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Grid-interactive Efficient Buildings Technical Report Series

Whole-Building Controls, Sensors, Modeling, and Analytics

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List of Acronyms and Abbreviations

AFDD	automated fault detection and diagnosis
BAS	building automation system
BEM	building energy modeling
BTO	Building Technologies Office
DER	distributed energy resource
DOE	U.S. Department of Energy
GEB	grid-interactive efficient building
HVAC	heating, ventilation, and air conditioning
MPC	model predictive control
M&V	measurement and verification
PV	photovoltaic
R&D	research and development
T&D	transmission and distribution

Glossary

These definitions are for the purposes of the *Grid-interactive Efficient Buildings Technical Report Series*. They may be defined differently or more generally in other contexts.

Grid services	Services that support the generation, transmission, and distribution of electricity and provide value through avoided electricity generation and/or delivery costs; this report series focuses on grid services that can be provided by grid-interactive efficient buildings.
Distributed energy resource (DER)	A behind-the-meter resource that provides electricity generation, storage, or demand flexibility. Examples of DERs include solar photovoltaics (PV), wind, combined heat and power, stationary batteries, electric vehicles, and demand flexibility mechanisms such as smart thermostats, connected building automation systems (BAS), and other remotely controllable loads (National Association of Regulatory Utility Commissioners 2016).
Energy efficiency	Ongoing reduction in annual energy use to provide the same or improved level of building function.
Demand flexibility	Capability of DERs to adjust a building's load profile across different timescales; energy flexibility and load flexibility are often used interchangeably with demand flexibility.
Demand response	Activation of demand flexibility in response to price signals or explicit commands from the grid.
Grid-interactive efficient building (GEB)	An energy-efficient building that uses smart technologies and on-site DERs to provide demand flexibility while co-optimizing for energy cost, grid services, and occupant needs and preferences in a continuous and integrated way.
Smart technologies for energy management	Controls, sensors, models and analytics used to manage energy efficiency and demand flexibility in buildings and DERs. GEBs are characterized by their use of these technologies.

Executive Summary

Buildings account for more than 70% of U.S. electricity use and a comparable share of peak electricity demand. Fittingly, they are also a promising source of grid services. Buildings can use the flexibility inherent in end uses such as heating, ventilation, and air conditioning (HVAC); lighting; and appliances to help balance demand with supply at different timescales and to avoid transmission and capacity constraints.

Currently, grid services such as peak load reduction and frequency regulation are disaggregated from one another and from electricity use. As a result, grid service provisioning is also implemented in a disaggregated fashion within buildings; although, unless for extremely large buildings or campuses, services are aggregated outside the building. Grid service provisioning today also rarely gives explicit and dynamic consideration to occupant impacts and preferences. Again, this is reasonable given that grid services are invoked infrequently, for short periods of time (e.g., a few hours), and can often be spread thinly over large numbers of customers.

In the future, population growth, economic growth, electrification, increased renewable penetration, and more frequent extreme weather will increase the demand for grid services. In this regime, it may become beneficial to integrate the provisioning of different grid services with one another, with energy efficiency, and with occupant needs and preferences. A building that integrates the flexibility available in its various end uses and in other behind-the-meter resources with energy efficiency to continuously optimize for energy cost, grid needs, and occupant preferences is a grid-interactive efficient building (GEB). This report explores the benefits and challenges of building-level grid service integration and identifies the gaps in building-level integration technologies, including control, sensing, and modeling.

There are a number of considerations for building-level grid service integration, mainly overall system performance on one side of the ledger and complexity and cost of integration on the other. We consider these and several others on a grid service and end-use basis, and this report is structured around groups of services and end uses that share integration characteristics.

The most basic and powerful grid service and the basis of GEBs is energy efficiency. Whole-building control and modeling for energy efficiency are not yet “solved” or maximized. Advances in the effectiveness, cost, and usability of these technologies will advance GEBs. Two important areas are interoperability and cybersecurity for building sensing and automation. Better integration between whole-building energy modeling and control implementation workflows is also needed.

From an aggregate capacity standpoint, the greatest potential exists in grid services that use the building’s thermal mass to shed and shift HVAC load. Coordination of multiple devices, coupling with building thermal mass, and mechanisms and processes that couple zones together (e.g., central plants, interzone airflow) make it likely that building-level approaches will outperform device- or zone-level approaches for these services. Integration at larger scales may be beneficial if shared thermal “district” systems are present. Implementation-wise, these services benefit from model predictive control (MPC) because of their weather dependence and direct impact on occupants. We use MPC in the broad sense to describe feedback control schemes that optimize over a receding time horizon—for HVAC that time horizon is typically a day, but it can be longer for configurations with significant active thermal storage like district systems. A model is needed to both evaluate control sequences and to calculate zone conditions for occupant comfort. There are a number of challenges associated with MPC, including model development, adaptation, and interpretability. Advances in occupant-comfort sensing and occupant interaction are also needed. It may be beneficial to integrate management of on-site generation and electrical storage with the provisioning of these services, because these are also building-, or district-, level resources, and because generation is also weather dependent.

Shedding and shifting services using other end uses such as lighting, refrigeration, appliances, and computing do not have to be tightly integrated with one another or with HVAC-based services. Except for in specific contexts like data centers and supermarkets, these end uses do not interact strongly with HVAC or one another. Grid services based on these end uses only need to be prioritized and allocated energy resources from a total energy budget; coordination mechanisms like transactive control suffice. These coordination schemes can scale to multiple buildings when end uses are not served by physically shared systems.

The final group of grid services are so-called “fast” services that target power signal characteristics like frequency and voltage. Because of latency constraints, these services are likely best implemented at the device level without the additional layering of whole-building control and telemetry. Energy-neutral fast services have no energy or occupant impacts and can be implemented independently of shedding and shifting. Fast services that are not energy neutral may need to be integrated with energy efficiency, shedding, and shifting. This integration is likely to be complex and may overwhelm the benefits of using buildings to provide these services.

The report concludes with a list of research and development needs and directions.

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1 Introduction

Energy efficiency, low annual energy use often accompanied by low peak demand, is the ultimate service a building can provide to the grid. At any given level of energy efficiency, a building has a certain degree of demand flexibility, the ability to temporarily reduce or shift some of its energy use without negatively impacting occupant comfort or building services. A building can provide significant value to the grid by strategically and responsively activating its demand flexibility.

Today, building demand flexibility is activated situationally and infrequently in response to price signals or explicit requests from the grid, and in a manner that is distinct from normal energy-efficient operation—this is demand response. Energy efficiency, demand response, and behind-the-meter distributed energy resources (DERs), including generation and storage, are typically valued, managed, and transacted separately.

In the future, growing renewable penetration and more frequent and extreme weather events will increase both the need and opportunity for demand flexibility and push it to be integrated into "normal" energy-efficient building operation in a more holistic and continuous fashion—this comprises grid-interactive efficient buildings (GEBs). The U.S. Department of Energy (DOE) Building Technology Office's (BTO's) GEB vision is the integration and continuous optimization of these resources for the benefit of the buildings' owners, occupants, and the grid.

1.1 Purpose of This Report

To help inform the greater building research community and advance BTO's research and development (R&D) portfolio, BTO has published a series of technical reports that evaluate the opportunities for GEBs. In addition to this report, an overview report and three other technology reports were published in 2019 as part of the *GEB Technical Report Series*, covering major relevant building technology areas with significant potential for demand flexibility:

- *Overview of Research Challenges and Gaps*[1]
- *Heating, Ventilation, and Air Conditioning (HVAC); Water Heating; Appliances; and Refrigeration*[2]
- *Lighting and Electronics*[3]
- *Windows and Opaque Envelope*[4]
- *Whole-Building Controls, Sensors, Modeling, and Analytics* (this report)

The *Overview of Research Challenges and Gaps* report serves as an introduction to these technical reports and provides background on core concepts of GEBs. It explains how flexible building loads can be integrated and controlled to benefit consumers, the grid, and society more broadly.

The individual technology reports evaluate current state-of-the-art and emerging technologies that have the potential to provide grid services. Each report identifies major research challenges and gaps facing a specific set of technologies and opportunities for additional technology-specific R&D. These reports will help inform and guide BTO's R&D portfolio and serve as a foundational resource for the larger building research community.

Although these reports focus on flexibility provided by buildings and technologies used to operate buildings, on-site behind-the-meter generation, battery storage, and electric vehicles are also an important part of GEB. This report specifically addresses where and how DERs like solar photovoltaics and battery storage can be integrated with other flexible loads to provide building-based grid services.

BTO's mission is to support the R&D, validation, and integration of affordable, energy-saving technologies, techniques, tools, and services for buildings, existing and new, residential and commercial. To advance this mission, BTO is developing a GEB strategy that aims to advance the role buildings can play in grid operations and planning. The GEB strategy supports broader goals, including affordability, resilience, sustainability, and reliability, recognizing that:

[1] Available online at: https://www.nrel.gov/docs/fy20osti/75470.pdf.
[2] Available online at: https://www.nrel.gov/docs/fy20osti/75473.pdf.
[3] Available online at: https://www.nrel.gov/docs/fy20osti/75475.pdf.
[4] Available online at: https://www.nrel.gov/docs/fy20osti/75387.pdf.

- Building end uses can be dynamically managed to help meet grid needs and minimize electricity system costs, while meeting occupant comfort and productivity requirements;
- Technologies such as rooftop photovoltaics (PV), battery and thermal energy storage, combined heat and power, electric vehicle charging stations, and other DERs can be co-optimized with flexible building loads to provide greater value to both utility customers and the electricity system; and
- The value of energy efficiency, demand flexibility, and services provided by other behind-the-meter DERs can vary by location, time of day, season, and year.

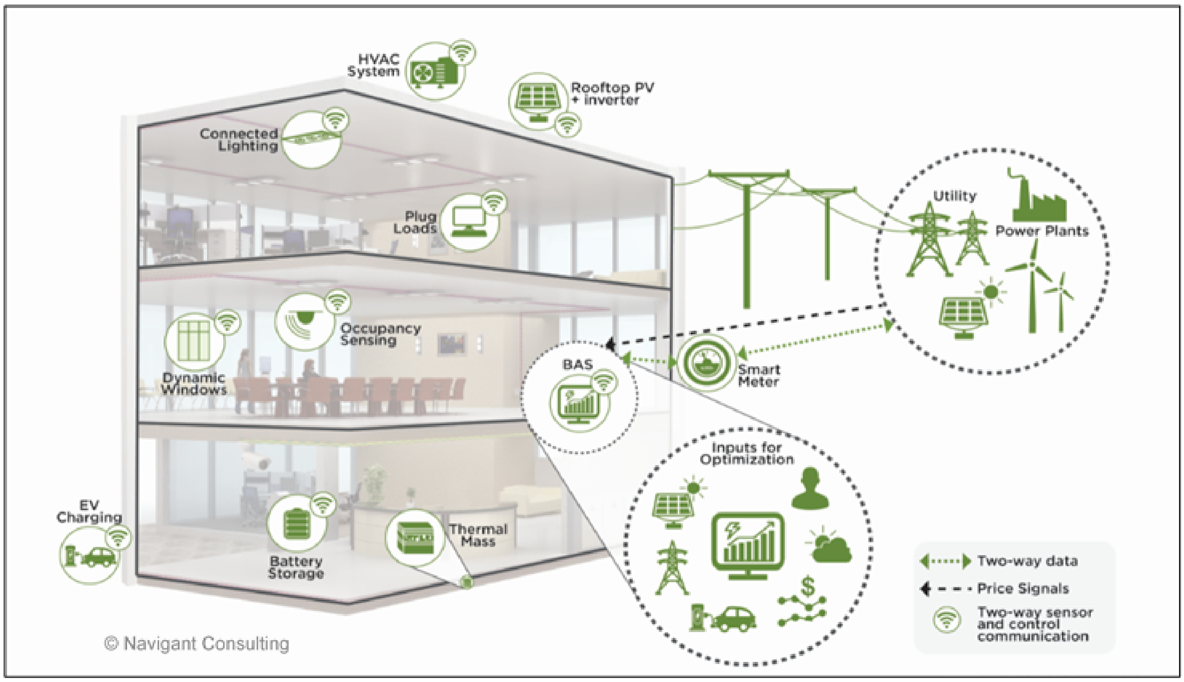

Figure 1. Example grid-interactive efficient commercial building.

Managing a range of energy assets, responding to changing ambient and grid conditions, saving energy, and meeting changing occupant needs present challenging optimization and coordination problems. Tackling these and realizing GEBs require advanced control, supported by sensing, modeling, and data analytics. These technologies are represented by the sensing and building automation system (BAS) elements in Figure 1. This report addresses the current state of these technologies and the challenges of adapting them to the GEB context. Note that BTO's controls and sensing program and its whole-building energy modeling program have each published draft Research and Development Opportunities documents. Those documents deal with some of the challenges discussed here, but are primarily focused on the use of these technologies to support energy efficiency.

1.2 Grid Services and Demand Flexibility Modes

As noted in the *Overview of Research Challenges and Gaps* document, buildings, their various end-use occupant services, and on-site DERs (such as PV and battery storage) have multiple flexibility modes that can support different grid services. Grid services represent a spectrum of timescales, power magnitudes, and market sizes. For the purposes of this report, we divide them into two categories:

- Services that target generation and transmission/distribution capacity—both various degrees of under capacity as well as over capacity—including traditional day-, hour-, and 15-minute-ahead energy, peak load shaving, standby and contingency reserves, avoidance of renewable curtailment, and "non-wires" transmission and distribution (T&D) solutions. These services are typically episodic, operate for multiple hours, have response times of minutes to hours, reduce (or sometimes increase) draw by hundreds of kilowatts to megawatts, and have large wholesale markets. Buildings can provide these services by shifting and shedding electrical load.

- Services that target nonload power characteristics, including frequency regulation and voltage support. These services operate continuously, with response times of seconds or less, and currently have much smaller markets. Buildings can provide some of these services by rapidly modulating electrical load in equipment such as light-emitting diodes and variable frequency drive motors.

Some services exist on the spectrum between these endpoints. To streamline and organize the report, we use the following categorization of grid services and building flexibility modes:

Table 1. Mapping Demand Flexibility Modes in Buildings to Grid Services

Flexibility Mode	**Grid Services**	**Definition**	**Key Characteristics**	
Efficiency (Sec. 2)	*Generation: Energy & Capacity; T&D: Non-Wires Solutions*	Persistent reduction in load. Not dispatchable.	Load change Duration Response time Annual events	Long-term reduction Equipment lifetime N/A Continuous
Shed (Sec. 4 & 5)	*Contingency Reserves*	Short-term load reduction to make up for a shortfall in generation.	Load change Duration Response time Annual events	Short-term decrease Up to 1 hr <15 min <20
	Generation: Energy & Capacity; T&D: Non-Wires Solutions	Load reduction during peak load periods.	Load change Duration Response time Annual events	Short-term decrease 30 mins to 4 hrs 30 min to 2 hrs <100 hrs, seasonal
Shift (Sec. 4 & 5)	*Generation: Capacity; T&D: Non-Wires Solutions*	Load shifting away from peak use periods.	Load change Duration Response time Annual events	Short-term shift 30 mins to 4 hours <1 hour <100 hrs, seasonal
	Renewable Curtailment Avoidance	Load shifting to periods of excess renewable generation. Not dispatchable.	Load change Duration Response time Annual events	Short-term shift 2 to 4 hours N/A Daily
Modulate (Sec. 6)	*Frequency Regulation*	Rapid load increase/reduction following a grid signal.	Load change Duration Response time Annual events	Rapid increase/decrease Seconds to minutes <1 minute Continuous
	Voltage Support		Load change Duration Response time Annual events	Rapid increase/decrease Subseconds to seconds Subseconds to seconds Continuous
	Ramping	Rapid load reduction/increase to offset short-term renewable generation changes.	Load change Duration Response time Annual events	Short-term decrease Seconds to minutes Seconds to minutes Continuous
Generate (Sec. 5)	*Ramping*	Feed on-site generated or stored electricity to the grid.	Duration Load change Response time Annual events	Seconds to minutes Short-term negative load Seconds to minutes Daily
	Generation: Energy & Capacity; T&D: Non-Wires Solutions	Feed excess on-site generated electricity to the grid.	Load change Duration Response time Annual events	Negative load Entire generation period <1 hour Continuous

- **Shedding and shifting using HVAC (Section 4).** Buildings can use thermal mass and storage to shift heating and cooling load ahead of peak periods with no impact on occupants. They can use thermostat setpoints to shed additional HVAC load during peak periods, albeit with some occupant impacts. HVAC loads are dependent on both weather and occupancy.

- **Shedding and shifting using other end uses (Section 5).** As with HVAC, end uses such as water heating and refrigeration can use thermal mass and storage to shift load away from peak periods and thermostat setpoints to potentially shed additional load during peak periods. We distinguish these from HVAC-related thermal loads because they interact with occupants indirectly, do not implicate building thermal mass, are less weather dependent, and are typically also implemented as distinct systems from HVAC. Appliances such as dishwashers, clothes washers, and clothes dryers have low and potentially flexible duty cycles and can be scheduled to operate outside of peak periods, shifting load. Computing equipment, conveyance, lighting, and other electrical loads can shed load. Shedding load from these end uses impacts occupants.
- **Shedding and shifting using on-site electricity generation and storage.** PV and wind (micro) turbines can generate electricity on-site, either effectively shedding load or actively feeding supply back to the grid. Battery storage can shift load. Both PV and wind production are weather dependent. Generation and storage impact occupants indirectly, by supporting or enhancing grid services from other end uses.
- **Modulation (Section 6).** Variable frequency drives, solid-state devices such as light-emitting diodes and electronics, and PV and battery inverters can be used to rapidly modulate load and provide services such as frequency regulation. Modulation-based grid services that are energy neutral interact minimally with occupants and with energy efficiency. Modulation-based grid services that impact energy use may have occupant impacts.

Table 1 relates this organization to grid services procured by utilities and grid operators and to the efficiency, shed, shift, and modulate taxonomy used in several of the other GEB technical reports.

1.3 Demand Flexibility Aggregation: Device, End Use, Building, Campus, or All of the Above?

An important "architectural" decision for a GEB is the level at which various flexibility modes are aggregated within a building, both for an individual grid service and across services. At one end, individual devices could interact with the grid, market, or service aggregator—any entity outside the building—directly. At the other end, the building could coordinate its resident devices and interact with the grid—or again, any entity outside the building—as a unit. Going further, co-located buildings could coordinate with one another and package services at the district, neighborhood, or campus level. The building seems like a natural unit of aggregation for grid services; it is, after all, the unit of aggregation for many other services, both energy-related (e.g., grid connection, metering, billing) and otherwise (e.g., design, construction, purchasing, leasing, etc.). Are there inherent technical or economic benefits for building-level aggregation of demand flexibility?

Manufacturers of connected equipment have emerged as alternative natural aggregators for grid services. By communicating with fleets of similar devices in the field and selectively and remotely controlling subsets of those fleets, manufacturers can provide well-understood and well-characterized services, sometimes with substantial capacity (Hudgins et al. 2018).

As noted previously, demand flexibility modes are largely independent of one another, and different modes can be aggregated at different levels within a building. We consider the relative merits and drawbacks of aggregation along several criteria:

- **Overall system performance**. The most compelling advantage of aggregation within the building is overall system performance. By considering multiple options and evaluating their impacts on energy efficiency, the grid, and occupants, a GEB may be able to identify combinations of strategies that provide better performance and value than when individual strategies are considered and activated in an uncoordinated manner. This holistic approach is one of the premises (and promises) of GEBs and has been proven in the field. A 2016 trial successfully employed sensing (e.g., room occupancy, room temperature, ambient temperature, and solar radiation) and a predictive analytical model to optimize and deliver integrated load shedding in a medium-sized office building (Kjaergaard et al. 2016). Additional studies have shown that integrated control is also effective in other building types (Hviid and Kjorgaard 2018). At the least, it is intuitive that devices that are part of the same end use (e.g., fans and compressors in an HVAC system) should be coordinated.

- **Implementation complexity.** The flip side of overall system performance is the complexity and cost associated with integrating multiple disparate systems. Costs may go beyond additional hardware and software. They often include project-specific technical barriers, such as incompatibility or lack of interoperability, either in communication protocols or control algorithm design. They may also include nontechnical barriers, such as lack of staff bandwidth and expertise as well as poor fit with certain operational contracts. As is the case with energy efficiency and demand response, for most demand flexibility modes and grid services, the primary trade-off is between performance on one hand and complexity and cost on the other.
- **Latency.** Building-level aggregation may impose additional latency on communication. This additional latency may be prohibitive for fast, modulation services.
- **Scalability.** Scalability refers to the relationship of the limiting step in an algorithm or process to the "size" of the problem. In the case of grid services, scalability typically refers to the relationship of the number of steps in the market clearing algorithm or the number and size of messages sent as they relate to the number of individual providers of the service. Grid operators, service markets, and aggregators want to deal with as few individual actors as possible. Scalability is often managed using hierarchy, with aggregation of different types taking place at different levels. The difference between building- and device-level aggregation is how much and which type of aggregation takes place at different levels in the system. In building-level aggregation, a building coordinates all devices capable of providing a given service and packages those as a single service actor. In device-level aggregation, a manufacturer aggregates similar devices across multiple buildings and presents those as a service actor. Given that the number of devices manufacturers is significantly smaller than the number of buildings, device-level aggregation offers better scalability to the grid at the expense of reduced scalability for each manufacturer.
- **Security.** The goal here is to reduce both vulnerabilities in individual devices and the likelihood that a vulnerability in one device can spread to and compromise other devices and perhaps the entire system. Building-level aggregation reduces individual device vulnerability by hiding devices within a building behind a single gateway that can be secured. Device-level aggregation could reduce the likelihood that vulnerability in one device may compromise other devices, because it does not require devices to interact with other devices in the building. Device-level aggregation has an additional built-in benefit in that it allows the manufacturer to remotely update and patch devices in the field (Fairley 2015). However, this capability can also be used in a building-level aggregation setting. Security, therefore, is a neutral consideration.

Multibuilding coordination. Service aggregation within a building is one issue. With the exception of large commercial or industrial buildings, individual buildings do not provide grid services. Services are provided by groups of buildings. Multibuilding coordination can potentially improve grid services while minimizing impacts on individual buildings and their occupants.

Multibuilding coordination differs from the problem of coordinating different end uses (or zones) within a single building. On one hand, it is simpler because separate buildings do not physically interact with one another, nor do the preferences of their occupants. Only the cumulative effects of the resulting load shapes matter. On the other hand, the problem can encompass a much larger number of individual actors—tens of thousands of buildings as opposed to dozens of zones in a building—with limited capability to share information, especially bidirectionally. Some level of information sharing and coordination, even implicitly, is important because if many buildings execute the same control strategies and simultaneously produce the same load shapes, unintended negative coincident effects will result.

1.4 Assertions, Emphasis, and Structure of This Report

The characterizations of demand flexibility modes on one hand and demand flexibility aggregation on the other point to some conclusions:

- **HVAC-based shedding and shifting services are best aggregated and provisioned at the building level.** Coordination of multiple devices, coupling with building thermal mass, and mechanisms and processes that couple zones together (e.g., central plants, interzone airflow) make it likely that building-level approaches will outperform device- or zone-level approaches for HVAC-based shedding and shifting, and perhaps significantly so. In some configurations, notably homes and single-zone/packaged-system commercial buildings, building- and device-level provisioning are the same. On-site generation is already typically aggregated at the building or campus level. Because generation is also weather dependent and because generation and storage can enhance HVAC-based services, it may be beneficial to operate these in tandem with HVAC.

- **Shedding and shifting services using other end uses can be implemented at either the building level, the device level, or the end-use level.** Different end uses generally have only weak physical interactions with one another and with HVAC specifically. Certainly, lighting and other electrical appliances produce heat that increases cooling loads and decreases heating load. However, in most cases these loads are small relative to weather- and occupancy/ventilation-induced load, especially given increased use of solid-state lighting. Weak physical interaction indicates that demand flexibility for different end uses can be implemented independently, without accounting for physical interactions with other end uses. Notable exceptions include the tight interactions between computing and HVAC in data centers and between refrigeration and HVAC in supermarkets. Tighter coupling between end uses can also be created by occupants who activate different end uses at different times and who may, under constraint, prioritize different end uses.

  When communication latency is not an active constraint, and there is no coupling or weak coupling to the building fabric and to weather, choice of aggregation level is a purer function of performance benefit—of both building-level integration of the service or end use itself and integration with other building-level end uses, generation or storage—and implementation complexity and cost. At present, the high cost of building-level integration points to device- and end-use-level aggregation. As the costs of building-level integration of individual end uses and integration across end uses drop, building-level approaches may become more viable.

- **Energy-neutral modulation services are best provisioned at the device level.** Energy-neutral modulation services can be thought of as orthogonal to shedding and shifting services and can be analyzed, modeled, and perhaps even implemented separately. To the extent that building-based end uses and equipment make sense as a source of modulation services, there is little need to aggregate and coordinate that activity within the building. Latency constraints point to the need to minimize the number of communication hops and coordination layers.

- **The role of other modulation services in buildings is an open question.** Modulation services that are not energy neutral and have potential occupant impacts present particular implementation and integration challenges. Research is needed to determine whether the potential benefit of these services justifies investment in tackling these problems.

- **Centralized approaches with unidirectional coordination or fully distributed approaches are promising for multibuilding coordination.** The inherent scalability issues of bidirectional information exchange—not to mention multilateral bidirectional information exchange—point to approaches in which a centralized coordination entity unidirectionally sends either (1) different signals to different groups of buildings or (2) the same signals to all buildings, but individual buildings differentiate their responses stochastically or based on contextual variables such as local power signal measurements.

This report focuses on shedding and shifting services because these represent both the greatest near-term market opportunity and the most natural fit for large building loads. For HVAC, the focus is on building-level integration. For other end uses, the report addresses implementation issues independent of aggregation level. Modulation services currently represent a smaller market opportunity, although this has the potential to increase with greater levels of renewable generation. We discuss some of the challenges of building-based modulation services. Each discussion addresses four aspects of demand flexibility:

- **Occupants, operators, and owners.** This aspect concerns how demand flexibility impacts occupants, how those impacts are quantified and valued, and how they feed back into execution.

- **Execution.** This aspect covers how demand flexibility is implemented within the building. It implicates control and sensing, and in some cases modeling.

- **Characterization and measurement and verification (M&V).** This aspect comprises the activities needed to package demand flexibility into a dispatchable grid service.
- **Quantitative analysis.** This aspect deals with how demand flexibility is quantified analytically in use cases ranging from building design and rating to program planning. It largely deals with energy modeling and adjacent analyses.

We begin by discussing these four aspects in the context of energy efficiency and demand response. A final focus of the report is common communication and control infrastructure that can support demand flexibility at any level of aggregation and coordination within the building and facilitate transition to more integrated configurations where they make sense.

2 Energy Efficiency

Energy efficiency is the foundation of GEBs, and any initiative that enhances and promotes energy efficiency will lift GEBs as well. Building-energy-modeling (BEM)-driven integrated design and sensing-enabled automated building energy management both support energy efficiency, but are far from established, especially for residential and small commercial buildings. Initiatives that facilitate and encourage the adoption of integrated design, automated energy management, and other energy efficiency mechanisms and practices also support GEBs. BTO has identified a number of technology gaps in these areas and is working to address them.

2.1 Occupants, Operators, and Owners

By definition, energy efficiency is implemented under the constraints of occupant health, comfort (for commercial buildings, ventilation and thermal comfort requirements are required by standards such as ASHRAE 62 "Ventilation for Acceptable Indoor Air Quality" and 55 "Thermal Environmental Conditions for Human Occupancy") and desired level of service for different end uses. Occupant behavior—from thermostat setpoints to hot water usage to plug-load management—plays a significant role in energy efficiency, especially in residential buildings. Various studies have shown that for identical homes or apartments, occupants can account for factor of three variance in energy use (Delzendeh et al. 2017; Haldi and Robinson 2011). There are various programs for engaging, educating, and even prompting occupants about energy efficiency behavior modifications (Laskey and Kavazovic 2011; D'Oca et al., n.d.).

The nonbehavioral component of energy efficiency consists of physical assets, including the structure itself and its heating, cooling, lighting, and hot water systems, along with appliances and other plug loads that are procured, replaced, and upgraded at various intervals. The decisions to procure energy efficiency alternatives, often at a first-cost premium, are also subject to consumer attitudes. Labels such as ENERGY STAR® for appliances, certificates such as LEED (U.S. Green Building Council 2019) and PassivHaus (Passivhaus Institut 2019), and ratings such as HERS (RESNET 2019), Home Energy Score (U.S. Department of Energy), Commercial Building Energy Asset Score (U.S. Department of Energy 2019), and Building Energy Quotient (bEQ) (ASHRAE) inform consumers about the energy efficiency characteristics of products, appliances, equipment, and entire homes and buildings. Many energy efficiency technologies and upgrades have short payback periods. Utilities incentivize others with programs such as Home Performance with ENERGY STAR (U.S. Department of Energy and U.S. Environmental Protection Agency 2019) to reduce payback periods to acceptable levels. For others, financing arrangements such as Property Assessed Clean Energy or Energy Saving Performance Contracts can produce positive or at least neutral cash flow. When different actors are responsible for capital and operating costs, incentives for capital energy efficiency upgrades become split. These can be mitigated with special green lease language.

In addition to cost savings, energy efficiency has been shown to deliver additional benefits, including improved occupant health and productivity as well as higher tenancy and tenant satisfaction rates.

2.2 Execution

Although many elements of energy efficiency are passive, some components, such as HVAC, have to be "executed" dynamically. Execution may be manual or automated, and automation ranges from simple thermostats to more sophisticated energy management systems.

Building automation systems. Large commercial buildings use BAS to monitor and control HVAC. Some BAS also integrate control of lighting and other subsystems. BAS integrate information from a range of outdoor environmental (temperature, humidity), indoor environmental (temperature, humidity, CO_2), and equipment (on/off state, inlet and outlet temperatures, flow rates) sensors and then implement schedules (e.g., thermostat setpoints for occupied and unoccupied hours) and rules (e.g., economizer setpoint resets based on outdoor temperature and humidity) to reduce energy use. Advanced rule-based controllers that optimize energy efficiency have been described in ASHRAE Guideline 36 (ASHRAE 2018). Newer high-end BAS may also include the ability to detect and diagnose HVAC equipment faults—many of which can degrade energy efficiency—and provide actionable recommendations to the building operator. Many newer commercial buildings over 100,000 square feet (which account for about 2% of all commercial buildings and 35% of total floor space in the United States) have BAS. Retrofitting existing buildings with BAS and upgrading older BAS is critical to achieving energy efficiency.

Home automation systems. As with small commercial buildings, integrated energy management systems for homes have historically received little attention. However, there is currently rapid adoption of technologies such as smart thermostats that support energy management as well as voice-activated home assistants that integrate with "connected" water heaters, appliances, lighting, and electronics.[1] This transformation makes widespread automated integrated energy management a nearer-term proposition for homes than for small and medium commercial buildings (NEEP 2016). Integrated home energy management faces adoption challenges, including the absence of binding technical standards (Wallace 2016) as well as privacy (Balta-Ozkan et al. 2013) and cybersecurity (Brush et al. 2011) concerns.

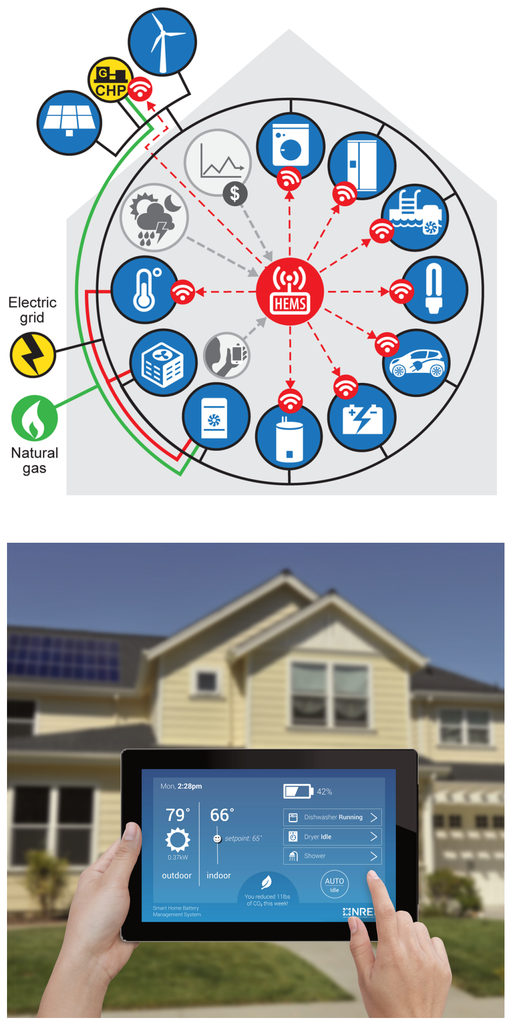

Figure 2. FORESEE is a home energy management system (HEMS) that allows homeowners to track energy use as well as balance, prioritize, and control end uses including lighting, space conditioning, water heating, and appliance usage. ***Images courtesy of the National Renewable Energy Laboratory (NREL).***

Medium and small commercial buildings. Medium and small commercial buildings often have a number of packaged unitary systems (e.g., rooftop units) instead of a central HVAC system. In these configurations, there may be lower operational and convenience benefits to a centralized BAS, and the capital cost of one may become pro-

[1] A recent study estimates that by 2023, 28% of U.S. households will deploy smart thermostats, with 36% of those using voice assistance devices as smart home control platforms (Chen 2018).

hibitive.[2] As a step toward developing low-cost BAS capability for this market, DOE has funded the development of VOLTTRON™ (Lutes et al. 2015), an open-source messaging platform capable of running on low-cost hardware and tying together multiple disparate controllers into a "virtual" centralized BAS. Other platforms, such as XBOS (Fierro and Culler 2015) and BEMOSS, promise similar integration capabilities (Zhang et al. 2016).

Additionally, small commercial buildings may benefit from the same solutions that are being applied to residential systems, including communicating thermostats and smart lighting controls.

Controls advancements. In addition to new platform development, BTO also works to advance the state-of-the-art and practice for building control in any context. On the algorithm side, one area of research is model predictive control (MPC), which uses optimization techniques to find optimal control sequences over a given time horizon. A second area is transactive coordination, which uses distributed, market-style mechanisms to synthesize a global allocation of energy resources from local (i.e., zone, end-use, or individual user) preferences. Automated fault detection and diagnosis (AFDD) is a third area. BTO is also working to reduce control installation and upgrade costs with projects on automated point mapping.

Bridging the continents of BEM and controls. Designing an energy-efficient building also requires selecting and customizing energy efficiency control algorithms for that building. To date, however, building energy modeling (BEM) has not played a significant role in control algorithm design. One of the reasons is that most modern BEM engines—even advanced ones like EnergyPlus®—do not model physically realistic dynamic control. They use quasistatic solution techniques to model state transitions at regular time steps and have no visibility into the path that the building or its systems take from one time step to the next. In BEM, control is described at a high level rather than as rules tied to specific sensors, setpoints, and actuators as real-world control sequences are. This gap in level and type of description has kept control implementation and BEM workflows largely separate. EnergyPlus does allow users to define custom control functions using sensor and actuator hooks, but this feature is still bound by the quasistatic solution methods. To address this shortcoming, BTO is developing a next-generation BEM engine called Spawn. Spawn reuses the existing envelope, lighting, and loads modules of EnergyPlus and couples them to a new set of HVAC and controls modules that use dynamic, equation-based simulation rather than traditional implicit quasistatic methods and are able to simulate physically realistic control. They are also able to accept control descriptions in real-world control languages such as python and Modelica. These simulated control sequences can then be compiled and executed on control hardware.

Sensing. Energy-efficient operation requires monitoring of both indoor and outdoor environmental conditions as well as equipment and system operation and health. Advances in wireless, battery-powered, or power-harvesting sensing have made retrofitting additional sensors more economical.

Occupancy is a key driver of energy use, and occupancy—both presence and occupant count—is an important input to energy-efficient operation. Motion sensors are prevalent in modern buildings, having been integrated with automated lighting control. Motion sensor switches are available for as low as $20 (Sarkisian 2017). These sensors provide only binary presence information, which is largely sufficient for energy-efficient lighting control. Advanced HVAC control requires occupancy count, which factors into both ventilation requirements and internal heat gains (Zhang et al. 2013). CO_2 concentration is often used as a proxy for occupancy in demand control ventilation applications, although CO_2 sensors are notorious for drifting and require frequent calibration. WiFi connectivity has also been proposed as a proxy (Jain et al. 2016). Direct occupancy counting requires expensive hardware, such as cameras, and comes with privacy issues (Ahmad et al. 2018).

2.3 Characterization and M&V

Energy billing has been performed for more than a century. An electrical meter measures voltage and current and uses those to calculate power and energy use. For flat-rate billing, meter readings at the billing interval are sufficient.

Lower energy bills are one financial benefit of energy efficiency, but for additional payments associated with utility energy-efficient programs and for utility regulatory reporting, a counter-factual baseline is needed to which ac-

[2]However, a recent study (Katipamula et al. 2012), showed that cost savings from an energy efficiency BAS in a small commercial application can be significant (up to several thousand U.S. dollars per year), potentially yielding a payback period of 3–5 years for installed BAS and advanced sequences for energy efficiency operation.

tual energy use can be compared. For an existing building, an energy efficiency baseline is generally created using historical meter data. Energy use data for a sufficiently long time window (typically six months to a year) is used to develop correlations of energy use to contextual variables such as time (time of day, day of week, day of year, etc.), weather conditions (outdoor temperature, humidity, and so on), and sometimes operational inputs (e.g., occupancy, thermostat setpoint, etc.). Such correlations benefit from greater time resolution, which is available via one-way automatic meter reading or two-way smart meters. Where historic data are not available or where more specificity is desired, calibrated BEM can be used to create estimated energy use forecasts and to establish an estimated baseline for energy efficiency. Standard industry protocol for energy efficiency M&V includes ASHRAE guideline 14 (ASHRAE 2014), BPI 2400 (Building Performance Institute 2015), and IPMVP (Efficiency Valuation Organization 2014).

Submetering at the end-use, system, or device level can help make correlations more robust (e.g., lighting energy is probably related to time of day and occupancy but not to outdoor temperature) and zero in on specific energy efficiency contributions and interventions. Submetered energy use may be available through the BAS (Johnson and Saleem 2017). Nonintrusive load monitoring or virtual submetering—which disaggregates a power signal to end uses—is a lower-cost alternative but is not a mature technology and is not in broad use today (Abubakar et al. 2017).

2.4 Quantitative Analysis

Physics-based BEM engines simulate thermal loads placed on the building by outdoor conditions, indoor processes, and the intended and unintended exchange of air between indoor and outdoor environments. They calculate the response of the HVAC system to those loads needed to meet temperature and humidity setpoints. They can evaluate lighting, thermal comfort, airflow, and indoor air quality. Architects and engineers often use BEM to design both the passive elements of the building as well as its active systems. BEM-informed "integrated" design can result in buildings that achieve high levels of energy efficiency at low or no capital premiums relative to conventional buildings. BEM helps uncover capital cost savings by enabling the use of lower-capacity, cheaper HVAC systems and by identifying areas in the building where energy efficiency measures are most cost-effective. BEM itself can be thought of as an ultra-cost-effective energy efficiency measure. Preliminary evidence shows that BEM usually pays back in only a few months, with some cases showing immediate payback because of first cost savings (Roth 2016).

In addition to design, BEM supports energy efficiency code compliance, certification, and financial incentives. These performance documentation tasks use BEM to isolate inherent building performance from the effects of occupancy, specific use, and weather. This is done by simulating a building under "standard" operating conditions—this is the analog of measuring the energy efficiency rating of a piece of equipment under standard rating conditions—and often by comparing the simulated performance building to the simulated performance of a variant that meets minimum prescriptive code requirements.

Finally, BEM performed at the level of an entire building stock supports activities such as program design and implementation, policy analysis, product design, and research. Stock-level analysis is used for building portfolios, entire urban areas, and even at the regional and national scales. In this report, we use the term design as a proxy for the range of activities enabled by quantitative physics-based simulation.

DOE has played an active historic role in BEM R&D. Specifically, it has funded the development of several BEM engines, including DOE-2 and EnergyPlus. EnergyPlus specifically has advanced capabilities that allow it to model both passive energy efficiency measures and active energy efficiency systems and their impacts on occupants. EnergyPlus is open source and embedded into a number of public and private sector applications. The OpenStudio software development kit facilitates this integration and also supports BEM process automation and large-scale analysis.

3 Demand Response

Demand response is an expansive term that covers a range of services and invocation, implementation, verification, and compensation mechanisms. Demand response includes locally executed load reductions by large industrial customers arranged in advance by telephone calls to site operators, aggregated direct load control of residential air conditioners and water heaters, and autonomous response to real-time pricing—the latter is essentially GEBs. Most demand response targets capacity markets with load shedding services, although demand response is also used for services such as frequency regulation. Demand response currently does not provide local services. This section focuses on the more traditional, common, and direct forms of demand response.

Similar to energy efficiency, increased adoption of and improvements in control, sensing, and analytics could improve demand response in terms of both occupant experience and efficiency of grid service provision.

3.1 Occupants, Owners, and Operators

Most direct demand response programs (i.e., programs that explicitly invoke or call demand response at customer sites) do not account for occupant impacts on a per instance basis—an acceptable arrangement when call frequency is low (e.g., several times a year for several hours a time). Some air-conditioning-based direct demand response programs limit internal temperature drift during an event (e.g., 5°F). In some direct demand response programs, occupants have the ability to override a call.

Indirect demand response relies on voluntary scheduling by the customer and is therefore more accommodating of occupant preferences and needs.

3.2 Execution

In the presence of time-of-use pricing—and even in its absence—buildings can use programmed or manual scheduling to reduce load during peak periods or to shift load to off-peak periods. Examples include thermostat setbacks, light dimming, and scheduled use of appliances such as dishwashers.

Demand response 1.0. Large commercial and industrial customers have for decades been able to negotiate individualized demand response contracts. Customers receive a payment for interrupting operations and drastically reducing energy demand on request. Because these customers provide significant capacity individually and are few in number, the use of slow, manual communication mechanisms such as telephone calls is acceptable.

Demand response 2.0. Advances in communication and automation have enabled a greater range of equipment and systems to provide a greater range of grid services. Many direct demand response programs rely on direct load control (direct load control) via one-way radio frequency or satellite communication. Signals are sent either directly to the equipment (e.g., thermostat or water heater) or to utility-installed controllers that disconnect or modulate power to the equipment.

Communicating thermostats, modern BAS, and advanced metering infrastructure enable additional demand response capabilities such as temperature setbacks. Some demand response programs use smart thermostats to precool before either setting back or turning off air-conditioning units during peak hours, avoiding both occupant discomfort and unintended "recovery spikes."

Model predictive control for demand response. With time-of-use or real-time pricing, and either sufficient advance notice of demand response calls or the ability to predict grid needs based on weather forecasts, buildings can use MPC to provide grid services with minimal occupant impacts (Borsche, Oldewurtel, and Andersson 2014; Gorecki et al. 2017). MPC has been deployed by several companies, such as QCoefficient (*QCoefficient* 2019), Enbala (*Enbala* 2019), and Viridity (*Viridity Energy* 2019).

3.3 Characterization and M&V

If flat-rate billing can be thought of as the most fundamental form of energy efficiency M&V, the most fundamental form of demand response M&V is variable-price billing enabled by high-frequency meter reading.

Figure 3. Residential water heaters are a flexible load that can provide a range of grid services—including load shifting and frequency regulation—without impacting occupants. This GE heat pump water heater is shown being tested at NREL's Advanced Home Energy Management Laboratory. ***Image courtesy of NREL.***

M&V. All participants in grid service delivery need to use shared baselines when committing to, delivering, and verifying a grid service (Bondy et al. 2016).

Dispatchable demand response events are short, well defined, and generally share certain independent variable values (e.g., weekday afternoons with high ambient temperatures). As a result, fewer historical data are needed to establish correlations (e.g., winter night data are not needed). As with energy efficiency, physical or virtual submetering leads to better correlations. Multiple methods exist for establishing demand response baselines (Association of Edison Illuminating Companies 2009), for example:

- Day matching: using energy use from the same day the prior week
- Previous days: using a weighted average of energy use from prior days or weeks
- Weather correlation: using energy use from the most similar weather day from the past year (while constraining to weekday or weekend as needed).

The use of small amounts of recent historical data supports regular updates that capture events, such as equipment replacement and operating schedule changes. More sophisticated techniques, such as regression analysis, do exist, but some independent system operators have reported only marginal gains in accuracy from these approaches, so they are not used as often in practice.

Some ancillary services use simple "before" and "after" event M&V, where the consumption used immediately before the event serves as the baseline (e.g., PJM (PJM 2019)). Establishing appropriate demand response baselines is an active research topic (Wang et al. 2018).

M&V is important for program evaluation, but utilities typically incentivize all customers on an equal basis, (e.g., a fixed annual payment for participation). This disincentivizes customers from delivering the maximum possible grid service. The typical absence of opt-out capability limits the pool of participants.

Characterization. The above baselining methods are used not only to M&V delivered services, but also to accurately estimate service delivery capacity for program participation or bidding into wholesale markets.

In large commercial buildings, demand response is characterized using engineering calculations of various kinds—from simple counts and power consumption of different types of equipment to BEM.

In small commercial buildings and homes, demand response is not explicitly characterized at the individual building level. Because large numbers of buildings are recruited, average characteristics of buildings and equipment are used to approximate the available reduction.

3.4 Quantitative Analysis

Buildings are not designed specifically for demand response, and therefore the use of BEM to evaluate demand response during building design is not common in practice. BEM can certainly be used to design a building and minimize cost under tiered electricity pricing structures. BEM engines can also simulate demand response and its effects on occupants using schedules—in EnergyPlus for instance, "availability schedules" can be used to lock out equipment during prespecified periods—or using built-in and custom control sequences. Recent work using BEM stock-modeling techniques has begun to characterize the demand response potential of the building stock (Hale et al. 2018), although the use of BEM is still not common in demand response program design.

4 Demand Flexibility: Shedding and Shifting HVAC Loads

Using building thermal mass to shift the loads associated with space conditioning, especially cooling, represents the largest opportunity for building-based grid services. Summer afternoon cooling loads already strain electricity production, transmission, and distribution capacity in many regions. Growing populations as well as more frequent, longer-lasting, and more extreme heat events will exacerbate this problem. Precooling can directly reduce system-straining demand peaks and, if done effectively, with minimal or no impact on occupants and similarly minimal or no "recovery" effects. On-site generation, electrical storage, and thermal storage can be used to augment precooling.

As discussed in the introduction, shifting and shedding space-conditioning load is likely best implemented at the largest level at which storage and opportunities for load balancing are available—typically the whole-building level, where storage is provided by the building's own thermal mass. This is the case for both large commercial buildings with central HVAC systems and in single-zone buildings such as homes. In commercial buildings with multiple, separate HVAC systems (e.g., rooftop units), each HVAC system can provide services independently or the systems can be federated to provide services collectively. The latter may be desirable if the zones served by the systems are coupled by airflow, occupancy, or both. Where district systems provide thermal storage and load balancing beyond the building, this larger level of aggregation may yield better performance.

The need to proactively shift loads ahead in time combined with dependence on future weather and occupancy point to MPC as a promising control approach. We use the term MPC in a broad sense to mean any control system that uses an internal model of system response to optimize operation over a finite but sliding time horizon, potentially incorporating external predictions, and reevaluating at regular intervals while updating its internal model parameters using measurements. We do not specify the type of model, which may be linear or complex; physics-based, data-driven, or hybrid; or hand-crafted or automatically learned.

4.1 Occupants, Operators, and Owners

Shifting HVAC loads using thermal (and electrical) storage is attractive because it does not negatively impact occupant comfort, at least in theory.

Occupants. Maximizing demand flexibility without impacting occupants is critical because the alternative presents several economic challenges. Building owners typically spend two orders of magnitude more on employee salaries and benefits than they do on energy—in commercial building real estate, this is often referred to as the 3/30/300 rule. Therefore, any loss in employee productivity and wellness must be offset by saving energy charges that are at least two orders of magnitude greater than the baseline. When a clear economic case for thermal load shedding can be made, the end result may be a split incentive situation where the owner and operator reap the financial benefit while the occupants bear the cost of discomfort. One possible approach in this case could be to concentrate the payouts over a smaller number of buildings and then to shut down cooling and ventilation in those buildings completely, along with commercial activity.

BTO-sponsored research just getting underway looks to improve the accuracy, reduce the cost, and address privacy issues associated with direct measurement of occupant thermal comfort (e.g., low-resolution infrared measurement of occupant skin temperature relative to temperature of nearby surfaces). Additional data collection and research is needed to better understand occupant thermal comfort and ventilation preferences under a range of conditions. This research is needed not only in order to maximize the thermal demand flexibility while maintaining comfort, but also to better understand the discomfort regime and where and how quickly it transitions to severe discomfort, distress, and even danger.

Whereas occupants are likely to tolerate inconvenience and discomfort for a few hours at a time, several times a year, maximizing demand flexibility likely requires taking actions that will impact occupants with greater frequency, perhaps even multiple times a day. What is the impact of different modes of demand flexibility on occupants? What value do occupants place on this impact and how much do they want to be compensated in order to accept it? What impacts will cause occupants to override system actions or even opt out of programs? What impact will occupants not accept under non-emergency circumstances?

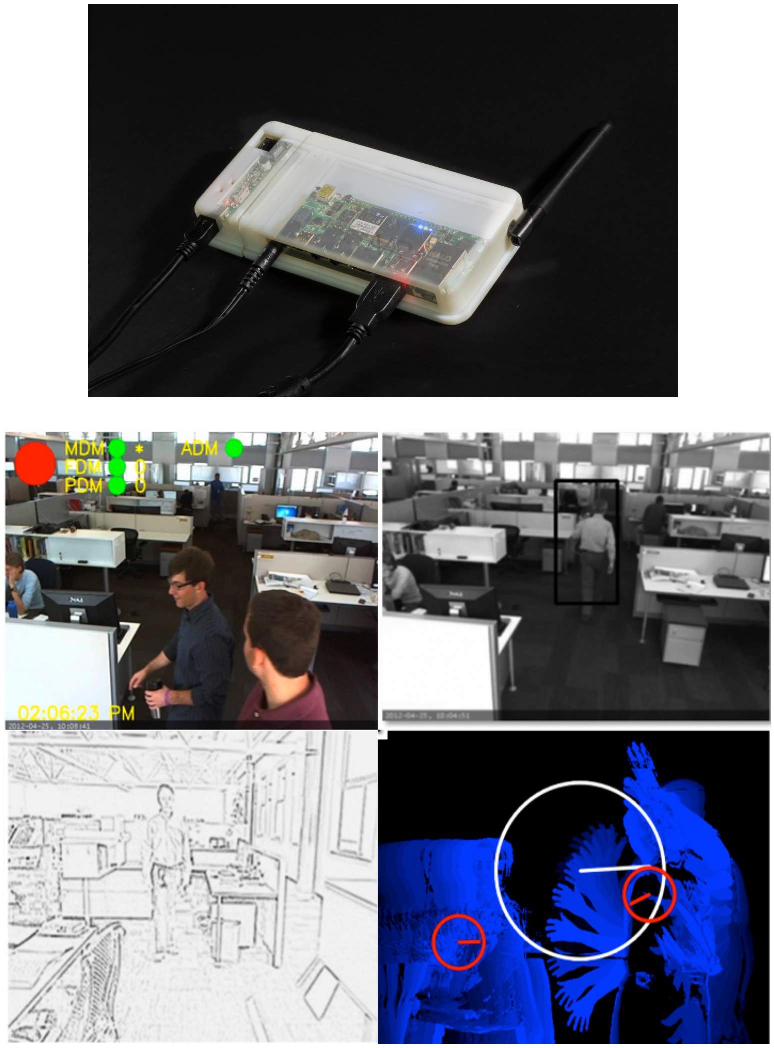

Figure 4. Occupancy sensing is an important component of thermal management for energy efficiency and load flexibility. The Image Processing Occupancy Sensor (IPOS) uses onboard image-processing hardware to count occupants accurately, while preserving privacy. *Images courtesy of NREL.*

Collecting occupant preferences and values is one of the most critical open questions in demand flexibility. What is the right frequency and mode of interaction with building occupants? How much can be inferred from occupant actions and other proxies, and how much must be asked explicitly and directly?

A key challenge is that occupant preferences and valuations are often subjective, and they could be even time-varying and scenario-driven. When directly surveyed, occupants may not be able to clearly and completely articulate their preferences, and this can often not be done in a privacy-preserving manner. Therefore, it is important to explore alternative ways to assess preferences and valuations. Indirect assessment can be explored by observing occupant behaviors through various measurements collected from sensors, including thermostats, lighting switches, etc. Direct assessment requires data collection. Design of personal comfort and preference data-collection interfaces—usually as smartphone applications—is an active area of research (Cosma and Simha 2019; Jain, Singh, and Chandan 2017; Vaizman et al. 2018; Gao and Keshav 2013).

Building occupants may also provide input on their comfort flexibility in a dynamic manner and at the time when their preferences and needs change. It is expected that when occupants are presented with information on demand flexibility and potential value associated with grid services, they might change their nominal behavioral patterns, altering the overall building demand flexibility.

Usability and interaction. Careful attention to usability is needed to support demand flexibility in buildings. Users must have easy access to the system (e.g., through a web interface) for real-time two-way feedback. Beyond interacting with the energy management system to obtain real-time information about the building (e.g., indoor conditions, equipment state, and energy usage), the users need to provide their preferences or priorities and feel empowered to change or reverse situations that are disliked. How the information is presented or acquired is crucial. Both legacy rule-based systems and newer optimizing control systems will benefit from a human interface that accepts and dynamically incorporates feedback from building operators and occupants. The emerging body of research on human-computer interaction can be leveraged to create innovative and effective ways of interaction that foster demand flexibility (Fabi, Spigliantini, and Corgnati 2017; Zhao and Zhang 2016).

Owners and operators. GEB owners and operators need information on building state, currently committed services, expected compensation, expected risk to not deliver the commitment, and expected impact to building functions and occupants. Beyond immediate impact, building operators need to understand implications of demand flexibility on equipment degradation and maintenance and replacement costs. Building operators and owners may also prioritize certain grid services, as well as select particular systems and equipment that should participate and others that should not regardless of their demand flexibility availability.

4.2 Execution

The introduction to this section makes a brief case for MPC as the right approach for thermal shedding and shifting. This section builds out this argument and outlines the gaps that must be addressed in order to leverage this valuable demand flexibility resource.

Although MPC is the focus of this section, any other feedback control method that can proactively optimize over multiple objectives, adapt to changing operating contexts, and manage uncertainties is a good candidate.

Recent research efforts have explored machine learning methods such as reinforcement learning to learn energy efficiency control strategies. These methods learn the relationship between control variables (such as zone temperature setpoints and variable air volume airflow rates), other variables (such as outdoor temperature, time of day, and day of week), and energy use and cost and represent these relationships in structures such as neural networks (Wei, Wang, and Zhu 2017). Machine-learning-based building control may be competitive, especially when scalable accurate control-oriented models are difficult to develop. State-of-the-art reinforcement learning for building control is limited to few decision variables. Its application to demand flexibility is challenged by the need for effective exploration of long-term control strategies like precooling, which cannot be learned unless the building is already executing those strategies. Because learning-based control algorithms rely on a form of modeling (or function approximation) and optimization, it can be argued that they are encompassed in the broad definition of MPC explained previously.

Broadly, work is needed to advance and refine MPC fundamentals and to tackle practical considerations common to all advanced control systems, such as data acquisition, system integration, configuration, and commissioning. At the same time, work is needed to evaluate the degree to which thermal demand flexibility can be leveraged without predictive optimization techniques like MPC.

A more detailed case for MPC. HVAC control is a hierarchical process. At the lowest level, individual devices or small groups of tightly coupled devices use local controllers that respond to high-level settings like temperature setpoints and mass flow rates. On top of this are more supervisory levels that orchestrate multiple local controllers and implement high-level algorithms and strategies, such as precooling and temperature and pressure reset.

Supervisory control algorithms are typically implemented as rules, such as thermostat setpoint schedules for occupied and unoccupied hours or economizer setpoint resets based on outdoor air temperature and humidity. HVAC control rules are specified in various standards, such as ASHARE Standards 90.1, 189.1, and IECC Chapter 4. Advanced rule-based controllers that optimize energy efficiency have been described in the ASHRAE Guideline 36 and ASHRAE RP-1455 (Taylor 2015). Rule-based controllers are characterized by a large number of tuning parameters that must be selected for each system and building and are often reset during seasonal transitions.

Rule-based systems are intuitive, but do not necessarily lead to optimal operation. Their complexity and the number of tuning parameters increases dramatically when they target multiple objectives. Recent research (Serale et al. 2018) has demonstrated the energy efficiency benefits of supervisory MPC, which uses optimization over a sliding finite time horizon to find control strategies that optimize for selected criteria. MPC is attractive because of its conceptual simplicity and its ability to effectively control systems with complex dynamics and multiple control inputs. MPC can find optimal control sequences while accounting for constraints such as upper and lower bounds on setpoints and available actuators. MPC can also optimize control decisions when faults are present in the system, provided that their effects are captured by models. It can also optimize for multiple objectives (Rawlings 2009). Some early experiments at building sites have shown that MPC can yield significant energy savings (up to 17%–65%) compared to the performance of installed control sequences (Bengea et al. 2014; Li et al. 2014). MPC algorithms have been developed to formally deal with inaccurate equipment models and load forecasts and to find optimized control decisions when the predicted variables have uncertainty. These methods are known as stochastic MPC (Ma, Matusko, and Borrelli 2015). Distributed formulations of some MPC algorithms provide increased implementation scalability (Moroşan et al. 2010).

Despite significant recent development and several field demonstrations, MPC has not been widely adopted for building control. One challenge is legacy BAS hardware that is limited in memory and computation. Cloud-based BAS services sidestep these limitations but present additional challenges such as latency and the potential for intermittent or lost connectivity (Callahan 2017). Development, training, and calibration of models that are sufficiently accurate and robust is another significant challenge, as is lack of acceptance by building operators. These lead to increased costs and long estimated periods for return on investment despite the demonstrated energy efficiency potential.

The ability to operate and plan over a time horizon, to incorporate multiple inputs including forecasts (which are then updated with measured data), and to optimize complex objectives makes MPC extremely attractive for integrating demand flexibility based on thermal shedding and shifting with energy efficiency. Realizing these benefits means overcoming these challenges.

Optimization framework. The optimization framework, within which the model is evaluated, is characterized by the time horizon, the re-evaluation interval, the objective function, and the optimization algorithm.

For thermal shifting and shedding, the time horizon is typically a day, although in buildings with battery and active thermal storage it may be possible to optimize over longer time horizons. The re-evaluation interval is typically between 5 and 15 minutes. Thermal dynamics are slow enough that shorter re-evaluation intervals are not needed. On the flip side, high-frequency modulating grid services act on short time horizons and do not need MPC, nor can they tolerate the latencies associated with MPC. This is another practical argument for why low-frequency shedding and shifting and high-frequency modulation services should be managed independently.

The need to optimize for multiple, often conflicting objectives—energy efficiency, grid benefits, and occupant preferences—is a key challenge. Conflicting objectives require careful problem formulation to achieve the best balance between the objectives. Traditional approaches that use a weighted cost function to represent multiple optimization goals can be difficult to use. Finding appropriate weights that reflect the relative priorities of the objectives in the presence of constraints is usually performed iteratively through simulation, resulting in costly retuning during deployment (Vallerio, Impe, and Logist 2014). New methods adaptively weigh control objectives based on building stakeholder preferences.

One of the benefits of thermal shifting over thermal shedding is that it does not impact occupant comfort, at least in theory. Occupant impacts and their effect on optimization are discussed in greater detail in the next section.

Model selection, development, and calibration. Planning and optimizing the shifting and shedding of space-conditioning loads requires a model of: (1) the internal and external thermal loads on the space, (2) the thermal time constant of the space (i.e., how quickly it gains or loses heat), and the capacity and efficiency of the system that serves the space (i.e., how quickly it can add or remove heat and with what electrical use profile and operational constraints). This model would be parameterized by inputs such as time of day, day of week, day of year, current indoor conditions and system states, current and predicted outdoor weather conditions, current and predicted occupancy, current and predicted electricity prices, and tariffs or other grid signals and conditions. It would have outputs such as predicted future indoor conditions and systems states as well as energy and demand use and charges. This model can take on multiple forms that fall roughly into three classes:

- Physics-based white-box models calculate building response directly from first principles. They are capable of modeling complex dynamics and responses to previously unobserved conditions, but are computationally intensive and take significant effort to develop, calibrate, and maintain over time as the building and its use change. For energy efficiency and thermal shifting and shedding, white-box models would use a BEM engine such as EnergyPlus or similar.

- Data-driven black-box models such as neural networks learn the relationships between inputs and outputs from measurement. They can capture nonlinear dynamics and are computationally cheap, but may not be able to model building response to previously unobserved conditions. They require a significant amount of training data (in both type, frequency, and range of values) in order to map a meaningful range of building behavior. For buildings with tightly controlled operating conditions, the range of available data may be limited.
- As suggested by their name, gray-box models hybridize white-box and black-box approaches in an attempt to use the advantages of one to offset the drawbacks of the other. They use simplified, typically linear physical models (e.g., resistance-capacitance networks), to capture major thermal dynamics and data-driven approaches to derive model coefficients. They are computationally cheaper and require less effort to set up than white-box models and less training data than black-box models. Their shortcoming is that they may only be valid under a narrow range of operating conditions because building loads and responses are characterized by high nonlinearity.

To date, no approach has emerged as a clear front-runner. One possible approach is to hybridize models of different types; for example, to combine white-box models of the HVAC system with black-box or gray-box models for loads.

Integration with fault detection, diagnosis, and prognosis. Sensor and equipment faults interact in multiple ways with demand flexibility and MPC. Equipment faults change baseline energy consumption and may alter the availability of demand flexibility. Equipment and sensor faults may impact the data that are used to train and calibrate models. Sensor faults also impact model inputs at runtime.

In an ideal world, an independent automated fault detection and diagnosis (AFDD) process would identify faults and trigger prompt interventions allowing fault-free equipment and sensing to train and update models. In reality, MPC is continuous, new faults arise intermittently, and AFDD is neither instantaneous nor perfect. The possibility that new faults cause mismatches between models and reality and pollute training and input data is real and significant. Refining AFDD and its relationship with model training is a critical component of establishing MPC.

Automated fault prognosis—prediction of pending faults—is closely related to AFDD. Incorporating fault prognosis into the process can both avoid faulty data and inform the optimization algorithm about equipment health and suitability for various demand flexibility actions, helping to extend equipment life and ensure continuous system operation.

Adaptivity. The availability of thermal demand flexibility may change seasonally and month to month; occupancy patterns and preferences may also vary throughout the year. Adaptive control integrates data-driven parameter estimation methods to refine and update system parameters over time based on measured data and is closely linked to reinforcement learning (Sutton, Barto, and Williams 1992). This can enhance GEBs and support their persistence. DOE-sponsored efforts are advancing adaptive control strategies for building energy systems (Bengea et al. 2015; U.S. Department of Energy Office of Energy Efficiency and Renewable Energy 2016).

Uncertainty management and robustness. Energy efficiency operation under uncertainty is almost always better than no energy efficiency operation at all. Uncertainty in demand flexibility affects the reliability of commitments to deliver grid services and the compensation for providing those services.

Sources of uncertainty in MPC include sensing limitations in type, resolution, and frequency; sensor measurement error, especially from sensors that are not frequently calibrated; and model errors. For thermal shedding and shifting, weather and occupancy forecasts are another source of uncertainty.

There are several complementary approaches to managing uncertainty. All of them require uncertainty to be characterized, which for many parameters is a difficult task. The first approach is to reduce uncertainty where necessary using additional sensing and improved forecasting algorithms. The second is to propagate the uncertainty through the model (e.g., using Monte Carlo approaches) and expose it to the optimization framework. Adaptive control is one approach to tackling tackling parameter uncertainty in an optimization framework. Adaptive control can be complemented by passive methods, in which the optimization algorithm produces solutions that are robust or insensitive to the uncertain parameters (Ma, Matusko, and Borrelli 2015).

It should be noted that a certain level of uncertainty at the building level can be tolerated by large-scale aggregation across many buildings.

Control interpretability. Rule-based control algorithms are "expert systems," automating traditional building operator logic. In contrast, optimization methods are qualitatively different. While effective, they appear as "black boxes." The solutions they find may be unintuitive because they were not arrived at by a traditional rule-following process, but rather by the more mysterious process of evaluating multiple possibilities and choosing the "best" one. It is not only more difficult to trust these solutions, it is also more difficult to tune them by hand.

In order to gain acceptance—in both fully automated settings and human-in-the-loop settings (in which models generate candidate solutions that are implemented and adjusted by human operators (Munir et al. 2013))—optimization-based methods must be accompanied by improved interpretability. This is a widely recognized challenge not specific to building automation (Lipton 2018). The European Union's General Data Protection Regulation stipulates a "right to explanation" for algorithms that "significantly affect" users (Weinberger 2018).

Recent efforts in domains including computer science and mathematical optimization are focusing on making optimization- and machine-learning-based "black-box" methods interpretable to end users. Application of these techniques to building automation algorithms can improve their interpretability, and therefore acceptability, to all stakeholders (owners, operators, and occupants). One potential approach could be to express MPC results in terms of contextual parameters (such as time of the day, day of the week, weather, and occupancy and equipment operating models), essentially to *ex post* map MPC results onto a rules framework that would be easy for building operators to understand and verify.

Advanced actuation. Current demand response implementations either manipulate setpoints or switch equipment off. These actuation approaches have well-understood limitations (e.g., loss of building function, occupant inconvenience, equipment degradation) and are therefore called infrequently.

In order to enable broader, more frequent, and more effective use of demand flexibility, new actuation opportunities are needed at different levels in the building control system hierarchy. Equipment could communicate and possibly adjust its settings for minimum and maximum run time and minimum off time. Such constraints are typically set conservatively to avoid short cycling and overheating and to extend equipment useful life. Equipment could modify these currently fixed operating parameters and increase the demand flexibility available to the building. Tracking, estimating, and reporting demand flexibility, along with exposing additional demand flexibility, require more accurate monitoring of equipment state though additional sensing, more sophisticated equipment level control, and equipment-level automated fault detection and health estimation. At the supervisory level, MPC can change energy use patterns by adjusting setpoints of multiple subsystems concurrently. Supporting this capability may require modifications to existing control loops.

Integration with envelope and lighting control. Space conditioning and thermal comfort are strongly influenced by the building envelope. At the same time, it is less clear whether control of dynamic envelope elements (e.g., dynamic windows, automated shades) and lighting must be tightly integrated with HVAC control and MPC in order to implement effective thermal load shifting and shedding. It may be possible to control the envelope and HVAC system in an implicitly coupled "cascading" fashion. The envelope would be controlled for energy efficiency (i.e., to minimize load) in a conventional nonpredictive way. The HVAC system would be controlled predictively, assuming this reduced load. If the model is a black- or gray-box model or even an adaptive-physics-based model, reduced envelope load would be learned naturally.

Tighter, explicit coupling between the envelope and HVAC could be needed for several reasons. The envelope could include automated vents or windows that support natural or mixed-mode ventilation. The dynamic elements of the envelope could have long response times (e.g., dynamic windows can take up to 30 minutes to switch states), such that the HVAC system may want to modulate them predictively rather than reactively. Finally, the occupant could couple the envelope and HVAC by overriding one or the other (e.g., raising shades when they would otherwise be lowered to reduce load). Research is needed to identify the appropriate degree of coupling between HVAC and envelope control.

Integration with electricity generation and storage control. On-site electricity generation and storage do not interact tightly with thermal shifting and shedding, but can be used to enhance it. Stored electricity can be used to operate the HVAC system during peak periods if the thermal load cannot be completely shifted away. Solar production is also weather driven and should be predictively accounted for using the same predictions as those used for space conditioning.

Multibuilding coordination. The control of multiple buildings has been shown to be able to smooth out the demand for electricity during times of peak use. Zheng and Cai (2014) examine the distributed scheduling and control of HVAC units to smooth out demand for power throughout the day and increase the adoption of stochastic renewable energy resources (Zheng and Cai 2014). El Geneidy and Howard (2018) demonstrate the use of MPC to control HVAC systems to maintain operational constraints, minimize costs, and flatten out the demand curve (El Geneidy and Howard 2018). An important research direction looks at the kind and intensity of interbuilding communication needed to avoid unintentional coincident behavior.

4.3 Characterization and M&V

As is the case with demand response, variable-rate billing for energy and demand is a direct way to communicate the value of thermal shifting and shedding.

Sans variable-rate billing or for additional compensation, thermal shifting and shedding must be characterized in terms of energy, demand, response time, and duration for bidding into a service market; committed; and finally measured and verified to receive compensation.

Both characterization and M&V require establishing a baseline against which the shift and/or shed can subsequently be measured. For two entities to agree on the service provided, they must use a common consensus baseline. This is not the case today. Utilities typically uses statistical/heuristic models, whereas a building using an advanced controller predicts its future energy use and benchmarks service using a model-predictive baseline.

Trusted data. Utilities today typically do not share real-time energy metering data with building owners at full temporal resolution. This may lead building owners to install additional power sensors to have high-fidelity energy data. Discrepancy between these readings, which can occur for many reasons, including lack of time synchronization, accuracy/uncertainty or calibration differences, and different methods of measurement, can lead to meaningful and unintended differences in calculated service measurement.

Meter data are not the only data needed to develop a baseline; sensor data are also needed. Baseline algorithms typically correlate energy use with outdoor temperature, and some may use additional variables, including solar radiation, indoor temperature, and occupancy. The building and utility must agree on the values of these data streams. Secure, authenticated sensing are necessary to provide a foundation of trusted data. The BTO-sponsored Hamilton project is developing infrastructure for trusted sensing (*Hamilton* 2019). For any given service, the minimally sufficient sensing requirements, including type and placement of sensor, accuracy, frequency, and reporting interval, must be established.

Baseline algorithms. An MPC controller essentially uses weather and occupancy predictions to create a sliding baseline for thermal shifting and shedding. This baseline is not fixed; it is updated as new measurements are recorded. This baseline also necessarily incorporates actions previously taken by the controller to implement shifting and shedding. In order to establish a true counterfactual baseline, the MPC controller may need to run a shadow optimization process with an objective function that does not incentivize thermal shedding and shifting (e.g., one that optimizes for energy efficiency, assuming flat-rate billing and a tight comfort envelope, although pure energy efficiency objectives also incentivize thermal shifting when weather conditions provide "free precooling." Because it would not actually be used to control the building, this process could employ a simpler, coarser model. This counterfactual optimization process would need to update exogenous input data, such as outdoor temperature and occupancy, but would otherwise internally book-keep endogenous variables such as indoor temperature and system state. Of course, the counterfactual MPC cannot be completely and indefinitely detached from the primary active MPC, because delivering one grid service perturbs the baseline for other services, at least for some period of time. Developing consensus baseline algorithms that are continuously calibrated, resilient in the face of uncertainty (present in measurements, forecasts, and models (Mathieu, Callaway, and Kiliccote 2011)), and can be composed to support characterization and M&V of multiple service instances (potentially targeting multiple service markets), is a challenging task.

The difficulties associated with collecting trusted data and developing baselines for continuous services—thermal shifting and shedding may not be inherently continuous, but its implementation via MPC is—suggest that these are best implemented as nondispatchable price-driven services.

4.4 Quantitative Analysis

The origins of BEM are in thermal loads analysis and HVAC system sizing, and many modern BEM engines are largely capable of performing thermal analysis at the level required to support evaluation of thermal shedding and shifting, including calculations of operative temperatures and occupant comfort. They can also simulate PV production and battery storage.

Equipment cycling. Most BEM programs do not explicitly model HVAC equipment cycling, a phenomenon that may not be relevant to energy efficiency but is significant to demand flexibility. EnergyPlus, for instance, assumes that HVAC equipment such as fans, compressors, and coils operate at "partial load" over the entire time step as opposed to running at peak load until the load is met and then cycling off. The (heat balance) algorithms in EnergyPlus are valid to a time step of one minute, and reducing the time step to this value will expose cycling behavior that has a frequency of two minutes or greater. Spawn, which will use a dynamic time step for HVAC, will naturally produce physically realistic cycling. If realistic but not specific cycling behavior is sufficient, cycling can be characterized and then post-super-imposed onto a lower-resolution load shape by post-processing. Additional laboratory testing or detailed component modeling may be needed to characterize cycling behavior, especially for equipment containing variable speed components and advanced controls.

Control sequences and algorithms. There are two separate but related use cases that connect evaluation of a building's thermal performance evaluation and control of its relevant active element—primarily the HVAC system, but potentially also the facade and lighting system. In "offline" use cases such as design (including control design) and rating, a building's thermal performance must be evaluated in the context of the thermal control algorithm. In "online" use cases, a model may be embedded within the control algorithm.

A flexible and powerful way to support both of these use cases is to make a simulated building look like a physical building to real-world control sequences (i.e., allowing control sequence to read simulated sensor values and manipulate simulated setpoints and actuators using standard protocols such as BACnet and standard naming conventions such as Haystack). Industry has already shown examples of using this approach to commission customer sites for advanced controls (Yang et al. 2018). This functionality is currently being implemented in the Alfalfa/BOPTEST platform, which will also provide standard test cases and benchmarks that can be used to compare algorithms on both energy efficiency and demand flexibility metrics.

District systems. Shared thermal systems (i.e., district heating and cooling systems) have the potential to play a significant role in demand flexibility (Nuytten et al. 2013) because they offer a significant amount of active, controllable thermal storage and can also leverage low-level waste heat resources. District systems are still uncommon in the United States (outside of dense cities and university campuses), and most BEM tools currently do not model them. Several exceptions include EQUA's IDA ICE (EQUA), the Modelica Buildings Library (*Modelica Buildings Library* 2019), Big Ladder Software's District Zero (Ellis 2016), and the National Renewable Energy Laboratory's URBANopt (Polly et al. 2016). District Zero and URBANopt simulate buildings individually, aggregate building thermal loads, and then feed those loads into a district system model as static input. This loosely coupled modeling is computationally efficient and may work well for certain types of conventional district thermal systems with tight temperature and flow-rate setpoints but not as well for others, such as fifth-generation systems that have lower temperature lifts between supply and return and whose performance is more heavily dominated by pumping energy and effects like flow friction and pressure imbalances. They also do not adequately represent district system control. IDA ICE and the Modelica Buildings Library use tightly coupled co-simulation (i.e., parallel simulation of buildings and district systems are simulated in parallel at the time-step level, and more accurately capture these dynamics). BTO is funding an extension to URBANopt that will leverage Spawn to add tightly coupled co-simulation for district systems and explore the use of whole-building models of different resolutions (e.g., EnergyPlus, resistance-capacitance networks) in district system simulation.

Occupant preference models. Occupants have diverse needs or preferences for indoor temperature and humidity and amount of fresh air; their tolerances also vary. Different occupants may prioritize different end uses (e.g., some occupants may prefer to dim lights or reduce ventilation, while others may prefer to adjust temperature first). A broad survey or measurement study of occupant preferences is needed to support modeling and evaluation of GEB technologies and strategies.

Weather data. BEM weather data currently are available at an hourly resolution, which BEM engines interpolate as needed. Modeling solar gain and PV production under variable cloud cover is also a challenge. Weather data with greater temporal resolutions that includes information about cloud cover may be needed to properly evaluate demand flexibility. Weather data that include extreme weather events are also needed.

Output metrics. In addition to higher-resolution inputs, BEM engines also need to generate higher temporal resolution electricity use load shapes to support calculations of metrics such as Title 24's Time Dependent Valuation (California Energy Commission 2016) and the GridOptimal rating from the U.S. Green Building Council New Building Institute (New Buildings Institute and U.S. Green Building Council 2017). Time Dependent Valuation schedules for other locations and other assumptions (e.g., further distributed generation penetration) would be useful for evaluating demand flexibility in region-specific ways both for individual buildings and at scale. Extending the Utility Rate Database (NREL 2019) to handle higher-frequency rate and rating structures would better support GEBs.

In addition to grid-oriented energy and power metrics, evaluating GEBs would benefit from metrics that address loss of service, including lost productivity and equipment wear. New measurements and models may be needed to develop and calculate these metrics.

5 Demand Flexibility: Shedding and Shifting Other End-Use Loads

Space conditioning is an important and unique end use for many reasons. It is large, weather dependent, and contributes significantly to peak demand and grid congestion. It is occupancy dependent and directly impacts occupant comfort, productivity, and health. It interacts with the building envelope. It has a wide spectrum of configurations that range from simple packaged systems to complex hierarchical systems spanning multiple buildings. Space conditioning has the most complex control strategies, sensing requirements, and occupant interactions and requires the most comprehensive approach to demand flexibility.

Other end uses are simpler than space conditioning in one or more dimensions. They may be weather independent, have light duty cycles, or may not directly impact occupant comfort. These end uses can leverage simpler approaches to demand flexibility. Common end uses include water heating, refrigeration, lighting, computing, networking, office equipment, displays, conveyance, and battery charging for both consumer electronics and electric vehicles. Many end uses do not reject enough heat to significantly influence heating and cooling loads and can often be managed independently from space conditioning, at least for demand flexibility activation purposes. Coupling between these end uses and space conditioning can be stronger in some contexts, requiring close coordination for both energy efficiency and demand flexibility. Examples include computing and networking in server rooms and data centers as well as refrigeration in supermarkets.

5.1 Occupants, Operators, and Owners

As with HVAC load shifting, manipulating end uses in ways that produce no negative or even noticeable impact on occupants is the preferred approach to leveraging demand flexibility for grid services. End uses that include storage, either thermal or electrical, and can be proactively shifted ahead in time can be managed in a similar way to HVAC loads. These end uses include water heating, refrigeration, and battery charging. End uses with low duty cycles and some scheduling flexibility can be used to defer loads and shift them back in time. These end uses include dishwashing, clothes washing and drying, and some computing applications. End uses like lighting, conveyance, displays, and interactive networking and computing applications have no storage and cannot be scheduled without impacting building service levels. Of course, end uses with storage and scheduling flexibility can also be shifted and curtailed to a degree that eventually impacts occupants.

Leveraging demand flexibility in a range of end uses begins with identifying and quantifying demand flexibility modes and identifying those that may be activated without impacting occupants. The remaining end-use demand flexibility modes and regimes must be valued and prioritized by occupants and, depending on the end use and context, aggregated over multiple occupants. This essentially creates a (potentially occupant-specific) hierarchy of end uses whose demand flexibility can be invoked in a cascading manner depending on grid needs; end uses with no occupant impacts are called when grid service demands (electricity prices) are low, and end uses with increasing occupant impacts are recruited as service demand and prices rise. Acquiring and establishing these hierarchies is an active topic of research, e.g., Lipton 2016; Kim and Katipamula 2017; University of Colorado Boulder 2019.

5.2 Execution

Individual end-use-based shedding and shifting. Demand flexibility execution begins with the ability to provide services from individual end uses. In commercial buildings, end uses such as central lighting and conveyance may already be controlled by the BAS and able to provide services via BAS control.

Some end uses that are packaged as appliances have the capability to provide grid services—water heaters are the most notable example. For these, demand flexibility control may be implemented as direct response to commands (i.e., direct load control), supporting aggregation. Demand flexibility control may also allow programmed scheduling, potentially incorporating external variables such as occupancy or electricity prices. Finally, the equipment may record use patterns and autonomously identify and activate opportunities for flexible scheduling again using electricity price forecasts (Butzbaugh et al. 2017). Appliances such as refrigerators, washers, dryers, and electric vehicle chargers could provide similar capabilities.

Diffuse end uses that directly contribute to occupant comfort and productivity, including lighting and interactive computing, present the greatest challenge because using them to provide grid services requires understanding both occupant tolerances and priorities. Supporting shedding and shifting using these end uses likely requires explicit occupant interaction, both to acquire general preferences and priorities as well as to provide override opportunities on a per demand-flexibility-event basis.

Service coordination across end uses. A second challenge arises if and when services from different end uses within a building must be coordinated. Tight coordination requiring lock-step control of multiple end uses may be needed in some contexts (e.g., in supermarkets where HVAC and refrigeration may both be set-back in tandem). More commonly, however, end uses may need to coordinate in order to simply determine how much each can and should contribute individually to a given service.

In these cases, traditional supervisory control is not needed. Instead, distributed price-based (i.e., transactive) mechanisms can be used to establish priorities and building service levels. The price "within the building" can be the price of electricity or a price that will be attached to a service bid. Note that HVAC control would also participate in this process, as would on-site solar production and storage.

Multibuilding coordination. As with HVAC loads, other end uses may also benefit from multibuilding coordination. In particular, researchers have studied the abilities of water heaters (Kondoh, Lu, and Hammerstrom 2011) and heat pumps (Parkinson et al. 2011) to work together to provide shedding- and shifting-based services.

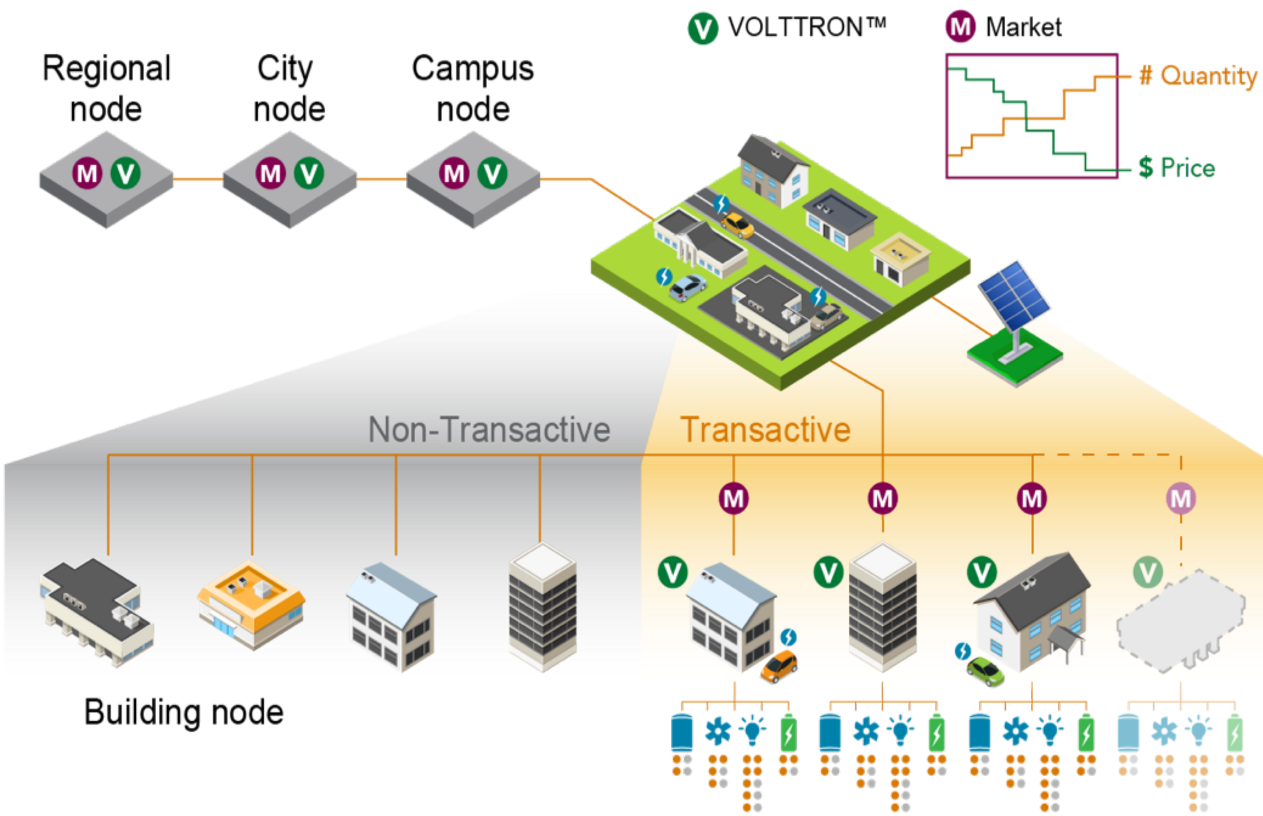

Figure 5. Transactive coordination is a distributed mechanism for allocating energy among different zones and end uses in a building. Transactive coordination can be used hierarchically to allocate energy among entities at different granularities, such as buildings in a campus. ***Image courtesy of Pacific Northwest National Laboratory.***

5.3 Characterization and M&V

As with execution, characterization and subsequent M&V may operate at the level of both the individual end use and of the building as a whole.

Individual end-use-based services. Connected packaged end-use equipment like water heaters may be able to provide grid services using direct load control methods that are characterized by the manufacturer and do not require individual, unit-specific M&V. If packaged equipment can also provide load services using programmed, price-responsive scheduling, it may also be able to explicitly characterize its demand flexibility capabilities for in-building aggregation purposes.

More diffuse end uses, such as lighting and computing (if they can be automatically controlled to leverage demand flexibility), should also also able to automatically characterize their available demand flexibility. Alternatively, if demand flexibility for these is activated using an external controller like a smart strip, manual characterization using a combination of engineering specifications, inventory, and submetering may be needed to calculate demand flexibility characteristics and program them into the controller.

Trusted submetering, potentially combined with other equipment-level or environmental sensing, may be used to verify grid service delivery.

Service coordination across end uses. An in-building "service market" can be used as the basis for building-level service aggregation, service bid creation, and subsequent disbursal of service payout. M&V can be disaggregated and performed at the end-use level using the techniques mentioned previously.

5.4 Quantitative Analysis

BEM engines such as EnergyPlus simulate end uses with complex internal thermal dynamics and control such as water heating, refrigeration, and some IT equipment in physical detail to account for thermal effects both within the end use and interactions with other end uses, primarily space conditioning. End uses with simple or irrelevant internal thermal dynamics and control, like lighting, are characterized by service-level, power-draw, and rejected heat profiles. Again, these loads are modeled at zone time step resolution, typically 15 minutes. If realistic but not specific load profiles are needed for these end uses—analogous to cycling versus constant part-load profiles for HVAC equipment—higher frequency shapes could be superimposed using post-processing.

Occupant schedules, preferences, and behavioral models. BEM workflows typically use deterministic schedules for occupancy, occupant activity, lighting, and plug loads that capture average values appropriate for annual energy calculations. Realistic schedules will vary stochastically, impacting electricity use at greater temporal resolutions that are important to demand flexibility and GEBs. Several stochastic schedule models have been developed for occupancy (Chen, Hong, and Luo 2018), hot water usage (Hendron, Burch, and Barker 2010), and multifamily equipment (Kung et al. 2019). Further development of these models and models for other types of equipment including laundry, dishwashing, cooking, entertainment, IT, and electric vehicle charging are needed. Models should logically and realistically order sequential activities as opposed to randomly assigning activities from independent probability distributions.

6 Demand Flexibility: Load Modulation

Modulation services contribute to grid reliability and stability and delivered power quality by helping to regulate power characteristics such as frequency, voltage, and current-voltage phase lag. This report categorizes services with response times of one minute or less as "fast" modulation services and focuses on frequency regulation, voltage support, and primary frequency response. Recent advances in sensing, control, and communication enable building and DER-based modulation services.

The fastest modulation services are primary frequency regulation and voltage support, which provide local and essentially immediate response to grid or solar-production disturbances, usually on the timescales of milliseconds to seconds. Qualified resources respond autonomously to local measurements of frequency and voltage rather than to explicit control or price signals from a central entity (Donnelly M. and J.E. 2012). Building technologies that can provide these services, which are often considered to be energy neutral, include smart water heaters, PV inverters, and battery inverters.

Secondary and tertiary frequency regulation services are deployed to correct imbalances at timescales of seconds to minutes. Frequency regulation resources are qualified by system operators and must respond to control signals with a regular communication period, usually 2–4 seconds. Battery storage and water heaters are currently participating in these markets (PJM 2019). Recent research has shown that other building assets, such as residential air conditioners and electric vehicles, are capable of providing frequency regulation with appropriate coordination by a service aggregator (Baker et al. 2016). Variable frequency drives in fans, compressors, and chillers are potential sources of frequency regulation in commercial buildings. Frequency regulation services themselves constitute a range of response times, duration, and power magnitudes. On the faster end, frequency regulation services such as PJM's Regulation D service are considered energy neutral; they have negligible impact on occupants and interactions with energy efficiency and other demand flexibility modes and can be implemented separately. On the slower, higher-capacity end, frequency regulation services such as PJM's Regulation A begin to resemble slower shedding and shifting services. Here, interactions with energy efficiency and other demand flexibility modes become more significant and integration with other demand flexibility modes becomes more valuable. There are a set of open research questions surrounding modulation services that are not energy neutral; specifically, at what point do they need to be accounted for by energy efficiency and demand flexibility control, at what point do they need to be integrated with energy efficiency and demand flexibility control, and whether there is enough potential in these services to justify the increased complexity.

6.1 Occupants, Operators, and Owners

Fast energy-neutral modulation services do not impact occupants. The ability to provide these services using mechanical devices such as variable frequency drives may be limited either by hard operational constraints on ramp-up and ramp-down speeds or cycling limits, which are enforced to prevent damage and wear on the equipment, or by operator reluctance to use equipment for services that may shorten its life or compromise its performance.

Slower frequency regulation services may not impact equipment performance or lifetime, but may impact occupants if they are provided by HVAC fans or compressors. The choice here may be between limiting the frequency bandwidth of these devices' response to avoid occupant impacts and integrating frequency regulation into the larger HVAC control framework.

6.2 Execution

Autonomous services. A key requirement of autonomous response is the ability to monitor grid state and identify thresholds for initiating and terminating service delivery. Measurements include supply voltage, frequency, the rate of change in either of these, or the profile of voltage or frequency shift over time. Most building equipment does not actively monitor the electricity supply, but newer inverter-driven equipment often does ("IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces" 2018). PV and battery inverters are a potential source of behind-the-meter autonomous services.

Supporting these services at the building level requires the device or building system to sense power distribution state, communicate, and provide coordinated response on time frames of seconds or less. No standardized communications exist within modern building controls to execute autonomous responses at these speeds. Support for these types of services might eventually exist only at the device level.

Frequency regulation. Frequency regulation control is geographically aggregated to both achieve the total service level needed and mitigate uncertainty associated with individual loads. Local resource controllers adjust the power consumption of individual devices using simple classical feedback proportional-integral or feed-forward control.

Most work on frequency regulation in commercial buildings focuses on air handling ventilation fans. The load is modulated directly by controlling fan speed or indirectly by modifying the mass flow rate or duct static pressure setpoint to the local control loop that regulates the fan speed. Both methods have been successfully demonstrated in real buildings to yield satisfactory tracking results (Lin et al. 2015; Adetola et al. 2018). The direct method results in faster response; however, its acceptability may be limited by reliability concerns. The indirect method is slightly slower and more complex because the control design must account for the physics of the supply duct and the response of the pressure or mass flow controller. Other building equipment, such as variable speed chillers (Su and Norford 2015a, 2015b) and heat pumps (Kim, Fuentes, and Norford 2016), has also been demonstrated for frequency regulation. Experimental studies (Adetola et al. 2018; Lin et al. 2015; Su and Norford 2015b) have tested these devices using PJM Regulation A and D standard signals to demonstrate their adequacy. Other systems that could provide frequency regulation in commercial buildings include electric vehicles (Jin and Meintz 2015) and water pumping systems (Sparn and Hunsberger 2015).

Additional simulations and/or field demonstrations (preferably over a longer time period) are needed to establish these capabilities. The impact of frequency regulation on HVAC equipment and system efficiency and on long-term equipment reliability needs to be better understood. Though the frequency regulation control signal is typically energy neutral on average, the time-average efficiency of the HVAC system when providing frequency regulation may result in increased energy consumption (Beil, Hiskens, and Backhaus 2015).

Service coordination across devices. As with shedding and shifting services, additional challenges arise when services must be coordinated across multiple devices. Although components providing modulation services generally do not interact with one another physically, tight coordination may still be necessary to achieve synchronization and avoid destructive interference. Depending on response time requirements, unidirectional synchronization could be implemented at the building level, at the equipment manufacturer/aggregator level outside the building, or a combination of both.

Multibuilding coordination. For modulation services, coordination across buildings is similar to coordination within a building. Researchers have studied the potential for building-based frequency regulation via distributed multibuilding control (Colavitto et al. 2018; Hao et al. 2014; Hoke 2018). Future research is needed to quantify the robustness of this approach.

Integration with shedding and shifting services. HVAC systems may provide both shedding and shifting services and modulation services. The degree of coupling depends on the bandwidth of the regulation signal and the magnitude of the load perturbation. Work is needed to evaluate the degree of coupling between energy efficiency, demand flexibility, and different frequency regulation services provided by different HVAC components and to develop effective decoupling or coordination strategies that identify the optimal balance between regulation provision, energy efficiency, and demand flexibility.

6.3 Characterization and M&V

Autonomous response. Because autonomous response is not activated by the utility or grid operator, it does not require characterization and M&V on an instance basis. Depending on the need for autonomous grid services, the capability may be regulated (e.g., IEEE standard 1547-2018 ("IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces" 2018) requires frequency response as part of the new smart inverter standard) and customers could be given a rebate for installing them.

Frequency regulation. Behind-the-meter resources can offer frequency regulation via service aggregation. As with shedding and shifting services, a power-consumption baseline is used to forecast available reserve capacity.

Frequency regulation is quantified in terms of power reserve magnitude and bounds on how often and how quickly power consumption can be changed (Hao et al. 2017; Adetola et al. 2018). If frequency regulation is provisioned by mechanical components such as variable frequency drive fans, characterization requires short-term mechanical and momentum dynamics (such as variable frequency drive rate limits and supply duct dynamics) as well as response parameters if direct device control is not available. Historical data can be used to extract these parameters.

M&V for frequency regulation requires high-temporal-resolution power meters, which may not be available at the device level. Calculating these metrics based on building-level HVAC consumption is challenging. Disaggregation (e.g., into fan and chiller power) may be impractical because of possible interactions between the devices and their control loops. Communication latency may create (slight) discrepancy between the power readings at the device and aggregator levels, impacting tracking accuracy. Research is needed to establish technologies for measuring fast modulation service response.

6.4 Quantitative Analysis

Detailed electrical modeling. High-frequency and distribution-level grid services rely on reactive power and specific power characteristics such as voltage and frequency. BEM engines model only real power and energy, and typically assume a stable grid supplying power at nominal voltage and frequency.

The extent to which modulation services have to be analytically evaluated at the whole-building level (and therefore the necessary degree of coupling between detailed high-frequency electrical system modeling and BEM) is an open question. For some applications and some grid services (e.g., large-scale analysis of energy-neutral modulation services in support of activities such as program planning), it may be sufficient to model detailed electrical characteristics at the component level and then use BEM to tabulate them or even to superimpose detailed electrical behavior onto lower-frequency energy use load profiles. This approach may not be sufficient for modulation services that are not energy neutral and interact more closely both with shedding and shifting services and with energy efficiency.

Going forward, the value proposition of individual devices will increasingly be determined by their ability to contribute to both energy efficiency and demand flexibility and to both load and modulation services. Modeling is an important mechanism for demonstrating the value of a device both at the individual specific building level and the building stock level.

Different characteristics are important for different analyses. Consider the case of motors: inrush current is important in fast services, and not important for energy efficiency, shedding, or shifting. Cycling behavior is important for shedding, shifting, and fast services, but not for energy efficiency. Motor efficiency is important for energy efficiency, shedding, and shifting, but not for fast services. Equipment models and inputs across all scales should reflect the same equipment. Ensuring that modulation service device models are compatible with and transferable to standard BEM frameworks used to model shedding and shifting will help building owners and operators as well as design professionals, utilties, and service aggregators value components more holistically.

7 Enabling GEBs: Interoperability and Cybersecurity

GEBs are enabled by communication between building equipment, whole buildings, and the grid. This section discusses improvements needed in building and grid communications for buildings to provide grid services on an automated, continuous, and integrated basis.

7.1 Interoperability

Interoperability, the ability of devices or software systems to reliably exchange data, is a key technical and market gap/barrier to enabling system-wide benefits of connected energy efficiency (U.S. Department of Energy 2015). Interoperability is even more significant in the context of GEBs, which rely heavily on communication within the building and between buildings and the grid (National Institute of Standards and Technology 2014). Because GEBs involve numerous previously separate industries—HVAC, major appliances, DERs, IT and network security, and control vendors, not to mention utilities—which have developed their own communication approaches and protocols, GEB-relevant interoperability is not easily achieved, and the value of interoperability has not been sufficiently proven to manufacturers such that they pursue it independently.

Even within industries, individual vendors have an incentive to create systems that can operate only with other systems from that vendor or their partners. Developing common interoperable platforms and communication protocols is critical to maximizing grid service provision and ensuring that vendor lock-in does not curtail consumer interest in demand flexibility technologies. The ENERGY STAR program is in the process of formulating its voluntary connectivity guidance for large-load end uses. During the specification-setting process, a number of stakeholders have expressed a philosophy of requiring end-use manufacturers and vendors to offer at least one open standard for communications in addition to any manufacturer- or vendor-specific proprietary communications (U.S. Environmental Protection Agency and U.S. Department of Energy 2019). Stakeholders view this approach as advantageous because it provides consumers with more choices for demand flexibility as well as enables market competition as a means to develop demand flexibility approaches without direct involvement of manufacturers.

Telecommunication protocol stacks. Electronic telecommunication is typically thought of as a stack with a hierarchy of protocols operating at different layers. Interoperability at a given layer requires the use of the same (or compatible) protocols at that layer and all of the layers below. The Open System Interconnection model defines seven layers ("Information Technology–Open Systems Interconnection–Basic Reference Model: The Basic Model" 1996), but at a high level, these comprise three groups. At the bottom are physical data layers that define the physical medium and the properties of signals that are exchanged on it; examples include Ethernet and Wi-Fi. In the middle are network layers that define the form, routing, and delivery of messages; examples include Transmission Control Protocol/Internet Protocol (TCP/IP) and Secure Sockets Layer/Transport Layer Security (SSL/TLS). On top are application layers that define the internal structure and semantics of the messages being sent; examples include Internet Message Access Protocol for email and Hypertext Transfer Protocol (HTTP) for the web. Internal message structure and semantics are also often hierarchical and leverage standard data models, formats, and schema for different types of data; examples include HyperText Markup Language (HTML) for web pages and Portable Network Graphics (PNG) for images.

Messages in a protocol stack are like nested envelopes. To send a message, an application protocol takes the message content, places it in an application envelope (i.e., an envelope that identifies the receiving application), and passes it to the networking protocol. The networking protocol reads the application envelope (but does not "open" it to look at its contents), translates some of the application-layer information to networking-layer information, wraps the application envelope in a network envelope, and passes it to the data protocol. The data protocol repeats this exercise; it looks at the network envelope, translates some network information to data-layer information, adds a data envelope, and sends it out either on a wire or wirelessly. On the receiving end, the protocols activate bottom up. The receiving data protocol receives the package, strips off the data envelope, and passes the networking envelope to the correct networking protocol above. Similar, the networking protocol peels off the networking envelope and passes the application envelope to the correct application above. Finally, the application opens the application envelope and presumably knows what to do with the contents. Protocols do not open envelopes and interpret data passed to them by higher-level protocols.

GEB-relevant protocols do not always map cleanly to traditional Open System Interconnection layer definitions, with some protocols spanning multiple layers, partial layers, or both. Generally speaking, however, most GEB-specific activity takes place at and above the application layers, leveraging common data and networking protocols like WiFi, TCP, and TLS. One notable exception is CTA-2045 ("Modular Communications Interface for Energy Management" 2018), a cross-layer hardware and software protocol designed to enable two-way communication and energy-related information exchange for equipment like water heaters and pool pumps that traditionally do not have embedded computing and communications capabilities. Interfaces to traditional communications protocols like Wi-Fi along with additional computing is provided by plug-in modules. Another exception is the automated meter reading and advanced metering infrastructure suite of protocols, which specify data, networking, and some application-layer functions for connected electricity meters.

Application layer protocols. The most commonly used application-layer building control protocol is BACnet ("BACnet™–A Data Communication Protocol for Building Automation and Control Networks" 2016). BACnet standardizes functions for discovering devices on a network, for reading device status and data, and for sending device commands. BACnet does not standardize the contents of these individual communications (e.g., it provides a mechanism for sending commands to devices but does not say anything about what those commands can be or what actions they initiate). Put another way, BACnet is analogous to HTTP, which tells you how to load web pages but says nothing about the content of those web pages. Modbus/TCP is another application-layer device communication protocol.

Data schema. There is no single HTML for building operations, but rather a range of data models schema that standardize individual aspects. For grid services, the most well known of these is OpenADR, which specifies the exchange electricity prices and demand response commands between buildings and the grid (*OpenADR 2.0 Specifications* 2018). Other well-known schemas include Green Button (*GreenButton Alliance* 2018), which schematizes electricity use time series data, and Haystack (*Project Haystack* 2019), which standardizes context-sensitive naming conventions for networked devices and their ports. The emerging Brick schema (*Brick: A Uniform Metadata Schema for Buildings* 2019) is attempting to standardize the representation of relationships between building elements, both active (e.g., connected devices) and passive (e.g., rooms and zones). These schema do not cover the full range of information required for interoperable building automation. Standard models and schema are needed for describing various aspects of connected building equipment, including capabilities and operating modes, available commands and their semantics, performance, health, and current status—specifically the status and availability of storage that can be used to provide grid services.

Some of the relevant data models and schema abut on or even overlap with schema used in building design (architectural design, HVAC system design, and control design), auditing, energy use disclosure, and other activities and transactions. Example schema include Industry Foundation Classes (IFC), BuildingSync, Home Performance XML (HPXML), Standards Data Dictionary (SDD), Green Building XML (gbXML), CityGML, and others. Work is needed to align existing standards and the development of new standards to address specific gaps.

Use cases and interoperability requirements. A device or software does not have to support every protocol and data schema to be interoperable in a useful way. Support for a subset of capabilities, protocols, and schema is sufficient to enable different use cases, such as AFDD or dynamic-price response. Defining use cases and their interoperability requirements is needed.

7.2 Cybersecurity

As more and more devices and software systems interconnect and interact, a vulnerability in one component can be used to access data on, attack, and/or compromise other components. Such vulnerabilities can even lead to impacts on nonenergy corporate enterprise IT systems, slow down digital business processes, or even cause them to cease operating altogether. Previous cyberattacks have demonstrated the ability to damage or compromise targeted hardware equipment, though this requires significantly greater skills, time, and system knowledge (Langner 2011). If buildings and the grid are more tightly integrated, vulnerabilities in building software and devices could be used to attack the larger grid. Even if the grid is not directly compromised, a grid that is more heavily reliant on building-based services to maintain stability is indirectly made more vulnerable by greater building-level automation and interconnectivity.

Cybersecurity is often defined as a combination of confidentiality (i.e., privacy or the inability to leak data), integrity (i.e., the inability to corrupt or delete existing data), and availability (i.e., the inability to take down, interrupt, or degrade a service). A cybersecure grid service is one in which the building and the service aggregator or utility know (1) what service is being provided and when, (2) that the M&V information is accurate, and (3) that devices that support service delivery and M&V are available when needed.

Secure telecommunications. As with interoperability, cybersecurity must be implemented at multiple layers, from physical media to networking protocols to applications. At the networking layers, this means using existing secure (i.e., encrypted) communications protocols such as SSL/TLS, restricting access to service ports, and using firewalls as necessary. At the application layers, it means authenticating the identities of communicating devices. There are significant ongoing IT-based efforts to protect BAS (see Fisher, Isler, and Osborne 2019; Mylrea, Gourisetti, and Nicholls 2017; *Buildings Cybersecurity Capability Maturity Model (B-C2M2)* for examples). Some work has been done to identify cybersecurity standards for DERs such as PV and batteries (Johnson and Saleem 2017).

Cybersecurity must also be implemented at multiple logical levels, from individual devices to systems, whole buildings, service aggregators, and the grid. As such, some system architectures are more compatible with cybersecurity than others. Where intrabuilding device-to-device coordination is important but building-to-grid communication latency is not, it may be better to hide devices behind a firewall. Conversely, where latency is important but coordination is not, it may be better to allow devices to bypass firewalls and potentially limit their communication with other devices in the building. One cybersecurity advantage of manufacturer-based grid services—where manufacturers aggregate installed equipment across multiple buildings—is that the same communications path could be used to remotely patch and upgrade software in installed equipment to address vulnerabilities as they are discovered.

Cybersecurity and resilience. Cybersecurity is an arms race. It is not enough to defend against known attacks, it is also necessary to detect, diagnose, mitigate, quarantine, and recover from new and unknown attacks. In that sense, cybersecurity is a resilience issue. Recent work has shown that AFDD can be used to detect not only physical equipment faults or unintended control faults, but also cyberattacks. If cyberattacks are detected, a control system could account for any compromise by adapting the control algorithm until full function is restored.

Future-proofing. Most enterprise IT equipment is replaced or significantly upgraded every two years or so, and much of it is patched on a much more frequent basis. The IT components of smart, connected building equipment are upgraded much less frequently than that. Communication devices and protocols, firmware and application software, data encryption, and computational requirements are expected to rapidly evolve over the lifetime of connected building systems. Approaches that enable low-cost retrofit of IT platforms within building equipment will help to ensure their long-term security and viability.

Many manufacturers are sidestepping these issues by minimizing IT capabilities at the equipment, providing those instead in the cloud, which can be patched and maintained centrally. Equipment and the cloud communicate using proprietary protocols and data schema, allowing manufacturers to develop and sell devices in advance of interoperability standards as well. This approach represents a long-term interoperability risk and relies on customers to trust manufacturer data management practices. These are all issues of active research, but cross-industry solutions have not been identified.

8 Recommendations

From the previous discussions, we synthesize a set of general areas of need for continuing investment.

- **Develop and deploy cost-effective controls, sensing, modeling, and analytics solutions that enable and support energy efficiency throughout the building life cycle.** Energy efficiency is the foundation of GEBs, and the potential of BEM, sensing, and controls to support it has not been realized.
- **Develop technical solutions that support the deployment and maintenance of digital monitoring and automation in both commercial and residential buildings.** The potential of digital monitoring and automation specifically—core technologies on which GEBs rely—has not been fully realized, with deployment generally limited to large commercial buildings. Solutions are needed for both upgrading existing systems and introducing these capabilities into small commercial buildings and homes.
- **Support the development and adoption of standard data models and formats and communication protocols for building and behind-the-meter equipment.** Digital control and monitoring are enabled by hardware and software communication protocols. Standard protocols and data schema reduce deployment costs and increase adoption.
- **Support the adoption of secure system architectures and cybersecurity best practices.** Hardware and software communication protocols enable new functionality but also abuse. Promoting cybersecurity reduces a major risk associated with digital automation and improves adoption.
- **Develop the fundamental and practical aspects of model predictive control.** MPC—used in the broad sense—is a promising approach to managing HVAC loads in a way that maximizes the availability and responsiveness of load flexibility, while minimizing occupant impacts. Advances in model acquisition, interpretability, tunability, adaptability, and robustness to uncertainty are needed in order establish this approach.
- **Develop methods of acquiring occupant comfort states and preferences.** Occupant thermal comfort and thermal comfort preferences are key inputs to operationalizing the significant demand flexibility available in HVAC loads that is enabled by building thermal mass. Reliable, noninvasive ways to measure or collect these states and preferences are needed.
- **Develop methods of registering occupant prioritization and valuation of different end uses.** HVAC is only one flexible end use. Lighting, computing, refrigeration, and various appliances are others. Occupants need convenient ways to register their preferences and priorities for making these end uses available to different grid services.
- **Develop methods of prioritizing different zones and end uses within a building and coordinating energy efficiency and grid service delivery across those zones and end uses.** Buildings can provide different grid services from multiple DERs, end uses, and zones. Methods are needed for prioritizing and coordinating these various sources of demand flexibility.
- **Develop requirements for shared, trusted metering and sensing for measuring and verifying the delivery of grid services.** In the absence of pricing structures that reflect real-time localized conditions, grid services have to be procured and called separately. Advances in sensing, metering, and analytics are needed to improve the ability to measure, verify, and compensate grid service delivery.
- **Determine the degree of interaction between shedding and shifting services, energy-neutral modulation services, and nonenergy neutral modulation services, as well as the feasibility of providing more than one of these from within the same control domain.** Buildings and on-site DERs are capable of providing different grid services at different timescales, ranging from subseconds to hours. Research is needed to determine the interactions between these different categories of services and the potential and desirability of providing more than one kind of service from a given piece of equipment, zone, or building.
- **Determine the role that whole-building energy modeling plays in the provision of modulation services.** Detailed co-simulation at multiple timescales is complex and costly. BEM plays a key role in supporting both energy efficiency and shifting and shedding grid services that operate on thermal timescales of minutes to hours. The role of BEM in modulation services and the extent BEM needs to feed into or incorporate results from models of higher-frequency behavior is not clear.

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