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Grid-interactive Efficient Buildings Technical Report Series

Overview of Research Challenges and Gaps

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Disclaimer

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List of Acronyms and Abbreviations

AC	alternating current
ACEEE	American Council for an Energy-Efficient Economy
BTO	Building Technologies Office
CAISO	California Independent System Operator
CHP	combined heat and power
DC	direct current
DER	distributed energy resource
DOE	U.S. Department of Energy
ERCOT	Electric Reliability Council of Texas
GEB	grid-interactive efficient building
GW	gigawatt
GWh	gigawatt hour
HVAC	heating, ventilation, and air conditioning (also heating, *ventilating*, and air conditioning)
ISO	independent system operator
ISO-NE	New England Independent System Operator
kW	kilowatt
LED	light-emitting diode
MEL	miscellaneous electric load
MISO	Midcontinent Independent System Operator
MW	megawatt
MWh	megawatt hour
NYISO	New York Independent System Operator
PLMA	Peak Load Management Alliance
PV	photovoltaic
R&D	research and development
RTO	regional transmission organization

SEPA	Smart Electric Power Alliance
SPP	Southwest Power Pool
T&D	transmission and distribution
TAS	thermally anisotropic systems
TOU	time-of-use

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 system costs (generation and/or delivery costs); this report focuses on grid services that can be provided by grid-interactive efficient buildings.
Distributed energy resource (DER)	A resource sited close to customers that can provide all or some of their immediate power needs and/or can be used by the utility system to either reduce demand or provide supply to satisfy the energy, capacity, or ancillary service needs of the grid.
Load profile	A building's load profile describes when—time of day or hour of the year—the building is consuming energy (typically used to refer to electricity consumption but can also describe on-site fuel use); load shape and load curve are often used interchangeably, but all refer to the timing of energy use.
Energy efficiency	Ongoing reduction in energy use to provide the same or improved level of 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	Change in the rate of electricity consumption in response to price signals or specific requests of a grid operator.
Demand-side management	The modification of energy demand by customers through strategies, including energy efficiency, demand response, distributed generation, energy storage, electric vehicles, and/or time-of-use pricing structures.
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	Advanced controls, sensors, models, and analytics used to manage DERs. GEBs are characterized by their use of these technologies.

Table of Contents

1 Background 1
1.1 Strategy and Vision 1
2 Building Demand-Side Management and Associated Grid Services 3
2.1 Building Demand Flexibility 3
2.2 Grid Services 6
2.3 Grid Services Potential 9
3 Grid-interactive Efficient Buildings 13
3.1 Characteristics of a Grid-interactive Efficient Building 13
3.2 Key Technologies 14
3.3 GEB Operational Strategies 17
3.4 Knowledge Gaps and Future Research Opportunities 19
4 References 21
Appendix 26
A.1 Grid Services 26
A.2 Key GEB Technologies 29
A.2.1 Heating, Ventilation, and Air Conditioning (HVAC) 29
A.2.2 Windows and Envelope 30
A.2.3 Water Heating 31
A.2.4 Refrigeration, Appliances, and Miscellaneous Electric Loads 31
A.2.5 Electronics 31
A.2.6 Lighting 32
A.2.7 Cross-Cutting Technologies 32
A.2.8 Natural Gas Technologies 33

List of Figures

Figure 1. Example grid-interactive efficient commercial building 2
Figure 2. Building flexibility load curves 4
Figure 3. GEB load curves 5
Figure 4. Levelized cost of energy resources 6
Figure 5. Demand response classifications 8
Figure 6. Demand response evolution 8
Figure 7. Characteristics of GEBs 13
Figure 8. Total and peak period 2018 electricity consumption by end use and building type 16
Figure 9. Energy sharing in a high-efficiency district 18

List of Tables

Table 1. Potential Grid Services Provided by Demand-Side Management in Buildings 10
Table 2. Mapping Demand-Side Management Strategies to Grid Services 12
Table 3. Summary of GEB Technical Report Findings 16
Table 4. Grid Services Avoided Cost, Buildings Market Size, and Example Building Technologies 27

1 Background

To help inform the building research community and advance the U.S. Department of Energy (DOE) Building Technologies Office's (BTO's)[1] research and development (R&D) portfolio, BTO has published a series of technical reports that evaluate the opportunities for grid-interactive efficient buildings (GEBs). This overview report provides background on core concepts of GEBs[2] and serves as an introduction to these technical reports. In addition to this report, four other reports covering major relevant building technology areas were published in 2019 as part of the *GEB Technical Report Series*:

- *Overview of Research Challenges and Gaps* (this report)
- *Heating, Ventilation, and Air Conditioning (HVAC); Water Heating; Appliances; and Refrigeration*[3]
- *Lighting and Electronics*[4]
- *Windows and Opaque Envelope*[5]
- *Whole-Building Controls, Sensors, Modeling, and Analytics*[6]

These reports evaluate state-of-the-art and emerging building technologies that have significant potential to provide grid services. The reports also identify major research challenges and gaps facing the technologies as well as opportunities for technology-specific R&D. The *GEB Technical Report Series* will help inform and guide BTO's portfolio and serve as a foundational resource for the larger building research community. On-site behind-the-meter generation, battery storage, and electric vehicles are also an important part of the distributed energy resource (DER) optimization strategy for buildings. In general, the component technology reports do not focus on distributed generation or battery storage, but the *Whole-Building Controls, Sensors, Modeling, and Analytics* report discusses how a building can optimize across all DERs.

This report addresses core concepts related to how flexible building loads can be integrated and controlled to benefit consumers, the electric grid, and society more broadly. The scope of the *GEB Technical Report Series* is intentionally focused on technological capabilities and the potential of residential and commercial buildings to enable and deliver grid services. The *GEB Technical Report Series* does not address the following topics that are important in practice, but are considered out of scope: utility programs and policies, business models and value streams, potential future grid services/resource mixes, technology adoption and market constraints, product measurement and verification, commissioning, and implementation and scaling challenges. However, BTO recognizes that many of these topics represent significant barriers that will be addressed in future work and research to fully realize the potential of GEBs.

1.1 Strategy and Vision

BTO's mission supports the R&D, validation, and integration of affordable, energy efficiency technologies, techniques, tools, and services for U.S. buildings (existing and new, residential and commercial). In support of this mission, BTO is developing a GEB strategy that aims to optimize energy use across DERs to advance the role buildings can play in energy system operations and planning. The GEB strategy supports broader goals, including greater affordability, resilience, sustainability, and reliability, recognizing that:

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[1] For more information, see: https://www.energy.gov/eere/buildings/building-technologies-office.
[2] For more information, see: https://www.energy.gov/eere/buildings/grid-interactive-efficient-buildings.
[3] Available online here: https://www.nrel.gov/docs/fy20osti/75473.pdf.
[4] Available online here: https://www.nrel.gov/docs/fy20osti/75475.pdf.
[5] Available online here: https://www.nrel.gov/docs/fy20osti/75387.pdf.
[6] Available online here: https://www.nrel.gov/docs/fy20osti/75478.pdf.

- Building end uses can be dynamically managed to help meet grid needs and minimize electricity system costs, while meeting occupants' comfort and productivity requirements;
- Technologies such as rooftop photovoltaics (PV), battery and thermal energy storage, combined heat and power (CHP), and other DERs can be co-optimized with buildings to provide greater value, reliability, and resiliency to utility customers and the overall electricity system; and
- The value of energy efficiency, demand response, and other services provided by behind-the-meter DERs can vary by location, hour, season, and year.

A key part of this strategy will include utilizing smart technologies (sensors, actuators, controllers, etc.) for building energy management. This is a core area of technological investment for BTO. Integrating state-of-the-art sensors and controls throughout the commercial building stock has the potential to save as much as an estimated 29% of site energy consumption through high-performance sequencing of operations, optimizing settings based on occupancy patterns, and detecting and diagnosing inadequate equipment operation or installation problems (Fernandez et al. 2017). Furthermore, state-of-the-art sensors and controls can curtail or temporarily manage 10%–20% of commercial building peak load (Kiliccote et al. 2016; Piette et al. 2007). Accordingly, these strategies are available and necessary for implementing flexible, grid-interactive strategies to optimize building loads within productivity or comfort requirements.

BTO's GEB vision involves the integration and continuous optimization of DERs for the benefit of the buildings' owners, occupants, and the electric grid. As shown in Figure 1, the example GEB utilizes analytics supported by sensors and controls to optimize energy use for occupant patterns and preferences, utility price signals, weather forecasts, and available on-site generation and storage. In the building depicted in Figure 1, a suite of advanced building technologies—including the HVAC system, connected lighting, dynamic windows, occupancy sensing, thermal mass, and distributed generation and battery storage—are optimized to meet occupant and grid needs. In many buildings, smaller sets of existing technologies could be integrated and controlled.

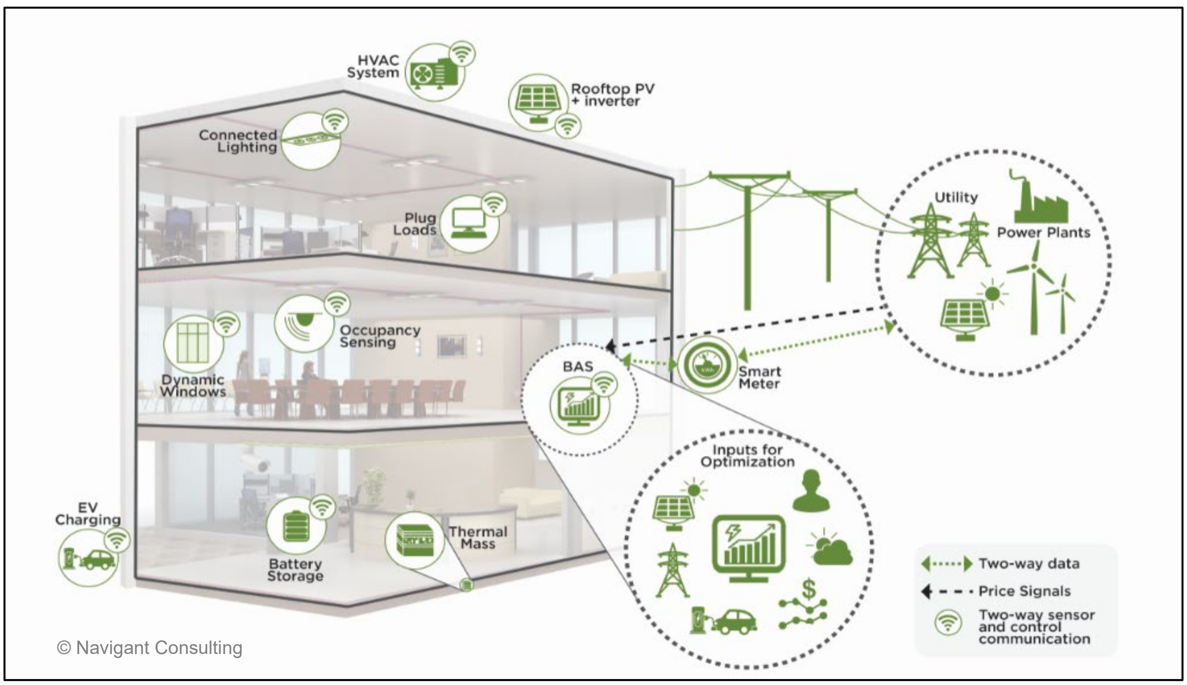

Figure 1. Example grid-interactive efficient commercial building

The building automation system utilizes analytics supported by sensors and controls to optimize energy use for occupant patterns and preferences, utility price signals, weather forecasts, and available on-site generation and storage.

2 Building Demand-Side Management and Associated Grid Services

2.1 Building Demand Flexibility

Demand flexibility *is the 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.*

Growing peak electricity demand, transmission and distribution (T&D) infrastructure constraints, and an increasing share of variable renewable electricity generation are stressing the electrical grid (U.S. Energy Information Administration 2019a; Nadel 2017). Flexible electricity loads can be used to reduce grid stress, creating a more resilient and reliable grid, while simultaneously lowering costs for consumers.

Operating an electricity grid is tantamount to balancing supply and demand for different timescales under the constraints of limited supply resources and T&D capacity. Demand must be met through matching services provided by supply-side entities: integrated utilities, grid operators, generators, and/or distributed generation resources. Demand-side entities such as buildings and electric vehicles may also contribute to balancing supply and demand, and in this regard, demand-side contributions can be just as viable as supply-side counterparts. For instance, avoided energy use through energy efficiency is often the least-cost system resource. Beyond using less total energy, an energy-efficient building benefits the grid by reducing capacity constraints by lowering energy demand during peak periods.

Buildings offer a unique opportunity for cost-effective demand-side management, because they are the nation's primary users of electricity: 75% of all U.S. electricity is consumed within buildings,[7] and perhaps more importantly, building energy use drives a comparable share of peak power demand. The electricity demand from buildings results from a variety of electrical loads that are operated to serve the needs of occupants. However, many of these loads are flexible to some degree; with proper communications and controls, loads can be managed to draw electricity at specific times and at different levels, while still meeting occupant productivity and comfort requirements. On-site DERs such as rooftop PV, electric vehicle charging, and batteries can be co-optimized with building loads to expand demand-side management options. Passive technologies (envelope, windows, daylighting) increase the efficacy of these strategies. The increased flexibility can benefit the grid while providing value to owners through reduced utility bills and increased resilience, among other benefits.

Electric grid needs vary significantly by location, time of day, day of week, and season. Accordingly, a building may need to manage its electricity load in different ways during these times by reducing load through year-round energy efficiency, shifting load to different times of the day, and/or increasing load to store for later use.

This report considers demand-side management strategies that can be implemented in buildings to manage load:

1. **Efficiency:** the ongoing reduction in energy use while providing the same or improved level of building function.[8]

[7] Buildings consumed 74.6% of electricity in 2018 according to the U.S. Energy Information Administration (2019b).
[8] This would have the greatest impact for the grid during high-cost periods and minimize utilization of costly generation resources.

2. **Load Shed:** the ability to reduce electricity use for a short time period and typically on short notice. Shedding is typically dispatched during peak demand periods and during emergencies.

3. **Load Shift:** the ability to change the timing of electricity use. In some situations, a shift may lead to changing the amount of electricity that is consumed. Load shift in the *GEB Technical Report Series* focuses on intentional, planned shifting for reasons such as minimizing demand during peak periods, taking advantage of the cheapest electricity prices, or reducing the need for renewable curtailment. For some technologies, there are times when a load shed can lead to some level of load shifting.

4. **Modulate:** the ability to balance power supply/demand or reactive power draw/supply autonomously (within seconds to subseconds) in response to a signal from the grid operator during the dispatch period.

5. **Generate:** the ability to generate electricity for on-site consumption and even dispatch electricity to the grid in response to a signal from the grid. Batteries are often included in this discussion, as they improve the process of dispatching such generated power.

Figure 2 shows the changes in building load profiles as a result of the first four demand-side management strategies.

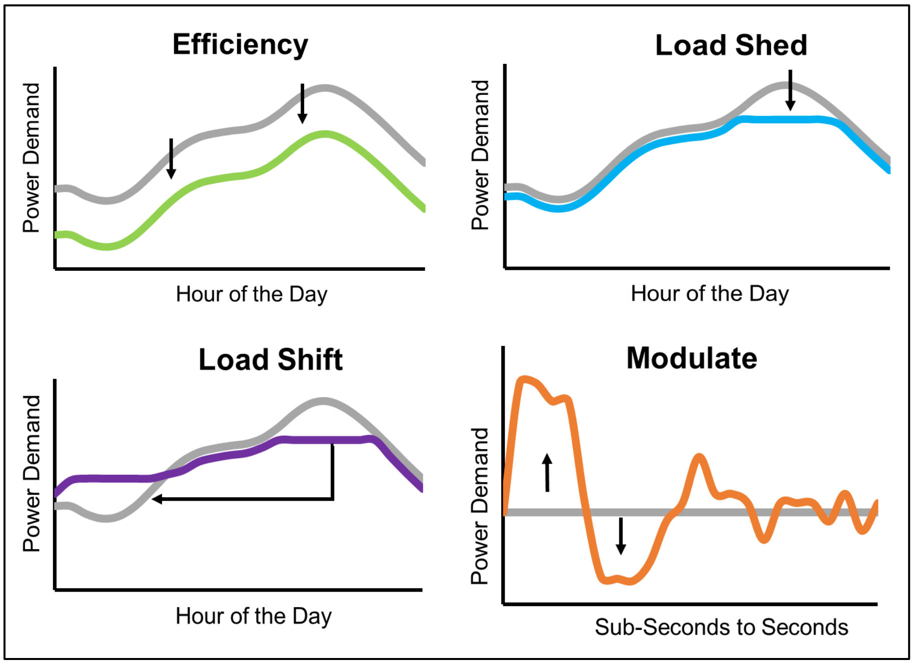

Figure 2. Building flexibility load curves

In these graphs, the gray curve represents an example baseline residential building load and the colored curves (green, blue, purple, and orange) show the resulting building load. The baseline represents a residential aggregate annual daily load curve. This baseline curve was generated using the Scout[9] time-sensitive efficiency valuation framework, which attributes annual baseline energy use estimates from the U.S. Energy Information Administration Annual Energy Outlook[10] across all hours of the year using energy load shapes from the Electric Power Research Institute.[11] All resulting building load curves (green, blue, purple, and orange) were estimated for illustrative purposes.

The focus of the GEB technical reports is primarily load shed, load shift, and modulating load (referred to throughout the series as demand flexibility), which are typically enabled by the controls and analytics found in a GEB.

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[9] For more information, see: https://scout-bto.readthedocs.io/en/latest/index.html.
[10] For more information, see: https://www.eia.gov/outlooks/aeo/.
[11] For more information, see: http://loadshape.epri.com/enduse.

Figure 3 depicts the daily average load profiles for a building employing various forms of energy efficiency and demand flexibility. Energy efficiency and distributed generation (in this case, rooftop PV) achieve reductions in overall energy use. However, the building load peaks coincide with utility peaks. Demand flexibility (shedding or shifting) is needed to flatten and reduce the building net load profile to provide the greatest support to the grid.

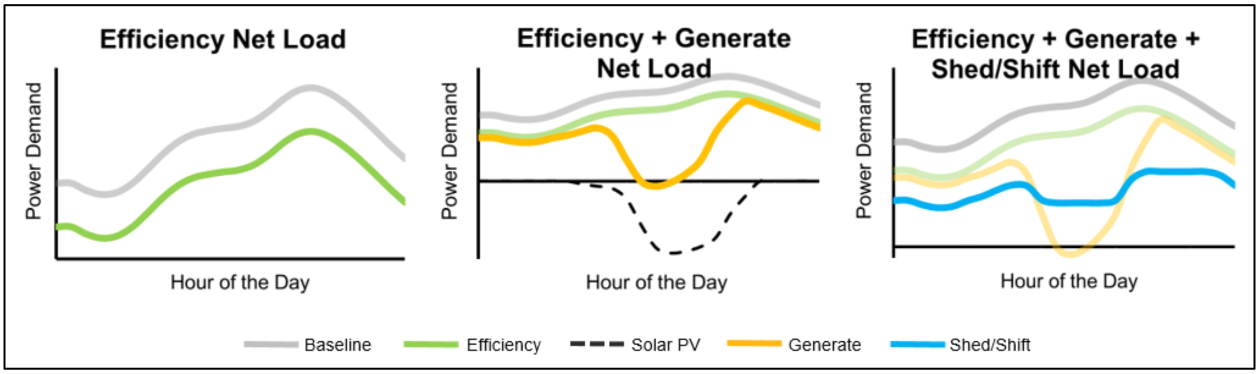

Figure 3. GEB load curves

In these graphs, the gray curve represents an example baseline residential building load curve generated using the Scout time-sensitive efficiency valuation framework, as in Figure 2. All resulting building load curves (green, yellow, and blue) were estimated for illustrative purposes and are meant to show the additive effects of efficiency, solar PV, and flexibility in a single building.

Building owners or occupants that use demand-side management strategies may do so for a variety of motivations, including compensation through lower utility bills, lower rates, or negotiated payments. In addition, building operating costs may be reduced by avoiding utility demand charges or time-of-use (TOU) peaks, which may or may not align with the real-time grid needs. Furthermore, owners or occupants may be motivated by environmental or other nonfinancial considerations. These strategies also have the potential to provide grid services that benefit the grid across the three major dispatchable categories: energy, capacity, and ancillary services. Some of these grid services provide benefits to the grid by avoiding or deferring T&D upgrades and associated capital expenditures, which can prevent utility customer rate increases. There are numerous benefits that both the utility system and society can realize from utilizing demand-side management strategies, including:

- Increased system reliability and resilience
- Increased DER integration
- Improved power quality and reduced customer outages
- Increased owner/occupant satisfaction, flexibility, and choice
- Reduced generation capacity, energy, and ancillary service costs
- Reduced utility operation and maintenance costs
- Reduced T&D costs and losses
- Reduced environmental impacts, including carbon dioxide emissions
- Reduced environmental compliance costs and greater economic development benefits (Woolf et al. 2019).

2.2 Grid Services

Grid services *refer to services that support the generation, transmission, and distribution of electricity and provide value through avoided electricity system costs (generation and/or delivery costs).*

Buildings can provide a number of grid services across energy, capacity, and ancillary markets when proper incentives are available. Utility programs and retail/wholesale markets are structured and operated differently across the nation, with varying requirements, incentives, and compensation. Typically, the potential *value* of a DER can be estimated using the *cost* of avoiding the acquisition of the next least expensive alternative resource that provides comparable services; that way, building owners/occupants can be compensated accordingly for engaging in demand-side management strategies.[12] Energy efficiency and demand response are the most mature and established demand-side resources that provide grid services today (Potter et al. 2018) and are described in more detail throughout this report. According to the American Council for an Energy-Efficient Economy (ACEEE), energy efficiency has become the nation's third largest electricity resource after coal and natural gas, and efficiency-related savings are estimated to be about 58 quads, which is equivalent to more than half of today's energy consumption (Molina et al. 2016). Utility energy efficiency programs remain the lowest-cost energy resource at an average of 3.1 cents per kilowatt-hour, which is estimated to be between one-fifth and one-half the cost of some other options (see Figure 4) (Molina and Relf 2018). Supported by the decisions and policies of state regulators of investor-owned utilities (and their counterparts for publicly owned utilities), utilities are investing on the order of $6 billion per year in energy efficiency programs today, with increased investment expected in coming years (Goldman et al. 2018).

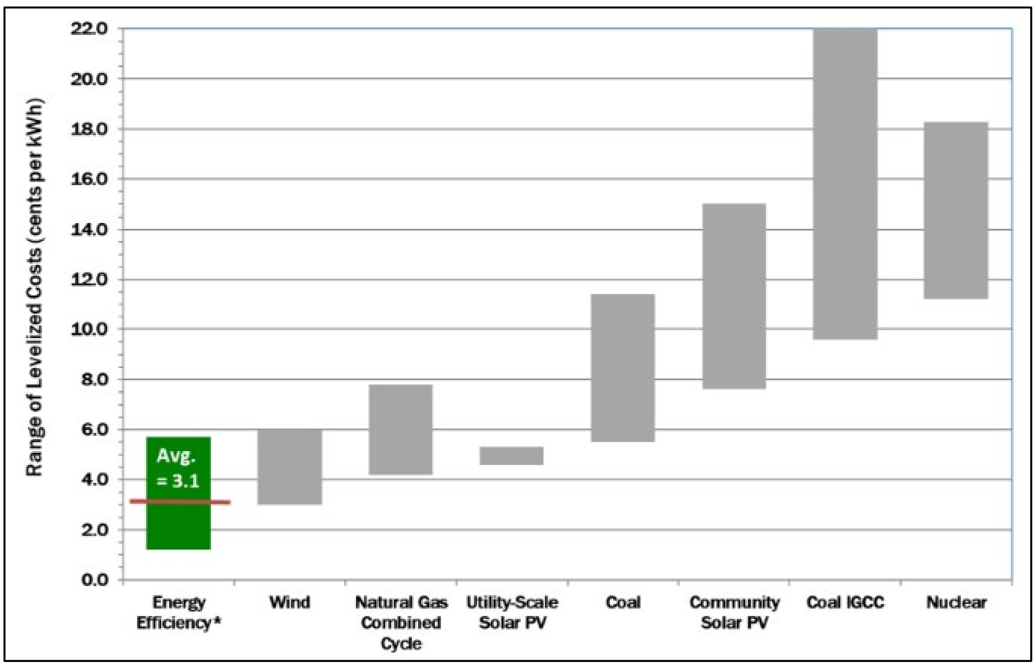

Figure 4. Levelized cost of energy resources

Figure from ACEEE (Molina and Relf 2018)

In addition to overall energy savings, energy efficiency plays an important role in supporting grid reliability by decreasing peak demand and easing strain on the T&D system. As far back as 2001, a study for DOE noted that peak-demand reductions from energy efficiency measures could enhance electricity system reliability in

[12] Some markets use an auction process, which allows all resources to participate to ensure the lowest possible cost.

areas experiencing generation shortages or T&D constraints (Osborn and Kawann 2001). By reducing load, energy efficiency increases the system's capability to serve demand reliably both on the supply side (by offsetting otherwise needed generation and thereby boosting the system's reserve margin) as well as on the T&D side (by increasing capacity in both the low- and high-voltage systems) (Relf, York, and Kushler 2018). Several utilities have even started using geographically targeted energy efficiency improvements as a so-called "non-wires alternative" to defer expensive T&D upgrades in congested areas (Neme and Sedano 2012). In addition, some regional transmission organizations (RTOs) and independent system operators (ISOs) allow energy efficiency to bid into capacity markets alongside other resources.

The value of the demand reduction achieved by customer energy efficiency programs is a function of the amount, timing, and location of the savings, as well as the utility system's physical and operational characteristics, such as the timing of peak demand (summer or winter and time of day), load factor, and reserve margin (Relf, York, and Kushler 2018). Energy efficiency improvements that reduce load during times of electric system peaks are more valuable from a grid perspective than those that occur during off-peak periods (Mims Frick, Eckman, and Goldman 2017). Some energy efficiency improvements are load following, yielding high electricity savings during daily and seasonal system peaks. For example, high-efficiency air conditioning uses less energy and reduces peak demand in summer peaking areas compared to inefficient air conditioning (Relf, York, and Kushler 2018).

An important and easily overlooked peak capacity benefit of energy efficiency is the reduction in marginal T&D line losses it can deliver. Most analysts who consider line losses at all use the system-average line losses, not the marginal line losses that are avoided when energy efficiency measures are installed. During peak load, marginal losses can be up to 2–3 times the average loss, because resistive losses scale nonlinearly with the load (Lazar and Baldwin 2011). Because a utility's generating reserve requirements have to cover these marginal losses, on-peak energy efficiency can produce twice as much ratepayer value as the average value of the energy savings alone, once the generation, transmission, and distribution capacity, line loss, and reserves benefits are accounted for (Lazar and Baldwin 2011). Additional benefits include reduced fuel usage, improved air quality, and lower consumer bills.

In contrast to energy efficiency, which emphasizes lower annual energy use, demand response emphasizes the timing of energy use to focus on peak demand, sometimes with the consequence of increases in overall energy use. Building owners benefit from demand response by avoiding high peak charges or receiving incentive payments, whereas the grid benefits from increased reliability, avoided operating costs, and deferred or avoided capital upgrade costs. Demand response is the main form of demand flexibility already utilized in both residential and commercial buildings.

Figure 5 shows the two classifications of demand response, dispatchable and nondispatchable, which depend on who has the authorization to modify the building's controls (Smart Electric Power Alliance [SEPA] 2017). Dispatchable demand response relies on communication and control technologies that respond directly to signals from the grid operator, utility, or a third-party aggregator. Nondispatchable demand response activates at the discretion of the building owner in response to price signals. Currently, predetermined TOU electricity prices and demand charges are common forms of nondispatchable demand response, but dynamic real-time pricing is a future opportunity.

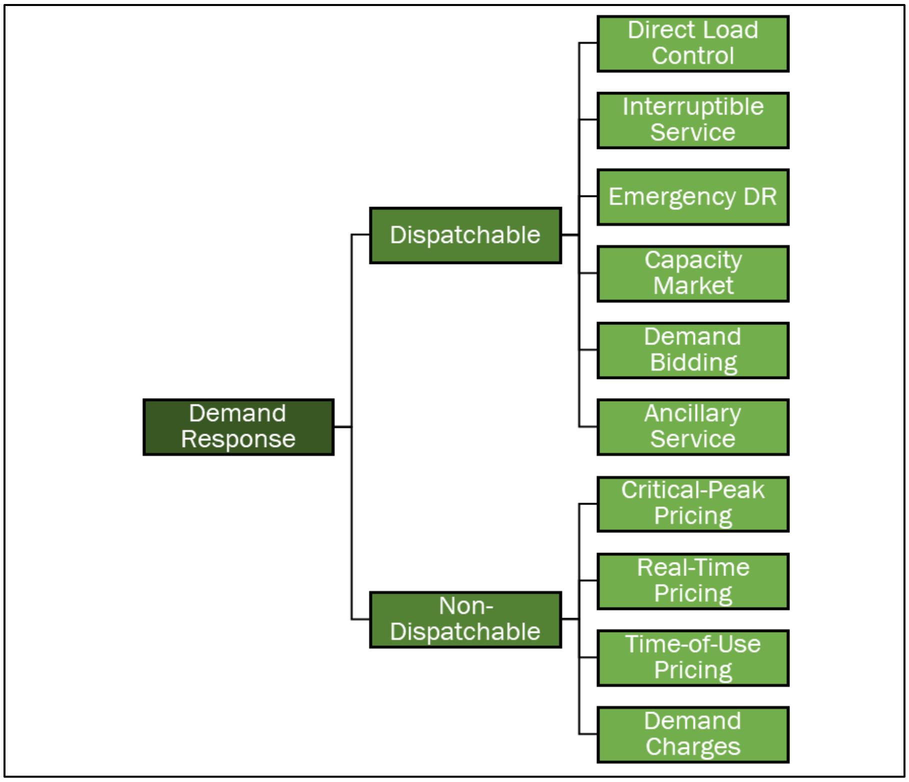

Figure 5. Demand response classifications

Adapted from *Smart Grid* (Prindle and Koszalka 2012)

The Peak Load Management Alliance and the Smart Electric Power Alliance summarize the evolution of dispatchable demand response as DR 1.0, DR 2.0, and DR 3.0, as shown Figure 6 (SEPA 2017; Peak Load Management Alliance [PLMA] 2017).

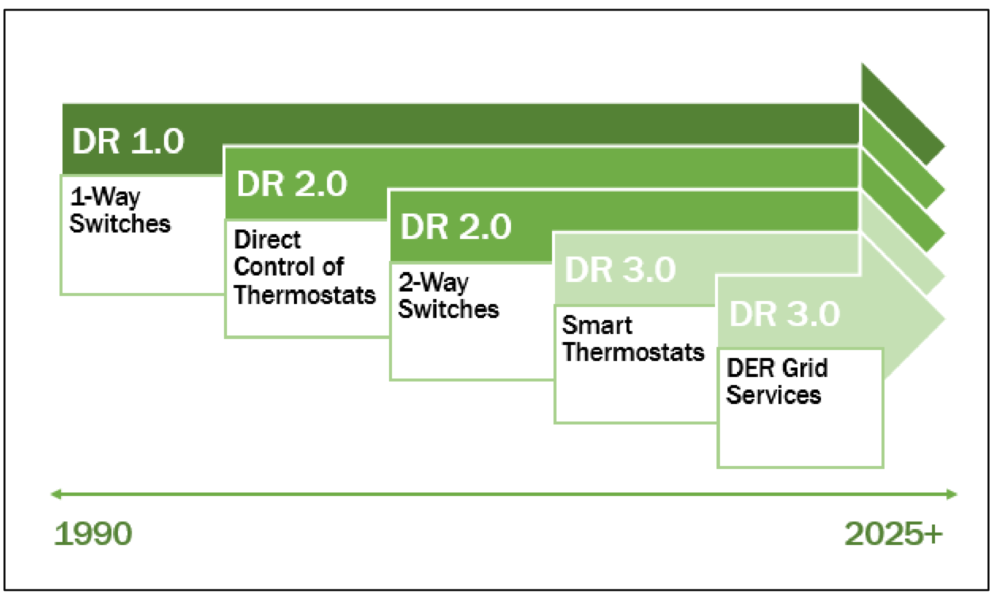

Figure 6. Demand response evolution

Modified from SEPA (2017)

DR 1.0 describes original demand response initiatives, in which utilities communicate to customers through a pager or telephone message to manually change energy consumption during periods of high wholesale power prices, limited generation capacity, or constrained delivery capacity (SEPA 2017). DR 1.0 techniques began in the 1990s and early 2000s with interruptible tariffs for large commercial and industrial customers (SEPA 2017; PLMA 2017). DR 1.0 also included direct load control water heaters and air conditioners for load shedding at times of grid stress.

DR 2.0 describes bilateral utility communications, including two-way switches and programmable communicating thermostats. Starting in the early 2000s, increasing use of automation and two-way communications improved the precision of demand response dispatch and allowed timely and accurate measurement and verification (SEPA 2017; PLMA 2017). DR 2.0 allows for increased participation in wholesale electricity markets and grid operations through ancillary services. DR 2.0 also may be used to shift load to off-peak times when renewable resources are abundant (SEPA 2017).

DR 3.0 describes demand response as a component of DERs. DR 3.0 initiatives, including technologies such as smart thermostats, energy storage, and PV, can provide services including renewable energy integration and distribution congestion management. In DR 3.0, demand response transitions from an ad hoc service dispatched by utilities and grid operators to more of an autonomous and holistic function orchestrated by building automation systems and other connected devices in response to dynamic electricity prices and/or other grid signals. BTO's GEB vision involves a similar focus as DR 3.0, in which shedding, shifting, and modulation are optimized and integrated by an energy management system.

2.3 Grid Services Potential

Buildings can provide significant benefits to the grid through a combination of actions that reduce or adjust electricity consumption to avoid electricity system costs. Grid services that can provide economic value can be characterized as services that:

- *Reduce generation costs* by offsetting generation capacity investments, avoiding power plant fuel costs, avoiding operation and maintenance costs, or providing ancillary services such as frequency and voltage support as well as regulation and contingency reserves at lower cost, and/or
- *Reduce delivery costs* by offsetting T&D capacity investments, increasing T&D equipment life, reducing equipment maintenance, or supporting T&D ancillary services such as distribution-level voltage control at a lower cost.

Table 1 summarizes the potential of buildings to provide grid services and the associated market size (based on today's markets and building technologies). The market sizes are based on two factors: the typical wholesale generation market size (see Appendix A.1, Table 4) and the potential for buildings to provide the service relative to other supply-side resources. As more renewables are added to the grid, market sizes and services offered could significantly change (e.g., frequency regulation and ramping services may have a higher demand and new products may emerge that support renewable curtailment).[13]

[13] The data used to generate these potential market sizes were derived from available data from ISO/RTOs. Today, ISO/RTO electricity markets serve two-thirds of electricity consumers in the United States (ISO/RTO Council 2019). The map given in Federal Energy Regulatory Commission (2015) illustrates the footprint of each ISO/RTO region. ISO/RTO electricity markets are used as proxy for overall market size.

Table 1. Potential Grid Services Provided by Demand-Side Management in Buildings

Grid Services	Potential Avoided Cost	Potential Market Size[14] Addressable by Demand-Side Management in Buildings
Generation Services		
Generation: Energy	Power plant fuel, operation, maintenance, and startup and shutdown costs	**Large.** The market potential for reducing generation operations is large because it is a service in every RTO/ISO. Reducing generation operations involves optimizing operation conditions and utilizing lowest-cost generation. For buildings, energy efficiency has the greatest potential to reduce generation operations. Demand response also has moderate potential, though the market size is limited by peak/off-peak price spread and hourly marginal costs, which vary by RTO/ISO (and some utilities) and change over time.
Generation: Capacity	Capital costs for new generating facilities and associated fixed operation and maintenance costs	**Large.** Deferred generation capacity investment results primarily from peak demand reduction. The size of the market varies by region based on the marginal generation costs and system load profiles. Buildings can play a large role in reducing the peak demand because they are the primary driver of peak electricity demand. Buildings can contribute to this service by both lowering the overall need for generation through energy efficiency as well as providing short-term load reduction to address system peaks. For buildings, demand response has the greatest potential to address capacity needs.[15]
Ancillary Services		
Contingency Reserves[16]	Power plant fuel, operation, maintenance, and associated opportunity costs	**Moderate.** The market for contingency reserves is significantly smaller than those for generation capacity or generation operations, making up less than 3% of U.S. peak demand (Ela et al. 2011; Denholm et al. 2015). Despite the small market, buildings are well positioned to provide contingency reserve products by reducing demand for short periods of time.
Frequency Regulation	Power plant fuel, operation, maintenance, and opportunity costs[17] associated with providing frequency regulation	**Small.** Each RTO/ISO requires less than 1,000 megawatts (MW) of frequency regulation—less than 1% of total U.S. generation capacity (Denholm et al. 2015; Tacka 2016). In addition to the small market, demand-side resources must compete against cost-effective distributed supply-side resources that provide frequency regulation. In some RTO/ISOs, generators are required to provide frequency regulation, but rules are changing to allow distributed resources to participate. Multiple technologies (variable frequency drives, water heaters, batteries, solar inverters) can provide frequency regulation.
Ramping	Power plant fuel, operation, maintenance, and startup and shutdown costs	**Small.** Ramping services are an emerging market that is currently not offered in most RTO/ISOs. Ramping services include resources that offset rapid changes in generation output. It is expected to grow as more variable renewable generation is added to the grid. Buildings can provide quick response ramping services from technologies that can dispatch/store electricity (batteries) and can be cycled to offset generation shortfalls (HVAC).
Delivery Services		
Non-Wires Solutions[18]	Capital costs for T&D equipment upgrades	**Moderate.** Opportunities to defer or avoid the need for investments in T&D infrastructure are highly location dependent. Further, the resource must be located electrically downstream from the transmission or distribution equipment to provide this service. Buildings can provide non-wires solutions in a variety of ways, including energy efficiency, demand response, distributed generation, voltage support, and energy storage.
Voltage Support	Capital costs for voltage control equipment (e.g., capacitor banks, transformers, smart inverters)	**Small.** Payments available for voltage support (or reactive power compensation) from demand-side resources vary significantly depending on the utility context and the size. Multiple building technologies can provide limited voltage support, including rooftop solar inverters and battery inverters, though they must compete against cost-effective supply-side resources, including transformers, fixed capacitor banks, and line regulators.

[14] See Appendix A.1 for citation and basis for sizing potential markets.
[15] See Appendix A.1, Table 4, for further information.
[16] Including reserves products with various timescales, including spinning/nonspinning reserves and other reserves products that exist in some regions.
[17] E.g., not selling power in order to be ready for up-regulation.
[18] Also referred to as deferred T&D upgrades or non-wires alternatives.

Grid benefits provided by buildings must be aggregated across a number of buildings to be a meaningful grid resource. Grid services also require certain duration and response times, load changes, and event frequencies. In some situations, the building owner/operator may not even be aware how the building's flexibility is being aggregated or what grid services are provided. The most important inputs needed for building owners/operators to make building-level energy management decisions include how the end-use operations need to change, the duration and amount of change needed, and the compensation for that change.

Table 2 shows how changes in building operations map to the grid services in Table 1.

Table 2. Mapping Demand-Side Management Strategies to Grid Services

Response time is defined as the amount of time between receiving a signal from the utility/operator and the building asset responding to change the load. Duration is the length of time that the load change occurs.

Demand-Side Management Strategies	Grid Services	Description of Building Change	Key Characteristics	
Efficiency	Generation: Energy Generation: Capacity T&D: Non-Wires Solutions	Persistent reduction in load. Interval data may be needed for measurement and verification purposes. This is not a dispatchable service.	Typical duration	Continuous
			Load change	Long-term decrease
			Response time	N/A
			Event frequency	Lifetime of equipment
Shed Load	Contingency Reserves	Load reduction for a short time to make up for a shortfall in generation.	Typical duration	Up to 1 hr
			Load change	Short-term decrease
			Response time	<15 min
			Event frequency	20 times per year
	Generation: Energy Generation: Capacity T&D: Non-Wires Solutions	Load reduction during peak periods in response to grid constraints or based on TOU pricing structures.	Typical duration	30 mins to 4 hrs
			Load change	Short-term decrease
			Response time	30 min to 2 hrs
			Event frequency	<100 hrs per yr/seasonal
Shift Load	Generation: Capacity T&D: Non-Wires Solutions	Load shifting from peak to off-peak periods in response to grid constraints or based on TOU pricing structures.	Typical duration	30 mins to 4 hrs
			Load change	Short-term shift
			Response time	<1 hour
			Event frequency	<100 hrs per yr/seasonal
	Contingency Reserves	Load shift for a short time to make up for a shortfall in generation.	Typical duration	Up to 1 hr
			Load change	Short-term shift
			Response time	<15 min
			Event frequency	20 times per year
	Avoid Renewable Curtailment	Load shifting to increase energy consumption at times of excess renewable generation output. This is not a dispatchable service but can be reflected through TOU pricing.	Typical duration	2 to 4 hrs
			Load change	Short-term shift
			Response time	N/A
			Event frequency	Daily
Modulate Load	Frequency Regulation	Load modulation in real time to closely follow grid signals. Advanced telemetry is required for output signal transmission to grid operator; must also be able to receive automatic control signal.	Typical duration	Seconds to minutes
			Load change	Rapid increase/decrease
			Response time	<1 min
			Event frequency	Continuous
	Voltage Support		Typical duration	Subseconds to seconds
			Load change	Rapid increase/decrease
			Response time	Subseconds to seconds
			Event frequency	Continuous
	Ramping	Load modulation to offset short-term variable renewable generation output changes.	Typical duration	Seconds to minutes
			Load change	Rapid increase/decrease
			Response time	Seconds to minutes
			Event frequency	Continuous
Generate	Ramping	Distributed generation of electricity to dispatch to the grid in response to grid signals. This requires a generator or battery and controls.	Typical duration	Seconds to minutes
			Load change	Rapid dispatch
			Response time	Seconds to minutes
			Event frequency	Daily
	Generation: Energy Generation: Capacity T&D: Non-Wires Solutions		Typical duration	30 mins to 4 hrs
			Load change	Dispatch/negative load
			Response time	<1 hour
			Event frequency	<100 hrs per yr/seasonal
	Generation: Energy *Generation: Capacity* *T&D: Non-Wires Solutions*	Distributed generation of electricity for use on-site and, when available, feeding excess electricity to the grid. This is not a dispatchable service, though metered data is needed.	Typical duration	Entire generation period
			Load change	Reduction/negative load
			Response time	N/A
			Event frequency	Daily

3 Grid-interactive Efficient Buildings

3.1 Characteristics of a Grid-interactive Efficient Building

*A **grid-interactive efficient building** (GEB) is 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. The key characteristics and strategies of GEBs are discussed in this section.*

The ability to take an integrated approach to demand-side management requires smart technologies, including advanced controls, sensors and models, and data analytics, that can meet occupant requirements and respond to changing grid and weather conditions. Today, behind-the-meter DERs—including energy efficiency, demand response, distributed generation, electric vehicles, and storage—are typically valued, scheduled, implemented, and managed separately. BTO's GEB vision involves the integration and continuous optimization of these resources for the benefit of the buildings' owners, occupants, and the grid. BTO recognizes that this is a long-term vision and that there is continuum—from manual operation of buildings to fully automated energy management platforms—that allows for continuously improving integration and optimization.

GEBs are generally characterized by four features, as outlined in Figure 7. They are energy efficient—high-quality walls and windows, high-performance appliances and equipment, and optimized building designs are used to reduce both net energy consumption and peak demand. Second, they are connected—the ability to send and receive signals is required to respond to grid needs that are time dependent. They are also smart—analytics supported by ubiquitous sensing and optimized controls are necessary to manage multiple behind-the-meter DERs in ways that are beneficial to the grid, building owners, and occupants. Finally, they are flexible—the building energy loads can be dynamically shaped and optimized through behind-the-meter generation, electric vehicles, and energy storage.

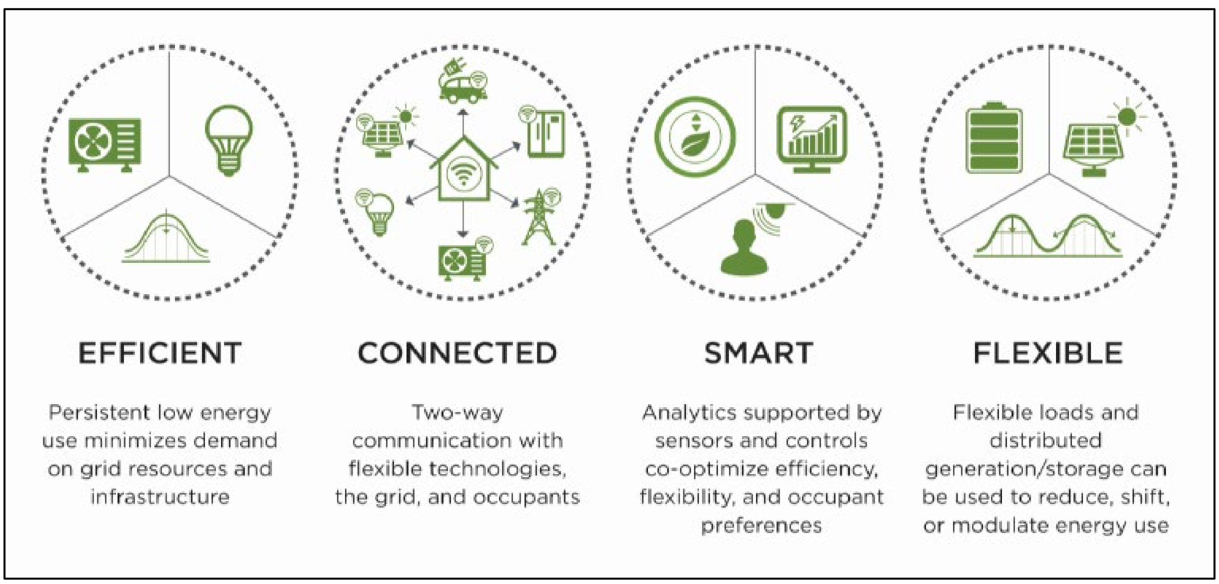

Figure 7. Characteristics of GEBs

These key characteristics are enabled by capabilities at both the individual equipment level and the centralized system level. First, individual devices, appliances, and equipment within the building can monitor and communicate their operating conditions and respond to control commands to provide demand flexibility. Second, the building can better coordinate across loads with the following attributes:

- Equipment and control systems support two-way connectivity and communications with devices, equipment, and appliances within the building, as well as the grid
- Equipment is designed to monitor, report, and provide flexibility to shed, shift, or modulate load by responding to control commands
- Control system can monitor, incorporate, predict, and learn from building-level conditions (occupant needs and preferences) and outdoor conditions (weather and grid needs)
- Control system can coordinate and execute complex control strategies that adapt based on changing conditions over multiple timescales
- Control system can quantitatively estimate and verify the energy and demand savings of different strategies and impacts from stochastic building conditions (e.g., occupancy behavior)
- Control system optimization techniques can choose among multiple strategies and balance efficiency with flexibility and occupancy comfort
- The system is interoperable, having the ability to effectively and securely exchange data and control signals among connected devices/equipment/appliances and control systems
- The system is resilient to cyberattacks and threats, having the ability to perform the services described above while maintaining end-to-end data security and protection against unauthorized access.

3.2 Key Technologies

The *GEB Technical Report Series* evaluates a suite of building technologies based on their potential to provide grid services through energy efficiency and demand flexibility. Technologies spanning thermal storage and electrical loads from nine different building systems and components are evaluated: HVAC, water heating, appliances, refrigeration, miscellaneous electric loads, electronics, lighting, windows, and envelope. In addition, several cross-cutting technology areas and natural gas technologies are also evaluated. Each report evaluates technologies within the same technical area (HVAC, water heating, etc.) and classifies them as high, medium, or low potential. It is important to note that these reports do not identify the highest potential technologies across all technical areas; this is an opportunity for future analysis. More information on each technology and the evaluation process is available within each technical report.[19] A summary of findings across the GEB technical reports is presented in Table 3.

[19] See Section 1 for relevant links to each report.

Table 3. Summary of GEB Technical Report Findings

Technology Area	High Potential	Medium Potential	Low Potential
Windows	• Dynamic Glazing • Automated Attachments	• Photovoltaic Glazing	• None
Envelope	• Thermally Anisotropic Materials • Envelope Thermal Storage • Tunable Thermal Conductivity Materials	• Moisture Storage and Extraction • Variable Radiative Technologies	• Building-Integrated Photovoltaics
Lighting	• Advanced Sensors and Controls	• Hybrid Daylight Solid-State Lighting Systems	• Solid-State Lighting Displays
Electronics	• Continuous-Operation Electronics	• Battery-Powered Electronics	• Electronic Displays
HVAC	• Smart Thermostats • Separate Sensible and Latent Space Conditioning • Liquid Desiccant Thermal Energy Storage	• Advanced Controls for HVAC Equipment with Embedded Thermostats	• Hybrid Evaporative Cooling • Dual-Fuel HVAC
Water Heating	• Water Heaters with Smart, Connected Controls	• None	• Dual-Fuel Water Heaters
Appliances, Refrigeration, and Relevant Miscellaneous Electric Loads (MELs)	• MELs: Water Heating[20]	• Modulating, Advanced Clothes Dryers • Advanced Dishwasher and Clothes Washer Controls • Advanced Refrigerator and Freezer Controls • Advanced Controls for Commercial Refrigeration • MELs: Motors[21] • MELs: Water Circulation[22] • MELs: HVAC[20] • MELs: Refrigeration[20]	• None
Natural Gas	• Building-Scale CHP • Water Heaters with Smart, Connected Controls	• Smart Thermostats • Modulating, Advanced Clothes Dryers	• Dual-Fuel HVAC • Dual-Fuel Water Heaters
Cross-Cutting (applies to more than one technology area)	• Building Automation System[23] • Embedded Thermal Energy Storage[24] • Non-Vapor-Compression Materials and Systems[21] • DC Technologies[20] • Batteries[20]	• Modulating Capacity Vapor Compression[21]	• None

[20] Examples include dehumidifiers, ceiling fans, furnace fans, and kitchen ventilation.
[21] Examples include fans, pumps, small kitchen appliances, and refrigeration.
[22] Examples include pool pumps, boiler pumps, condensate drainage pumps, spa/hot tub pumps.
[23] These technologies are discussed in the Appendix A.2 in this report, but are not included in the individual technical reports.
[24] These technologies are discussed in the *HVAC, Water Heating, Appliances, and Refrigeration* report.

Additional information on each high-potential technology is provided in Appendix A.2. Though technologies were not compared across technology areas, the relative magnitude of total and peak period electricity use affected by each technology serves as a proxy for its potential to impact the grid through efficiency and demand flexibility. Figure 8 shows the breakdown of U.S. residential and commercial building electricity use in 2018 by major end use, across all hours and daily peak period hours (2–8 p.m.). The figure shows that cooling is the primary contributor to residential peak (36% of major end uses), while end-use contributions to peak are more evenly split in the commercial sector.

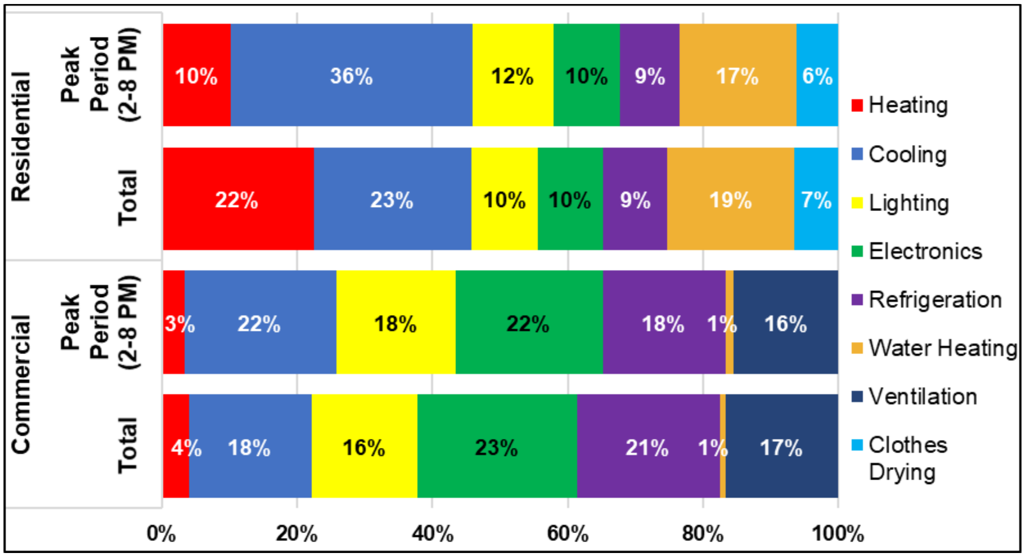

Figure 8. Total and peak period 2018 electricity consumption of major end uses by building type[25]

[25] Data are generated using the Scout time-sensitive efficiency valuation framework (Satre-Meloy and Langevin 2019), which attributes annual baseline energy use estimates from the EIA's 2019 *Annual Energy Outlook* across all hours of the year using energy load shapes from ResStock (NREL) (https://www.nrel.gov/buildings/resstock.html) and the Commercial Prototype Building Models (https://www.energycodes.gov/development/commercial/prototype_models). Contributions of each end use to total peak period energy use were calculated with Scout using the energy savings from a measure representing 100% energy use reduction for the entire end use for one hour (e.g., 3–4 p.m.) during the peak period. The energy savings from each hour for a given end use were then summed across the peak period.

3.3 GEB Operational Strategies

In contrast to the other GEB technical reports, the *Whole-Building Controls, Sensors, Modeling, and Analytics* report discusses the operational implementation of demand flexibility. The focus of the report is on communication, control, and sensing infrastructures that can support demand flexibility within a GEB (or set of GEBs) while considering critical operational aspects, including the impact on occupants and how the impact is quantified and valued. One key operational consideration is if demand flexibility should be managed at the device, end-use, or building level, which requires evaluating the impact of performance, complexity, latency, scalability, and security. Given these considerations, the following conclusions can be drawn:

- HVAC shedding and shifting is best aggregated at the building level because coordination of multiple devices, coupled with building thermal mass and mechanisms and processes that couple zones together, make it likely that building-level approaches will outperform a device-level approach.
- Other end uses providing shedding or shifting can be implemented at either the building level, device level or end-use level. Different end uses generally have only limited physical interactions with one another and with HVAC. (Although lighting and electrical appliances produce heat loads, in most cases the load is small relative to weather and occupancy/ventilation induced loads.) Limited physical interaction indicates that demand flexibility for different end uses can be implemented independently, without accounting for physical interactions with other end uses.
- End uses being used for modulation (fast services such as frequency regulation) are best provisioned at the device level. Given the time response requirements to provide these services, latency constraints point to the need to minimize the number of communication hops and coordination layers.

If managing for demand flexibility at the building level, which may be needed for optimal HVAC potential, a GEB should be able to gather data from grid/weather signals as well as daylighting and occupancy sensors, process them through an intelligent energy management system, and execute a control strategy that optimizes benefits to occupants and the grid. For example, an energy-efficient building with an insulated, tight envelope and efficient HVAC system can provide occupant thermal comfort with low energy use. In that same building, demand response could be provided by changing temperature set points or cycling HVAC systems in response to external grid signals. However, a GEB goes beyond the traditional capabilities of energy efficiency and demand response to enable buildings to shed or shift loads through advanced equipment and system controls. Examples include:

- A building that can take occupancy and occupant preferences into account and can change cooling set points by varying amounts depending on electricity prices and grid signals
- A building that integrates owner and occupant priorities for thermal comfort and other services and sheds load in priority order
- A building that can adjust solar heat gain to reduce heating/cooling needs through dynamic windows with automatic shading
- A building that has significant amount of thermal mass, potentially using phase change materials, to support precooling/coasting for long periods.

As described in the previous section, the GEB technical reports evaluate technologies based on their capability to provide efficiency and demand flexibility. However, the reports do not provide detail on technology interactions/integration and the subsequent impact on efficiency or demand flexibility potential. Integration strategies between building technologies are an active area of research. For instance, exploring when and how energy efficiency and demand flexibility are synergistic or in conflict is an important consideration. Another aspect is better understanding which end uses have strong interactions for shedding and shifting building loads.

For example, a tight envelope may enable greater load shifting for HVAC, and an integrated lighting and thermal comfort system must balance the benefits of daylighting with unwanted solar heat gain. The discussion above is on a single GEB, but there are also opportunities for demand-side management optimization across a set of buildings. Building owners, designers, and managers should consider the increased resilience, sustainability, and energy savings gained through demand-side management in clusters of buildings, which could range from microgrids, campuses, districts, and neighborhoods.

An example of optimizing across buildings is Alabama Power's Smart Neighborhood. The homes built in this community include important GEB characteristics. They are all high-performance homes and are connected as a neighborhood-level microgrid, which includes PV, a battery storage system, and natural-gas-fired power generation. The Smart Neighborhood homes employ state-of-the-art HVAC and water heating systems, including variable capacity heat pump HVAC, hybrid electric/heat pump water heaters, and internet-connected controls. This allows for the ability to optimize energy use across building loads. Novel control strategies are being tested to achieve grid-interactive control of the loads while homeowner comfort requirements are maintained. This is the first microgrid in the Southeast to support an entire residential community, while also helping to support community-scale power resilience. Research results to date show that these Smart Neighborhood homes consume 44% less energy (kWh) than a sample of comparable, new construction homes in the Birmingham metro area—a finding that has exceeded what the team's building models had initially anticipated. Researchers are also learning that these homes reduced their peak winter heating demand (kW) by 34% from what a traditional, all-electric community would have otherwise needed.

Alternatively, in a district thermal system that services offices, retail buildings, and multifamily housing, one set of buildings may be operating in heating mode while another set of neighboring buildings may be operating in cooling mode, creating an opportunity to share waste heat among buildings. Figure 9 illustrates a similar example of energy sharing in a district in Georgia.

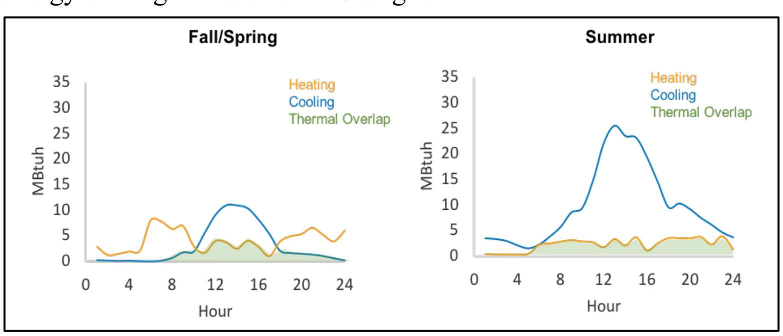

Figure 9. Energy sharing in a high-efficiency district

Example plots of estimated heating and cooling loads of live-work-play district in Atlanta, Georgia, for example days in fall/spring and summer. Shaded (green) area represents overlapping load that indicates potential for energy sharing through a district thermal system. Sample analysis and graphs provided by the NREL URBANopt team.

Smart Neighborhood

This Smart Neighborhood in Birmingham, Alabama, integrates high-performance homes, energy-efficient systems and appliances, connected devices, and a microgrid on a community-wide scale for the first time in the Southeast.

With 62 homes, it supports the community's energy needs by using microgrid technology with PV panels, battery storage, and a backup natural gas generator. These features help maximize the efficiency of the grid, while providing cost savings. The microgrid can operate both independently or together with the wider grid and can also control individual end-use equipment such as appliances and HVAC equipment in the homes. This adds to community resilience, though it should be noted that GEBs in general can never guarantee optimized energy use.

Alabama Power partnered with homebuilder Signature Homes, researchers at Southern Company, Oak Ridge National Laboratory, the Electric Power Research Institute, and others on this project.

3.4 Knowledge Gaps and Future Research Opportunities

Integrated demand-side management is a nascent and rapidly developing area of research, and benefits and co-impacts are largely unknown. Insufficient research has been done on technologies and strategies to optimize the interplay of energy efficiency and demand response, much less fully explore an optimized and integrated approach to demand flexibility and demand-side management. GEBs provide an opportunity to optimize and improve demand-side management, but additional work is needed to better understand the interactions and capacity of energy efficiency and demand flexibility to provide grid services. Key future research areas include:

Technology Characterization and Development

- Determining which end-use equipment (e.g., HVAC, lighting, etc.) has potential to provide demand flexibility, and then determining which technologies options (both emerging and on the market) for these end uses have the greatest potential to provide such demand flexibility
- Improving cost-effectiveness of smart technologies (e.g., sensors, communication mechanisms), including increased interoperability and more automated configuration
- Determining how to incorporate and update state-of-the-art security features into the design process of control architectures
- Quantifying how demand flexibility impacts building envelope durability (e.g., missing latent cooling with "shut down" sensible cooling)
- Determining the impacts of demand flexibility on equipment lifetime.

Valuation and Optimization

- Quantifying the impacts of demand flexibility strategies on one another and energy efficiency
- Quantifying the impacts of demand flexibility on occupant preferences as well as determining the value of those impacts
- Characterizing the type and amount of demand flexibility in different types of energy assets (traditional loads, on-site generation, and storage) and matching assets and grid services
- Determining the right node (device, end-use, zone, or building) for demand flexibility and different grid services
- Identifying the trade-offs between functionality and cybersecurity
- Quantifying the potential of demand flexibility in groups and districts of buildings
- Developing easy-to-use and scalable tools that facilitate the assessment of building load flexibility and provision of grid services from buildings.

Field Validation and Implementation

- Gaining understanding of how occupants will respond to technologies that can provide load flexibility
- Determining modes and mechanisms for engaging occupants in valuing and activating demand
- Determining the role of demand flexibility in organized markets distinguished from vertical utilities

- Understanding regulatory constraints for aggregation to exercise interbuilding demand flexibility and energy exchange
- Identifying business models that allow for aggregation and other interbuilding demand flexibility and energy exchange.

BTO intends to conduct further research to address these technical challenges and knowledge gaps. The *GEB Technical Report Series* serves as the first step in this process by identifying opportunities for additional technology-specific R&D. The forthcoming *State and Local Energy Efficiency Action Network (SEE Action) Report Series* will explore the state and local actions and initiatives needed to implement the vision of GEBs.

For more information, visit: energy.gov/eere/buildings/grid-interactive-efficient-buildings.

4 References

Alstone, Peter, et al. 2017. *Final Report on Phase 2 Results: 2025 California Demand Response Potential Study.* Lawrence Berkeley National Laboratory: Berkeley, CA. http://eta-publications.lbl.gov/sites/default/files/lbnl-2001113.pdf.

Baatz, Brendon. 2015. "Everyone Benefits: Practices and Recommendations for Utility System Benefits of Energy Efficiency." American Council for an Energy-Efficient Economy. https://aceee.org/sites/default/files/publications/researchreports/u1505.pdf.

Bhandari, Mahabir, et al. 2018. "Modeling the Impact of Flexible CHP on California's Future Electric Grid." U.S. Department of Energy Advanced Manufacturing Office. https://www.energy.gov/sites/prod/files/2018/01/f47/CHP%20for%20CA%20Grid%201-18-2018_compliant.pdf.

California Independent System Operator (CAISO). 2018a. "Q1 2018 Report on Market Issues and Performance." http://www.caiso.com/Documents/2018FirstQuarterReportonMarketIssuesandPerformance.pdf.

California Independent System Operator (CAISO). 2018b. "Flexible Resource Adequacy Criteria and Must Offer Obligation – Phase 2: Second Revised Flexible Capacity Framework." http://www.caiso.com/Documents/SecondRevisedFlexibleCapacityFrameworkProposal-FlexibleResourceAdequacyCriteriaMustOfferObligationPhase2.pdf.

Denholm, Paul, Yinong Sun, and Trieu Mai. 2019. *An Introduction to Grid Services: Concepts, Technical Requirements, and Provision from Wind*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-72578. https://www.nrel.gov/docs/fy19osti/72578.pdf.

Denholm, Paul, Joshua Eichman, Tony Markel, and Ookie Ma. 2015. *Summary of Market Opportunities for Electric Vehicles and Dispatchable Load in Electrolyzers.* National Renewable Energy Laboratory: Golden, CO. NREL/TP-6A20-64172. https://www.nrel.gov/docs/fy15osti/64172.pdf.

Ela, Erik, Michael Milligan, and Brendan Kirby. 2011. *Operating Reserves and Variable Generation*. National Renewable Energy Laboratory: Golden, CO. NREL/TP-5500-51978. https://www.nrel.gov/docs/fy11osti/51978.pdf.

Federal Energy Regulatory Commission, The Brattle Group, Freeman Sullivan & Co, and Global Energy Partners LLC. 2009. "A National Assessment of Demand Response Potential." https://www.ferc.gov/legal/staff-reports/06-09-demand-response.pdf.

Federal Energy Regulatory Commission. 2015. "ISO/RTO Map." https://www.ferc.gov/industries/electric/indus-act/rto/elec-ovr-rto-map.pdf.

Fernandez, N., S. Katipamula, W. Wang, Y. Xie, M. Zhao, and C. Corbin. 2017. "Impacts of Commercial Building Controls on Energy Savings and Peak Load Reduction." Pacific Northwest National. Laboratory: Richland, WA. Vol. 25985. https://buildingretuning.pnnl.gov/publications/PNNL-25985.pdf.

Glasgo, Brock, Ines Lima Azevedo, and Chris Hendrickson. 2016. "How Much Electricity Can We Save by Using Direct Current Circuits in Homes? Understanding the Potential for Electricity Savings and Assessing Feasibility of a Transition Towards DC Powered Buildings," *Applied Energy*, vol. 180, no. 15, pp. 66–75. https://www.sciencedirect.com/science/article/pii/S0306261916309771.

Goldman, Charles, Sean Murphy, Ian Hoffman, Natalie Mims Frick, Greg Leventis, and Lisa Schwartz. 2018. *The Future of U.S. Electricity Efficiency Programs Funded by Utility Customers Program Spending and Savings Projections to 2030*. Electricity Markets and Policy Group, Energy Analysis and Environmental Impacts Division, Lawrence Berkeley National Laboratory: Berkeley, CA. http://eta-publications.lbl.gov/sites/default/files/future_of_ee_final_report_20181205_final.pdf.

Hildebrandt, Eric, et al. 2018. "2017 Annual Report on Market Issues and Performance," California Independent System Operator (CAISO). http://www.caiso.com/Documents/2017AnnualReportonMarketIssuesandPerformance.pdf.

Hledik, Ryan, Judy Chang, and Roger Leuken. 2016. "The Hidden Battery: Opportunities in Electric Water Heating." The Brattle Group. https://www.electric.coop/wp-content/uploads/2016/07/The-Hidden-Battery-01-25-2016.pdf.

Holmes, C., and S. Mullen-Trento. 2017. "State Level Electric Energy Efficiency Potential Estimates." Electric Power Research Institute for the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy. https://www.energy.gov/sites/prod/files/2017/05/f34/epri_state_level_electric_energy_efficiency_potential_estimates_0.pdf.

Hutchinson, Lois. 2018. "DC Lighting: Empowering Our Digital Future." *West Coast Lighting Insider* https://www.lightshowwest.com/dc-lighting-empowering-our-digital-future.

ISO New England Inc. 2018a. "Finalized Results Confirm 12th Capacity Auction Procured Sufficient Resources for 2021–2022." https://www.iso-ne.com/static-assets/documents/2018/02/20180228_pr_fca12_final_results.pdf.

ISO New England Inc. 2018b. Internal Market Monitor. "2017 Annual Markets Report." https://www.iso-ne.com/static-assets/documents/2018/05/2017-annual-markets-report.pdf.

ISO/RTO Council. 2019. "ISO/RTO COUNCIL: IRC History." https://isorto.org/#about-section.

Kiliccote, Sila, Daniel Olsen, Michael Sohn, and Mary Ann Piette. 2016. "Characterization of Demand Response in Commercial, Industrial, and Residential Sectors in the U.S." *WIREs Energy Environ.*, vol. 5, pp. 288–304. https://onlinelibrary.wiley.com/doi/full/10.1002/wene.176.

Lazar, Jim, and Xavier Baldwin. 2011. "Valuing the Contribution of Energy Efficiency to Avoid Marginal Line Losses and Reserve Requirements." Regulatory Assistance Program. https://www.raponline.org/wp-content/uploads/2016/05/rap-lazar-eeandlinelosses-2011-08-17.pdf.

Li, F. Fran, John Kueck, Tom Rizy, and Tom King. 2006. "A Preliminary Analysis of the Economics of Using Distributed Energy as a Source of Reactive Power Supply." Oak Ridge National Laboratory and Energetics Incorporated. ORNL/TM-2006/014. https://info.ornl.gov/sites/publications/files/Pub1771.pdf

Macdonald, Jason, Sila Kiliccote, Jim Boch, Jonathan Chen, and Robert Nawy. 2014. "Commercial Building Loads Providing Ancillary Services in PJM." Lawrence Berkeley National Laboratory: Berkeley, CA. Paper presented at *2014 ACEEE Summer Study on Energy Efficiency in Buildings*, Pacific Grove, CA. https://eta.lbl.gov/publications/commercial-building-loads-providing.

Mayhorn, E.T., S.H. Widder, S.A. Parker, R.M. Pratt, and F.S. Chassin. 2015. *Evaluation of the Demand Response Performance of Large Capacity Electric Water Heaters.* Pacific Northwest National Laboratory: Richland, WA. https://labhomes.pnnl.gov/documents/PNNL_23527_Eval_Demand_Response_Performance_Electric_Water_Heaters.pdf.

Midcontinent Independent System Operator (MISO). 2016a. "Ramp Capability Product Performance Update." https://cdn.misoenergy.org/20161129%20MSC%20Item%2005f%20Ramp%20Capability%20Post%20Implementation%20Analysis74816.pdf.

Midcontinent Independent System Operator (MISO). 2016b. "Corporate Information." https://cdn.misoenergy.org/Corporate%20Fact%20Sheet147649.pdf.

Midcontinent Independent System Operator (MISO). 2018. "2018/2019 Planning Resource Auction Results." https://cdn.misoenergy.org/20190412_PRA_Results_Posting336165.pdf.

Mims Frick, Natalie, Tom Eckman, and Charles Goldman. 2017. *Time-varying value of electric energy efficiency*. Lawrence Berkeley National Laboratory: Berkeley, CA. https://emp.lbl.gov/publications/time-varying-value-electric-energy.

Molina, Maggie, Patrick Kiker, and Seth Nowak. 2016. "The Greatest Energy Story You Haven't Heard: How Investing in Energy Efficiency Changed the US Power Sector and Gave Us a Tool to Tackle Climate Change." American Council for an Energy-Efficient Economy. https://aceee.org/sites/default/files/publications/researchreports/u1604.pdf.

Molina, Maggie, and Grace Relf. 2018. "Does Efficiency Still Deliver the Biggest Bang for Our Buck? A Review of Cost of Saved Energy for US Electric Utilities." 2018 American Council for an Energy-Efficient Economy, Summer Study on Energy Efficiency in Buildings. https://aceee.org/files/proceedings/2018/index.html#/paper/event-data/p191.

Monitoring Analytics LLC. 2018. "PJM State of the Market 2017: Section 10: Ancillary Service Markets." https://www.monitoringanalytics.com/reports/PJM_State_of_the_Market/2017.shtml.

Motegi, Naoya, Mary Ann Piette, David Watson, Sila Kiliccote, and Peng Xu. 2007. "Introduction to Commercial Building Control Strategies and Techniques for Demand Response." Demand Response Research Center. https://pdfs.semanticscholar.org/f427/bf21ae18932064e051959f31bd3fbef247ef.pdf?_ga=2.178652068.1828998816.1570639214-608911769.1559763512.

Munoz-Alvarez, D. 2017. "Non-Wires Alternatives Projects: Emerging Utility Revenue Sources for the Distributed Energy Market." Greentech Media.

Nadel, Steven. 2017. "Electricity Consumption and Peak Demand Scenarios for the Southeastern United States." *American Council for an Energy-Efficient Economy*. Washington, D.C. https://aceee.org/sites/default/files/publications/researchreports/u1704.pdf.

National Rural Electric Cooperative Association (NRECA). 2018. "GridBallast." https://gridballast.com/.

Neme, Chris, and Richard Sedano. 2012. "US Experience with Efficiency as a Transmission and Distribution System Resource." Regulatory Assistance Project. https://www.raponline.org/knowledge-center/us-experience-with-efficiency-as-a-transmission-and-distribution-system-resource/.

New York Independent System Operator (NYISO). 2018a. "NYISO 2017 Annual Report on Demand Response Programs."

New York Independent System Operator (NYISO). 2018b. "Locational Reserve Requirements."

New York Independent System Operator (NYISO). 2018c. "NYISO Regulation Requirements."

Osborn, Julie, and Cornelia Kawann. 2001. *Reliability of the U.S. Electricity System: Recent Trends and Current Issues.* Energy Analysis Department, Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory: Berkeley, CA. http://eta-publications.lbl.gov/sites/default/files/report-lbnl-47043.pdf.

Peak Load Management Alliance (PLMA). 2017. "Evolution of Demand Response in the United States Electricity Industry." https://www.peakload.org/DefiningEvolutionDR.

Piette, Mary Ann, David Watson, Naoya Motegi, and Sila Kiliccote. 2007. "Automated Critical Peak Pricing Field Tests: 2006 Pilot Program Description and Results." Lawrence Berkeley National Laboratory: Berkeley, CA. vol. LBNL-59351. https://drrc.lbl.gov/publications/automated-critical-peak-pricing-field.

PJM Interconnection Inc. 2018. "2021/2022 RPM Base Residual Auction Results." https://www.pjm.com/-/media/markets-ops/rpm/rpm-auction-info/2021-2022/2021-2022-base-residual-auction-report.ashx.

Potomac Economics. 2017. "2016 State of the Market Report for the MISO Electricity Markets." https://www.potomaceconomics.com/wp-content/uploads/2017/06/2016-SOM_Report_Final_6-30-17.pdf.

Potomac Economics. 2018a. "2017 State of the Market Report for the ERCOT Electricity Markets." https://www.potomaceconomics.com/wp-content/uploads/2018/05/2017-State-of-the-Market-Report.pdf.

Potomac Economics. 2018b. "2017 State of the Market Report for the New York ISO Markets."

Potter, Jennifer, Elizabeth Stuart, and Peter Cappers. 2018. *Barriers and Opportunities to Broader Adoption of Integrated Demand Side Management at Electric Utilities.* Energy Analysis Environmental Impacts Division, Lawrence Berkeley National Laboratory: Berkeley, CA. http://eta-publications.lbl.gov/sites/default/files/barriers_and_opps_idsm_final_03222108.pdf.

Prindle, William, and Michael Koszalka. 2012. "Chapter 14 – Succeeding in the Smart Grid Space by Listening to Customers and Stakeholders." *Smart Grid. Integrating Renewable, Distributed & Efficient Energy.* Pages 343–369. https://www.sciencedirect.com/science/article/pii/B9780123864529000140.

Relf, Grace, Dan York, and Martin Kushler. 2018. "Keeping the Lights On: Energy Efficiency and Electric System Reliability." American Council for an Energy-Efficient Economy. https://aceee.org/research-report/u1809.

Robinson, Jen, Ram Narayanamurthy, Bienvenido Clarin, Christine Lee, and Pranshu Bansal. 2016. "National Study of Potential of Smart Thermostats for Energy Efficiency and Demand Response." *ACEEE Summer Study on Energy Efficiency in Buildings*. https://aceee.org/files/proceedings/2016/data/papers/2_1172.pdf.

Satre-Meloy, Aven, and Jared Langevin. 2019. "Assessing the time-sensitive impacts of energy efficiency and flexibility in the U.S. building sector." Environmental Research Letters. https://doi.org/10.1088/1748-9326/ab512e.

Seguin, Rich, Jeremy Woyak, David Costyk, Josh Hambrick, and Barry Mather. 2016. *High-Penetration PV Integration Handbook for Distribution Engineers*. National Renewable Energy Laboratory: Golden, CO. NREL/TP-5D00-63114. https://www.nrel.gov/docs/fy16osti/63114.pdf.

Smart Electric Power Alliance (SEPA). 2017. "2017 Utility Demand Response Market Snapshot." https://sepapower.org/resource/2017-utility-demand-response-market-snapshot/.

Tacka, Natalie. 2016. "Update: RTO/ISO Regulation Market Comparison." PJM Interconnection, Inc.. https://www.pjm.com/~/media/committees-groups/task-forces/rmistf/20160212/20160212-item-02-rto-iso-benchmarking-update.ashx.

U.S. Department of Energy: Advanced Manufacturing Office. 2018. "Flexible Combined Heat and Power (CHP) Systems." https://www.energy.gov/sites/prod/files/2018/01/f47/Flexible%20CHP%20Comms_01.18.18_compliant.pdf.

U.S. Energy Information Administration. 2019a. *Annual Energy Outlook 2019.* "Reference Case Simulations." Washington, D.C. https://www.eia.gov/outlooks/aeo/

U.S. Energy Information Administration. 2019b. *Annual Energy Outlook 2019*. "Reference Case Projections Tables." https://www.eia.gov/outlooks/aeo/tables_ref.php.

U.S. Government Accountability Office. 2017. "Electricity Markets: Four Regions Use Capacity Markets to Help Ensure Adequate Resources, but FERC Has Not Fully Assessed Their Performance." Report to Congressional Committees. GAO-18-131. https://www.gao.gov/assets/690/688811.pdf.

Walawalkar, R., R. Tongia, and B. Colburn. 2007. "Web Enabled Metering and Controls for Demand Response." *Web Based Enterprise Energy and Building Automation Systems*, Fairmont Press Inc.

Ware III, Joel D. 2013. "A Low-Cost-Solar Liquid Desiccant System for Residential Cooling." Florida State University Library. http://fsu.digital.flvc.org/islandora/object/fsu:185082/datastream/PDF/view.

Warren, Greg, et al. 2018. "State of the Market 2017." Southwest Power Pool, Inc., Market Monitoring Unit. https://www.spp.org/documents/57928/spp_mmu_asom_2017.pdf.

Woolf, T., B. Havumaki, D. Bhandari, M. Whited, and L. Schwartz. 2019. *Benefit-Cost Analysis for Utility-Facing Grid Modernization Investments.* Lawrence Berkeley National Laboratory: Berkeley, CA.

Appendix

A.1 Grid Services

Table 4 provides additional details on the potential market sizes addressable by demand flexibility in buildings. The table includes citations to data sources, an extended discussion of the market size addressable by buildings, and region-specific information for the seven U.S. independent system operators (ISOs) and regional transmission organizations (RTOs). Today, ISO/RTO electricity markets serve two-thirds of electricity consumers in the United States (ISO/RTO Council 2019).

The estimates reported in Table 4 are limited to those published in readily available reports and do not reflect the product of new detailed analysis. Because these reports were prepared independently, calculation methodologies differ. For example, the estimated avoided cost potentials of generation operating costs, frequency regulation, and contingency reserves reflect the range of average prices in each market. For the California Independent System Operator (CAISO), these constitute the ranges of the 24 average prices per hour over the entire year; for the Electric Reliability Council of Texas (ERCOT), they are averaged per month; and for the Independent System Operator New England (ISO-NE), they are the ranges of yearly averages. These prices should not be directly compared against the reported reductions in generation capacity costs, which reflect the full range of prices over the cited period.

Cost benefits of deferred T&D are gathered from utility surveys taken between 2010 and 2018, but only reflect the benefits of energy efficiency (which at that time was the largest individual capacity component). Utilities employ markedly different methodologies in estimating these costs. Moreover, the methodologies themselves may be in flux, considering that 79% of overall T&D deferral capacity for recent projects remains “to be determined,” a significant increase relative to projects announced before 2014.

Table 4. Grid Services Avoided Cost, Buildings Market Size, and Example Building Technologies

These data are derived from U.S. wholesale generation market data, avoided utility cost studies, and other relevant sources. References from which data are derived are cited in each entry of the table.

Grid Service	Estimated Avoided Cost Potential	Size of Market Addressable by Buildings	Example Building Technologies
Generation Services			
Generation: Energy	Peak/Off-Peak Shift: **$7–$60/megawatt hours (MWh)**[26] Off-Peak Reduction: **$20–$30/MWh**[27] On-Peak Reduction: **$25–$80/MWh**[28]	Energy efficiency potential: **Large** 741,000 gigawatt hours (GWh) national cost-effective energy efficiency potential (Holmes and Mullen-Trento 2017) Demand response shift potential: **Moderate–Large** 5 GWh/year cost-effective commercial HVAC load-shifting estimated by 2025 in California (Alstone et al. 2017). Market potential largely limited by low peak/off-peak price spread.	Efficient HVAC, improved envelope (Mims Frick, Eckman, and Goldman 2017)
Generation: Capacity	**$0.4–$226 per kilowatt (kW) reduction in peak system demand per year (U.S. GAO 2017)** $36–$216/kW-year (ISO-NE) $6–$89/kW-year (PJM Interconnection, Inc. [PJM]) $0.4–$55/kW-year (Midcontinent Independent System Operator [MISO]) $1–$226/kW-year (New York Independent System Operator [NYISO])	**Large (38–188 gigawatts [GW]) (4%–20% of U.S. peak demand) (Federal Energy Regulatory Commission et al. 2009)** *Current procured capacity:* PJM: 11,126 MW (DR); 2,832 MW (EE) (PJM Interconnection Inc. 2018) ISO-NE: 3,600 MW (EE+DR) (ISO-NE 2018a) MISO: 6,694 MW (DR); 173 MW (EE) (Miso 2018) NYISO: 1,237 MW (DR) (NYISO 2018a)	Energy management systems (Motegi et al. 2007), smart thermostats (Robinson et al. 2016)
Ancillary Services			
Provide Contingency Reserves	**$0.1–$11/MW per hour** of commitment to reduce load if necessary for system stability $3–$11/MW per hour (ERCOT) (Potomac Economics 2018a) $1–$3/MW per hour (ISO-NE) (ISO-NE 2018b) $0.1–$4/MW per hour (PJM) (Monitoring Analytics LLC 2018) $1–2/MW per hour (MISO) (Potomac Economics 2017) $4–$6/MW per hour (NYISO) (Potomac Economics 2018b) $1–$6/MW per hour (Southwest Power Pool [SPP]) (Warren et al. 2018) $0.4–$6/MW per hour (CAISO) (Hildebrandt et al. 2018)	**Moderate (Less than 3% of U.S. peak demand (Ela et al. 2011; Denholm et al. 2015)** *Total system requirements:* 3,700-4,400 MW (ERCOT) (Potomac Economics 2018a) 1,950-2,200 MW (ISO-NE) (ISO-NE 2018b) ~2,500 MW (PJM) (Monitoring Analytics LLC 2018) ~3,900 MW (NYISO) (NYISO 2018b) ~1,500 MW (SPP) (Warren et al. 2018) ~1,600 MW (CAISO) (Hildebrandt et al. 2018)	Variable frequency drives (Macdonald et al. 2014), water heaters (Hledik et al. 2016; Mayhorn et al. 2015)

[26] Range based on observed differences between average peak and off-peak prices reported for ERCOT ($8.41/MWh; Potomac Economics 2018a), ISO-NE ($7.30/MWh; ISO-NE 2018b), and CAISO ($50-$60/MWh; Hildebrandt et al. 2018).
[27] Range based on average off-peak prices reported for ERCOT ($18-$27/MWh; Potomac Economics 2018a), ISO-NE ($30/MWh; ISO-NE 2018b), and CAISO ($15-$25/MWh; Hildebrandt et al. 2018).
[28] Range based on average on-peak prices reported for ERCOT ($24-$45/MWh; Potomac Economics 2018a), ISO-NE ($38/MWh; ISO-NE 2018b), and CAISO ($60-$80/MWh; Hildebrandt et al. 2018).

Grid Service	Estimated Avoided Cost Potential	Size of Market Addressable by Buildings	Example Building Technologies
Provide Frequency Regulation	**$3–$29/MW per hour** of demand flexibility provided $6–$9/MW per hour (ERCOT) (Potomac Economics 2018a) $25–$29/MW per hour (ISO-NE) (ISO-NE 2018b) $16–$24/MW per hour (PJM) (Monitoring Analytics LLC 2018) $7–$12/MW per hour (MISO) (Potomac Economics 2017) $8–$10/MW per hour (NYISO) (Potomac Economics 2018b) $5–$10/MW per hour (SPP) (Warren et al. 2018) $3–$16/MW per hour (CAISO) (Hildebrandt et al. 2018)	**Small (<10 GW) (<1% of U.S. peak demand) (Mims Frick et al. 2017; Lazar and Baldwin 2011)** *Total system requirements:* 500–900 MW (ERCOT) (Potomac Economics 2018a) 50–150 MW (ISO-NE) (ISO-NE 2018b) 525–800 MW (PJM) (Monitoring Analytics LLC 2018) 300–500 MW (MISO) (Tacka 2016) 150–300 MW (NYISO) (NYISO 2018c) 350 MW (SPP) (Tacka 2016) 600–800 MW (CAISO) (Hildebrandt et al. 2018)	Variable-frequency drives (Macdonald et al. 2014), water heaters (Hledik et al. 2016; Mayhorn et al. 2015)
Provide Ramping Reserves	**$0.02–$0.86/MW per hour** $0.09–$0.86/MW per hour (MISO) (MISO 2016a; 2016b) $0.02–$0.15/MW per hour (CAISO) (CAISO 2018a)	**Small (<10 GW) (<1% of U.S. peak demand)** 575MW–1614 MW (MISO) (Denholm et al. 2019) 300 MW–9051 MW (CAISO) (Denholm et al. 2019; CAISO 2018b)	Variable-frequency drives (Macdonald et al. 2014), water heaters (Hledik et al. 2016; Mayhorn et al. 2015)
Delivery Services			
Non-Wires Solutions	**$0–$200 per kW reduction in peak downstream demand per year** (Baatz 2015) Location and utility dependent. Based on a survey of utility companies.	**Moderate.** Opportunities to defer or avoid the need for investments in T&D infrastructure are highly location dependent. Further, the resource must be located electrically downstream from the transmission or distribution equipment to provide this service. However, energy efficiency provides the greatest share (274 MW) of procured non-wires solutions to date (Munoz-Alvarez 2017).	Energy management systems (Piette et al. 2007), smart thermostats (Robinson et al. 2016)
Voltage Support	**$3–$8/kilovolt-ampere reactive power per year (Li et al. 2006)** Based on the avoided cost of capacitor banks and the range of reactive power compensation payments offered to generation.	**Small.** Payments available for voltage support, or reactive power compensation, from demand-side resources vary significantly depending on the utility context and the size of utility customer (Li et al. 2006). Furthermore, multiple competing technologies ranging from traditional capacitor banks to “smart” solar inverters can provide voltage support (Denholm et al. 2019; CAISO 2018b).	Variable frequency drives (Li et al. 2006), water heaters (NRECA 2018).

A.2 Key GEB Technologies

The *GEB Technical Report Series* evaluates a suite of building technologies based on their potential to provide grid services through energy efficiency and demand flexibility. Technologies spanning thermal storage and electrical loads from various building systems and components are evaluated: HVAC, water heating, appliances, refrigeration, miscellaneous electric loads, electronics, lighting, windows, and envelope. In addition, several cross-cutting technology areas and natural gas technologies are also evaluated. Each report evaluates technologies within the same technical area (HVAC, water heating, etc.) to classify them as high, medium, or low potential. More information on each technology and the evaluation process is available within each technical report.[29] The highest potential technologies from the GEB technical reports are discussed in the following sections.

A.2.1 Heating, Ventilation, and Air Conditioning (HVAC)

Heating, cooling, and ventilation loads comprise approximately 42% of total energy use and 44% of daily peak energy use (2–8 p.m.) in residential and commercial buildings. HVAC technologies are particularly well suited to help control peak demand because air conditioning is the biggest single contributor to summer demand peaks and heating is the biggest single contributor to winter demand peaks. HVAC technologies can provide grid benefits through passive load reduction, nondispatchable demand response (load shifting), dispatchable demand response (load shifting), fast load modulation, and fuel-switching (load shifting).

Smart Thermostats. Smart thermostats offer features such as internet connectivity, advanced algorithm controls, and simple integration with home automation systems. The smart algorithms are contained in the smart thermostat or are cloud-based, and either method relays information about the set point and current temperature to the HVAC system. These thermostats can provide load shifting, including management of complex scheduling and day-ahead service requests, while optimizing operations to minimize impacts on customer comfort. However, smart thermostats cannot provide pure load shedding. HVAC equipment can shed load temporarily, but some of that load will be required postcurtailment to bring the temperature back up/down, which constitutes load shifting.

Liquid Desiccant Thermal Energy Storage. Storage of liquid desiccants for dehumidification in separate sensible and latent HVAC systems provides flexibility for latent load management during cooling season (but not during heating season).[30] Regenerated liquid desiccants store energy chemically without the need for insulated containers, so storage durations can be lengthy if needed. Liquid desiccants absorb moisture from indoor air and then reject it outdoors via a heating cycle, i.e., regeneration (Ware 2013). It is well suited to peak shaving and predictable daily load shifting/leveling to avoid demand charges. Liquid desiccant air-conditioning systems have been demonstrated in the field, though no products are commercially available. In general, this technology is much less developed than thermal energy storage for heating and cooling, so costs are much higher for these systems.

Separate Sensible and Latent Space Conditioning. HVAC systems control both sensible heat (temperature) and latent heat (moisture) in the building to maintain occupant comfort. Traditional vapor-compression cooling systems use oversized evaporators, operate at a lower temperature, or extend the operating cycle to remove moisture (latent heat) from supply air. This coupled sensible and latent cooling process often overcools supply air and may require reheating, which significantly increases energy consumption and demand in humid locations. Liquid and solid desiccants, membrane dehumidifiers, and other air-conditioning system components can remove moisture from supply air without changing its temperature, and can coordinate with a sensible cooling stage to enable independent control of sensible and latent cooling. During peak periods, the combined system could provide grid flexibility by ramping down the sensible cooling stage and using the high-efficiency latent cooling stage to remove indoor humidity and maintain occupant comfort, enabling extended curtailment.

[29] See Section 1 for report links.
[30] Sensible heat is related to changes in temperature, while latent heat is related to changes in humidity.

A.2.2 Windows and Envelope

Building envelopes do not use energy themselves, but they influence heat and moisture conditions within the building, which directly impacts heating and cooling needs and corresponding energy use. Heating and cooling loads in buildings constitute approximately 34% of total energy and 36%[31] of daily peak energy use (2–8 p.m.) from major energy loads[32] in buildings. Windows and window attachments also affect lighting energy use by admitting or blocking daylight. High-performance building envelopes more effectively control the influence of outdoor conditions on the interior environment than typical existing buildings and code-minimum new construction, reducing the heating and cooling requirements to maintain the desired indoor conditions. In addition, there are envelope/window materials and technologies—both prospective and currently commercialized—that can dynamically modify their properties to improve envelope performance under varying interior and ambient conditions.

Thermally Anisotropic Systems (TASs). TASs describe both materials with intrinsic thermal anisotropy ("thermally anisotropic materials") and composites specifically assembled with to have thermal anisotropy ("thermally anisotropic composites"). Regardless of the formulation, TASs consist of layer(s) with alternating high and low thermal conductivities. TASs have anisotropic thermal transport properties, because the high conductivity layer(s) are the least resistive paths for heat transfer, thus diverting heat flow through envelope to the connected heat sink or source. TASs can be dynamically controlled by changing the heat transfer characteristics of the connection between the TAS and the heat sink or source. TAS provide benefit to the grid primarily through efficiency and load shifting.

Envelope Thermal Storage. Thermal storage materials store and release heat when charging and discharging. These materials can thus reduce and shift the timing of heating or cooling energy demand. The primary grid benefit of thermal storage is load shifting by supplanting HVAC system operation during peak hours and using the HVAC system to recharge the storage during off-peak hours. Some efficiency benefits come from shifting HVAC system operation to periods when the system can operate more efficiently (because of ambient conditions and/or thermostat set point).

Tunable Thermal Conductivity Materials. Tunable thermal conductivity materials can dynamically adjust their thermophysical properties with the ultimate objective to enable control over the operation of the envelope assembly in a manner that provides energy efficiency and/or HVAC load shifting. In the cooling season, a tunable thermal material would have high thermal conductivity (low R-value) when ambient temperatures are lower than the indoor temperature, thereby providing "free cooling," and low thermal conductivity (high R-value) when relative indoor and outdoor temperatures are reversed, minimizing thermal losses to the exterior. Tunable thermal materials could also be combined in assemblies with other envelope materials (e.g., thermal storage) to create a system that can actively store and release thermal energy to provide HVAC load shifting.

Dynamic Glazing. Dynamic glazing includes a range of chromodynamic coatings applied to glazing that can switch between two or more states and that block varying portions of the wavelengths that lead to solar heat gain in buildings. Electrochromic glazing offers grid-integrated operational potential because it can be actively adjusted in response to a control signal to reduce energy use or provide grid services, though the response time of the electrochromic glazing might be faster than the correlated reduction in electricity demand. Dynamic glazing provides benefit to the grid primarily through efficiency and load shedding (assuming the system is responsive to utility control signals) by controlling solar heat gain.

Window Attachments. Window attachments include interior devices, such as blinds, shades, and drapes, and exterior devices, including awnings and shutters. In some cases, these attachments are operable so that they can be repositioned to control glare, control perimeter zone heating, and provide privacy. Adding electric

[31] Data are generated using the Scout time-sensitive efficiency valuation framework (Satre-Meloy and Langevin 2019), which attributes annual baseline energy use estimates from the U.S. Energy Information Administration (EIA) Annual Energy Outlook (AEO) across all hours of the year using energy load shapes from the Electric Power Research Institute.
[32] Includes heating, cooling, lighting, office electronics, refrigeration, water heating, and ventilation and drying.

actuation, network connectivity, and lighting sensors enables the operation of attachments to minimize HVAC and lighting energy use while maximizing occupant comfort. Automated window attachments provide benefit to the grid primarily through energy efficiency and load shedding by controlling solar heat gain.

A.2.3 Water Heating

Water heating comprises approximately 10% of total energy use and 9% of peak energy use (2–8 p.m.) in residential and commercial buildings. Water heaters are available in two primary configurations: tankless and storage. Storage water heaters can provide value to the grid because of their inherent ability to store thermal energy, enabling them to decouple power demand from end-use consumption. Through thermal energy storage, storage water heaters can be controlled to shift demand away from peak times while still providing the same function to consumers. Modulation services can also be provided by many water heaters.

Water Heaters with Smart, Connected Controllers. Advanced water heater controllers (prepacked or external retrofits) can provide multiple forms of value to the grid, depending on the algorithm that is implemented. For example, preheating during off-peak periods (load shifting) enables reduced or no power draw during the peak period. Preheating provides grid value without loss of functionality to the consumer. Temporary load shedding can also be done for emergency demand response curtailment by shutting down the unit during emergency events to mitigate grid stress. Frequency regulation can also be possible with electric resistance water heaters or heat pump water heaters that operate on electric resistance, given the right market rules via direct utility control of the unit. However, as water heater power consumption is not constant throughout the day, this service would only be available intermittently.

A.2.4 Refrigeration, Appliances, and Miscellaneous Electric Loads

Refrigeration and clothes drying comprise approximately 19% of total energy use and 17% of daily peak energy use (2–8 p.m.) in residential and commercial buildings. Appliances constitute a diverse group of end uses with various load shapes and operating behaviors, which necessitates different opportunities and different challenges in providing grid services. Appliances that run in finite cycles, such as dishwashers and clothes dryers, have traditionally been considered candidates for demand response programs because of the relative ease with which the load can be shifted away from peak periods via a delayed start with relatively little customer impact. Appliances that run continuously, such as refrigerators, require more careful planning to ensure that proper consumer utility is maintained. Those appliances are more likely to provide load modulation services or, in the case of refrigeration, load shifting through careful precooling strategies to prevent damage to the contents. In addition, some miscellaneous electric loads[33] are emerging as new opportunities for demand-side management through direct load control strategies.

Water Heating Miscellaneous Electric Loads. This category consists of portable electric spa heaters and pool heaters and provides grid value in the same way as domestic water heaters, as described previously. These hot water reservoirs provide thermal energy storage for preheating during off-peak or high renewable energy generation periods and can shift load away from peak demand periods.

A.2.5 Electronics

Electronics comprise approximately 16% of total energy use and 16% of peak energy use (2–8 p.m.) in residential and commercial buildings. Electronics and computing technologies today have yet to be used to provide demand response or any grid service outside of energy efficiency, though direct load control may be enabled through smart plugs/load control switches and communication hubs.

Continuous-Operation Electronics. Continuous-operation electronics are used for computing, data storage, network supply, and related purposes and require constant power supply to operate. This consists of desktop personal computers, network equipment, set-top boxes, game consoles, servers, digital media players, and audio/video equipment. The primary grid benefit is energy efficiency through power management controls that

[33] Miscellaneous electric loads represent electricity consumed by end uses that fall outside core building functions.

can automatically transition computers and electronics into low-power modes as well automatically power down devices after periods of inactivity. In addition, computers and electronics in continuous connectivity (e.g., servers) can potentially modulate or shed loads.

A.2.6 Lighting

Lighting constitutes approximately 13% of total energy and 15% of daily peak energy use (2–8 p.m.) in residential and commercial buildings. Connected lighting systems offer opportunities to reduce consumption during peak times and provide additional grid services, such as fast response shedding or modulating. Connected lighting systems are composed of devices, including light-emitting diode (LED) lamps and/or luminaires, network communication interfaces, as well as sensors and controls.

Advanced Lighting Sensors and Controls. Advanced lighting sensors and controls are connected lighting systems utilizing advanced controls and algorithms to automatically modulate lighting levels or potentially other power-consuming features (e.g., spectrum, reduced sensor or network communication interface power) in response to external grid signals. Technologies include advanced concepts for control-LED integration, integration with grid signaling capabilities, application program interfaces for demand response, luminaire-level energy use reporting, and adaptive algorithms for optimized LED and control performance (including artificial intelligence and machine learning). These technologies interact with both the grid and building-level sensors and control systems to reduce lighting loads and potentially provide quick response services, such as shedding and modulation. However, these capabilities are limited in scope because of the necessity of lighting for occupant productivity, comfort, and safety.

A.2.7 Cross-Cutting Technologies

Energy Management Systems. Energy management systems vary substantially between large commercial buildings and small commercial/residential buildings. Large commercial buildings use building automation systems to monitor and control HVAC, lighting, and other subsystems. Building automation systems integrate information from a range of outdoor environmental (temperature, humidity), indoor environmental (temperature, humidity, carbon dioxide), and equipment (on/off state, inlet and outlet temperatures, flow rates) sensors and then implement schedules (e.g., thermostat set points for occupied and unoccupied hours) and rules (e.g., economizer set point resets based on outdoor temperature and humidity) to reduce energy use and provide direct load control demand response. In the residential and small commercial building space, recent years have seen rapid adoption of home energy management technologies such as smart thermostats and voice-activated home assistants that integrate with connected water heaters, appliances, lighting, and electronics. Energy management systems may enable both energy savings and demand flexibility (shedding, shifting, and/or modulating) depending on the configuration of the system and the technologies that are being controlled (though they are not required to provide flexibility in all cases). These systems implement control as direct responses to commands or through programmed scheduling that can potentially incorporate variables, such as occupancy patterns or TOU pricing.

Direct Current (DC) Technologies. DC technologies and DC buildings are powered through direct current rather than alternating current (AC) from the electric grid. This makes them well suited to pair with distributed generation (e.g., solar PV, generators, etc.) and battery storage, which both naturally supply DC power. In addition, DC-powered technologies eliminate the losses that occur from converting DC power from a battery or distributed generation to AC or from converting AC to DC within the device/equipment. For example, avoided inverter losses in DC appliances operating on DC motors can provide 5%–15% savings over AC induction or universal motors, which are common in appliances (Glasgo, Azevedo, and Hendrickson 2016). Similar, DC lighting has been shown to provide additional energy efficiency gains by reducing the 10%–15% energy losses in the conversion (Hutchinson 2018).

Batteries. Building-level battery systems or embedded batteries in HVAC, lighting, and other building equipment allow batteries to store electricity and provide grid services through shifting and modulating loads without impacting building occupants. For example, the battery could be charged during off-peak hours or during time of high variable renewable generation, to be discharged during a demand response event. Batteries may also be used to align power draw from the grid with the lowest price electricity rates where TOU rates apply. Generally, embedded battery equipment costs are higher than for whole-building batteries because the capacity would be split between several devices, as opposed to being installed as a centralized solution; however, embedded batteries have the added advantage of little to no incremental installation cost. The primary value of a building/home battery or embedded-battery equipment currently is resilience to power outages, though utilities are beginning to offer payment for utilizing energy stored in building-level batteries. However, efficiency losses also occur through standby power consumption, losses in charging/discharging, and power conversion from DC to AC (if applicable).

Embedded Thermal Energy Storage. Thermal energy storage packaged within, or integrated with, HVAC systems or refrigeration equipment enables tremendous flexibility for their power draw. The storage medium can be regenerated during off-peak hours, stored, and then discharged to the building at any point throughout the day. Water/glycol mixtures are a common medium used as the thermal distribution mechanism between the thermal storage (e.g., ice vats) and the building's thermal distribution system. Advanced controls are required to determine when to charge or discharge the thermal storage. Because storage mediums are held at higher or lower temperatures than their surroundings, they will experience efficiency losses to the ambient environment.

Non-Vapor-Compression Materials and Systems. Non-vapor-compression technologies can serve space cooling/heating, water heating, and refrigeration systems by using unique properties of specialized materials or alternative system designs without the use a traditional vapor-compression cycle. Solid-state non-vapor-compression technologies, such as thermoelectric, magnetocaloric, and electrocaloric systems, produce useful temperature differences based on the intrinsic material properties of their core solid-state substance when activated through electrical input. Other non-vapor-compression technologies, such as membrane, thermoelastic, Stirling, liquid desiccant, and thermoacoustic systems, use electrical or thermal input to alter the phase or other properties of a working fluid or material to pump heat. Several non-vapor-compression technologies could offer grid interactivity benefits through modulating capacity, separate sensible and latent cooling, and energy storage capabilities.

A.2.8 Natural Gas Technologies

Building-Scale Combined Heat and Power (CHP). Building-scale CHP or cogeneration systems use natural gas or other fuel sources (e.g., engine, turbine, fuel cell) to generate electricity and simultaneously provide thermal energy to satisfy space, water, and process heating loads. These systems can be large (>1 MW) to serve campuses, industrial facilities, and large healthcare facilities or smaller micro-CHP systems suitable for a wider range of residential (1–50 kW) and commercial building applications (50–500 kW). CHP systems improve the combined energy efficiency of electricity and thermal energy supply in buildings. Although primarily designed to directly serve campus or building energy loads, CHP and micro-CHP systems are also very well suited to provide flexibility benefits to the grid. CHP operators can adjust the system's dispatch schedule to align with day-ahead and real-time electricity prices and participate in capacity, energy, and demand response markets, which is already done by some large system operators (DOE Advanced Manufacturing Office 2018). In some cases, operators can increase the output of their CHP system beyond normal capacity ratings to provide short-term grid flexibility (Bhandari et al. 2018).

Water Heaters with Smart, Connected Controls. Natural gas water heaters with advanced controllers provide grid benefits primarily through efficiency and load shifting. Smart control algorithms reduce overall energy use, but they offer little in terms of operating efficiency improvements. They can also shift loads by preheating water before or after expected peak demand periods. Preheating enables grid value without loss of functionality to the consumer. They also offer some load shedding by allowing temperatures to drift during demand response events, but this must be followed by a period of higher demand to bring the tank back to the set point.

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