal operating number of pumps for a given condition is the one with the minimum total power consumption while still satisfying the system head and water flow rate requirements. Ma et al. [64] proposed an optimal MBC algorithm to reset the number of operating pumps and the pump speed in order to achieve energy savings. Their simulation results demonstrated energy savings of 12.67 %.

For load shedding, temporary shutdown of limited operating equipment can provide power reductions for a short duration with the presence of passive thermal storage in the building and can provide greater power reductions for a longer duration when active thermal storage is also available. Both RBC and MBC can be used to achieve real-time grid service delivery. Wang's group [63,65–67] studied the capability to shut down one or more of the operating chillers and associated pumps to respond to load curtailment requests using MBC. Although the reduction is immediate, extra attention, such as designing a predictive controller that rebalances water and air flow distribution during the curtailment event, is required to avoid an imbalance of fluid distribution and a power rebound. They also relaxed thermal comfort requirements, which led to significant demand reduction, ranging from 23 % to 66.45 % of total baseline HVAC system power for a DR duration of 1–2 h. Motegi et al. [51] experimentally reduced the fan quantity for DR in an office, an auditorium and a cafeteria. Half of the constant air volume (CAV) AHU fans were turned off for 3 h in the auditorium and for 1 h in the cafeteria and the office. The demand reduction was estimated to be as high as 28 %. Bianchini et.al. [44] designed a MPC to enable space heaters to provide the load curtailment upon request.

For load modulating, this strategy is usually considered in an aggregated way to provide overall load following to the desired power profiles. Load following requires that resources adjust their output up or down in a short period of time, on the order of minutes. The control resolution is limited to minutes instead of seconds due to the physical constraints of load devices and practical communication limitations. The use of distributed heat pumps as dispatchable resources has been proposed as a means to avoid transformer overloading using a predefined RBC [68], and to follow the power profile in the energy market, also by use of RBC [69]. Biegel et al. numerially demonstrated how the aggregator can manage the portfolio of distributed heat pumps to collectively provide upward and downward regulation by a RBC [32]. However, the RBC was only experimentally demonstrated to follow an hourly power reference signal due to the practical communication limitations [26]. Large-scale electric heaters were also proposed to provide frequency reserve for the grid by formulating and solving the dispatch process as a binary linear optimization problem [70].

This strategy has advantages in terms of its response time and the magnitude of load reductions in a short time. When implemented together with passive or active thermal storage, this strategy can provide a longer duration of load curtailment without compromising occupants' thermal comfort. The disadvantages lie in four aspects: first, the strategy may lead to a rebound effect during the post DR period, where HVAC system tends to use some extra energy to bring systems back to normal conditions [63,65–67]; second, shutting down critical equipment (e.g., chillers and pumps) would lead to an imbalance of fluid distribution [63,66]; third, the HVAC's available capacity will be reduced with this strategy due to the deactivation of key equipment. The remaining online equipment may have to work at their full capacities to mitigate the effects, which could result in an unexpected power increase [51]; forth, this strategy must avoid short-cycling equipment to minimize wear [32].

4.4. Strategy 4 – chiller/heat pump discharge temperature setpoint

Resetting the discharge temperature setpoint in a primary loop with chillers or heat pumps has been proposed for energy efficiency, load shedding and load modulating. Chillers usually have a built-in controller to regulate the CHWST, and an additional discharge temperature controller can be installed on heat pumps. The transient power response to changing setpoint in a chiller or a heat pump depends on the details of their proprietary onboard control algorithms and their efficiency curves. Take chillers as an example: an adjustment of the chilled water supply temperature setpoint (CHWSP) is a part of the traditional chiller operation and can influence the chiller power without modifying unknown proprietary internal control logic. Presumably, the chiller's onboard logic considers physical limitations to meet the CHWSP without negative consequences. Due to the proprietary onboard control in the chiller, the response time of the chiller to the CHWSP change is usually unpredictable, but within minutes. The literature shows response times of 5 ~ 20 min [71].

Resetting CHWSP has been considered a cost-effective strategy to improve energy efficiency in HVAC systems. Because a chiller is typically the largest single electricity consumer in a commercial HVAC system, and its power and capacity are tightly related to its supply chilled water temperature, a lot of researchers have proposed scheduling the CHWSP to achieve device-level or system-level energy efficiency [72–74]. Numerical and experimental studies have shown a relative energy saving of 3.5 %~58 % can be achieved if this strategy is optimally designed [73].

Some researchers have demonstrated short-term power reductions by increasing CHWSP [51,55,57]. Most chillers perform with a higher efficiency at a higher CHWST, however, if chilled water pumps or AHU fans are equipped with VFDs, the energy use of the distribution loop increases under this strategy. Warmer water temperatures require more chilled water to maintain the SAT, or more air to maintain the room air temperature. Therefore, this strategy has to come with additional sequences such as adjusting the SAT simultaneously [55], and limiting pump/fan speed prior to the curtailment [51,57]. Simple rules are typically used for this application, such as increasing the temperature by a certain amount to achieve a desired level of load shedding.

There is also research exploring the capability of fast DR to provide FR, by constantly resetting the discharge temperatures (supply chilled water for chillers and supply air for heat pumps). Su et al. [34,75] described the experimental development and performance of a practical controller that modified the chiller-level power demand to provide FR aimed at the PJM regulation market. The authors designed a FR controller using PID to track the desired power profile by adjusting the CHWSP. Controller demonstrations using standard electric system operator test routines showed that the chiller power response could meet the qualification requirements while providing up to ±25 % of chiller nameplate power as the secondary FR capacity. Kim et al. [15] controlled discharge water temperature for an air-to-water heat pump, and experimentally demonstrated that this strategy was able to provide FR service with a performance score of around 0.8 and a FR capacity ranging from 25.72 %~37.16 % of the heat pump nominal power with a well-designed PI controller.

The chillers in commercial buildings are typically equipped with a built-in control panel, which facilitates the modifications of supply chilled water temperature at users' request. The cons lie in two aspects; one is that if used for temporary load reductions, this strategy must include locking fan/pump VFDs to avoid increased energy use in the distribution loop [51,63]. The other con is that if used to continuously modulate power, this strategy can lead to an unpredictable response of the chiller power to the continuous changes of CHWSP due to the proprietary built-in controller that tracks the setpoint [34]. This strategy is barely studied for the air-to-air heat pump system because such heat pumps typically have no control of discharge temperature. Instead, they are controlled to maintain the zone air temperature. To use this strategy, one would need to install additional software and hardware, which might not be cost-effective.

4.5. Strategy 5 – Pressure setpoint adjustment

For a variable flow distribution loop, pumps or fans with VFDs are usually controlled by a feedback controller to track a pressure setpoint (for fans) or a differential pressure (DP) setpoint (for pumps). Reducing the setpoint results in a reduction of fan or pump speed. The setpoint then can be reset to provide the demand flexibility.

This strategy has been widely studied for achieving energy efficiency. For a chilled water system, if a higher-than-design-value DP setpoint is set, cooling coil valves will partially close under a part-load condition, which may increase the system resistance, and may result in more pump energy consumption depending on the pump and system characteristic curves. If a lower DP setpoint is set, the valves will open more, and some of them would be 100 % open even at a small load, which would lead to the uncontrollable valves and their competition for chilled water (i.e., starved coils). Therefore, a proper DP setpoint should be scheduled to achieve energy efficiency. The authors in [64,72–73] numerically investigate this strategy for a large HVAC system, and by optimally resetting the setpoint, they can achieve 2 %–32 % energy savings compared with fixed DP setpoints.

For load shedding, this strategy is more widely studied for fans than pumps. Blum et al. [57] numerically investigated the impact of changing the fan static pressure setpoint to shed loads from a chiller system with an AHU. Large-scale dynamic simulations were conducted to investigate the power reduction in 10- and 30-minute intervals in response to a reduction in static pressure setpoint. The simulation results showed that this strategy could achieve a similar system-level power reduction compared with the strategy of zone temperature adjustments, and much larger reductions compared with the strategy of chilled water temperature adjustments.

For load modulating, this strategy can provide rapid power changes. Maasoumy et al. [76] modulated the static pressure setpoint for the main supply air duct to provide FR service to the grid. The response time of the fan to the pressure setpoint changes was experimentally demonstrated to be within a minute. The ramping rate of power changes can be as large as 18 % of the nominal power per second. The setpoint was manipulated by a simple proportional controller to deliver desired power changes in response to grid signals. Zhao et al. [61] evaluated the adjustment of static pressure setpoint for the provision of FR using MPC.

This strategy, as a part of currently available local control for the HVAC system in a typical commercial building, needs minimal retrofit for GEB applications. The limitation is that it might not work well for fans when fans are operated to maintain the minimum air flowrate due to ventilation requirement [51].

4.6. Strategy 6 – Flowrate setpoint adjustment

In a typical HVAC system, water or air flowrate is controlled by regulating valve or damper positions, respectively. When these positions change, pressure in a water or air loop changes accordingly if the loop is equipped with variable speed pump or fan. Hence modulating loop pressure (Strategy 5) results in pump or fan load modification. It is also possible to keep the loop pressure setpoint to be a constant and by adjusting flowrate setpoint to affect pump/fan energy. When the motor speed is manipulated to track the flowrate setpoint, rescheduling the flowrate setpoint can provide demand flexibility. This strategy is available only when the normal BAS regulates fan/pump speed to track the flow rate setpoint. Otherwise, retrofit of the BAS is required for demand response control. The literature has mostly investigated this strategy for load modulating applications [77–78].

For load modulating, numerical and experimental studies have been conducted for FR provision. Lin et al. [77] first designed an MBC to adjust the supply air flow in a VAV system and numerically investigated its performance. They then experimentally demonstrated the use of one AHU supply air fan in a commercial building to provide FR service [78]. The flowrate setpoint in the experiment consisted of two parts: the amount required by the original BAS to maintain the room air temperature, and the changes calculated by an ancillary service controller to track the service signals from the market. The fan was shown to be able to provide 40% of its nominal power as a FR capacity in the PJM market.

4.7. Strategy 7 – Electrical storage power charging rate adjustment

Electrical storage, such as batteries, is not commonly used in current commercial buildings, but in recent years it has been widely studied and proposed as an efficient way to manage power demand. The capacity of electrical storage can also be used for load shifting and load shedding, and the fast charging and discharging characteristics of electrical storage empowers it to be a perfect candidate for ancillary services in the near future.

Batteries as electrical storage have been widely proposed to provide load shifting for electric grids [79–80], micro grids [81–82] and smart buildings [83–85]. The batteries are charged when the electricity price is low or the on-site generation is high and discharged when the electricity price is high. In such a way, batteries can shift the electrical load from high-price periods to low-price periods. However, researchers have reported that current battery technologies are economically unattractive at the building level because of the high cost of new batteries [83–85]. For this reason, Beer et al. [81] resorted to using second-hand batteries (e.g., from electric vehicles), to reduce capital costs.

As capacity resources, batteries can also be used for load shedding. Pardo et al. [86] proposes a scenario-based programming method to schedule the day-ahead operational power of chillers with electrical storage to minimize the daily expected cost under the forecasted ambient temperatures and DR scenarios. The considered DR events are load curtailment under a duration of 2 h at different on-peak hours.

Due to the fast charging and discharging characteristics of electrical storage, many researchers consider batteries as modulating loads to provide ancillary services from buildings. Batteries alone can deliver a fast response to the grid signal, but due to their limited capacity, coordinating fast-responding batteries and slow-responding resources such as heat pumps has been widely studied to provide ancillary services. Kim et al. [18] and Biegel et al. [27] utilized batteries and heat pumps to provide FR to the grid. The benefit of utilizing fast resources together with slow resources in FR was numerically demonstrated to increase the regulation capacity, which increases the monetary revenues from the regulation electric market [71].

In summary, this strategy can enable electrical storage for load shifting, load shedding and load modulating. However, due to large initial costs and operating costs, electrical storage is currently economically unattractive for building-level integration [83–85]. In terms of load shifting, if participating in real-time pricing programs, the strategy needs careful attention in the design phase, because a real-time price is difficult to predict, which causes problems in making optimal decisions about charging and discharging periods.

4.8. Strategy 8 – Supply air temperature adjustment

For cooling applications, an increased SAT setpoint may lead to an increase of the chilled water return temperature, which might lead to improved chiller efficiency, depending on the chiller efficiency curve. However, an increased SAT setpoint will lead to an increased supply air flowrate, for VAV AHU systems, and hence an increased fan power consumption. An increased SAT setpoint will not change fan power consumption for CAV AHU systems but might lead to under-cooling of zones. The tradeoff in energy use between the air side and the water side should be considered when utilizing this strategy.

This strategy has been studied mainly for load shedding and load modulating. Olivieri et al. [55] investigated the potential of short-term load curtailment using a typical chilled water VAV system. The authors found that utilizing the SAT together with other strategies, such as zone air temperature adjustment, can significantly increase the demand

flexibility. Douglass et al. [28] presented their experimental results using demand as a frequency-controlled reserve on appliances with programmable thermostats. Electric space heaters considered in this paper were treated as thermostatic loads, which were controlled by following a SAT setpoint. The tests showed that electric space heaters were able to provide frequency reserves of a magnitude of 2.7 times their average power consumption.

This strategy needs additional attention for load shedding if used for a VAV system. First, the fan VFD must be locked at the position prior to the DR operation to prevent an increase in fan power [51]. Second, cooling demand savings will not be achieved until some VAV dampers begin to fully open. Therefore, there will be a time lag between the strategy initiation and the achievement of demand shed. Third, it is hard to predict the SAT increase that can result in demand savings in real-time, and therefore a field test or dynamic simulations are needed prior to the actual implementation.

4.9. Strategy 9 – Power usage level adjustment

The power input of some devices, such as space heaters, can be modulated with existing power level controls or additional pulse width modulation. This strategy has been proposed for load shifting and load modulating.

Nolan et al. [87] assumed the power input of an electric heater is adjustable, and formulated a load shifting problem to minimize the building's operation costs in response to electricity prices. The load shifting was provided by electric heaters together with water tanks. The shifting was controlled by an MPC. Gorecki et al. [33] and Fabietti et al. [29] utilized space heaters equipped with a pulse width modulation function to provide the FR service. The power of electric heaters was manipulated to track the FR signals continuously. Their simulation and experimental results showed that the proposed control framework could provide a real-time FR with minimal comfort violations.

Although this strategy can provide similar benefits as direct load control, it requires the targeted equipment, such as electric heaters, have adjustable power input levels. For single stage equipment, additional hardware, such as a pulse width modulation, needs to be installed and controlled.

4.10. Strategy 10 – Thermal heat charging rate adjustment

Active thermal storage has been widely studied as a DSR. There are also a few reviews on the utilization of thermal storage systems for DR. Sun et al. [88] provided a review on peak load shifting control using cold thermal storage in commercial buildings. Arteconi et al. [89] provided a review on using thermal storage as a demand side resource for both cooling and heating systems. Thermal storage equipment, such as a chilled water tank, cannot provide demand flexibility by itself unless it is integrated with other electrical equipment such as chillers and heat pumps. Active thermal storage systems may not provide system-level energy efficiency, but have been widely studied to demonstrate their benefits in terms of increasing energy efficiency of equipment such as chillers and heat pumps since a thermal storage system allows chillers etc. to be operated at a more favorable weather conditions (during the evenings, for example) [90–93].

Load shifting is the most widely studied grid service using this strategy for a coupled HVAC system. The thermal storage charging rate can be controlled to respond to different pricing schemes. MPC is mostly used for this purpose. Cao et al. [43] considered a chiller system with an ice storage system for load shifting purposes. The charging rate of the storage was optimized to minimize the energy and demand costs using an MPC scheme. Brahman et al. [94] studied the load shifting capability of thermal storage in the context of an energy hub in response to TOU price tariffs and renewable energy generation.

Thermal storage can also be used in load shedding with other electrical devices. Cui et al. [95] considered a chiller system with active thermal storage as a source of spinning reserve. The authors developed a control strategy to provide an immediate and stepped power demand reduction through shutting chiller(s) down when requested. Simulation results showed that the developed strategy could provide significant power demand reduction (up to 34.9 % of chiller power) through shutting down chiller(s) during a DR event without significant sacrifice of indoor thermal comfort when a relatively small storage (i.e., 7.3 % of the daily cooling load) was used.

The utilization of thermal storage for load modulating purposes has recently emerged. Van Asselt et al. [96] presented a strategy for load following by controlling cool thermal energy storage systems to enable an increased penetration of intermittent wind and solar generation. The chilled water tank was charged by chillers whenever there was sufficient renewable energy, such as during the peak solar production period in the middle of the day or, with significant wind power generation, during the off-peak periods at night. It would then be discharged to cool the buildings during the peak demand hours that occur in the late afternoon or evening. For fast load modulation such as FR, Fu et al. [39] proposed using a chilled water tank together with chillers to provide the FR service. The numerical study demonstrated a FR performance score of around 0.94 by tracking the historical RegD signal from the PJM regulation market.

Thermal storage has traditionally been used for load shifting and load shedding. Recently, it has been proposed as an emerging technique for slow and fast load modulation [39,96]. However, experiments are still needed to demonstrate its capability for providing fast DR.

4.11. Strategy 11 – Direct AHU valve/damper position adjustment

For a chilled water system with AHUs, the supply fan power can be indirectly influenced by adjusting the waterside valve position or the damper position in the air-side economizer. Some researchers have proposed using this strategy to enable the provision of the grid service. For example, by limiting or closing the cooling valve positions, this strategy reduces chilled water flow and saves electric demand at the central plant. The investigated flexibility modes include load shedding and load modulating.

For load shedding, Motegi et al. [51] applied this strategy to a cooling system for a campus library at the University of California Santa Barbara. The experiment was conducted during a day in November, when the maximum outdoor air temperature was about 21 °C. The chilled water was supplied from a campus-wide chilled water network, and during the DR event the cooling valve was completely shut off to reduce chiller demand at the central plant. The fan was kept operating at a lower speed (e.g., 60% − 70%) to deliver the fresh air to the zones. The possible side effects on the thermal comfort and the indoor air quality were not reported. This strategy can provide a significant decrease in power demand. However, they also observed that the cooling power demand had a rebound peak at the end of the shed period and was greater than the baseline demand for that time period.

For load modulating, Zhao et al. [61] numerically evaluated four control strategies for providing FR from a commercial building using a high-level MPC. One of the strategies was to adjust an outside air damper position without violating ventilation requirement. The simulation results showed that adjusting the outdoor air damper results in lower FR performance scores because the outdoor air fraction was determined by an open-loop controller based on outdoor and indoor air temperatures; thus, superimposing the FR signal on top of the outdoor air fraction could not result in accurate tracking of the FR signal with HVAC systems and would reduce the performance score.

This strategy is not commonly used, especially when other strategies are available. The reasons are multi-fold. First, it is difficult to accurately measure the opening of dampers and valves. Second, this strategy requires additional attention to the system and equipment operation [51]. For example, the cooling valve limits should not be set lower than the threshold to shut off the chiller that may lead to a significant loss of

cooling, and the damper limit should consider the ventilation requirements in the zones. Third, to compensate for the increase in the speed of the supply fans, the fan VFDs have to be locked at their positions prior to the DR operation to achieve demand savings [51]. Therefore, this strategy might be more suitable as an auxiliary strategy to other approaches.

4.12. Strategy 12 – Dynamic optical and thermal properties adjustment

Dynamic windows and envelope can change their optical or thermal properties as needed to increase energy efficiency. Using the building envelope thermal mass for active or passive thermal storage has been explicitly or implicitly utilized in previous strategies. Here Strategy 12 specifically refers to a very dynamic operation of windows and envelope. This strategy is mostly studied for energy efficiency, and its potential as a DR measure is not well-studied.

As an energy efficiency measure, this strategy can provide significant energy and demand savings. Dynamic windows, such as electrochromic devices, can be controlled to respond to changes in external (temperature, solar radiation), or internal (temperature, artificial and natural lighting levels, heat intakes, presence of people) climatic conditions, or the needs of users. The control of dynamic windows allows for the adjustment of the intensity of penetrating visible and infrared radiation without the use of screening systems, and can significantly reduce energy consumption for air conditioning and lighting [97]. Khandelwal et al. [98] experimentally demonstrated the use of a fabrication of electrically switchable broadband infrared reflectors based on the properties of cholesteric liquid crystals, and numerically demonstrated the energy saving performance by using simple temperature-based RBC. DeForest et al. [99], Firlåg et al. [100] and Grynning et al. [101] evaluated the control performance using different RBCs based on surface temperature, glaring index, thermal load, insolation, darkness values, etc.

Dynamic insulation has also been proposed for energy efficiency. Antretter et al. [102] assessed the potential of dynamic insulation using tunable thermal conductivity materials to reduce energy consumption and enhance electrical grid services. Different RBCs leveraging wall surface temperatures and indoor air temperature were evaluated. Park et al. [103] evaluated potential energy savings associated with variable reflectivity envelope systems, including cool roofs, and examined the combination of applying coatings that can change their reflective properties over time depending on outdoor conditions with desired control strategies.

This strategy is barely demonstrated in field experiments for GEB applications. There are a couple of reasons: first, this technology is still under development, including the design of suitable material, structures, etc. [98], which makes it as a cost-ineffective option currently; second, appropriate control design is still needed to fully exploit the potential of this strategy [100].

4.13. Comparison and discussions

Table 2 summarizes the application cases in the literature for each strategy. Although these strategies have been exploited mostly for utilizing different demand flexibility modes, and their advantages and disadvantages are analyzed, it is difficult to compare these strategies without considering the application scenarios and the studied HVAC systems. However, qualitative comparisons are still possible:

- Different strategies have different response time in terms of achieving the desired power changes. Strategy 1, which adjusts zone air temperature setpoint, and strategy 12, which dynamically changes the envelope properties, have the slowest response times of up to hours, while the other strategies have relatively fast response time. The different scales of response time determine their applicability to different GEB services. The response time of power changes also is influenced by the communication interval in the BAS. To provide a fast response, in addition to selecting the strategies with fast response times, the communication interval in the BAS needs to be setup to balance the power tracking performance and the communication overheads with a small time interval.
- For energy efficiency, these strategies are related to control system design or retrofit. The availability of the strategies is determined by the type and the size of the HVAC systems. Although a single strategy can be used for energy efficiency purposes (e.g., strategy 1, improving energy efficiency by adjusting zone temperature setpoint), coordinating all possible strategies can help achieve the maximum efficiency possible, although at the cost of expensive computation.
- For load shifting, zone air temperature setpoint adjustment together with passive or active thermal storage has been demonstrated numerically and experimentally in the literature. This strategy is popular for its easy implementation in the BAS and wide applicability for all commercial buildings. The other strategies are also feasible to provide load shifting with thermal storage, but they are limited by the type of HVAC system, and thus cannot be treated as a general solution, like strategy 1.
- For load shedding, except for strategy 12, all the other strategies have been investigated by utilizing implicitly passive thermal storage or explicitly active thermal storage for short-term load curtailments. Strategy 1 reduces the building load at the system level, while others target at the local level, which must consider the interactions among different local thermo-fluid loops for real implementation. All the strategies for load shedding should avoid rebound effect after the shedding event. Strategy 1 is also the most popular for load shedding.
- For load modulating, preferred strategies mostly target the local equipment level with fast response time, e.g., strategy 2 that regulates the motor speed. The selection of strategy depends on the HVAC system and its original control design. Although the zone air temperature setpoint adjustment cannot timely track a fast-changing reference power signal in a single building, it can be used to activate/deactivate a group of electrical equipment such as heat pumps in an aggregator to provide load modulating to the grid.

5. Integrated constraints in building-level delivery control

With the development of GEBs, integrated constraints such as thermal comfort and indoor air quality, occupancy and occupant behaviors, grid operations and combined demand flexibility modes, are being considered gradually in the control design.

The main purpose of a commercial building is to serve its occupants. Hence the majority of the building energy consumption is to maintain thermal comfort and indoor environmental quality. For the thermal comfort, zone air temperature setpoint is widely used for GEB applications in part due to the minimal amount of information required about occupancy. The zone air temperature is typically bounded within an acceptable range when a controller is designed for load shifting [22–23,54] and load modulation [10–11], and is limited by an upper bound for load shedding during cooling [63,65–67]. The group-level thermal comfort indicators such as the predicted mean vote or the predicted percentage of dissatisfied is being considered as a more comprehensive estimation of thermal comfort during grid service, even though much more information (e.g., mean radiant temperature) in addition to the dry-bulb temperature in a thermal zone are required [20]. Moreover, recent research starts to utilize individual thermal comfort of each occupant in the design of a demand response controller. Kim [104] presented a price-based load shifting framework to minimize the operation costs and the individual thermal discomfort in the building. Additional attentions to the accurate representation of the individual thermal comfort and the prevention of occupant interruption to the optimal demand response schedules should be paid when the individual occupant behavior is considered in the design.

Control of the CO_2 level has recently started to be included in the design of GEB controls. In 2018, Martin et al. [21] studied the influence of the demand response on indoor air temperature and CO_2 concentration in an office building with both CAV and VAV ventilation systems. They found that both the thermal comfort and CO_2 concentration can be maintained at an acceptable level. In 2020, Vand et al. [105] studied the DR potential of a VAVventilation system by regulating the zone air temperature, SAT, and CO_2 setpoint, and found up to 11 % of district heating energy cost can be saved for an education office building in Finland without violating air quality constraints.

Occupancy information has increasing importance in the context of GEB control. Dong et al. [106] proposed an occupancy driven building-to-grid integration framework for large commercial buildings. The occupancy predictor was integrated into building-level control to influence the zone temperature setpoint, and thus influence the building power demand. They then utilized the framework to study the impact of occupancy on the FR [107], and concluded that occupancy-aware control can save around 56 %~66 % of costs. However, this savings will be subject to the accuracy of the occupancy predictor. Korkas et al. [20] considered occupant behaviors such as window openings with temperature reset for DR for each building in a microgrid. Different occupancy schedules in different buildings allow some unoccupied buildings to switch off their HVAC systems and occupied buildings to use available renewable energy. Putra et al. [108] studied the building occupants' reactions to load-shedding events in commercial buildings. The studied behaviors include changing clothing, turning on/off space heaters and portable fans, and thermostat adjustments. Their simulation results indicated that with adaptive occupant behaviors, the building can be over-cooled before load shedding events while maintaining occupants' thermal comfort. Geneidy and Howard [109] pointed out that MPC with occupancy awareness might lead to zero demand flexibility for the buildings especially residential buildings when the DR event coincides with the building's unoccupied period.

Integrating power grid operations in GEB control is also an active research topic. Constraints in the power grid are being considered when formulating GEB controls. Most current studies simplified the interactions between the power grid and building operations by assuming that buildings participating in DSM programs would not affect the grid signals. However, this assumption is invalid when the penetration of GEBs in a power grid is high. Power grid may not be affected by one individual GEB but can be affected by a cluster of GEBs. Power grid operation requires grid-level control for economic dispatch and unit commitment as part of an optimal power flow (OPF) problem formulated to balance the supply and the demand. The OPF problem takes into consideration physical constraints such as grid frequency, voltage stability and transmission limits. The solution to the OPF problem would result in time-varying grid signals. With a high penetration of GEBs in a power grid, the flexible power demand can influence the procurement of the supply and thus the energy price significantly. Patteeuw et al. [22] co-optimized the grid operations and building operations to study the load shifting incentives to attain grid flexibility benefits. They mentioned that with a high penetration of flexible heat pumps, direct load control programs would outperform price-based programs in terms of minimizing grid-level operational costs. However, without considering capital costs for implementing these two types of programs, it is still unclear which type should be selected. Fontenot et al. [110] proposed an integrated framework coupling commercial and residential buildings, and various DERs, with the power distribution network, enabling buildings and the distribution networks to be optimized simultaneously while respecting both building and distribution network constraints. The framework was used to minimize the distribution network active power losses and enhance the voltage regulation.

Another research trend is to combine different demand flexibility modes simultaneously to minimize the operation costs in GEBs. Common combinations are load shifting with load modulating [39,111], and load shifting with load shedding [43]. Currently, load shifting and load modulating are mostly studied for the provision of FR, where a power usage baseline and a FR capacity bid need to be scheduled hourly. Load shifting can be used to schedule the baseline power, and thus influence the capacity bid. A typical shifting resource is thermal storage, such as building thermal mass or an active thermal storage tank. Load modulating resources such as variable speed fans are used to track the FR power signal at an interval of seconds. Fu et al. [39] scheduled the baseline power for a chilled water system with chilled water tanks to maximize the capacity bids for FR, and adjusted the CHWST together with the computer server CPU frequency to track the fast FR power signal in a data center. Tang and Wang [111] formulated an optimal dispatch problem with multiple slow and fast resources participating in multiple electrical markets such as energy market, regulation market and reserve market. The simultaneous coordination of the slow and fast resources at the central level leads to a large optimization problem to solve, which might be impractical for real-time implementation. One other potential but not well studied use case of using load shifting with load modulating is to schedule the baseline power to provide a symmetric upward and downward regulation capacity.

For load shifting with load shedding, by leveraging load shifting resources, GEBs can provide a deeper and/or longer load shedding capability. For example, building operators usually receive load curtailment notices hours ahead, and they can utilize load shifting resources (e.g., thermal storage) during the notice period to pre-cool the building. During the curtailment period, the thermal storage could be discharged, which may provide a deeper curtailment by eliminating the needs of chillers [43]. Chen et al. [112] experimentally investigated thermal storages in improving the demand flexibility for load shedding events. However, the rule-based control may not fully exploit the improvement potentials. More researches are still needed in this direction.

6. Conclusions and future work

This review paper provides a systematic review of the development and applications of grid service delivery control strategies for commercial grid-interactive efficient buildings. Twelve strategies have been studied for energy efficiency, shifting, shedding and modulating numerically or/and experimentally in the literature. Heuristic rule-based control and model-based control are typically used to enable the automatic control delivery of grid services. Each strategy is analyzed in detail in terms of their pros and cons. Zone temperature adjustment is most recommended for load shifting and load shedding because of its applicability to all HVAC systems and ease of implementation. Indirect control of the motor speed of pumps and fans through differential pressure setpoint or mass flowrate setpoint are most recommended for load modulating applications.

With the development of grid-interactive efficient buildings, more constraints are being considered in the control design, such as thermal comfort, occupancy behavior, grid operation and combined demand flexibility modes, etc. CO_2 and other indoor environmental factors are gaining increasing attention for evaluating indoor environmental quality and occupant satisfaction when providing grid services, and the behaviors of occupants under DR events are being increasingly studied to understand their impact on demand flexibility. Other trends include considering power grid operations in the building control design and combining different demand flexibility modes to gain maximum revenues from electric markets.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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