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Grid-interactive Efficient Buildings Technical Report Series

Heating, Ventilation, and Air Conditioning (HVAC); Water Heating; Appliances; and Refrigeration

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Disclaimer

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List of Acronyms and Abbreviations

A/C	air conditioner
AIA	American Institute of Architects
ARPA-E	Advanced Research Projects Agency–Energy
BAS	building automation system
BTO	Building Technologies Office
CHP	combined heat and power
CO_2	carbon dioxide
DER	distributed energy resource
DOE	U.S. Department of Energy
GEB	grid-interactive efficient building
GENSETS	Generators for Small Electrical and Thermal Systems program
GHG	greenhouse gas
GWP	global warming potential
HFC	hydrofluorocarbon
HPWH	heat pump water heater
HVAC	heating, ventilation, and air conditioning (also heating, *ventilating*, and air conditioning)
HVAC&R	heating, ventilation, air conditioning, and refrigeration
HVAC-ET	heating, ventilation, and air conditioning equipment with embedded thermostats
ISO	independent system operator
kW	kilowatt
kWh	kilowatt-hour
M&V	measurement and verification
mCHP	micro-CHP
MEL	miscellaneous electric load
PV	photovoltaic
R&D	research and development
SHEMS	smart home energy management systems
TES	thermal energy storage
TOU	time-of-use (utility rates)

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.

Executive Summary

Through its grid-interactive efficient building (GEB) research, the U.S. Department of Energy (DOE) Building Technologies Office (BTO) seeks to build on existing energy efficiency efforts and develop technological capabilities to optimize the interplay between building loads and the electric grid. This effort builds on energy efficiency research and development (R&D) to also consider impacts of distributed energy resources (DERs), including demand response and energy storage to increase the flexibility of demand-side management. BTO's mission is to support R&D of emerging efficient technologies, techniques, and tools for both existing and new residential and commercial buildings. To help inform BTO's R&D portfolio and the greater building research community, BTO is publishing a series of technical reports to explore the potential of specific building technologies and capabilities to provide grid benefits. This report is part of that series. The scope of this report and the *GEB Technical Report Series* is intentionally focused on technical capabilities and the potential of residential/commercial buildings to enable and deliver grid services. Accordingly, the GEB report series will not address in-depth topics related to policies, business models, market constraints, measurement and verification (M&V), or implementation/scaling challenges.

Building technologies have significant untapped potential to provide cost-effective grid services through advanced demand-side management strategies. This potential is significant in part because buildings are the primary users of electricity: 75% percent of all U.S. electricity is consumed within buildings (U.S. Energy Information Administration 2018). Figure ES-1 shows the breakdown by end uses for both residential and commercial buildings. The loads in this report comprise approximately 80% and 61% of residential and commercial electricity use, respectively, from major end use loads annually.[1]

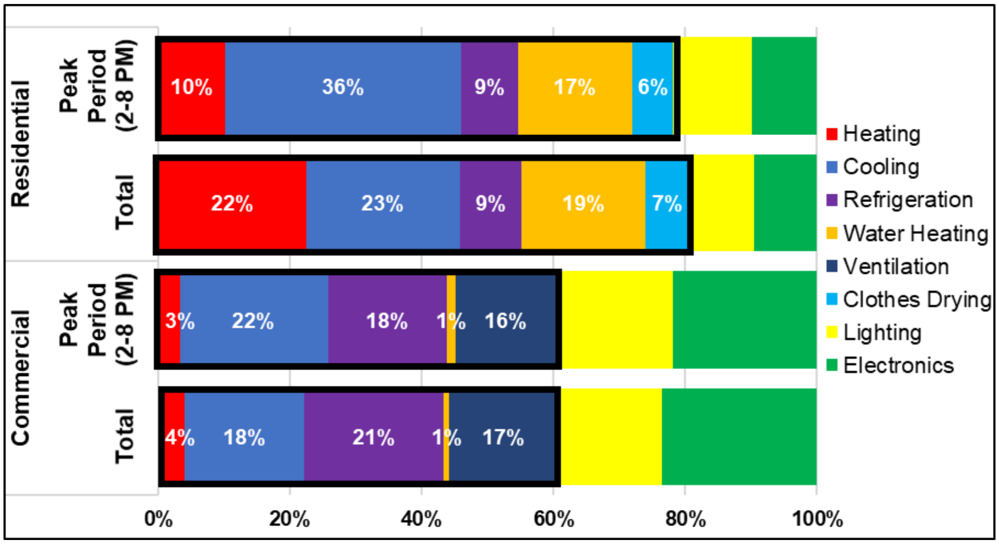

Figure ES-1. Total and peak period 2018 electricity consumption by major end use and building type[1]

Each colored bar represents a single end use. The end uses affected by technologies described in this technical report are outlined in black.

This report focuses on heating, ventilation, and air conditioning (HVAC); water heating; appliances; and refrigeration; as well as related cross-cutting equipment. On-site, embedded controls pertaining directly to these types of equipment are included, whereas other communication devices and controls are beyond the

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[1] 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.

scope of this report. Many of the relevant nonembedded controls and communications devices, many of which are required to enable grid interactivity, are discussed in the *Whole-Building Controls, Sensors, Modeling, and Analytics*[2] report. Further, many technologies covered in this report interact directly with other systems in buildings (e.g., HVAC and envelope) and the design considerations and grid interactivity in each technology may warrant broader systems-level analysis that is not conducted here.

The analysis for this report began with a characterization of key technologies in HVAC, water heating, appliances, and refrigeration. These technologies are listed in Table ES-1.

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[2] See Section 1 for a link to this report and other GEB reports.

Table ES-1. HVAC, Water Heating, Appliances, Refrigeration, and Related Technologies

Technologies		Description
HVAC[3]	HVAC#1: Smart Thermostats (electric or natural gas)	Thermostats with internet connectivity, advanced algorithm controls, and compatibility with home automation systems
	HVAC#2: Separate Sensible and Latent Space Conditioning	Independent control over space cooling and dehumidification for more precise, comfortable, and efficient control
	HVAC#3: Liquid Desiccant Thermal Energy Storage (TES)	Dehumidification energy storage via chemical means without the need for insulated containers
	HVAC#4: Advanced Controls for HVAC Equipment with Embedded Thermostats	Hardware/software control solutions for HVAC equipment has its own thermostat (in the unit or in the remote control)
	HVAC#5: Hybrid Evaporative Precooling	Evaporative and vapor-compression hybrid space cooling equipment
	HVAC#6: Dual-Fuel HVAC Systems (electric or natural gas)	Cooling/heating systems that can run on fuel (natural gas, oil or propane) and/or electricity as needed
Water Heating	WH#1: Water Heaters with Smart, Connected Controls (electric or gas)	Advanced water heater controllers (embedded or external) with connected capabilities and smart algorithms
	WH#2: Dual-Fuel Water Heaters (electric or natural gas)	Water heating systems that can run on fuel (natural gas, oil or propane) and/or electricity as needed
Appliances, Refrigeration, and Relevant Miscellaneous Electric Loads (MELs)*	APP#1: Modulating, Advanced Clothes Dryer	Connected clothes dryers that can run at lower power by modulating heat input and delay operation based on utility need
	APP#2: Advanced Dishwasher/Clothes Washer Controls	Dishwasher/clothes washer controls that enable grid interactivity with minimal impact on customer usability
	APP#3: Advanced Residential Refrigerator/Freezer Controls	Refrigerator/freezer controls that enable grid-friendly operation with little to no impact on customer usability
	APP#4: Advanced Controls for Commercial Refrigeration	Advanced controls (embedded or external) that enable grid-friendly operation with limited impact on operations
	APP#5: MELs: Motors	Multispeed or variable speed motors that increase overall efficiency and can be used for fast response grid services
	APP#6: MELs: Water Circulation	Variable or multispeed pumps that can shed load for noncritical equipment by transitioning to a standby/off state or by modulating to lower speeds. May be considered a subset of APP#5.
	APP#7: MELs: Water Heating	Like other hot water heaters, hot water reservoirs provide thermal energy storage value
	APP#8: MELs: HVAC	Advanced embedded controls with multispeed or variable speed fans to optimize power and increase energy efficiency
	APP#9: MELs: Refrigeration	Refrigerators and freezers that enable load shifting of defrost cycles and other advanced strategies via embedded controls
Related Natural Gas Technologies	NG#1: Building-Scale Combined Heat and Power (CHP)	CHP systems for use in buildings
	NG#2: Smart Thermostats	See HVAC#1, above
	NG#3: Dual-Fuel HVAC	See HVAC#6, above

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[3] No ventilation-specific technologies are included in this analysis because all demand flexibility from relevant ventilation technologies considered as part of the development of this report is provided by either an integrated HVAC solution (e.g., a rooftop unit) or via sensors and controls systems, which are covered separately under the *Whole-Building Controls, Sensors, Modeling, and Analytics* report.

Technologies		Description
	NG#4: Water Heaters with Smart, Connected Controls	See WH#1, above
	NG#5: Dual-Fuel Water Heaters	See WH#2, above
	NG#6: Modulating, Advanced Clothes Dryers	See APP#1, above
Cross-Cutting	CC#1: Thermal Energy Storage (TES)	Storage of heated or cooled material for later use of the thermal energy; may store sensible and/or latent heat
	CC#2: Modulating Capacity Vapor Compression	HVAC systems that can modulate capacity (and power draw)
	CC#3: Non-Vapor-Compression (NVC) Materials and Systems	Heat pump technology for space heating/cooling, refrigeration, and water heating without the use of refrigerants

*Miscellaneous electric loads (MELs) are described further in Section 2.1.3.

The building technologies from Table ES-1 were evaluated based on their ability to provide grid services and the type of value provided. The analysis considered the following demand-side management strategies:

- **Efficiency**: the ongoing reduction in energy use while providing the same or improved level of building function.[4]
- **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.
- **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.
- **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.

The technologies were qualitatively ranked as having high, medium or low potential to provide grid services based on a number of criteria; they are summarized in Table ES-2.

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[4] This would have the greatest impact for the grid during high-cost periods and minimize utilization of costly generation resources.

Table ES-2. Evaluated Grid Service Potential for Each Technology

Category	High Potential	Medium Potential	Low Potential
HVAC	• HVAC#1: Smart Thermostats • HVAC#2: Separate Sensible and Latent Space Conditioning • HVAC#3: Liquid Desiccant TES	• HVAC#4: Advanced Controls for HVAC Equipment with Embedded Thermostats	• HVAC#5: Hybrid Evaporative Cooling • HVAC#6: Dual-Fuel HVAC
Water Heating	• WH#1: Water Heaters with Smart, Connected Controls	• None	• WH#2: Dual-Fuel Water Heaters
Appliances, Refrigeration, and Relevant MELs*	• APP#7: MELs: Water Heating • None	• APP#1: Modulating, Advanced Clothes Dryers • APP#2: Advanced Dishwasher and Clothes Washer Controls • APP#3: Advanced Refrigerator and Freezer Controls • APP#4: Advanced Controls for Commercial Refrigeration • APP#5: MELs: Motors • APP#6: MELs: Water Circulation • APP#8: MELs: HVAC • APP#9: MELs: Refrigeration	• None
Natural Gas	• NG#1: Building-Scale CHP • NG#4: Water Heaters with Smart, Connected Controls	• NG#2: Smart Thermostats • NG#6: Modulating, Advanced Clothes Dryers	• NG#3: Dual-Fuel HVAC • NG#5: Dual-Fuel Water Heaters
Cross-Cutting	• CC#1: Thermal Energy Storage • CC#3: NVC Materials and Systems	• CC#2: Modulating Capacity Vapor Compression	• None

*Residential refrigerators, freezers, and refrigerator/freezers are included in the Appliances category. Also, note that MELs are described further in Section 2.1.3.

The technologies considered to have medium or high potential were then selected for additional evaluation. The benefits and challenges of each of these technologies were listed considering the following system attributes: reliability, resilience, system readiness, usability, manufacturability, human health, environment, and cost-effectiveness. Each of the high- and medium-potential technologies was analyzed with respect to these system attributes, but not all attribute-technology combinations were found to have significant benefits or challenges. This analysis generated a list of relevant benefits and challenges that helped frame the R&D opportunities.

The R&D opportunities were developed based on the benefits and challenges of each technology, as well as input from stakeholders, which included professionals from utilities, industry associations, manufacturers, research laboratories, and nongovernmental organizations. The R&D opportunities presented here include: (a) opportunities that affect all GEB technologies, such as research on reducing manufacturing costs; (b) opportunities that affected all connected GEB technologies, such as the need to improve interoperability; and (c) opportunities that only apply to specific types of equipment, such as the need to support the development of self-dispatching equipment. The R&D opportunities uncovered in this report are summarized in Table ES-3.

Table ES-3. Summary of GEB Technology Area R&D Opportunities

	Technology	Challenges	R&D Opportunities
All	All Connected Technologies	Interoperability	• Support the development and adoption of standardized semantic and syntactic specifications for connected devices and software systems
		Cybersecurity	• Support the adoption of secure system architectures and cybersecurity best practices
		Cost	• Develop manufacturing processes that have low capital costs or can use existing manufacturing equipment with minimal investment • Develop materials and technologies compatible with scalable manufacturing methods that enable increasing production volumes
HVAC	All HVAC GEB Technologies	Limited understanding of duration, temperature, and humidity constraints for curtailment	• Model and test to characterize curtailment limitations.
	HVAC#1: Smart Thermostats	None identified beyond sensors and controls content (refer to *Whole-Building Controls, Sensors, Modeling, and Analytics* report—see Section 1 for relevant links)	
	HVAC#2: Separate Sensible and Latent Space Conditioning	Complex installation and commissioning	• Develop packaged systems to reduce installation and commissioning complexity
	HVAC#3: Liquid Desiccant TES	Complex installation and commissioning	• Develop packaged systems to reduce installation and commissioning complexity
		Generally high floorspace needs	• Develop novel TES materials with increased energy storage density (volumetric and gravimetric) • Develop novel ways to package storage systems
	HVAC#4: Advanced Controls for HVAC Equipment with Embedded Thermostats	Lack of nonpremium products with grid-interactive functionality	• Develop inexpensive retrofit grid-interactive packages
Water Heating	WH#1: Water Heaters with Smart, Connected Controls	Lower heat-pump-only preheat capabilities from HPWH vs. elec. resistance	• Evaluate the optimal approach for hybrid electric resistance/heat pump water heaters (HPWHs) for curtailment • Develop low-GWP refrigerant-based (e.g., carbon dioxide [CO_2]) HPWHs for higher-temperature capabilities
Appliances, Refrigeration, and MELs	APP#7: MELs: Water Heating	Lack of nonpremium products with grid-interactive functionality	• Develop inexpensive retrofit grid-interactive packages
	APP#1: Modulating, Advanced Clothes Dryers	Lack of nonpremium products with grid-interactive functionality	• Develop inexpensive retrofit grid-interactive packages
		High product cost (heat pump models)	• Conduct cost-reduction R&D for heat pump clothes dryers
	APP#2: Advanced Dish and Clothes Washer Controls	Lack of nonpremium products with grid-interactive functionality	• Develop inexpensive retrofit grid-interactive packages
	APP#3: Connected Refrigerator/Freezer Advanced Controls	Lack of nonpremium products with grid-interactive functionality	• Develop inexpensive retrofit grid-interactive packages

	Technology	Challenges	R&D Opportunities
	APP#4: Advanced Controls for Comm. Refrigeration	Lack of broad understanding of duration and temperature constraints for curtailment	• Model and test to characterize curtailment limitations
Natural Gas	NG#1: Building-Scale CHP	High product and installed costs	• Conduct cost-reduction R&D with a focus on smaller-scale (e.g., <50 kilowatt [kW]) systems
	NG#4: Water Heaters with Smart, Connected Controls	None identified beyond sensors and controls content (refer to *Whole-Building Controls, Sensors, Modeling, and Analytics*—see Section 1, including relevant links)	
	NG#2: Smart Thermostats	None identified beyond sensors and controls content (refer to *Whole-Building Controls, Sensors, Modeling, and Analytics*—see Section 1, including relevant links)	
	NG#6: Modulating, Advanced Clothes Dryers	Lack of nonpremium products with grid-interactive functionality	• Develop inexpensive retrofit grid-interactive packages
Cross-Cutting	CC#1: Thermal Energy Storage	Complex installation and commissioning	• Develop packaged systems to reduce installation and commissioning complexity
		Large space requirements/footprint	• Develop novel TES materials with increased energy storage density • Develop novel ways to package storage systems
		Limited flexibility of thermal storage materials for year-round use	• Develop novel ways to modify TES materials to dynamically manipulate their transition temperature (e.g., for both heating and cooling energy storage) • Determine the conditions for thermal storage operation that offer the greatest GEB service provision potential and energy savings potential
	CC#2: Modulating-Capacity Vapor Compression	High product costs	• Develop lower-cost modulating-capacity systems, with a focus on heat exchangers and compressors
	CC#3: Non-Vapor-Compression (NVC) Materials/Systems	High product costs	• Develop lower-cost NVC materials, systems, and components
		Nascent solutions have limited field validation of architectures and approaches	• Expand development of NVC for a broad range of HVAC and refrigeration (HVAC&R) applications

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1 Introduction

To help inform the building research community and advance the U.S. Department of Energy (DOE) Building Technologies Office's (BTO's)[5] research and development (R&D) portfolio, BTO has published a series of technical reports that evaluate the opportunities for grid-interactive efficient buildings (GEBs)[6]. In addition to this report, an overview report and three other technology reports were published in 2019 as part of the *GEB Technical Report Series*, covering major relevant building technology areas with significant potential for energy flexibility:

- *Overview of Research Challenges and Gaps*[7]
- *Heating, Ventilation, and Air Conditioning (HVAC); Water Heating; Appliances; and Refrigeration* (this report)
- *Lighting and Electronics*[8]
- *Windows and Opaque Envelope*[9]
- *Whole-Building Controls, Sensors, Modeling, and Analytics*[10]

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

The GEB technical reports evaluate state-of-the-art and emerging building technologies that have the potential to provide grid services. These 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 R&D portfolio and serve as a foundational resource for the larger building research community. On-site behind-the-meter generation, batteries, 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 batteries, but the *Whole-Building Controls, Sensors, Modeling, and Analytics* report discusses how a building can optimize across all DERs.

1.1 Strategy and Vision

BTO's mission supports the R&D, validation, and integration of affordable, energy-saving 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:

- 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 both utility customers and the overall electricity system; and

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[5] For more information, see: https://www.energy.gov/eere/buildings/building-technologies-office.
[6] For more information, see: https://www.energy.gov/eere/buildings/grid-interactive-efficient-buildings.
[7] Available online here: https://www.nrel.gov/docs/fy20osti/75470.pdf.
[8] Available online here: https://www.nrel.gov/docs/fy20osti/75475.pdf.
[9] Available online here: https://www.nrel.gov/docs/fy20osti/75387.pdf.
[10] Available online here: https://www.nrel.gov/docs/fy20osti/75478.pdf.

- 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). In addition, studies have shown that 10%–20% of commercial building peak load can be temporarily managed or curtailed to provide grid services with the use of state-of-the-art sensors and controls (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.

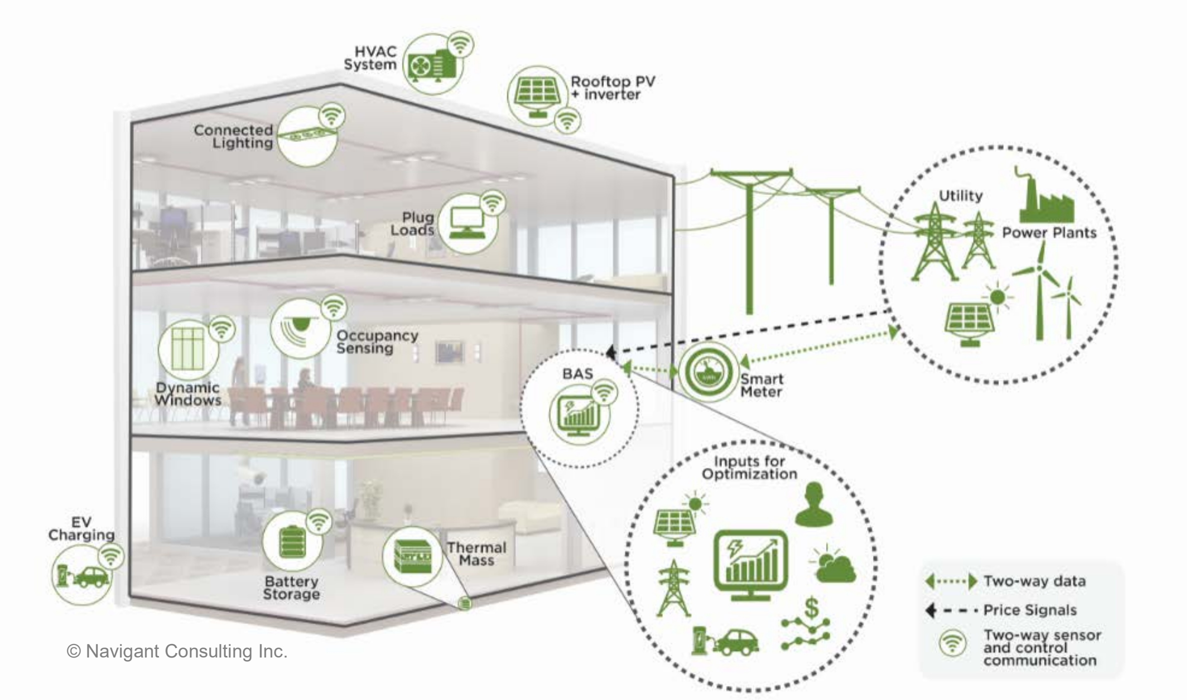

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Figure 1. Example grid-interactive efficient commercial building

The building automation system (BAS) 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.

1.2 Report Scope and Approach

This report focuses on HVAC, water heating, appliances, and refrigeration, as well as related cross-cutting equipment. As part of the appliance discussion, this report includes miscellaneous electric loads (MELs) that relate to HVAC, water heating, appliances, and refrigeration. Embedded controls and accessories, including smart thermostats, are also included, whereas on-site building-level controls (e.g., building management system/BAS/BEMS and smart home energy management systems [SHEMS]) and off-site devices and controls are beyond the scope of this report. Some of the external devices are discussed in the *Whole-Building Controls, Sensors, Modeling, and Analytics* report, which will be referenced in this report as appropriate. Figure 2 summarizes the scope of this report.

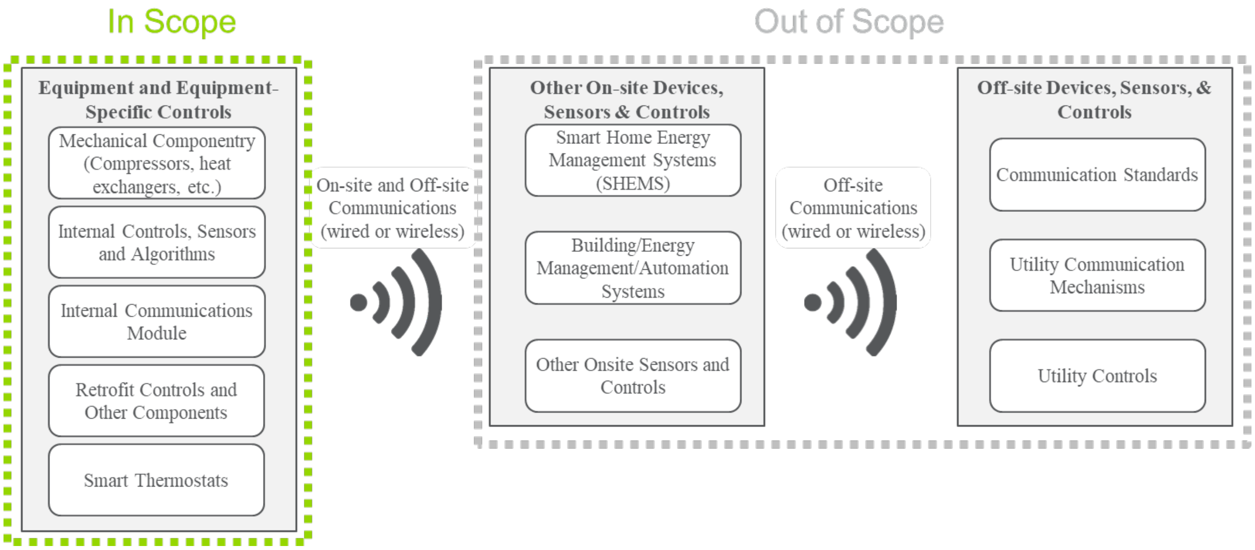

Figure 2. Report scope definition[11]

This report first identifies and characterizes a list of HVAC, water heating, appliances, and other technologies (Section 2) that provide grid value (see Section 1.3 for a discussion of grid value) either directly or indirectly.

Next, these technologies are evaluated according to their potential ability to provide flexibility (Section 3) via grid services. The technologies are categorized as having low, medium, or high technical potential. Technologies considered to have medium or high potential are analyzed further.

Technology attributes are discussed in Section 4 for each identified GEB technology. These attributes include energy efficiency, reliability, resilience, system readiness, usability, manufacturability, and health and environmental impacts. Finally, R&D activities and opportunities are identified in Section 5 based on current technical challenges facing the identified high- and medium-potential GEB technologies. Figure 3 summarizes this approach.

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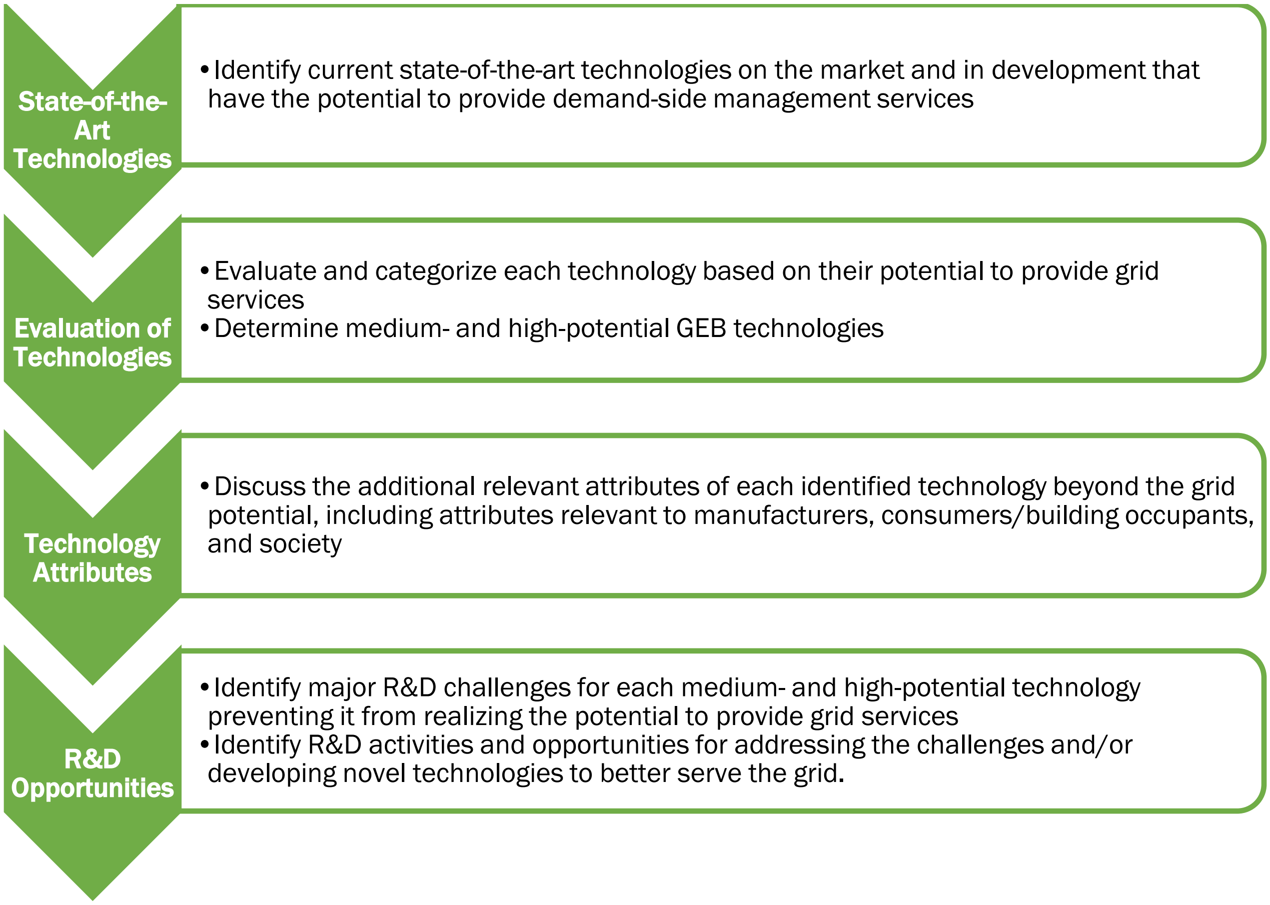
[11] The HVAC, water heating, and appliances report covers all internal componentry of the equipment and related on-site devices and controls. Off-site devices and controls are handled in the *Whole-Building Controls, Sensors, Modeling, and Analytics* report.



State-of-the-Art Technologies

- Identify current state-of-the-art technologies on the market and in development that have the potential to provide demand-side management services

Evaluation of Technologies

- Evaluate and categorize each technology based on their potential to provide grid services
- Determine medium- and high-potential GEB technologies

Technology Attributes

- Discuss the additional relevant attributes of each identified technology beyond the grid potential, including attributes relevant to manufacturers, consumers/building occupants, and society

R&D Opportunities

- Identify major R&D challenges for each medium- and high-potential technology preventing it from realizing the potential to provide grid services
- Identify R&D activities and opportunities for addressing the challenges and/or developing novel technologies to better serve the grid.

Figure 3. HVAC, water heating, appliances, and refrigeration report approach

The scope of the *GEB Technical Report Series* is focused on technical capabilities and potential of residential and commercial buildings to enable and deliver grid services. The GEB report series will not address in-depth the following topics that, although important in practice, 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 (M&V), commissioning, and implementation and scaling challenges. However, BTO recognizes many of these topics represent significant barriers that must be addressed in future work and research to realize BTO's GEB vision.

1.3 Grid Services Provided by Buildings

This report characterizes connected HVAC, water heating, appliance, and refrigeration technologies to help identify R&D opportunities to improve the demand flexibility for these technologies and the associated ability to provide grid services. Depending on the market and the grid need, that could be on only a few days per year (e.g., reliability-based demand response), or it could be on a daily, hourly, or even continuous basis. Table 1 summarizes seven different grid services that may be provided by building technologies.

Table 1. Grid Services Definitions

For more information on these grid services, see the *Overview of Research Challenges and Gaps* report.

Grid Services		Potential Avoided Costs
Generation Services	Energy	Power plant fuel, operation, maintenance, and startup and shutdown costs
	Capacity	Capital costs for new generating facilities and associated fixed operation and maintenance costs
Ancillary Services	Contingency Reserves[12]	Power plant fuel, operation, maintenance, and opportunity costs associated with providing contingency reserves
	Frequency Regulation	Power plant fuel, operation, maintenance, and opportunity costs[13] associated with providing frequency regulation
	Ramping	Power plant fuel, operation, maintenance, and startup and shutdown costs
Delivery Services	Non-Wires Alternatives[14]	Capital costs for transmission and distribution equipment upgrades
	Voltage Support	Capital costs for voltage control equipment (e.g., capacitor banks, transformers, smart inverters)

The grid services listed in Table 1 can be delivered via four different mechanisms: efficiency, load shedding, load shifting, and load modulation (i.e., frequency regulation or voltage support), which are discussed in more depth in Section 3.1 and in the *Overview of Research Challenges and Gaps* report. HVAC, water heating, and appliances can deliver value via these mechanisms in different ways, given their different operating patterns and customer benefits.

1.4 Advanced Grid Services Potential

1.4.1 Electric Equipment

The technologies covered in this report include HVAC, water heating, appliances (including drying and residential refrigerators), and commercial refrigeration. These loads use 740 and 544 TWh site electricity use annually in residential and commercial buildings (Figure 4), respectively, comprising 80% and 61% of total residential and commercial electricity use from major loads (Figure 5). During the peak period of 2–8 p.m., the loads addressed by this report use 212 TWh and 161 TWh site electricity annually in residential and commercial buildings, respectively, comprising 78% and 61% of residential and commercial electricity use from major loads during this peak period.

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[12] Note that this includes reserves products with various timescales, including spinning reserves, nonspinning reserves, and other particular reserves products that exist in some regions.

[13] For example, not selling power in order to be ready for up-regulation.

[14] Also referred to as deferred transmission and distribution upgrades.

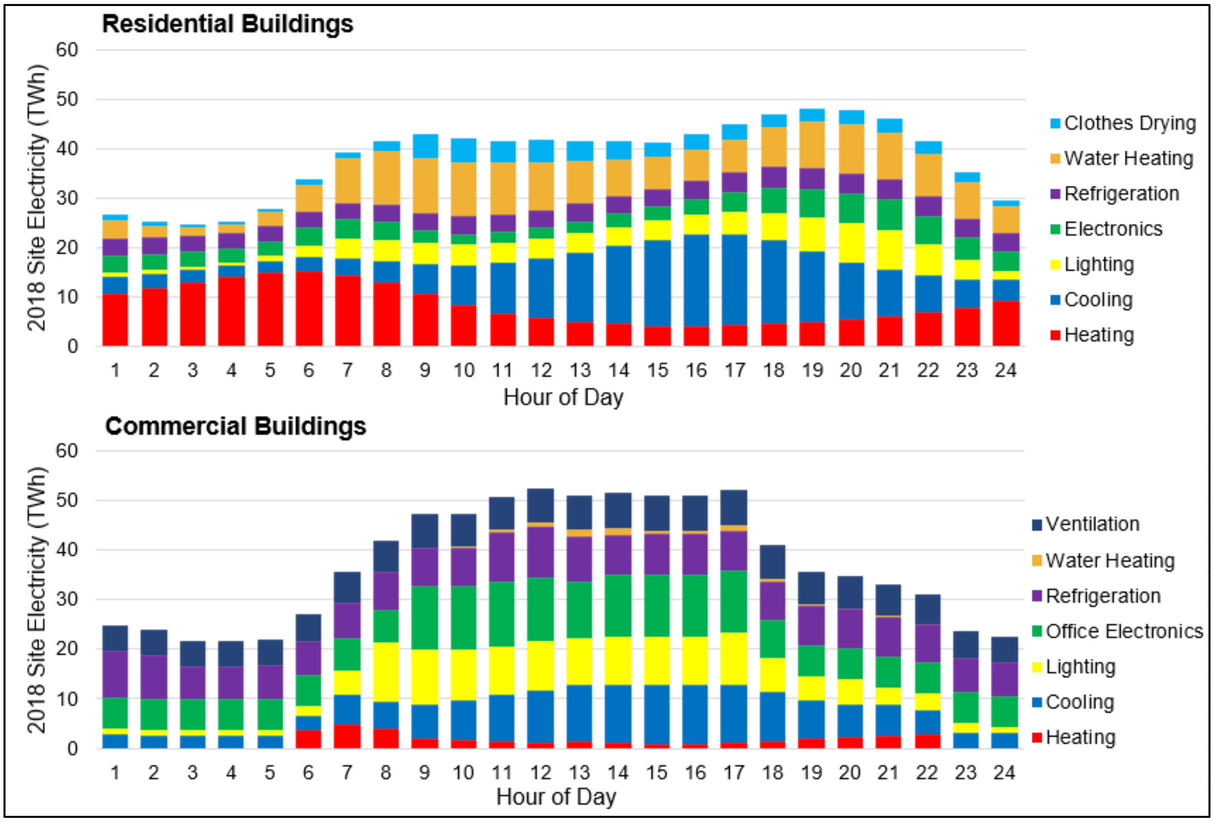

Figure 4. Hourly electricity use in residential and commercial buildings[15]

Total hourly electricity use in terawatt-hours (TWh) in U.S. residential buildings (top) and commercial buildings (bottom), broken out by major electric end use for the year 2018. Each colored bar represents a single end use, and bar labels indicate the total site electricity use that occurs during each hour across the course of the year.

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[15] 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). Energy load shapes for the commercial sector do not currently account for scheduling diversity across the stock of a given commercial building type in a given region, which would yield smoother utility-scale load shapes than those shown in this report. Ongoing efforts to collect residential and commercial end-use load shape data that better represent this scheduling diversity (https://www.nrel.gov/buildings/end-use-load-profiles.html) will be incorporated in future iterations of the residential and commercial load shapes. 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.

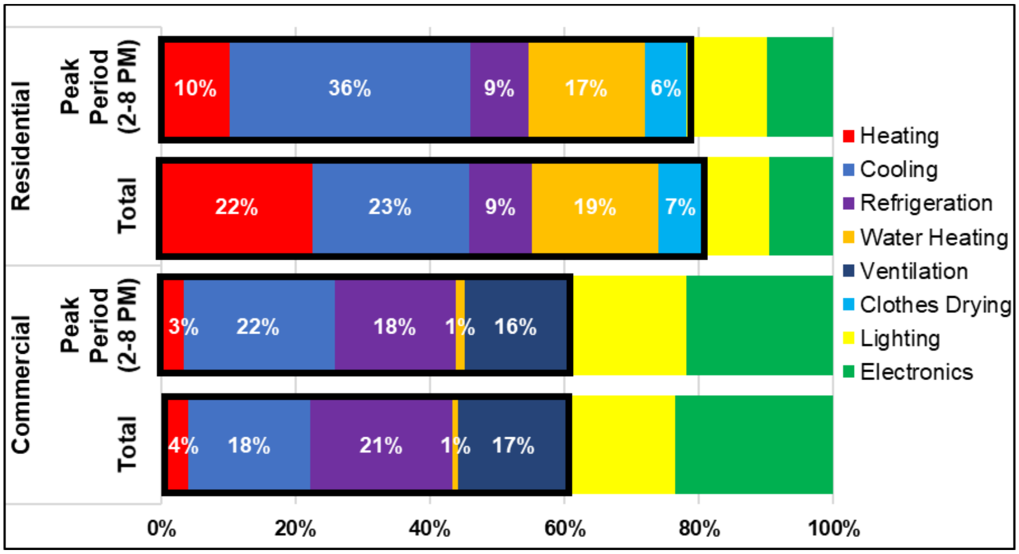

Figure 5. Total and peak electricity use by major end use and building type[16]

Total and peak period (2–8 p.m.) electricity use broken out by major electric end use in commercial buildings (top image) and residential buildings (bottom image) for the year 2018. Each colored bar represents a single end use, and the end uses affected by technologies described in this technical report are outlined in black (excluding ventilation and drying, which are included in "other"); the percentage contributions of the affected end uses to total and peak period electricity use are also shown. The end uses that pertain to this report comprise 80% and 61% of total residential and commercial electricity use from major loads and 78% and 61% of peak period residential and commercial electricity use from major loads.

Cooling loads are a particularly important point of focus because of their high coincidence with summer (June–September) system peak hours. In the residential sector, 74 TWh of summer cooling occurs between 2–8 p.m. (Figure 6, top image), comprising 43% of total residential summer cooling. In the commercial sector, these numbers are 40 TWh of electricity and 37% of commercial summer cooling. Cooling electricity in Figure 6 is driven by the Southeast region; the bottom image of Figure 6 shows that these regions also drive winter (December–February) heating electricity use, reflecting the large installed base of heat pumps and resistance heating in southern regions. Looking ahead, greater electrification of heating in the northern regions, with their large heating demands, would grow the overall potential of the electric heating load substantially.

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[16] 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.

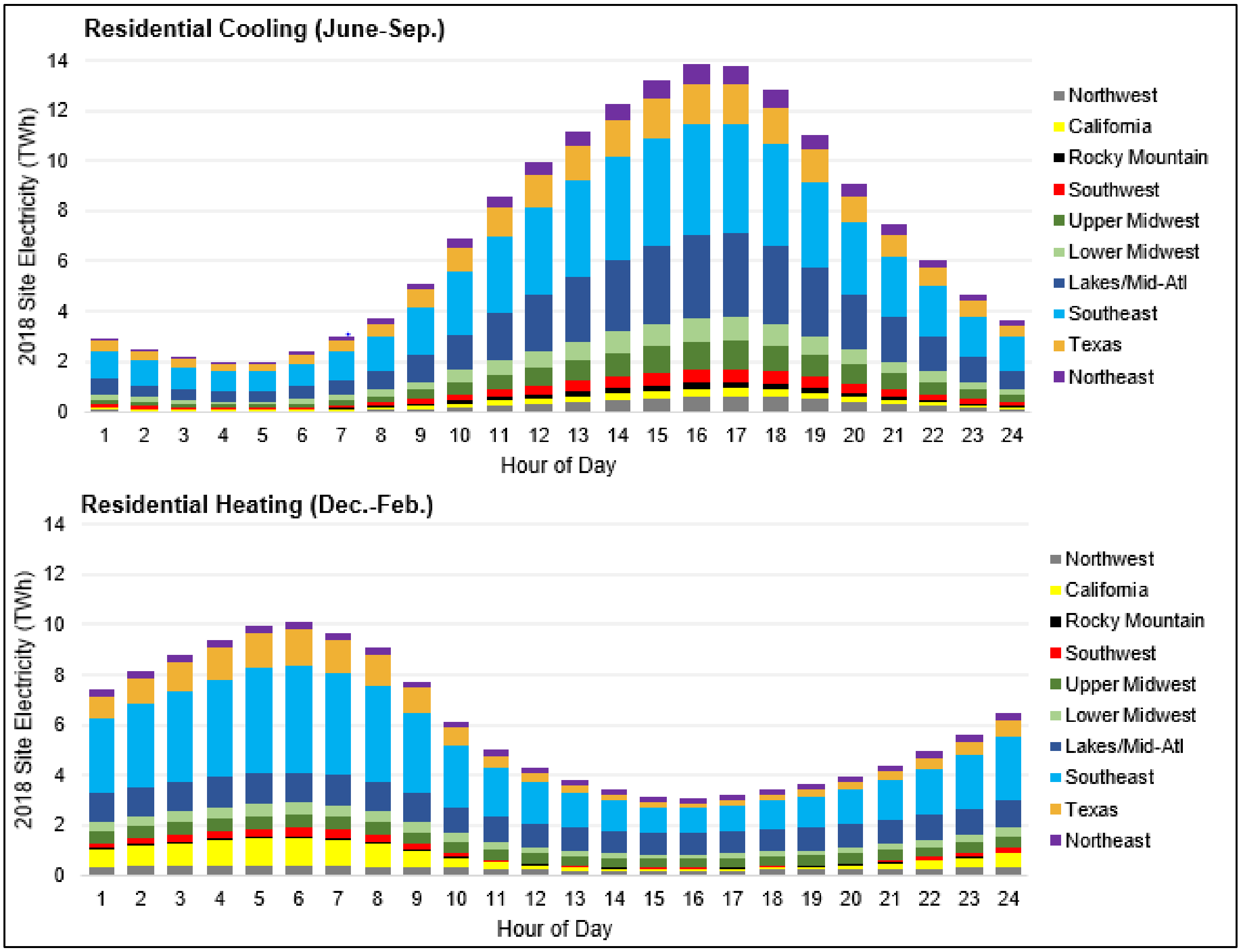

Figure 6. Residential cooling and heating hourly load profiles[17]

Total hourly summer cooling electricity use (top image) and winter/intermediate heating electricity use (bottom image) in residential buildings, broken out by region for the year 2018. Each colored bar represents one of the ten regions in the U.S. and bar labels indicate the total site electricity use that occurs during each hour across the course of the year. Cooling peaks by the early evening (~4 p.m.) and is driven by the Southeast and Lakes/Mid-Atlantic regions. The Southeast region also drives winter heating, which peaks in the morning (~6 a.m.), reflecting the large installed base of heat pumps and resistance heating in these cooling-dominated climate regions.

1.4.2 Natural Gas Equipment

Natural gas equipment can provide value to both the electric and natural gas grids. Reduced load from natural gas equipment provides direct value to the natural gas grid via curtailment of natural gas burners and to the electric grid via curtailment of supplemental electric loads, like furnace fans and boiler circulation pumps. In some regions, gas equipment curtailment can also provide value indirectly to the electricity grid by helping bring down natural gas prices for generators. This is particularly valuable in capacity-constrained areas like the northeast United States. Further, gas networks tend to have the greatest demand during extreme cold spells, when building heating loads are very high. In many parts of the country, where the generation mix heavily favors natural gas generation, these same periods see high demand for gas from the power sector, which drives

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[17] 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.

high real-time costs in both gas and electricity markets. Depending on grid conditions, duel-fuel systems (which can switch between fuel sources as needed) can also provide additional value and flexibility to electricity and gas system operators.

The coincidence between the gas and the electric grid peaks is illustrated in Figure 7. The figure shows a sample electric heating load shape (Northeast Power Coordinating Council—New England region) compared to a sample electric grid load shape (ISO—New England region). Both cover the New England region of the United States, so the two load shapes in Figure 7 pertain to the same geographic region. Gas peaks tend to occur during times of high heating loads in the winter, so the residential heating load shape is used here as a proxy for the gas heating load shape.

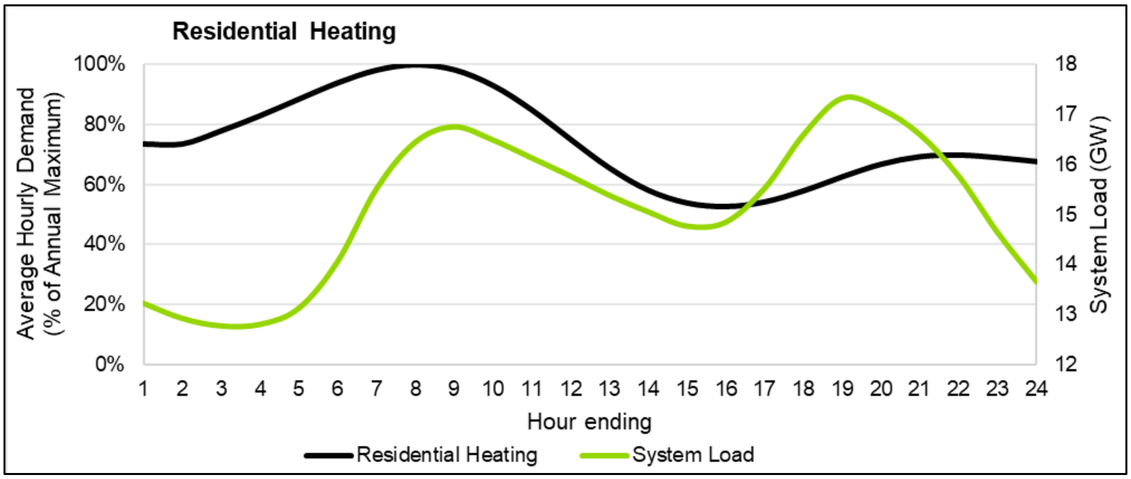

Figure 7. Sample system load compared to sample residential heating load shape[18]

Therefore, in locations that are natural-gas-supply constrained and rely heavily on natural gas for residential heating and electricity generation, this could lead to a situation where switching from gas to electricity could have unintended consequences. For example, an analysis of cold days in New England in 2018 found that gas generation was substantially underutilized. The data showed that home heating drove high demand for natural gas, forcing the power sector to rely more heavily on higher cost marginal fuels, like oil (Weiss et al. 2018).

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[18] Sample space heating load shape: Northeast Power Coordinating Council—New England region, peak weekday, off peak season; http://loadshape.epri.com/enduse. Sample system load shape: ISO New England on February 28, 2019; https://www.iso-ne.com/isoexpress/web/charts. The flat spot in the residential load shape is consistent with the source data but the cause is unclear.

2 State-of-the-Art Technologies

2.1 Current State-of-the-Art

The following subsections summarize key state-of-the-art technologies, including a description of the technology and its interaction with the grid, the current performance levels, the development phase, the applicable building sector and market, and the growth potential and projections. In the next section, each of these technologies will be evaluated by their ability to provide grid services. Furthermore, it should be noted that the opportunities for development of novel technologies that further advance the state-of-the-art HVAC performance and functionality will be discussed at length in the forthcoming HVAC Research and Development Opportunity publication (to be published in 2020).

The scope of this report is limited to built-in or purpose-built solutions for HVAC, water heating, appliances, and refrigeration; in other words, it covers the hardware and/or software (i.e., the “technologies”) that must be installed on-site to allow equipment to provide greater grid value. As described in Section 1.2, the communications technologies and protocols as well as grid-side controls are not covered in this report.[19] Those technologies are of course also required, in addition to having capable equipment, to provide significant grid value.[20] For example, an HVAC system with variable-speed compressors can provide capacity modulation, but this will only provide substantive grid value if it is modulated based on a direct grid signal (utility or third-party control) or in-building controller signals that are based on grid-indicative parameters (electricity price, weather forecasts, etc.). In this section of the report, it is assumed that the connections and necessary control hardware (in-building or external) are in place for each technology to operate properly and the discussion here is focused on the specific HVAC, water heating, appliances, and refrigeration technologies that can enable or enhance grid value.

This report excludes technologies that only provide efficiency or other value, but no grid-flexibility capabilities in response to grid needs (see Section 3 for discussion of demand-side management strategies). Examples include:

- Tankless water heaters: Despite their efficiency value, they only operate when there is a hot water draw and therefore only provide grid flexibility via behavioral or controls changes.
- Self-powered natural gas equipment: They add resilience value by enabling operation during a grid outage (when paired with embedded energy storage), but do not on their own enable or improve flexibility for providing grid services.

2.1.1 HVAC

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. Figure 8 shows the annual load shapes for heating and cooling residential and commercial applications in the United States.

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[19] Off-site devices and controls are discussed in detail in the *Whole-Building Controls, Sensors, Modeling, and Analytics* report. Refer to Section 1 for information about that report.

[20] Technologies whose main benefit is energy efficiency may be considered an exception. Improved energy efficiency at peak times leads to a reduction in demand regardless of the ability to communicate with the utility systems. This is valuable to the grid, but it does not provide additional grid flexibility.

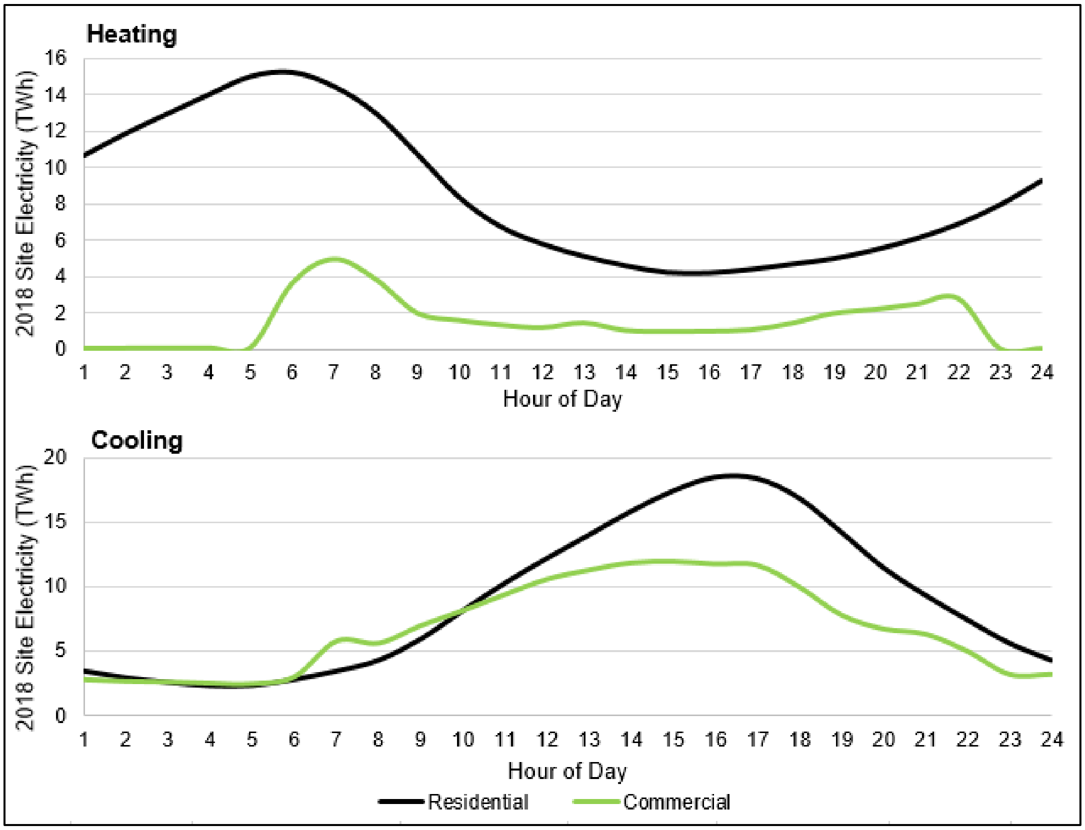

Figure 8. Load shapes for space heating and cooling[21]

The load shapes for space heating and cooling show peaks for both residential and commercial applications. The peak for heating tends to be in the morning, because the HVAC system must counter the lower overnight temperatures and the ramp up for the morning. Residential heating has an additional, smaller peak in the afternoon, as people return home and turn up the heat for a few hours before bedtime. Cooling demand tends to peak in the early evening for residential applications (indicating the need to cool the living spaces once people return to their homes) and in the early afternoon for commercial applications (as a result of the higher cooling load during the hottest hours of the day).

The duration over which the HVAC load can be reduced depends on the envelope design and thermal inertia of the building. Those buildings that employ advanced envelopes with high-performance windows and insulation and low outside-air infiltration can maintain comfortable indoor conditions for longer without operating the cooling equipment. See the *Windows and Opaque Envelope* report for additional discussion of the methodologies for improving envelope performance for providing grid value (refer to Section 1 for an overview of the GEB reports, including relevant links).

All buildings must maintain acceptable air quality through the ventilation system, even during load shedding or shifting. This is a standard function of HVAC systems in commercial buildings, but only an emerging consideration for residential buildings, because ventilation is generally only installed for new, ultra-tight-envelope homes; old homes with leaky envelopes are generally assumed to have sufficient air changes per hour

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[21] Data are generated using the Scout time-sensitive efficiency valuation framework as in Figure 4. Note that energy load shapes for the commercial sector do not currently account for scheduling diversity across the stock of a given commercial building type in a given region, which would yield smoother utility-scale load shapes than those shown in this report. Ongoing efforts to collect residential and commercial end-use load shape data that better represent this scheduling diversity (https://www.nrel.gov/buildings/end-use-load-profiles.html) will be incorporated in future iterations of the residential and commercial load shapes."

and do not have mechanical ventilation requirements. Figure 9 shows the annual load shape for commercial ventilation in the United States.

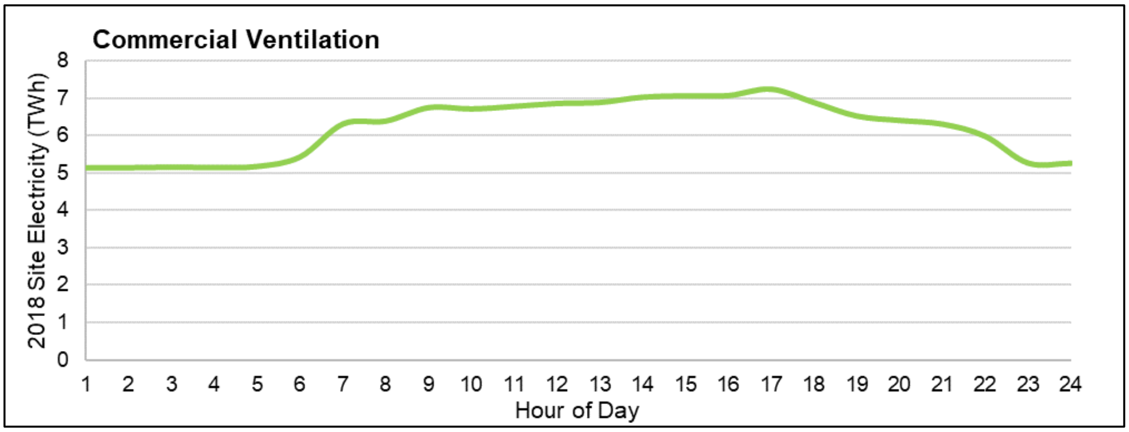

Figure 9. Load shape for commercial ventilation[22]

Commercial ventilation is characterized by a relatively flat load shape to maintain indoor air quality by introducing outdoor air to the building. Demand-controlled ventilation systems enable greater efficiency by reducing ventilation load when the building is unoccupied or at partial occupancy (determined based on monitored carbon dioxide [CO_2] concentrations). Demand-controlled ventilation or other advanced controls could be adapted to provide grid value by, for example, preventilating (load shifting) and closely monitoring air quality over the course of a curtailment period. The tighter the envelope, the shorter the duration for which the ventilation can be fully curtailed.

HVAC demand flexibility and associated value to the grid varies by climate, driven to a great extent by weather consistency and long-term predictability. For day-to-day value, cooling demand flexibility may be considered more valuable in hot climates and heating demand flexibility more valuable in cold climates. However, for atypical weather, the reverse could be true; for example, heating demand flexibility during an unexpected and long cold spell in the south (or cooling demand flexibility for a heat wave in the north) may have greater potential value to the grid than the day-to-day value because of the unexpected strain on the grid.

Table 2 profiles a selection of HVAC technologies that can be provide demand flexibility. This report does not contain discussion of specific GEB ventilation technologies because ventilation flexibility is either provided by an integrated HVAC solution (e.g., a rooftop unit) or via sensors and controls systems (for additional discussion, see the *Whole-Building Controls, Sensors, Modeling, and Analytics* report).

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[22] Data are generated using the Scout time-sensitive efficiency valuation framework as in Figure 4. Note that energy load shapes for the commercial sector do not currently account for scheduling diversity across the stock of a given commercial building type in a given region, which would yield smoother utility-scale load shapes than those shown in this report. Ongoing efforts to collect residential and commercial end-use load shape data that better represent this scheduling diversity (https://www.nrel.gov/buildings/end-use-load-profiles.html) will be incorporated in future iterations of the residential and commercial load shapes."

Table 2. State-of-the-Art GEB HVAC Technologies

HVAC #1: Smart Thermostats	
Overview	Smart thermostats offer features such as internet connectivity, advanced algorithm controls, and compatibility with home automation systems. Like regular thermostats, smart thermostats sense the conditions inside a building and control the attached HVAC equipment to maintain the target conditions (one thermostat per zone). Some communicate with a SHEMS, but communication with a commercial energy or building automation system (BAS) is less common because they are targeted to residential and light commercial applications. In this way, smart thermostats can serve as a less complicated alternative for SHEMS and BAS in the residential and light commercial market. Smart thermostats are usually designed for simplicity with intuitive app interfaces and do not offer the level of customization that BAS can offer. Smart thermostats offer the ability to introduce advanced controls for relatively simple HVAC systems. The smart algorithms are contained in the smart thermostat, which relays information about the set point and current temperature to the HVAC system. Future smart thermostats may be able to communicate more complex messages to the HVAC equipment, which can then itself make optimized decisions based on its own design and functionality (in which case both the smart thermostat and the HVAC system will have to be grid-interactive and follow a standard for communication of utility signals, room conditions, etc.). The *Whole-Building Controls, Sensors, Modeling, and Analytics* report provides additional detail on smart thermostat opportunities. Smart thermostats are also evaluated in Section 3 as part of the natural gas technology discussion (see technology NG#2) as they pertain to the natural gas grid.
Applicable Market	Smart thermostats are applicable to residential and light commercial use for retrofit and new construction applications. In larger facilities with BAS, smart thermostats are not as beneficial; in those cases, the BAS operates as a centralized control and communications platform while receiving information from simple zone sensors, so there is little benefit in adding more expensive smart technology to each zone in the form of a smart thermostat. Smart thermostats tend to provide the most benefit when attached to a forced air system; those systems can change the room temperature relatively quickly, which gives flexibility for the smart thermostat to tailor the set point according to need. Hot water and steam systems are slower to heat a room, so the thermostat cannot take advantage of sharp changes in temperature to maximize efficiency and comfort. Smart thermostats still provide benefits when used with non-forced-air systems, but those benefits tend to be less significant.
Status and Growth Potential	**Status:** Smart thermostats are readily available from many large, reliable manufacturers and are commonly part of utility efficiency rebate programs for their efficiency value and less frequently for their demand response capabilities. **Growth Potential:** They have seen a surge in popularity in recent years, driven at least in part by utility efficiency programs and relatively simple installation for existing buildings. Their main selling points have been the increased convenience of remote control and smart scheduling as well as the potential energy savings. The technology is well developed, though there may be opportunities for development in terms of cybersecurity, control algorithms, and interoperability with other on-site systems and with the utility control systems. Smart thermostats will play a central role in home automation and as a primary gateway to GEBs via direct communication with utilities and grid operators or alternatively via SHEMS, which are becoming increasingly popular. Smart thermostats with direct communications provide a relatively inexpensive solution to provide GEB features to HVAC equipment compared to more expensive BAS and SHEMS.

HVAC #2: Separate Sensible and Latent Space Conditioning	
Overview	HVAC systems control both sensible heat (temperature) and latent heat (moisture) in the building to maintain occupant comfort. Traditional vapor-compression cooling systems enlarge the evaporator, 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 on humid summer days. Liquid and solid desiccants, membrane dehumidifiers, and other A/C 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 high efficiency latent cooling stage to remove indoor humidity and maintain occupant comfort.
Applicable Market	This technology is applicable for residential and commercial space cooling systems. The latent cooling stage could be integrated into conventional HVAC equipment at the factory or installed as separate component in the field.
Status and Growth Potential	**Status:** Latent cooling systems, using solid and liquid desiccants or vapor-compression dehumidifiers, are commercially available for humid climates, particularly for commercial and industrial buildings. Researchers are exploring opportunities to incorporate desiccant wheels into conventional vapor-compression systems (Ling and Hwang 2018) as well as a variety of NVC cooling cycles (see cross-cutting technologies in Section 2.1.5 for CC#3: Non-Vapor-Compression Materials and Systems). **Growth Potential:** Further R&D is necessary to more closely integrate sensible and latent cooling stages and improve the operating efficiency, installed cost, and operational constraints such as size, weight, and maintenance that limit their adoption today. Furthermore, today's products are largely installed to reduce operating cost and peak demand and may not be optimized to provide grid flexibility.

HVAC #3. Liquid Desiccant Thermal Energy Storage	
Overview	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).[23] Regenerated liquid desiccants store energy chemically without the need for insulated containers, so storage durations can be very long if needed. While there are not expected to be any round-trip efficiency losses because the liquid desiccant is stored at room temperature, the efficiency of the system is dependent on the efficiency of the heating process used for desiccant regeneration. Whenever there is demand for dehumidification, the stored liquid desiccant can be pumped to a heat and mass exchanger (e.g., membrane module) without the need for additional energy input. HVAC systems with liquid desiccant TES also lend themselves to greater overall efficiency because removing the latent load from the vapor compression unit reduces the need for overcooling/reheating cycles to provide dehumidification and thereby also enables a reduction in capacity for the vapor compression system. Liquid desiccants absorb moisture from indoor air and then reject it outdoors via a heating cycle in a process known as regeneration (Ware 2013). Because cooling loads are typically highest when solar heat gain is highest, solar thermal is an effective way to provide the heat needed for regeneration. Advanced controls are required to determine when to charge or discharge the liquid desiccant TES. These controls would need to communicate either directly with the HVAC and liquid desiccant TES equipment, or with the equipment via a BAS. The system could be used in price-responsive behavior-driven load reduction (e.g., a critical-peak-pricing tariff), or for dispatchable demand response.
Applicable Market	Buildings in hot-humid regions or those with high internal humidity loads would see the greatest benefits from liquid desiccant TES. The technology could be applicable for residential and commercial buildings but would depend on the performance and cost of fully developed products. The primary benefit is to the utility in the form of peak load reduction; customers on tariffs that include demand charges or time-of-use (TOU) rates will benefit from lower utility charges.

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[23] Sensible heat is related to changes in temperature, while latent heat is related to changes in humidity.

HVAC #3. Liquid Desiccant Thermal Energy Storage	
Status and Growth Potential	**Status:** Liquid desiccant A/C systems have been demonstrated in the field, though there are currently no products commercially available. Liquid desiccant solutions can be corrosive and require specialized materials to achieve reliable long-term performance. In general, liquid desiccant TES is much less developed than TES for heating and cooling (see Section 2.1.5), so costs are much higher for these systems. **Growth Potential:** The overall system efficiency benefits provided by liquid desiccant TES may make it more attractive than TES and help promote faster growth. However, substantial changes in the system architecture (and potentially larger footprint) could limit potential adoption. Solutions that easily and cheaply integrate with rooftop units could help. The primary market for liquid desiccant TES will be hot, humid climates (e.g., Miami), but as costs come down, the south and broader eastern seaboard could be viable as well.

HVAC #4: Advanced Controls for HVAC Equipment with Embedded Thermostats	
Overview	HVAC equipment with embedded thermostats (HVAC-ET) operate without an external wall thermostat to provide control signals; all necessary sensors and control algorithms are built into the equipment itself or accessed by the equipment itself via a built-in communications device. Thus, the advanced controls for this equipment, including its connected capabilities, are also often built into the equipment itself. [24] This equipment category includes room air conditioners (A/Cs), portable A/Cs, packaged terminal A/Cs and heat pumps, and ductless minisplit A/Cs and heat pumps. Lacking smart thermostat connectivity, these technologies generally use Wi-Fi to communicate directly with grid operators or utilities. Demand response programs for this equipment category usually include signals to temporarily shut off the compressor and signals to change the set point to a less consuming temperature. Consumers can typically override controls as desired if comfort is more important than the financial incentive. HVAC-ETs are often paired with a mobile app that provides remote control functionality—this is typically the same mechanism that the utility uses for remote curtailment. This advanced functionality enabled by smartphone controls, such as scheduling and geofencing, is what is marketed to consumers. Only the most basic elements, however, are required by the utility for curtailment.
Applicable Market	Advanced controls for HVAC-ET are an additional feature for existing HVAC-ET. They can be used in any application where HVAC-ET is used. Given the usual small size of this equipment, the most common markets are the residential and the light commercial sectors. However, HVAC-ET is very versatile and commonly used in retrofit applications in old buildings, so the range of application extends beyond the residential and light commercial sectors.
Status and Growth Potential	**Status:** Multiple connected HVAC-ETs are already commercially available, and there are many manufacturers of connected appliances. Costs vary, but a review of a small selection of products online suggest a ~15% premium for connected room A/Cs versus nonconnected room A/Cs.[25] Many ductless heating/cooling products now have relatively expensive add-on controls packages that provide connectivity and could enable grid-interactive functionality, but none are known to currently have this technology. **Growth Potential:** Added premium features, like app-based controls, could promote growth for the high-end of the market. With enough cost reduction, perhaps through R&D, this technology could see more rapid adoption among a wider range of products, particularly as the minisplit market continues to grow in the United States—6% growth in 2018 (Turpin 2019).

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[24] The defining aspect of this type of equipment is the fact that it does not *require* an external thermostat to control it. For that reason, it cannot be assumed to be included in the smart thermostat technology, though some models can be controlled by a smart thermostat if desired by the consumer.

[25] GE lists its connected 8,000 BTU A/C unit at $229, while their standard 8,000 BTU unit sells for $199 at Walmart. For more details, see GE's listing at https://products.geappliances.com/appliance/gea-specs/AEC08LX and Walmart's listing at https://www.walmart.com/ip/GE-8K-BTU-Window-Air-Conditioner-with-Remote/158998939.

HVAC #5. Hybrid Evaporative Precooling for A/C	
Overview	Evaporative cooling can be combined with vapor-compression cooling to increase efficiency in low humidity regions. Typically, these systems are designed to limit water consumption while maintaining a high cooling efficiency. Packaged hybrid (evaporative and vapor-compression) cooling systems include controls to determine which method of cooling to operate and can employ various control strategies. In some cases, the vapor-compression system is used to provide all the cooling until the outdoor temperature rises above a predetermined set point, at which point the evaporative cooling system turns on to reduce the electric load. Hybrid systems that have sensors to monitor and analyze outdoor weather conditions can use these analyses to determine which cooling system to run. In either case, these systems can respond to a grid signal for curtailment by turning on their evaporative cooling modules, reducing the amount of electricity needed to run the compressor. Evaporative modules can also be added to existing vapor-compression systems for energy efficiency and grid flexibility. Evaporative modules can be controlled to balance efficiency with water consumption by, for example, delivering water (and reducing energy use) during curtailment periods. Communication between the evaporative module and the compressor is necessary to determine whether the module should be on or off, and the optimization of an algorithm for this control system is required to make the technology most cost-effective. This algorithm would need to consider the customer's preference for water use (and associated embedded energy use). Local water use could be a concern for some users or regions, but in general, water use for evaporative cooling can lead to a net reduction in water consumption when considering the fresh water consumed at power plants. The national weighted average (2003) for thermoelectric and hydroelectric water use is 2.0 gallon of evaporated water per kilowatt-hour of electricity consumed at the point of end use (Torcellini et al. 2003). This is compared to the cooling potential of evaporative cooling, which is ~0.4 gallons per kilowatt-hour.[26]
Applicable Market	Hybrid A/C-evaporative coolers are applicable to residential and commercial applications for new construction or as a replacement for old units, or an add-on module can be purchased to retrofit existing A/C units. They are most effective in dry climates, which is coincidentally where water use is often a major concern, so there is a need to understand how to better optimize energy use, water use, and associated economics.
Status and Growth Potential	**Status:** Several available products combine evaporative cooling and vapor-compression cooling for commercial and residential applications. Add-on evaporative cooling modules are also commercially available. **Growth Potential:** In relatively dry climates, evaporative cooling technologies provide a valuable, high-efficiency enhancement opportunity. Local water use could hinder adoption in some regions.

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[26] Conversion of the heat of vaporization of water (2,260 kJ/kg)

HVAC #6. Dual-Fuel HVAC Systems	
Overview	A dual-fuel HVAC system can provide curtailment by temporarily switching fuels. To provide meaningful value, however, the energy source requiring curtailment must be the lower-cost source and therefore be the one it operates using most of the year. For example, for it to provide electric grid value, it should be generally operating on electricity and then switch to the alternative fuel when there is a grid need. This report assumes that at least one of the energy sources is electricity. Example configurations could include: • [Heating] A residential fuel furnace paired with a ducted central electric heat pump—easily upgraded from commonly installed A/C-plus-furnace systems; • [Heating] A commercial heat pump rooftop unit plus furnace—easily upgraded from the common A/C-plus-furnace rooftop units • [Heating] A residential or commercial gas/propane/oil boiler paired with ductless heat pumps • [Cooling] An electric A/C or chiller paired with an absorption chiller or reversible heat pump. While the options are primarily focused on heating, cooling options that leverage gas-absorption or gas-engine cooling (last bullet above), are also potentially valuable. The current market for absorption equipment is essentially solely for large commercial applications, but emerging products are beginning to appear for residential applications. Dual-Fuel HVAC systems are also evaluated in Section 3 as part of the natural gas technology discussion (see technology NG#3) as they pertain to the natural gas grid.
Applicable Market	Dual-fuel HVAC can be applicable to all residential and commercial buildings. The highest grid-value market is from those systems that use delivered fuel (e.g., oil or propane) plus electricity, because the cost of the delivered fuel is high, driving them to operate on electricity primarily, and because use of delivered fuels does not impact electricity markets (see Section 2.1.4 for discussion of market interactions for natural gas). The low cost of gas today means that many potential target customers of dual-fuel systems will simply opt to run on gas continuously, negating any value for the electric grid. Duel-fuel systems can provide gas load shedding/shifting as well, but this may be conceptually more valuable as load curtailment as opposed to temporary fuel switching because of the interactive effects of the gas and electric markets. Equipment would likely be purchased by the building owner as an addition to existing HVAC technology or used in the construction of new buildings.
Status and Growth Potential	**Status:** Dual-fuel heating systems are already commercialized, most commonly as separate heat pump and furnace units,[27] but also as packaged units.[28] **Growth Potential:** Customers may be unwilling to purchase additional heating equipment without being able to enjoy the benefit of switching fuels based on TOU pricing, which is currently very limited among U.S. residential customers.

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[27] For more information, see: https://www.pickhvac.com/dual-fuel-heat-pump/.

[28] For example, Trane offers a packaged product: https://www.trane.com/residential/en/products/packaged-systems/xl16c-earthwise-hybrid/.

2.1.2 Water Heating

Water heaters are available in two primary configurations: tankless and storage. Tankless water heaters usually provide water on an on-demand basis; when hot water is requested, the water heater switches on and provides hot water. Storage water heaters heat the water inside a container and store it for later use.

Because of the on-demand nature of their operation, tankless water heaters have limited flexibility to provide grid services. To properly provide the customer function for which they are designed, tankless water heaters must be able to operate at the time of hot water demand, which greatly impairs their ability to provide load shifting benefits. This problem could be alleviated with the addition of a separate hot water storage solution, but this would negate some of the main benefits of tankless water heaters, which are the smaller footprint and the reduction in storage losses. For these reasons, tankless water heaters are not as readily suited to providing grid value as storage water heaters. Some manufacturers offer hybrid tankless water heaters with separate storage tanks that could provide some grid flexibility benefits, but these limited models have uncertain grid-interactive performance.

Storage water heaters can provide value to the grid because of their ability to store thermal energy, enabling them to decouple power demand from end-use consumption. This thermal storage is built into the equipment by design, unlike in the case of tankless water heaters. Through TES, storage water heaters can be controlled to shift demand away from peak times while still providing the same function to consumers.

Figure 10 shows annual load shapes for residential and commercial water heaters in the United States. Residential water heaters see the highest demand during daily morning and evening peaks, when residential electricity and gas usage are also often high. Commercial water heaters see the highest demand around the middle of the day, although there is some variation depending on the type of business (for example, restaurants often have greatest consumption around dinnertime).

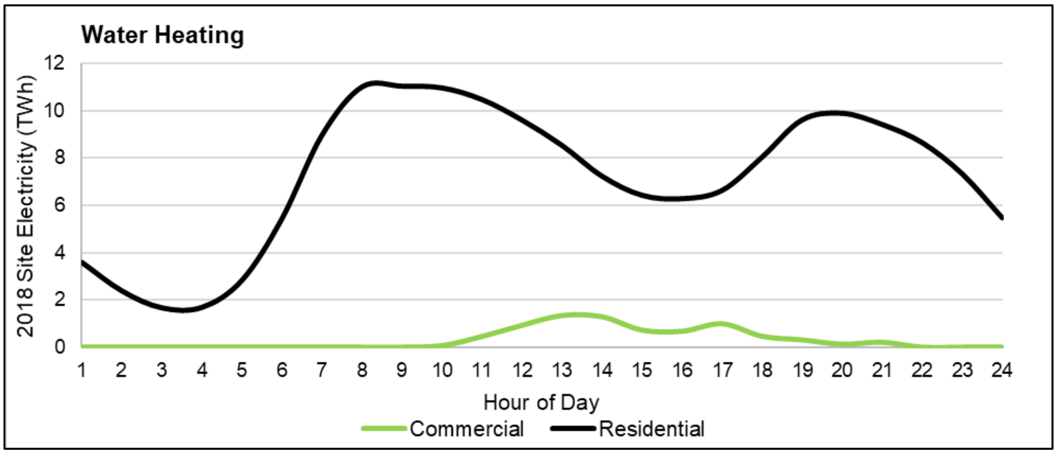

Figure 10. Load shapes for commercial and residential water heating[29]

Table 3 profiles a selection of water heating (WH) technologies that can provide demand flexibility.

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[29] Data are generated using the Scout time-sensitive efficiency valuation framework as in Figure 4. Note that energy load shapes for the commercial sector do not currently account for scheduling diversity across the stock of a given commercial building type in a given region, which would yield smoother utility-scale load shapes than those shown in this report. Ongoing efforts to collect residential and commercial end-use load shape data that better represent this scheduling diversity (https://www.nrel.gov/buildings/end-use-load-profiles.html) will be incorporated in future iterations of the residential and commercial load shapes."

Table 3. State-of-the-Art GEB Water Heating Technologies

WH#1: Water Heaters with Smart, Connected Controls	
Overview	Advanced water heater controllers (embedded or external) can provide multiple forms of value to the grid by leveraging the water heater's energy storage capabilities, depending on the algorithm that is implemented. Preheating during off peak periods (load shifting) to enable reduced or no power draw during the on-peak period (especially during annual peaks).[30] Preheating enables grid value with loss of functionality to a consumer. Load shedding can also be done for emergency curtailment by shutting down the unit during emergency events to mitigate grid stress. Similar strategies can also be applied to natural gas water heaters to reduce demand during peak gas network times. Frequency regulation can also be possible with electric resistance water heaters or heat pump water heaters (HPWHs) that operate on electric resistance given the right market rules via direct utility control of the unit.[31] Because water heater power consumption is not constant throughout the day, this service would only be available intermittently. This technology is not commercially available; preliminary conceptual design could be built on Oak Ridge National Laboratory's work to control HVAC systems for frequency regulation purposes.[32] Research at Oak Ridge National Laboratory focuses on using today's equipment with external controls, but the logic could be embedded into the equipment to enable plug-and-play functionality. Market evolution may also be required for this to be deployed, because only some markets have net-zero signals over set periods, which would presumably be required for water heater participation. For additional discussion of thermal storage (both for space and water heating), see Section 2.1.5. Water heaters with smart, connected controls are also evaluated in Section 3 as part of the natural gas technology discussion (see technology NG#4) as they pertain to the natural gas grid.
Applicable Market	This technology applies to any water heater with a storage tank, including storage water heaters, indirect water heaters, hybrid tankless water heaters (containing small storage tanks), and tankless coils (in boilers) connected to storage tanks. Utility demand response programs have generally focused on electric resistance storage water heaters because the controls are simple. HPWHs also have the potential to provide grid value, though with lower power use per unit, more are required to achieve the same grid flexibility as could be achieved with electric resistance water heaters. Gas-fired water heaters can provide load shifting. The technology is well suited for any new build or equipment replacement. The current economics will favor those customers for whom load shedding provides demand charge reductions and high-value energy savings for those on TOU rates. Currently, these are in place primarily for commercial customers only.
Status and Growth Potential	**Status:** Several grid-interactive water heaters are commercially available; some products are electric resistance water heaters that enable control of a second resistive element that can only be accessed by the utility, communicating via Wi-Fi.[33] Grid-interactive HPWH are also available.[34] Typical functionality is to preheat water (above safe output levels) and then uses a controlled-mixing valve to deliver water of the proper temperature.[35] In addition, there are multiple retrofit controls packages available for existing electric resistance water heaters that enable utility control.[36]

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[30] The higher temperatures in preheating are likely associated with slightly greater heat loss from the water heater tank, which could lead to an overall increase in energy consumption. However, a pilot program in Hawaii found no statistically significant differences in energy consumption between water heaters that used preheaters and a control group. For details, see https://aceee.org/sites/default/files/pdf/conferences/hwf/2015/3D-Rehberg.pdf.

[31] The kind of fast response required for frequency regulation may reduce the life of the vapor compression system in HPWHs, so their use is not recommended for frequency regulation. However, most HPWHs include electric resistance heaters, and those components can provide frequency regulation without the issues faced by the vapor compression system.

[32] For more details see Oak Ridge National Laboratory's site at: https://www.ornl.gov/news/grid-balancing-act.

[33] AO Smith offers a grid-enabled water heater with a second, utility-controlled heating element (https://www.hotwater.com/water-heaters/residential/electric/grid-enabled-residential-electric-water-heater-egt-80/). Sequentric and Battelle have developed an original equipment manufacturer control box that includes an additional utility-controlled element (https://sequentric.com/media/images/products/VC_Water_Heater_Information_Sheet.pdf).

[34] For example, Rheem's Builder Class Residential 50 Gallon Hybrid Electric Water Heater – see https://www.rheem.com/product/rheem-hybrid-builder-electric-water-heater-proh50-t2rh350bm/.

[35] This water heater was developed by and is manufactured by Steffes (Podorson 2016).

[36] Aquanta offers a water heater controller that can be installed on any electric resistance water heater and operated by a utility (https://aquanta.io/). PNNL has also developed a grid-friendly water heater controller that can be used for retrofit applications (https://availabletechnologies.pnnl.gov/technology.asp?id=287).

WH#1: Water Heaters with Smart, Connected Controls	
	Growth Potential: Grid-interactive functionality is becoming available on an increasing portion of available products and is expected to continue to grow. This is enabled by ANSI/CTA-2045 that provides clear articulation of grid-enabled requirements for manufacturers. Growth is further supported by the incorporation of ANSI/CTA-2045 into full product specifications, such as The Northwest Energy Efficiency Alliance's Advanced Water Heater Specification, which includes requirements for "Demand Response Features" based on the ANSI standard for tier's 4 and 5 (Optional for Tier's 1-3).[37]

WH#2. Dual-Fuel Water Heater	
Overview	A dual-fuel water heater can provide curtailment by temporarily switching fuels. To provide meaningful value, however, the energy source requiring curtailment must be the lower-cost source and therefore be the one it operates using most of the year. For example, to provide electric grid value, it should be generally operating on electricity and then switch to the alternative fuel when there is a grid need. This report assumes that at least one of the energy sources is electricity. The highest grid-value market is from those systems that use delivered fuel (e.g., oil or propane) plus electricity, because the cost of the delivered fuel is high, driving them to operate on electricity primarily, and because use of delivered fuels does not impact electricity markets (see Section 2.1.4 for discussion of market interactions with natural gas). Communication between these water heaters and the utility is required (typically with Wi-Fi). For customers that are enrolled in utility programs with TOU or critical-peak-pricing rates, advanced controls or algorithms are required to determine which source of fuel should be used. Dual-fuel water heaters are also evaluated in Section 3 as part of the natural gas technology discussion (see technology NG#5) as they pertain to the natural gas grid.
Applicable Market	Dual-fuel water heaters can be applicable to all residential and commercial buildings. The low cost of gas today means that many potential target customers of duel-fuel systems will simply opt to run on gas continuously, negating any value for the electric grid. Duel-fuel systems can provide gas load shedding/shifting as well, but this may be conceptually more valuable as load curtailment as opposed to temporary fuel switching because of the interactive effects of the gas and electric markets. Equipment would likely be purchased by the building owner as an addition to existing HVAC technology or used in the construction of new buildings.
Status and Growth Potential	**Status:** No known dual-fuel water heaters are commercially available, though one could be custom engineered by a knowledgeable contractor. As a result, this is a precommercial technology, but does not require any true R&D. **Growth Potential:** It is possible that hybrid gas-electric models will become more popular as more utility programs are developed that can provide the necessary financial incentives. High upfront costs will slow adoption at the residential level.

2.1.3 Appliances, Refrigeration, and Relevant MELs

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; because they run in finite cycles, the entire cycle can be shifted away from peak times 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 benefit from modulation or, in the case of refrigerators, load shifting careful precooling strategies to prevent damage to the contents.

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[37] The Northwest Energy Efficiency Alliance's Advanced Water Heater Specification states the following: "Units shall be configured and shipped with the capability of responding appropriately to Demand Response and grid emergency and efficiency messages over a standard communication protocol and hardware interface. Units to have communication port that operates in compliance with CTA 2045 (or equivalent open modular interface standard) with specific Demand Response signals such as shed, end shed and etc…." Full specification available at: https://neea.org/img/documents/Advanced-Water-Heating-Specification_181010_152257.pdf.

These various operating patterns make appliances a very heterogeneous equipment group where many different strategies may need to be employed to maximize grid value while reducing customer impact.

Figure 11 shows the annual load shape for residential refrigeration in the United States.

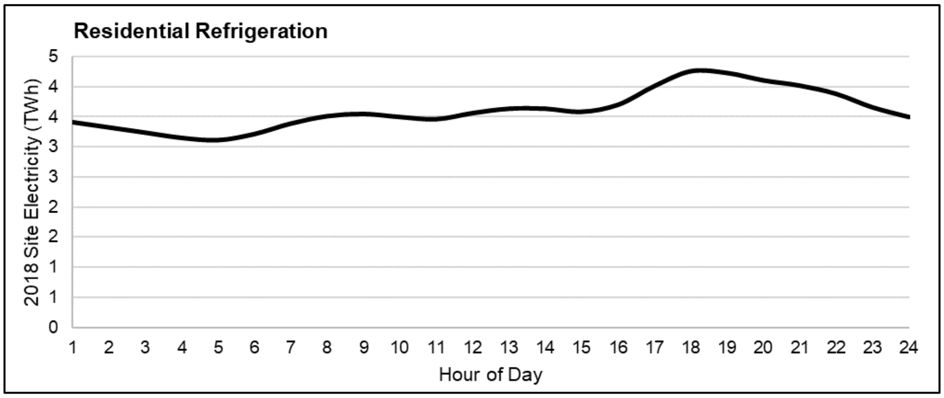

Figure 11. Load shape for residential refrigeration[38]

Refrigerators operate continuously to maintain a set temperature inside the refrigerated cavity, leading to the consistent load shape seen in Figure 11. The load increases slightly from the early morning to the early evening, before dropping back overnight. This is likely because people tend to open the refrigerator door most often during the day, and especially in the evening as they prepare dinner. Opening the door releases the cold air contained in the cavity, thus requiring the refrigerator to provide additional cooling to maintain the temperature inside the cavity.

In principle, refrigerators are very similar to A/Cs in that they run a vapor compression cycle to maintain the conditioned space cool while rejecting heat to the external environment. However, unlike A/Cs, refrigerators must continuously maintain the refrigerated cavity within specific temperature bounds to prevent food spoilage, so they cannot benefit as much from scheduled temperature setbacks. Further, refrigerators are typically located within a conditioned space, which means that their efficiency is consistent throughout the day, whereas A/C efficiency goes down as the ambient temperature increases during the hottest part of the day (coincident peak period).

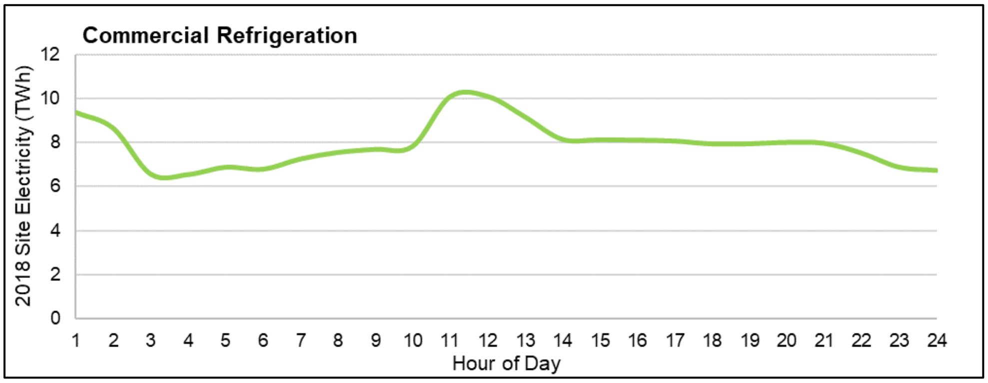

Figure 12. Load shape for commercial refrigeration[39]

Commercial refrigeration is a broad category involving many types of equipment, such as walk-in coolers, self-contained commercial refrigerators, ice makers, and food display cases. As with residential refrigeration (addressed

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[38] Data are generated using the Scout time-sensitive efficiency valuation framework as in Figure 4.

[39] Data are generated using the Scout time-sensitive efficiency valuation framework as in Figure 4. Note that energy load shapes for the commercial sector do not currently account for scheduling diversity across the stock of a given commercial building type in a given region, which would yield smoother utility-scale load shapes than those shown in this report. Ongoing efforts to collect residential and commercial end-use load shape data that better represent this scheduling diversity (https://www.nrel.gov/buildings/end-use-load-profiles.html) will be incorporated in future iterations of the residential and commercial load shapes."

in Section 2.1.3 with other appliances), commercial refrigeration equipment is tasked with maintaining the conditioned space within a specific temperature range always, leading to the relatively flat load shape seen in Figure 12.[40] The slight increases in demand during the early morning and midday hours reflect scheduled defrost cycles that prevent ice build-up on a cooler's evaporator coils with the introduction of humid air during restocking periods.

Figure 13 shows the annual load shape for residential drying in the United States.

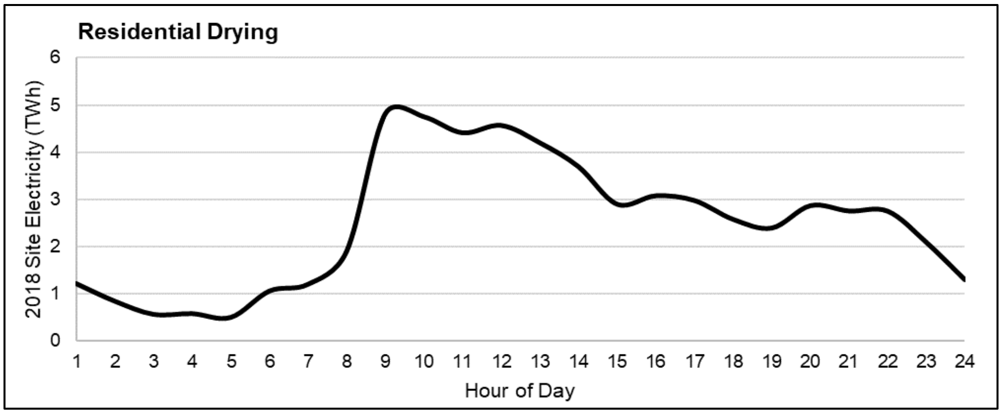

Figure 13. Load shape for residential drying[41]

Unlike refrigerators, clothes dryers run on a finite cycle, which is usually started manually by the user. Consequently, the load shapes primarily reflect the times when users are most likely to run this appliance (in the case of clothes dryers, Figure 13 indicates a preference for late morning and late afternoon usage). This is in contrast with the nearly constant load shape for refrigerators, shown in Figure 11. Other finite-cycle appliances, such as dishwashers and clothes washers, have similar consumption patterns to clothes dryers.

Possible strategies to provide grid value for appliances include delayed start for finite cycle appliances like dishwashers and low-power mode load shifting for continuous-operation appliances like refrigerators.

Table 4 profiles a selection of appliance (APP) technologies that can provide flexibility. Table 5 lists additional relevant MELs that could provide demand flexibility through efficiency, load modulation, thermal energy storage, and controllability based on external signals. Currently, there are few MELs commercially available that are designed specifically and independently to provide demand-side management beyond energy efficiency. However, many MELs are designed for use within a broader system (e.g., motors or pumps within HVAC systems) and their demand flexibility is driven primarily through their controls. Thus, the MELs listed here may not have the capabilities built directly into products. Their evaluation, including assigned ratings (see Section 3), reflects whether the potential exists to design or integrate existing, commercially available technologies into the MELs category to enable demand flexibility.

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[40] One potential exception is ice makers, whose energy consumption is highly variable during the day, depending on demand peaks.
[41] Data are generated using the Scout time-sensitive efficiency valuation framework as in Figure 4. A gas clothes dryer would be expected to have a similar load shape to an electric model.

Table 4. State-of-the-Art Appliance Technologies

APP#1: Modulating, Advanced Clothes Dryer	
Overview	Clothes dryers can be designed to run at lower power by modulating or staging the heating through simple controls. They can operate at lower temperature throughout the cycle (with longer cycle times) to improve efficiency, which enables more consistent, lower heat to avoid any localized overheating of garments, or they can be turned down on-demand for grid benefit. Electric resistance clothes dryers can easily accommodate modulation with upgraded controls. Heat pump clothes dryers, which use a vapor compression cycle to heat the drying air, would require more substantial upgrades to enable the compressor to operate at one or more slower speeds. These products tend to have longer cycle times than electric resistance units but are substantially more efficient.[42] (See additional discussion of modulating vapor compression in Section 2.1.5.) Natural Gas dryers can also be designed with modulating burner capabilities. In addition, all clothes dryers could provide load shifting through delayed start (akin to delayed start for dishwashers). Modulating, advanced clothes dryers are also evaluated in Section 3 as part of the natural gas technology discussion (see technology NG#6) as they pertain to the natural gas grid.
Applicable Market	Connected clothes dryers with advanced controls would be purchased as replacements for existing appliances in homes, or in construction of a new residential building. Most units are electric, but this could be applicable to natural gas dryers as well for gas load shedding/shifting. This technology can apply to both residential and commercial products, though the specific implementation may differ as the needs of the users will vary.
Status and Growth Potential	**Status:** Connected models are commercially available and are priced higher than nonconnected clothes dryers.[43] Several manufacturers also offer heat pump clothes dryers, though they do not currently have connected capabilities and are priced even higher.[44] Heat pump clothes dryers are more common in Europe but have seen very little adoption in the United States. Staged heating (but not fully modulating) is available on a small percentage of products on the market (limited to ENERGY STAR qualified products), and few, if any, existed before the introduction of the ENERGY STAR clothes dryer specification in 2015. Modulating or staged gas burners are readily available in many applications, but no dryers are known to use them at this time. **Growth Potential:** The longer dry times of heat pump clothes dryers have tended to reduce appeal to American customers, but recent developments such as hybrid heat pump clothes dryers have reduced drying times significantly.[45] This may also be instructive of the growth potential for modulating products, which would also increase cycle time (presumably only when required for curtailment purposes). Modulation and connected features of electric resistance products are likely to be well received among buyers of premium products.

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[42] For example, based on data available in the ENERGY STAR database, the average hybrid heat pump clothes dryer with capacity for 7.4 cubic feet consumes approximately 15% less energy than its electric resistance counterpart of same size; the average nonhybrid heat pump clothes dryer with capacity for 4.1 cubic feet consumes approximately 55% less energy than its electric resistance counterpart. The ENERGY STAR database is available at https://www.energystar.gov/productfinder/product/certified-clothes-dryers/details/2332281.

[43] AJ Madison lists the Whirlpool WED9620HW connected dryer at $1,254.10 (https://www.ajmadison.com/cgi-bin/ajmadison/WED9620HW.html), while it lists the Whirlpool WED6620HW (same capacity) at $949 (https://www.ajmadison.com/cgi-bin/ajmadison/WED6620HX.html).

[44] Reviewed.com lists the MSRP of Whirlpool's heat pump dryer at $1,699 (https://www.reviewed.com/laundry/content/whirlpool-duet-wed99hedw-heat-pump-dryer-review).

[45] Initial tests cited by the Super Efficient Dryer Initiative indicated that the drying time was twice as long for European heat pump clothes dryers compared to North American electric resistance clothes dryers (for details, see https://www.energystar.gov/ia/partners/pt_awards/SEDI_Fact_Sheet_H.pdf), which means they took 100% longer to conclude the drying cycle. Based on more recent data from the ENERGY STAR database, the difference has dropped to about 10% for hybrid clothes dryers, while for nonhybrid clothes dryers it varies between 15 to 100%. These numbers are examples and may vary depending on the specific models compared.

APP#2: Advanced Dishwasher/Clothes Washer Controls	
Overview	Advanced dishwasher and clothes washer controls can enable grid-interactive operation with minimal impact on customer usability. The controls are most likely to be embedded in the product itself, but could also be deployed via external controls, such as a mobile app or home internet-of-things controller/hub. These appliances can delay the start of their cycle until off-peak periods or until a utility-signal indicates the end of the curtailment period. This feature would require a customer override option. This technology requires controls that consider consumer preferences for the scheduling of their dishwasher and clothes washer use. For example, delaying the start of a clothes washer until 3 a.m. and having wet clothes sit in the washer until the user wakes up at 7 a.m. may be unacceptable to consumers. Combined clothes washer-dryer systems that start the drying cycle without input from the user could be used to avoid this usability issue.
Applicable Market	Connected appliances with advanced controls would be purchased as replacements for existing appliances in homes, or in construction of a new building. This technology can be deployed in both residential and commercial equipment, though the specific implementations may differ as the needs of the users will vary.
Status and Growth Potential	**Status:** Products with advanced/connected controls are commercially available. **Growth Potential:** A brief review of online product pricing suggests that some may even be available at no added cost compared to unconnected products.[46] However, the added hardware and software required for these products suggests that the lack of price premium is a marketing decision as opposed to a cost-based decision. The financial value for grid services per unit is expected to be low, which could impact payback.

APP#3: Advanced Residential Refrigerator/Freezer Controls	
Overview	Advanced refrigerator and refrigerator/freezer controls can enable grid-friendly operation with little to no impact on customer usability. Example functionality could include: • **Low-operation mode:** Upon receipt of a grid signal, or to provide scheduled peak load reductions (e.g., for TOU rates), connected refrigerators could shut off the compressor and anti-sweat heaters, thus stopping the unit from holding the set point; functionality could be impacted in long curtailment periods if the compartment temperatures increase too far (e.g., thawing of frozen foods). • **Defrost cycle delay**: If the compartment temperature cannot be left to fully float during the demand response event, the refrigerator can continue to use the compressor on a limited basis but delay the defrost cycle until the grid need has passed. • **Freezer precooling**: Prior to a curtailment period or for scheduled peak load reduction, the controls could overcool the freezer compartment then modulate the airflow from the freezer to the refrigerator space via an electronic damper to prevent freezing of the refrigerator compartment. Although some efficiency loss is expected from maintaining the freezer temperature below typical levels, this loss can be minimized by limiting the hours at overcooled temperatures. Because of food safety concerns, the controls need to ensure that temperatures are maintained within reasonable specifications. As residential refrigerators are a plug-and-play product, this technology is best executed as an embedded enhancement, but it could also be deployed via external controls, such as a mobile platform or home internet-of-things controller/hub.
Applicable Market	Connected residential refrigerators (or associated external controls) would be purchased for use in all types of homes and businesses, either in new construction or as a replacement for an old refrigerator. Residential Energy Consumption Survey data suggest that refrigerators are found in almost all

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[46] Appliances Connection lists the Maytag MHW8630H Smart Washer (https://www.appliancesconnection.com/maytag-mhw8630h.html) at $1119.10; the Maytag MHW8200FW washer, which has a similar capacity, is listed at the same price (https://www.appliancesconnection.com/maytag-heritage-mhw8200fw.html#specs).

	residences (117.4 million of 118.2 million) and are constantly plugged in, making them good candidates for providing grid value (Residential Energy Consumption Survey 2015).
Status and Growth Potential	**Status:** Models are commercially available and are typically priced about 15% higher than nonconnected premium models and about 75% higher than nonpremium models.[47] **Growth Potential:** The cost premium will hinder adoption, though the introduction of connected products that do not also contain other premium features could be substantially cheaper than the premium products. The financial value for grid services per unit is expected to be low, which could impact payback.

APP#4: Advanced Controls for Commercial Refrigeration	
Overview	Advanced commercial refrigeration controls (embedded or external) can enable grid-friendly operation with limited impact on operations. Example functionality could include: • **Low-operation mode:** Upon receipt of a grid signal, or to provide scheduled peak load reductions (e.g., for TOU rates), connected refrigeration equipment could shut off the compressor and anti-sweat heaters, which would stop the unit from holding the set point; functionality could be impacted in long curtailment periods if the compartment temperatures increase too far. • **Defrost cycle delay:** If functionality must be maintained, the equipment can continue to use the compressor but delay the defrost cycle until the grid need has passed. • **Freezer precooling:** In anticipation of a curtailment period, the set point on freezers can be lowered, which can allow for compressors to be turned off during periods of high demand. Although some efficiency loss is expected from maintaining the freezer temperature below typical levels, this loss can be minimized by initiating precooling as close as possible to the beginning of peak hours. These functionalities can provide additional benefits by staggering their operation across multiple refrigerated display cases, compressor racks, etc., to achieve lower peak demand. For example, the controls could stage the defrost cycles, such as delaying the start of defrost cycles for one display case until the end of the defrost cycle for another. Because of food safety concerns, the controls that operate this equipment would need to ensure that temperatures do not drift outside of the required specifications for the application. Temperature specifications are largely dependent upon the type of food and the type of refrigeration equipment. The U.S. Food and Drug Administration mandates that refrigerated food must be kept at 41°F or below, and frozen products must be kept at 0°F or below (U.S. Food and Drug Administration 2017). Further, changing temperatures of frozen foods can impact the consistency of the food and without careful monitoring can degrade food quality.
Applicable Market	Advanced controls for commercial refrigeration can be installed as a retrofit on existing refrigeration equipment (packaged or nonpackaged products) or as embedded controls in new products.
Status and Growth Potential	**Status:** Although commercial refrigeration controls that enable grid-interaction have been field tested successfully (Hirsch et al. 2015), there are no refrigeration systems with these controls embedded that are commercially available. This does not account for external controls available from original equipment manufacturers or demand response providers. **Growth Potential:** Commercial refrigeration is a large load in the United States and could be used for grid services at relatively low cost compared to other end uses, suggesting high growth potential. Some temperature-sensitive applications (e.g., medical refrigeration) may find curtailment without supplemental storage to be an unacceptable risk, but most applications do not face this challenge.

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[47] A 28 cubic foot connected Samsung refrigerator costs $3,499.20; a premium Samsung model of the same size costs $3,099.00 and a nonpremium model of that size is listed at $1,999.00. For more details, see: https://www.samsung.com/us/compare/#category/N0002401/products/RF28NHEDBSR%2FAA,RF28HMEDBSR%2FAA,RF28JBEDBSG%2FAA.

Table 5. Relevant Miscellaneous Electric Loads

Additional Miscellaneous Electric Loads	
APP#5: MELs: Motors	• Examples include fans, pumps, small kitchen appliances, and refrigeration. For the most part, these motors are controlled via their associated system (e.g., a hot water heating circulation pump is controlled by the heating system).
APP#6: MELs: Water Circulation	• Examples include pool pumps, boiler pumps, condensate drainage pumps, spa/hot tub pumps. These products may be considered a subset of APP#4, because they all are operated via a motor.
APP#7: MELs: Water Heating	• Examples include portable electric spas and pool heaters. Many of the same attributes apply here as described for water heaters in Section 2.1.2.
APP#8: MELs: HVAC	• Examples include dehumidifiers, ceiling fans, furnace fans, and kitchen ventilation. Because these are all small loads compared to central HVAC, they are assumed to be connected and controlled via SHEMS.
APP#9: MELs: Refrigeration	• Examples include laboratory refrigerators and freezers, coolers and cooler-refrigeration combination products. Although not as common as other refrigeration products, they tend to have higher consumption and therefore greater potential (per unit basis) to provide some grid services.

2.1.4 Related Natural Gas Technologies

Natural gas technologies can also provide grid (natural gas and electric) flexibility; this report considers three primary categories of natural gas (NG) technologies based on the natural of their grid value:

- **NG Type 1: Combined heat and power (CHP)**—Grid flexibility is provided via power generation, a unique and highly valuable characteristic, which can serve on-site loads or export to the grid depending on grid needs and local demand. Thermal output can be used on-site to offset other thermal loads or can be rejected to the environment when electric demand (on-site or grid) causes thermal overproduction relative to thermal demand. CHP systems also provide unique value among all other technologies in this report for resilience purposes. Their ability to operate independent of the electric grid to provide electric and thermal output makes them especially attractive in areas prone to electricity disruptions or natural disasters.
- **NG Type 2: Gas-fired variants of electric technologies**—Grid-flexibility is provided by shifting load to off-peak times. Value to the natural gas grid comes from direct curtailment of gas loads, whereas value to the electric grid comes from direct curtailment of associated electric loads, such as furnace fans and boiler pumps.
- **NG Type 3: Duel-fuel systems**—Grid-flexibility is provided by switching between fuels for some or all of the load if the grid operator of the in-use fuel requires curtailment. With this strategy, customer utility is maintained unless load on both fuels is simultaneously shed.

Natural gas HVAC and water heating technologies can be paired with energy storage systems to provide resilience value in the event of power disruptions. Independent or embedded energy storage systems, or self-powering capabilities can be leveraged to power electronic components such as controls, fans, and pumps. Although electric systems could do the same, the energy storage requirements for the same resilience value would have to be substantially larger and more costly. CHP with black-start capabilities provides this value in a single package, uniquely differentiating it from the other technologies in this report.

Table 6 profiles Natural Gas (NG) Type 1: CHP. Section 3 further evaluates NG Type 2 and NG Type 3 technologies that are profiled in prior subsections (Section 2.1).

Table 6. State-of-the-Art Natural Gas Technologies

NG#1: Building-Scale CHP	
Overview	Many large industrial, healthcare, and education facilities satisfy their electricity and thermal energy loads using on-site CHP or cogeneration systems. Using natural gas or other fuel sources, CHP systems capture wasted heat from the electricity generation system (e.g., engine, turbine, fuel cell) to satisfy space, water, and process heating loads. These large CHP systems (>1 megawatt-electric) can offer operating cost benefits compared to the consumption and demand charges from grid-tied electricity, particularly for campuses with significant year-round heating demand and on-site operations and maintenance staff. In addition, many facilities have absorption chillers that can utilize the heat production in summer months to satisfy space cooling demands and TES systems to shift the generation of chilled or hot water to off-peak periods. Several manufacturers and technology developers offer smaller micro-CHP (mCHP) systems suitable for a wider range of residential (1–10 kW) and commercial building applications (50–500 kW). Research efforts such as the Advanced Research Projects Agency–Energy (ARPA-E) Generators for Small Electrical and Thermal Systems (GENSETS) program has focused on the development of mCHP systems for single-family residential homes (e.g., 1 kW systems). Smaller mCHP systems are less common than the larger campus-sized CHP systems because of relatively higher installation and operating cost ($/kW basis) and longer project development and interconnection timelines than traditional methods (e.g., water heater and grid-tied electricity). Further research is needed to improve load following, part-load efficiency, and manufacturing cost to better enable mCHP technologies. Although primarily designed to serve the campus or building energy loads, CHP and mCHP systems can also provide flexibility benefits to the wider grid network. Many larger CHP operators 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 (DOE 2018a). 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). To support greater integration of CHP systems and electricity networks, DOE AMO has funded several R&D projects to develop flexible CHP systems capable of electricity supply, frequency regulation, reserve, and other grid services (DOE 2018b).
Applicable Market	CHP systems are common for industrial facilities and large healthcare, education, and other campuses with significant year-round electricity and heating demand. While less common, smaller mCHP systems can be attractive for lodging, healthcare, and multifamily buildings because of their significant year-round hot water loads. Most CHP systems are designed to offset grid-supplied electricity as well as space and water heating loads from gas-fired boilers, water heaters, and other systems.
Status and Growth Potential	**Status:** Both CHP and mCHP systems are commercially available in the United States today for long-term building operators where local conditions provide attractive economics. With support of DOE AMO and ARPA-e (GENSETS)[48], researchers are developing new CHP systems with improved generation components, power electronics and control systems, and cost-effective designs for small applications. **Growth Potential:** Because CHP systems use natural gas to generate on-site electricity, the relative price of grid-supplied natural gas and electricity, known as spark spread, has a significant impact on project economics. In addition, many utility energy efficiency programs provide incentives for CHP systems, and some states allow net metering and participation in grid services markets.

2.1.5 Cross-Cutting

Table 7 profiles a selection of cross-cutting (CC) technologies that can provide demand flexibility across more than one of the end-use areas covered by this report, including HVAC, water heating, appliances, and refrigeration.

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[48] For more information, see: https://arpa-e.energy.gov/?q=arpa-e-programs/gensets.

Table 7. State-of-the-Art Cross-Cutting Technologies

CC#1: Thermal Energy Storage	
Overview	TES allows HVAC and refrigeration systems to be more flexible with their power draw from the electric grid and/or natural gas network. This report covers all TES technologies that are either stand-alone products or embedded within HVAC or refrigeration equipment. Additional TES opportunities exist for systems that are integrated into the building envelope; for additional information, refer to the *Windows and Opaque Envelope* report. This technology does not include on-site or network storage of fossil fuels. The thermal storage medium can be regenerated during nonpeak hours, stored, and then discharged at any point throughout the day for daily load shedding. With appropriate controls, thermal storage can be used more strategically in other behavioral, price-driven curtailment scenarios or for emergency/economic demand response. Thermal storage is also valuable for applications where temperatures must be maintained precisely, which would disqualify precooling as an option. In its most simple form, passive TES systems can consist of larger thermal mass and/or better insulation to leverage thermal momentum to ride-out grid events. Among actively managed systems, water/glycol mixtures are a common medium used for thermal distribution between the thermal storage (e.g., ice vats) and the building's thermal distribution system. The fluid may be either distributed directly throughout the building in a chilled or hot water loop or be passed through a heat exchanger in the building's central conditioned supply air duct. Potential configurations include: • Heating only: Ceramic bricks, water, or phase change materials are preheated using a wide range of heat sources (e.g., gas/oil/propane burner or hot water boiler, electric resistance coil, or vapor compression heat pump) • Electric cooling only: Ice slurries or other phase change materials are precooled (or frozen) using a vapor compression cycle and stored in large insulated vats • Natural gas absorption cooling: Separate storage of the sorbent and refrigerant in the middle of the chiller cycle provides for long-term, no-loss, energy storage capacity. • Envelope-integrated, passive or active (heating or cooling): Covered in depth in the *Windows and Opaque Envelope* report. Because of losses to surroundings, the round-trip efficiency of typical thermal energy systems is approximately 80%, but it varies by application (Guess 2018; Energy Storage Association 2019). Advanced controls are required to determine when to charge or discharge the TES (except for passive systems).
Applicable Market	TES as part of an HVAC system provides grid value at both the residential and commercial level, though adoption at the residential level may be difficult because of high installation costs. The equipment would be purchased by the end user for new construction, replacement of an old heating/cooling system, or retrofit applications. Customers on tariffs that include demand charges or TOU rates are likely to be the most financially motivated adopters. TES for commercial refrigeration is primarily applicable to any large refrigeration operation; cold storage and supermarket refrigeration are the primary applications. Small applications (e.g., walk-in coolers/freezers) may also be applicable, but with different configurations.
Status and Growth Potential	**Status:** There are only a few commercially available products for TES systems. For HVAC, there is one prominent manufacturer of ice energy storage for commercial chillers and one for residential and commercial A/C systems, as well as only one prominent manufacturer of a TES heating system (which uses ceramic bricks). [49,50,51] For refrigeration, one manufacturer offers a storage system for supermarkets and cold storage facilities, while another offers one for cold storage.[52,53]

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[49] Calmac, a subsidiary of Ingersoll Rand, is a prominent U.S. manufacturer of TES for chillers. For more information, see: http://www.calmac.com/icebank-energy-storage-benefits.

[50] Ice Energy manufactures the Ice Bear, a TES system for air conditioning units. For more information, see: https://www.ice-energy.com/technology/.

[51] Steffes manufactures heating systems that incorporate ceramic bricks as a form of TES. For more information, see: http://www.steffes.com/electric-thermal-storage/.

[52] Axiom Energy manufactures a TES solution marketed towards both supermarkets and cold storage facilities. For more information, see: http://www.axiomexergy.com/solution.html.

[53] Viking Cold offers a TES solution for cold storage facilities. For more information, see: https://www.vikingcold.com/cold-storage/.

CC#1: Thermal Energy Storage	
	However, ice-based TES for HVAC has been available for decades; more than 1 gigawatt of TES is already installed around the world (CALMAC 2019). For all building applications, further R&D to improve the energy density, cost, and other characteristics, perhaps using alternative storage mediums, can increase the attractiveness of TES systems integrated with end-use appliances. **Growth Potential:** Space requirements for TES could provide to be a challenge for adoption as large-scale systems are unlikely to fit into the same footprint as existing equipment. Small add-on packages have been proven for certain types of customers and could be attractive with lower risk than large scale systems for early adopters. TES in large-scale commercial refrigeration also competes with the thermal mass of the refrigerated goods—in other words, a do-nothing strategy that is enabled by the refrigeration system's ability to curtail without substantive change in temperature for multiple hours.

CC#2: Modulating Capacity Vapor Compression	
Overview	Most vapor compression systems do not modulate and instead cycle on and off to maintain temperature. This includes A/Cs, heat pumps, dehumidifiers, HPWHs, and heat pump dryers. Modulating equipment enables greater value to the grid because of the greater precision of controls it affords and the increase in efficiency gained by running the unit continuously at low speeds versus on/off at full capacity. This increase in efficiency is reflected in the seasonal efficiency ratings for variable-speed HVAC, which tend to be greater than for single-speed HVAC.[54] Instead of raising the set point or turning the unit off completely (which can reduce occupant comfort), modulating HVAC can be ramped up and down as required for the grid. Therefore, it can provide much more localized ancillary services to improve hosting compacity for intermittent DERs. Nonmodulating products also can provide ancillary services, but the binary operation limits the load following capabilities on a hyper local level (e.g., single home or single street/neighborhood level). It is important to note that the reduction in capacity is not proportional to the reduction in power, with efficiency often improving when the output capacity is reduced.[55] This means that with a large network of connected HVAC systems, utilities can reduce demand to a greater degree than the associated impact on occupant comfort. There are several technologies that can be used to modulate the power draw of HVAC equipment. Variable speed drives are useful for powering motors in larger commercial systems, while modulating heat pumps and electrically commutated motors are more effective in residential or light commercial systems. Advanced control systems are also required for operation of modulating HVAC technologies.
Applicable Market	Applies to all commercial and residential HVAC systems. Although certain modulating technologies are better suited for certain applications, they can be used in equipment at both the residential and commercial level. Equipment would be purchased by the building owner as a replacement for existing equipment.
Status and Growth Potential	**Status:** HVAC products with modulation capabilities are widely available. These technologies are more expensive than their nonmodulating counterparts, which has limited modulating HVAC equipment to premium efficiency markets. R&D to improve cost-effectiveness and to help understand value and impact of modulation versus cycling in the context of GEBs will help improve market attractiveness. **Growth Potential:** Because of the added cost of modulating functionality, these products are generally limited to premium products currently. With cost reductions, the technology could be introduced on a wide range of products and thereby lead to increased production volumes (and further cost reductions).

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[54] The seasonal efficiency depends on many factors other than the compressor and motors, so modulating equipment can have lower seasonal efficiency than nonmodulating equipment depending on the specifics of the design. In most situations, however, modulating equipment can achieve higher seasonal efficiency than nonmodulating equipment. For example, Carrier residential modulating heat pumps can reach up to 20.5 SEER, while nonmodulating designs are limited to 16 SEER. For details, see https://www.utcccs-cdn.com/hvac/docs/1010/Public/04/01-825-094-25.pdf.

[55] As an example, the average cold climate heat pump listed in the Northeast Energy Efficiency Partnerships (NEEP) database in 15% more efficient at minimum capacity than at maximum capacity, when compared at an outdoor temperature of 17 ºF. The NEEP database is available at https://neep.org/initiatives/high-efficiency-products/emerging-technologies/ashp/cold-climate-air-source-heat-pump.

CC#3: Non-Vapor-Compression Materials and Systems	
Overview	NVC technologies are a series of space cooling and refrigeration systems that use unique properties of specialized materials or alternative system designs that do not use the traditional vapor-compression cycle. Solid-state NVC 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 NVC 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 NVC technologies could offer grid-interactivity benefits through modulating capacity, separate sensible and latent cooling, and energy storage capabilities: • Modulating capacity: Many NVC technologies have a high degree of capacity control by varying the speed of specific components (e.g., fan, pump, and other motors) or electrical input to solid-state cooling materials. During peak events, the systems could operate at lower capacity or cycle at different levels to achieve aggregate load shedding or modulation. • Separate sensible and latent cooling: Some NVC technologies (e.g., membrane, liquid desiccant) remove moisture from supply air without changing its temperature, enabling separate control for sensible and latent cooling. Operating latent cooling systems independently during peak demand periods can maintain occupant comfort in humid regions with less energy consumption. • Energy storage: Several NVC technologies (e.g., magnetocaloric, thermoelastic, liquid desiccant) use hydronic distribution systems, which can provide a form of short-term thermal storage in the piping or could connect with more traditional thermal storage systems. Some solid-state NVC technologies (e.g., thermoelectric, electrocaloric) can serve as battery-powered personal comfort devices to offset the need for larger, centralized cooling systems and provide grid flexibility.
Applicable Market	Researchers are developing NVC technologies for most residential and commercial space cooling and refrigeration applications, and some can also provide space and water heating capabilities. Nevertheless, each NVC technology will only be relevant for a subset of building applications because of the capabilities, temperature lifts, efficiencies, and operational characteristics of the cycle. Most NVC systems are designed for replacement of conventional appliances, although some may supplement existing systems (e.g., personal comfort devices, latent cooling stages).
Status and Growth Potential	**Status:** Many NVC technologies are available today for specialized applications (e.g., wine coolers, small refrigerators, and laboratory freezers use thermoelectric, Stirling, and absorption refrigeration systems). Most NVC technologies require additional R&D to meet the cost, efficiency, and performance of conventional HVAC&R systems and explore grid flexibility capabilities. BTO has supported NVC technology development through numerous R&D projects[56] based on their energy efficiency potential and the ability to use working fluids with low or no GWP (e.g., helium, salts, water). **Growth Potential:** NVC technologies, with sufficient R&D, have the potential to displace a substantial portion of the existing vapor-compression market, though early adoption is expected to be through small capacity, and small volume or niche products. The functionality from a user's perspective does not change, enabling an easy transition to NVC. No products are expected to be retrofit add-ons to existing systems and instead will be purchased as new packaged systems.

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[56] For more information on the HVAC/Water Heating/Appliance subprogram and projects, see: https://www.energy.gov/eere/buildings/hvac-water-heating-and-appliances.

3 Evaluation of Technologies

3.1 Technology Evaluation Criteria

In this section, the identified technologies are evaluated based on their ability to provide grid services (energy, capacity, contingency reserves, frequency regulation, ramping services, and non-wires alternatives).[57] In general, building technologies can provide these grid services through demand-side management strategies:

1. **Efficiency:** the ongoing reduction in energy use while providing the same or improved level of building function.[58]
2. **Load Shed:** the ability to reduce electricity use for a short time period and usually 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.

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.

Energy efficiency and demand response are the most mature and established demand-side management resources in buildings. In addition to overall energy savings, efficiency plays an important role in supporting grid reliability by decreasing peak demand and easing strain on the transmission and distribution system. Demand response is the main form of demand flexibility used today; however, it is fairly limited in scope. Most demand response programs are generally focused on reducing peak demand through shedding or shifting, through direct load control (by utilities/demand aggregators), or through behavioral load control programs in which utility customers make a decision to reduce their load in response to price signals. In large commercial buildings, load shedding and shifting may also be used for peak demand reduction to avoid demand charges.

Technologies that must maintain a certain set point, such as heating, cooling, water heating, and refrigeration, must bring the controlled conditions back to the set point after being curtailed. For that reason, those technologies often offer load shedding only in combination with load shifting. For example, a room A/C may respond to a curtailment signal in the following way:

1. The room A/C receives a signal to shed load during the summer peak;
2. The room A/C shuts itself off or increases the set-point temperature of the room to reduce consumption over the duration of a curtailment period;
3. Once the curtailment period is over, the room A/C reverts to the original set-point temperature, running for an extended period to bring the room back to the set temperature.

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[57] Voltage support is not included here; lighting/electronics are unlikely to provide this service.

[58] This would have the greatest impact for the gird during high-cost periods and minimize utilization of costly generation resources.

In such a scenario, the room A/C would shed load during step 2 by not running or running less during that time, but in step 3, it would increase the load at the end of the event to bring the room from a higher temperature back to the original set temperature (i.e., load shifting).

Alternatively, for precooling/heating, the equipment increases consumption prior to the curtailment period to allow the controlled conditions to remain acceptable during the period. In such a scenario, approximately the same amount of cooling/heating is still provided, but it is moved within the day. For A/Cs and heat pumps, the total energy consumption may be lower or higher during such a load shift relative to normal operation depending on the outdoor temperature at the time of the precooling/heating. For example, with an A/C, if the outdoor temperature is lower during the precooling period than during the curtailment period, the system will operate more efficiently (e.g., higher energy efficiency ratio) and result in lower overall energy consumption.[59]

In addition to peak demand reductions, a grid-interactive technology may also be able to help regulate power quality, provide contingency reserves, provide ramping services, or help avoid renewable energy curtailment.

Table 8 outlines requirements needed to provide each of these grid services, including the response time, load change, duration of event, event frequency, and other relevant requirements. These requirements inform the evaluation of the technologies in the following section.

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[59] The exact effect of precooling/heating on overall energy consumption depends on several variables, such as the outdoor temperature, the characteristics of the building envelope, the timing of the curtailment period, and the variation of equipment efficiency with time. Compared to a regular day, the overall energy consumption during a day with precooling/heating may increase, decrease, or remain constant depending on how these variables combine for each specific building.

Table 8. Mapping Demand-Side Management in Buildings and 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 Transmission and Distribution: Non-Wires Solutions	Persistent reduction in load. Interval data may be needed for M&V purposes. This is not a dispatchable service.	Typical duration	Continuous
			Load change	Long-term decrease
			Response time	N/A
			Event frequency	Lifetime of equipment
Load Shed	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 Transmission and Distribution: 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
Load Shift	Generation: Capacity Transmission and Distribution: 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 type of load shifting is not a dispatchable service but can be indicated through TOU pricing.[60]	Typical duration	2 to 4 hrs
			Load change	Short-term shift
			Response time	N/A
			Event frequency	Daily
Modulate	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.[61]	Typical duration	Seconds to minutes
			Load change	Rapid increase/decrease
			Response time	Seconds to minutes
			Event frequency	Continuous

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[60] TOU pricing specifically incentivizes energy use times when renewable generation output is high and electricity prices are low.

[61] This is not currently offered as a grid service by any regional transmission organization/ISOs.

3.2 Evaluation of Technology Characteristics

In this section, each technology is given a qualitative rating based on its capability to provide grid services through the energy efficiency and demand flexibility strategies outlined in Table 8. It should be noted that these ratings are *qualitative* and are based on estimated theoretical technological potentials, available research studies, and expert guidance. No lab testing or experimental pilot tests have been performed as part of this evaluation. The ratings are summarized as follows:

○ **Not Applicable:** Unable to provide the demand-side management strategy because it has no potential to meet the response time, data, and technology requirements for the corresponding grid services.

◑ **Low Capability:** May be able to provide the demand-side management strategy, but it is not well suited. It meets some or none of the response time, data, or technology requirements to provide the corresponding grid services and has low potential to meet all of them. Other technologies exist that are better fitted to perform the demand-side management strategy.

◐ **Medium Capability:** Able to provide the demand-side management strategy, but in a limited capacity. Meets all the response time, data, and technology requirements to provide the corresponding grid services or has the potential to meet all of them, but other barriers exist that limit the capacity.

● **High Capability:** Well suited to provide the demand-side management strategy and the corresponding grid services or possesses high potential through continued R&D. Current technologies meet all the response time, data, and technology requirements to provide the corresponding grid services and have been proven capable of providing the grid services through experimentation or field testing. Prospective technologies will possess characteristics that indicate a high likelihood to meet all grid service requirements following advances in R&D.

In addition, each grid service is weighted based on the opportunity space in the building sector. Building technologies provide the greatest value to the grid through energy efficiency and peak demand reductions based on addressable market sizes for these grid services.[62] Therefore, the ability to perform efficiency, shedding, and shifting is weighted higher than modulating loads. Based on the capability to provide each demand-side management strategy, the number of strategies provided, and the weighting of each (efficiency/shedding/shifting weighted higher than modulating), each technology is determined to have low, medium, or high potential to provide grid services in GEBs.

3.2.1 HVAC

Table 9 provides the ratings for HVAC technologies.

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[62] Further discussion on this is available in the *Overview of Research Challenges and Gaps* report.

Table 9. Evaluation of HVAC Technology Capabilities

HVAC Technologies	Efficiency	Load Shed	Load Shift	Modulate	Overall Potential
HVAC#1: Smart Thermostats	◑	◐	●	◑	High
• Smart thermostats are a key communication gateway to enable grid services from residential and light commercial HVAC equipment. They can provide load shifting, including management of complex scheduling and day-ahead service requests while optimizion operations to minimize impacts on customer comfort. • As HVAC controllers, smart thermostats cannot provide pure load shedding. As discussed in Section 3.1, HVAC equipment can shed load temporarily, but most of that load will be required postcurtailment to bring the temperature back up/down, which constitutes load shifting. Any load shedding comes from the increased efficiency achievable during off-peak, cooler times when the system is recovering from curtailment. • Third-party smart thermostats are not well suited to providing frequency regulation or voltage support on their own because they only have indirect equipment control via set points; it is possible that future smart thermostats (potentially made by the HVAC manufacturer) could have direct control and provide frequency regulation. • Smart thermostats can reduce total energy consumption through smart control algorithms, but they have no ability to improve efficiency of individual systems (e.g., annual fuel utilization efficiency, coefficient of performance). Therefore, this efficiency provides value to consumers, but only during off-peak periods.					
HVAC#2: Separate Sensible and Latent Space Conditioning	●	◐	◐	○	High
• Research estimates that separate sensible and latent cooling systems could provide energy savings of 30% and greater (Ling and Hwang 2018). Solid or liquid desiccant systems using solar thermal or waste heat resources would offer additional energy savings; equipment downsizing is also possible. • Systems could shed load by reducing the sensible cooling stage and only operating the high-efficiency latent cooling stage to maintain occupant comfort during peak events and allow for longer curtailment periods without causing discomfort. • Some systems may offer load shifting by using TES of liquid desiccants and other materials (see liquid desiccant TES below). • Separate sensible and latent cooling systems do not provide significant load modulation capabilities.					
HVAC#3: Liquid Desiccant Thermal Energy Storage	◐	◐	●	○	High
• Load shifting is the primary flexibility value from liquid desiccant TES because the liquid desiccant will always have to be recharged at a later time (as discussed in Section 3.1). • Use of solar thermal or renewable electricity overgeneration (e.g., midday PV on cool days) for desiccant regeneration enables substantial efficiency value. • Applicable in humid climates for cooling season only; generally coincides with summer-annual-peaking regions.					
HVAC#4: Advanced Controls for HVAC Equipment with Embedded Thermostats	○	◑	●	◑	Med
• Well suited to load shifting, especially because these products tend to be major drivers of summer peak demand. Widespread adoption is necessary because of the relatively small demand per unit. • Temporary load shedding is possible, with some load being completely avoided because the efficiency increases and heat losses decrease when the indoor temperature approaches the outdoor temperature. However, some load shifting will generally be involved as well because the temperature must be brought back to the original set temperature after the curtailment period (as discussed in Section 3.1). • As is the case for smart thermostats, advanced control can provide annual energy savings through smart management of the heating or cooling load, but it has no ability to improve efficiency of individual systems (e.g., annual fuel utilization efficiency, coefficient of performance). Therefore, this efficiency provides value to consumers but not to peak load management. • An individual unit has very limited ability to provide frequency regulation, but this may be possible as a fleet.					

HVAC Technologies	Efficiency	Load Shed	Load Shift	Modulate	Overall Potential
HVAC#5: Hybrid Evaporative Precooling	●	◑	◑	○	Low
• Well suited to providing efficiency value through substantial improvments to coefficient of performance, but limited load shedding and load shifting/leveling value. • Relatively fast response to switch from vapor-compression to evaporative cooling modes. • Limited applicability to relatively dry climates; efficiency improves as the ambient humidity decreases. • A hybrid liquid desiccant/evaporative system (i.e., in combination with HVAC#2 and/or #3, could have potential to provide additional capabilities, but are not explored in depth here.					
HVAC#6: Dual-Fuel HVAC	○	●	○	○	Low
• Capable and well suited for infrequent emergency load shedding given the right financial incentives; if the customer is using gas because it is lower cost, the electric grid will not benefit during an emergency. • The main value is likely for heat pump owners who could switch to gas as a backup during winter peak days. Secondarily, customers who could switch to delivered fuels (propane or oil) during curtailment periods could benefit. • Current economics hinder viability while gas prices are low, which makes it cheaper for customers who have gas service to simply use gas for heating. See discussion of potential for gas demand response programs in Section 3.2.4. • Greater analysis of temporarily fuel switching consequences is required to determine whether the load-shedding value of gas-electric dual-fuel systems is productive for grid operators (See Section 2.1.4).					

3.2.2 Water Heating

Table 10 provides the ratings for water heating (WH) technologies.

Table 10. Evaluation of Water Heating Technology Capabilities

Water Heating Technologies	Efficiency	Load Shed	Load Shift	Modulate	Overall Potential
WH#1: Water Heaters with Smart, Connected Controls	◑	◑	●	◐	High
• Very valuable for predictable, scheduled peak load shifting via preheating (thermal storage) or for emergency (no preheating) curtailment. • Some load shedding is possible, but only if water temperature remains low for an extended period of time, which reduces the standby losses. Ultimately the water temperature must be brought back to the set point after the curtailment period (as discussed in Section 3.1). Load shifting with preheating will not have accompanying load shedding because the standby losses will increase. • Capable of providing some short-time-scale services, such as frequency response and other operating reserve products aimed at increasing the grid's DER hosting capacity. • Grid value can be easily provided when controlling electric resistance water heaters, but with low efficiency. Use of HPWHs increases efficiency substantially and provides much of the same grid value (see Section 4.2 for broader discussion).					
WH#2: Dual-Fuel Water Heater	○	●	○	○	Low
• Capable and well suited for infrequent emergency load shedding given the right financial incentives; if the customer is using gas because it is lower cost, the electric grid will not benefit during an emergency. • This is a potential option for regions where both the electricity grid and the gas network are constrained at times. • Current economics hinder viability while gas prices are low, which makes it cheaper for customers who have gas service to simply use gas for heating. See discussion of potential for gas curtailment in Section 3.2.4. • Greater analysis of temporarily fuel switching consequences is required to determine whether the load-shedding value of gas-electric dual-fuel systems is productive for grid operators (see Section 2.1.4).					

3.2.3 Appliances, Refrigeration, and Relevant MELs

Table 11 provides the ratings for appliances, refrigeration, and related MELs.

Table 11. Evaluation of Appliance Technology Capabilities

Appliance Technologies and Related MELs	Efficiency	Load Shed	Load Shift	Modulate	Overall Potential
APP#1: Modulating, Advanced Clothes Dryers	◐	◑	◐	●	High
• Modulation of the heating system enables a better match of moisture removal rate to the heat input, reducing overdrying and improving efficiency (for heat-pump models that often run at a single-capacity heat output). • Lower temperature drying improves efficiency despite longer cycle times (reduced partial overdrying of linens). This allows the modulating clothes dryer to provide a small amount of load shedding along with load shifting. • Load shifting can also be provided through delayed start. • This approach has been proven in the lab. Response can be provided quickly for electric resistance products (within seconds) with no damage to the equipment. Fast response is valuable for load modulation.					
APP#2: Advanced Dishwasher and Clothes Washer Controls	○	○	●	○	Med
• Well suited to load shifting through delayed start. • No load shedding potential as the cycle must still run, just at a different time. The only potential load shedding comes from the improved grid fuel mix (not evaluated here) if the load is shifted off-peak.					
APP#3: Connected Refrigerator and Freezer Advanced Controls	○	○	◐	○	Low
• Refrigerators can provide load shifting. As discussed in Section 3.1, load shedding is most often accompanied by load shifting because of the need to recover the original set temperature after a curtailment period. The only potential load shedding comes from the improved grid fuel mix (not evaluated here) if load is shifted off-peak. • Need for maintaining temperatures to prevent spoilage may limit duration of curtailment. • Cost-benefit may be a significant barrier; the cost per unit for the controls is in line with other appliances, but the benefit per refrigerator is generally lower because of a low and consistent load (e.g., ~100–200 watts).					
APP#4: Advanced Controls for Commercial Refrigeration	◐	◑	●	○	High
• Well suited to load shifting via scheduled precooling or emergency curtailment. Annual energy savings are achievable via smart control of the equipment. However, there is no benefit in terms of continuous energy savings (e.g., coefficient of performance). Therefore, the efficiency provides benefit to consumers via reduced operating costs, but it offers little to no benefit to the grid because most savings will be achieved during off-peak hours. • Limited load shedding can be achieved in emergency grid events; usually this would be accompanied by load shifting because the equipment must bring the temperature back to the usual set point after the curtailment period, as discussed in Section 3.1. • Although temperature limits are generally stricter for refrigeration than for HVAC because of the need to prevent food spoilage, the potential is still substantial, particularly for large commercial refrigeration (e.g., warehouses) thanks to significant thermal mass to help maintain temperature set points.					
APP#5: MELs: Motors	◐	◐	◑	◐	Med
• Examples include fans, pumps, small kitchen appliances, and refrigeration. Motors shed load for noncritical equipment by transitioning to a standby/off state or by modulating to lower speeds using a multispeed or variable speed motor, particularly for nonsafety critical equipment.					

Appliance Technologies and Related MELs	Efficiency	Load Shed	Load Shift	Modulate	Overall Potential
• Multispeed or variable speed motors increase overall efficiency and can be used for fast response grid services. • Integration of brushless permanent magnet or electronically commutated motors can provide efficiency improvement and enable variable speed capabilities.					
APP#6: MELs: Water Circulation	◑	◑	●	◑	**Med**
• Examples include pool pumps, boiler pumps, condensate drainage pumps, and spa/hot tub pumps. • Pumps can shed load for noncritical equipment by transitioning to a standby/off state or by modulating to lower speeds using a variable or multispeed pump. • Pumps and water purification systems can be programmed to shift operation/load into high renewable energy generation periods (e.g., solar bulge) or off-peak periods. • Decrease the number of cycles per day while still providing proper circulation for health/safety needs.					
APP#7: MELs: Water Heating	●	◑	●	○	**High**
• Examples include portable electric spas and pool heaters. • Hot water reservoirs provide TES for loading up during off-peak or high renewable energy generation periods (e.g., solar bulge), and shifting load out of peak demand periods.					
APP#8: MELs: HVAC	◑	◐	●	○	**Med**
• Examples include dehumidifiers, ceiling fans, furnace fans, and kitchen ventilation. • Load shifting of dehumidification into high renewable energy generation periods (e.g., solar bulge) or off-peak periods to service the grid. • Temporary load shedding of ceiling fan air circulation during peak demand periods. • Integration of multispeed or variable speed fans in combination with sensors and controls to modulate fan speeds, thereby optimizing power and increasing energy efficiency.					
APP#9: MELs: Refrigeration	◑	◐	◐	○	**Med**
• Examples include laboratory refrigerators and freezers, coolers, and cooler-refrigeration combination products. • Load shifting of defrost cycles into high renewable energy generation periods (e.g., solar bulge) or off-peak periods to support the grid. • Temporary load shedding of refrigeration during peak demand periods in concordance with user behavior.					

3.2.4 Related Natural Gas Technologies

Table 12 provides the ratings for CHP (NG#1), as well as some of the technologies listed in the previous table (NG#2–NG#6), but representing their natural-gas-fired counterparts and the demand flexibility that they can provide to either the natural gas or electric grid. Modulating HVAC was not included here because the grid benefits of natural-gas-powered modulating gas HVAC are not expected to be nearly as significant as for electricity-powered modulating HVAC (single-speed electric HVAC is more limited in its ability to ramp capacity up or down, thus benefitting more from the introduction of modulating technology).

Table 12. Evaluation of Natural Gas Technology Capabilities

Natural Gas Technologies	Efficiency	Load Shed	Load Shift	Overall Potential
NG#1: Building-Scale CHP	●	◐	◐	High
• CHP systems can improve the overall energy efficiency of electricity and thermal energy consumed at the building by reducing grid-tied electricity losses and capturing waste heat. • CHP systems are typically designed for consistent electricity output for baseload demand, but some systems can increase their output for brief periods to provide short-term grid flexibility. • Many larger CHP systems include TES to shift the generation of chilled or hot water to off-peak periods (excluded in the evaluation of this technology and instead covered under TES[CC#1]).				
NG#2: Smart Thermostats	◑	◑	◐	Med
• Smart thermostats provide a convenient way to communicate with HVAC and shed load during peak times. However, much of the load is reintroduced at the end of the curtailment period to bring the temperature back to the original set point (that is, the value is in load shifting, not shedding, as discussed in Section 3.1). • Load shedding value is lower when managing gas HVAC equipment (heating) versus electric HVAC equipment, because gas systems do not change efficiency over the course of the day (unlike A/C systems, for example). So, shifting gas load to an off-peak hour does not result in improved efficiency. Some value for shedding could come from an improved fuel mix at a different time of day (location dependent) or via use of gas-fired heat pumps, whose efficiency is dependent on weather. • Smart thermostats can help shift load through preheating or precooling (precooling being less common in the case of natural gas). The ability to shift load is linked to the thermal inertia of the building, with poorly insulated buildings with large surface areas likely offering the lowest ability to hold temperature. • Smart thermostats can reduce total energy consumption through smart control algorithms, but they have no ability to improve efficiency of individual systems (e.g., annual fuel utilization efficiency, coefficient of performance). Therefore, this efficiency provides value to consumers, but only during off-peak periods.				
NG#3: Dual-Fuel HVAC	○	●	○	Low
• Dual-fuel gas HVAC can have both a gas burner and electric heat; the electric system can be used for heating in the event of gas network constraints to provide load shedding. • Greater analysis of temporarily fuel switching consequences is required to determine whether the load-shedding value is productive for grid operators (see Section 2.1.4).				
NG#4: Water Heaters with Smart, Connected Controls	◐	◐	●	High
• Smart connected water heater controllers shift load by preheating the water before or after expected high-demand periods. • Smart connected water heater controllers reduce energy consumption through smart control algorithms, but they offer little in terms of operating efficiency improvements (i.e., no uniform energy factor improvement). • Smart connected water heater controllers offer some load shedding by allowing temperatures to drift when curtailed, but this is generally followed by a period of increased demand; in other words, most of the value is in load shifting as opposed to load shedding (as discussed in Section 3.1).				
NG#5: Dual-Fuel Water Heaters	○	●	○	Low
• Dual-fuel gas water heaters could have both a gas burner and electric heat; the electric system could be used for heating in the event of gas network constraints to provide load shedding. • Greater analysis of temporarily fuel switching consequences is required to determine whether the load-shedding value is productive for grid operators (see Section 2.1.4).				
NG#6: Modulating, Advanced Clothes Dryers	◐	◑	◐	Med
• Modulation of the burner enables a better match of moisture removal rate to the heat input, reducing overdrying and improving efficiency. • Lower temperature drying improves efficiency despite longer cycle times (reduced partial overdrying of linens). This allows the modulating clothes dryer to provide a small amount of load shedding along with load shifting. • Load shifting can also be provided through delayed start.				

3.2.5 Cross-Cutting Technologies

Table 13 provides the ratings for cross-cutting (CC) technologies.

Table 13. Evaluation of Cross-Cutting Technology Capabilities

<table>
<tr><th>Cross-Cutting Technologies</th><th>Efficiency</th><th>Load Shed</th><th>Load Shift</th><th>Modulate</th><th>Overall Potential</th></tr>
<tr><td>CC#1: Thermal Energy Storage</td><td>◑</td><td>◑</td><td>●</td><td>◑</td><td>High</td></tr>
<tr><td colspan="6">• Well suited to predictable daily load shifting/leveling to reduce demand charges.
• Great applicability in all HVAC and most commercial refrigeration; more economical with large equipment.
• TES affords additional flexibility in providing services, because the stored energy maintains proper conditions.
• Some efficiency may be possible by leveraging favorable environmental conditions to charge the storage medium more efficiently (e.g., precooling at night with colder ambient temperatures for outdoor condensers).
• Primary value is for load shifting, but load shedding is possible where the shift in energy use enables improved efficiency (e.g., higher energy efficiency ratio operation at night). However, round-trip energy losses generally mean slight increases in total energy use. Maximizing this benefit requires careful scheduling.
• Individual units have limited ability to provide frequency regulation because of slow response time, but it is possible through advanced control algorithms that manage a portfolio/fleet of units.
• TES can also apply to natural gas systems; but for those systems, there is little efficiency benefit. The efficiency of gas furnaces and boilers does not vary with ambient temperature, so shifting operating time would not impact efficiency. There is some benefit in running gas heat pumps and chillers (engine or absorption) during more favorable weather conditions and storing the energy.
NOTE: Evaluation differs from that of TES in the <i>Windows and Opaque Envelope</i> report because of differences in scope of TES systems.</td></tr>
<tr><td>CC#2: Modulating Capacity Vapor Compression</td><td>●</td><td>◐</td><td>◐</td><td>◐</td><td>Med</td></tr>
<tr><td colspan="6">• Primarily promoted for efficiency and comfort value.
• Load shifting is accomplished by precooling/heating (a forward shift) prior to an anticipated curtailment period, then reducing the output capacity during the event.
• A combination of load shedding and load shifting can be accomplished by changing the set temperature without precooling/heating. In this scenario, some of the load would be incurred later as the set temperature is set to its original value and the system has to work longer to bring the temperature back to the set temperature (as discussed in Section 3.1).
• The ability to shift or shed load is limited while maintaining occupant comfort by the building's thermal inertia, which is the key driver of how long the building will maintain comfortable temperatures.
• Some load shedding may be achieveable in select instances when the set point does not need to be regained after a curtailment period, such as if the event is at the end of the day and the system is shutdown for the night.
• An individual unit can provide some frequency regulation, and this ability improves greatly with a fleet of units.
• With the addition of the power electronics for variable-speed drives, there could be an opportunity for power factor control and thus voltage support, though such capabilities are currently only conceptual.[63]</td></tr>
<tr><td>CC#3: Non-Vapor-Compression Materials and Systems</td><td>●</td><td>◐</td><td>●</td><td>◐</td><td>High</td></tr>
<tr><td colspan="6">• Researchers estimate energy savings of 20% and greater for some NVC technologies and building applications but require further R&D to develop the core material technologies and system designs.
• Some NVC technologies offer separate sensible and latent cooling and variable capacity control, which can allow buildings to shed load and operate at lower energy consumption levels during peak demand events.
• Some NVC technologies offer energy storage through hydronic thermal storage, or battery-powered personal comfort devices that can shift grid-tied energy use to off-peak periods and still maintain occupant comfort.</td></tr>
</table>

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[63] Voltage support is key to increasing hosting capacity of DERs, particularly at the end of radial feeders, where voltage fluctuations are more common (the end of radial feeders is farther from substations, so they receive less voltage support from a substation). Lightly loaded lines generate reactive power while heavily loaded lines consume reactive power, so modulation of power factor can help stabilize voltage on the grid at various points during the day.

Cross-Cutting Technologies	Efficiency	Load Shed	Load Shift	Modulate	Overall Potential
• Many NVC technologies have a high degree of capacity control and can modulate their load by varying the speed of specific components (e.g., fan, pump, and other motors) or electrical input to solid-state cooling materials.					

3.3 Evaluation Results

The high-, medium-, and low-potential GEB HVAC, water heating, appliance, and refrigeration technologies are listed in Table 14. These levels correspond to each technology's capability to provide the grid services outlined in Table 8. These levels are relative to other related technologies within the same end-use category and are not meant to be compared to other building technologies (e.g., lighting) which may have greater overall potential to provide energy savings, peak demand savings, and other grid services.

Table 14. Technology Priority Levels

End Use	High Potential	Medium Potential	Low Potential
HVAC	• HVAC#1: Smart Thermostats • HVAC#2: Separate Sensible and Latent Space Conditioning • HVAC#3: Liquid Desiccant TES	• HVAC#4: Advanced Controls for HVAC Equipment with Embedded Thermostats	• HVAC#5: Hybrid Evaporative Cooling • HVAC#6: Dual-Fuel HVAC
Water Heating	• WH#1: Water Heaters with Smart, Connected Controls	• None	• WH#2: Dual-Fuel Water Heaters
Appliances, Refrigeration, and Relevant MELs	• APP#7: MELs: Water Heating	• APP#1: Modulating, Advanced Clothes Dryers • APP#2: Advanced Dishwasher/ Clothes Washer Controls • APP#3: Connected Refrigerator/ Freezer Advanced Controls • APP#4: Advanced Controls for Commercial Refrigeration • APP#5: MELs: Motors • APP#6: MELs: Water Circulation • APP#8: MELs: HVAC • APP#9: MELs: Refrigeration	• None
Natural Gas	• NG#1: Building-Scale CHP • NG#4: Water Heaters with Smart, Connected Controls	• NG#2: Smart Thermostats • NG#6: Modulating, Advanced Clothes Dryers	• NG#3: Dual-Fuel HVAC • NG#5: Dual-Fuel Water Heaters
Cross-Cutting	• CC#1: Thermal Energy Storage • CC#3: NVC Materials/Systems	• CC#2: Modulating Capacity Vapor Compression	• None

The individual technology evaluations in Section 3.2 provide detailed technology-specific findings, but additionally, the analysis highlighted a series of broader points, many of which are cross-cutting, including:

- **Energy efficiency value:** Efficiency is the greatest and most common grid value provided by the evaluated technologies. For many technologies (such as high-SEER A/C), this is not a value of flexibility, because it is provided continuously or at least predictably; nevertheless, it may still provide the greatest magnitude in peak reduction. Other technologies (such as smart thermostats) may provide predictable efficiency, but that may have limited grid value because it is provided at off-peak times. Smart thermostats, however, also provide additional flexibility to boost grid value during peak periods.

- **Shedding without shifting:** The majority of evaluated technologies require some level of peak shifting, as opposed to completely shedding their load. This derives from the fact that the relevant end uses in this report are all providing a benefit to the building owner or occupant that will not be completely avoided and must be provided at a later or earlier time. For example, curtailed water heating will be made up in order to provide hot water to occupants and a delayed cycle on a dishwasher will still be run, just later. In contrast, shedding of lighting load would not require extra lighting later to make up for reduced lighting during the curtailment period. Despite the continued need to serve the benefit for the building occupant, many of the evaluated technologies do provide some pure load shedding as well. For example, load shifting with an A/C enables the unit to operate more efficiently during cooler, off-peak hours, thus reducing the overall energy consumption.
- **Regional differences**: HVAC equipment applicability and its associated grid value is highly dependent on the local climate and grid conditions. For example, it is unlikely that a heat pump with hot thermal storage would be installed in hot, dry climates such as the desert southwest because of limited potential grid value on a daily basis, but in an unexpectedly long and harsh cold snap it could provide substantial value. In an alternative case, the value of gas demand flexibility could be very high during a cold winter in a location with constrained natural gas supply.
- **Dual-fuel systems and low-cost gas**: So long as natural gas prices remain near historic lows, dual-fuel gas/electric systems will provide little value to the electric grid because they will run most frequently using natural gas, not electricity. Thus, when the equipment is called to curtail electricity use, for example, it will not be able to deliver. However, such systems could provide value to the gas network via gas load shedding or shifting. Dual-fuel systems using electricity plus a delivered fuel (oil/propane) may be very well suited to provide value to the electric grid, but the market of oil/propane systems is very small and likely to shrink in the future.
- **Voltage support**: Very few of the technologies covered here can provide voltage support, which is somewhat unique among grid services; where they do provide voltage support, it is associated with smart power electronics, or the capacity to introduce such power electronics into existing systems. The most common tool for distributed voltage support is from smart PV inverters, which can be controlled centrally to help manage reactive power on the grid on a very granular basis. Such solutions could also be applicable anywhere that DC-AC conversions are taking place, such as in homes with DC-power distribution, homes with battery energy storage systems, or even appliances with embedded battery systems.

4 Technology Attributes

Beyond the capability to provide grid flexibility, connected HVAC, water heating, appliance, and refrigeration technologies offer additional benefits to manufacturers, consumers, and society (see the *Overview of Research Challenges and Gaps* report for additional discussion of the value of demand flexibility.) However, market/consumer challenges need to be addressed to realize these benefits. Understanding these additional benefits and market/consumer barriers is vital to holistically assess and compare each technology. This section explores these issues by addressing key technology attributes of each medium- and high-potential technology. The attributes considered for each technology—reliability, resilience, system readiness, usability, manufacturability, human health, and environment—are defined in Table 15, though not all attributes are relevant to each technology.

Table 15. System Attribute Definitions and Criteria

These definitions are for the purposes of the *GEB Technical Report Series*. They may be defined differently in other reports or contexts.

System Attribute	Definition
Reliability	The ability of the technology to consistently perform grid services as intended over the lifetime of the product.
Resilience	The ability of the technology to improve the resistance of the building to electric power outages and/or natural disasters (including earthquakes, hurricanes, tornadoes, and floods) by providing energy, services, occupant comfort, protection, and/or damage resistance.
System Readiness	The ability of the technology to interoperate with other technologies, networks, and systems while maintaining cybersecurity.
Usability	The ease of use of the technology to the customer including ease of installation, ease of operation, and ease of maintenance.
Manufacturability	The ability of the technology to be manufactured at a large scale; this includes the environmental sustainability of the raw materials, the manufacturing costs, and the final capital cost of the technology.
Human Health	The extent to which the technology contributes to a healthy and safe living environment for the building occupants.
Environment	The total estimated operational emissions of the technology including CO_2, nitrous oxide, sulfur oxide, and particulate matter in the United States.

Sections 4.1 to 4.5 discuss the benefits and market/consumer barriers unique to each HVAC, water heating, appliance (excluding MELs), refrigeration, and cross-cutting technology. It is also important to note that R&D advancements to sensor and control technologies, while essential to the realization of grid benefits from lighting, are discussed further in the *Whole-Building Controls, Sensors, Modeling, and Analytics* report.

4.1 HVAC

There are several issues to consider when discussing the medium- and high-priority HVAC technologies:

HVAC #1: Smart Thermostats

HVAC #2: Separate Sensible and Latent Space Conditioning

HVAC #3: Liquid Desiccant Thermal Energy Storage

HVAC #4: Advanced Controls for HVAC Equipment with Embedded Thermostats

These considerations are detailed in Table 16.

Table 16. Attributes of Grid-interactive HVAC Technologies

Attribute	Consideration and Applicable Grid-interactive HVAC Technologies
System Readiness	**Simple interfacing with site HVAC equipment [HVAC#1]:** Smart thermostats provide a layer of abstraction between the on-site HVAC equipment and the utility communication platform. The utility communicates with a single, standardized interface, which then can enable specific control algorithms that are specific to the site and the equipment.
	Knowledge gap in advanced control algorithms for demand response [HVAC#1]: Smart thermostats must run algorithms, either built-in or cloud-based, to maximize the value provided to the grid. This includes smart scheduling of the demand signal and predictive algorithms based on artificial intelligence. The artificial intelligence component could help choose control strategies that maximize occupant comfort while providing a grid service (for example, the thermostat could learn how quickly the temperature increases in a house on a hot day and use that information to estimate how cold it needs to precool to maintain acceptable temperatures in other days). Additionally, the algorithm must be able to recognize the requested service and develop a strategy for demand response.
Usability	**Complex installation, commissioning, and troubleshooting [All technologies]:** Added components and subsystems introduce added time and cost for installation and commissioning of HVAC equipment. This complexity may also introduce troubleshooting challenges for end users who may have historically done some of their own maintenance and repair work. For nonpackaged products, there is extra time required for piping runs, extra wiring, and more extensive commissioning. Packaged products (e.g., built-in energy storage) will not have added installation complexity but will require extra programming and commissioning of the grid-interactive components. Products must seek to promote plug-and-play functionality that requires minimal effort by installers and reduces potential for incorrect scheduling.
	Increased space requirements [HVAC#3]: Liquid desiccant TES may require additional floorspace compared to traditional systems. In some buildings, this may be physically prohibitive; others who do have space (or for new construction) may opt to use the space for other purposes, particularly if there is an opportunity cost associated with lost leasing or retail revenue. Personal comfort devices (generally NVC-based) are the only likely candidates for decreased space requirements.
	Increased convenience for end users [All technologies]: Connected HVAC systems give users the ability to control their units remotely, giving them better control to optimize their comfort. Many of the commercialized connected A/Cs (e.g., room A/Cs) are marketed with focus on the remote (web-based) control capabilities, especially via mobile applications.[64] Any HVAC system can provide the same functionality as connected room/portable A/Cs if they are connected through Wi-Fi or other communication systems. Most likely, the equipment will be connected to a thermostat or BAS over which the user has remote control.
	Energy storage for renewables [HVAC#3]: For sites that have PV panels but do not have on-site battery energy storage, liquid desiccant TES would allow for the storage of excess energy from peak sunlight hours. The desiccant can be regenerated and stored with electric resistance heating or heat pumps during periods of excess renewable generation, which would otherwise be curtailed.
Human Health	**Improved air quality and indoor conditions [HVAC#2 and HVAC#3]:** Premium HVAC technologies, which often includes those with grid-interactive functionality, provide superior comfort via precise control over temperature and humidity, resulting in:[65] • Better optimization of temperature and humidity to increase occupant comfort • Avoided building maintenance associated with high indoor humidity (e.g., mold/mildew) • Improved ventilation and reduced contaminants.

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[64] For example, see: https://www.geappliances.com/ge/connected-appliances/air-conditioners.htm.
[65] For details, see: https://www.nrel.gov/docs/fy14osti/60655.pdf.

Attribute	Consideration and Applicable Grid-interactive HVAC Technologies
	Liquid desiccant-based HVAC systems include separate controls for temperature and humidity so that comfort level can be controlled more precisely; this can also help mitigate any risk of building operators overriding supply air requirements to maintain comfort.
Environment	**Use of high-global-warming-potential (GWP) refrigerants [All vapor compression systems]:** A/Cs and heat pumps use high-GWP refrigerants to operate. These refrigerants may leak, which increases the direct GHG emissions associated with the product. Use of CO_2 as the refrigerant would dramatically reduce the problem, while use of NVC technologies would eliminate it.

4.2 Water Heating

There are several issues to consider when discussing the medium- and high-priority water heating technologies:

WH#1: Water Heaters with Smart, Connected Controls

These considerations are detailed in Table 17.

Table 17. Attributes of Grid-interactive Water Heating Technologies

Attribute	Consideration and Applicable Grid-interactive Water Heating Technologies
Resilience	**Hot water during power outages [WH#1]:** Advanced water heater controllers can be used to preheat water in anticipation of a winter storm or hurricane when an outage may be possible. Assuming water pressure is still sufficient from the potable water supply (which may require on-site energy storage or backup generation), users could have some hot water available during the outage.[66]
System Readiness	**Limited preheating potential for HPWHs [WH#1 (HPWH only)]:** Hydrofluorocarbon (HFC)-based HPWHs are limited in the amount of energy they can store efficiently and could require a supplemental electric resistance coil to heat to very high temperatures. Their ability to load shift without impacting hot water availability to occupants is somewhat limited with the use of the heat pump alone.
Usability	**Energy storage for renewables [WH#1]:** For sites that have PV panels but do not have on-site battery energy storage, advanced water heater controls could enable energy storage via water preheating. This is particularly valuable for excess generation that is not being used on-site and might otherwise be curtailed.
	Added space heating load in winter [WH#1 (HPWH only)]: HPWHs transfer heat from the surrounding air into the water. This adds load to the space heating system in the winter, if the system is located in conditioned space. In addition, the HPWH could affect the preheating routine of the space heating system, or cause unanticipated temperature drops while the space heating system is off or at a reduced capacity for a curtailment period. This would have negative consequences to occupant comfort.
	Decreased space conditioning load in summer [WH#1]: Although HPWHs add to the space heating load in the winter, they also decrease the cooling and dehumidification load in the summer. As a result, they can help reduce the consumption from the summertime space conditioning systems.
Environment	**Use of high-GWP refrigerants [WH#1 (HPWH only)]:** The majority of today's HPWH products use high-GWP refrigerants to operate. These refrigerants very rarely will leak, which increases the direct GHG emissions of the product. Some models use CO_2 as the refrigerant, which dramatically reduces the impact, while use of NVC technologies eliminates the problem.

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[66] For example, in a house of people use about 10 gallons of hot water per shower, a 50-gallon water heater that is preheated to its normal set point could provide five showers during an outage (based on EERE estimate from: https://www.energy.gov/eere/femp/energy-cost-calculator-electric-and-gas-water-heaters-0).

4.3 Appliances and Refrigeration

There are several issues to consider when discussing the medium- and high-priority appliance technologies (excluding MELs):

APP#1: Modulating, Advanced Clothes Dryers

APP#2: Advanced Dishwasher/Clothes Washer Controls

APP#3: Connected Refrigerator/Freezer Advanced Controls

APP#4: Advanced Controls for Commercial Refrigeration

These considerations are detailed in Table 18.

Table 18. Attributes of Grid-interactive Appliance and Relevant MEL Technologies

Attribute	Consideration and Applicable Grid-interactive Technologies
Resilience	**Reduced energy consumption during power outages [APP#4]:** For a customer with on-site backup power, running a refrigerator in low-operation mode or delaying the defrost cycle during a power outage would reduce consumption temporarily. Moreover, freezers can be precooled in anticipation of an outage so that safe temperatures are maintained during the outage. For buildings equipped with backup generation, these measures would reduce the load and extend the runtime.
System Readiness	**Compatibility with Wi-Fi connected devices [All tech]:** Smart appliances are generally designed to connect to other devices through Wi-Fi, making them compatible with popular consumer electronics like smartphones and home voice assistants. This may require specific software, which is either packaged with the appliance or available to the consumer for download.
Usability	**Energy storage for renewables [APP#3]:** For sites that have PV panels but do not have on-site battery energy storage, advanced controls for refrigerators/freezers would allow them to precool their freezers as a form of energy storage. Pool and spa heaters could be used in a similar fashion for energy storage via preheating. This is particularly valuable for excess generation that is not being used on-site and might otherwise be curtailed.
	Increased convenience for end users [All tech]: Connected appliances give users the ability to control their units remotely as well as by voice, making it easier for them to run cycles at the desired time. They can also provide additional convenience features to consumers (for example, "smart" refrigerators may be able to find recipes and read them to the customer, create grocery lists and sync to a mobile app, send expiration date notifications, and double check items in the fridge from a mobile app). These appliances are marketed to consumers for this premium functionality.
	Increased convenience for operators [APP#4]: Connected refrigeration equipment gives operations staff the ability to monitor their units remotely. This will make it easier to detect faults or change set points, ultimately helping to reduce energy use and operating costs.
	Complex installation, commissioning, and troubleshooting [APP#4]: Added components and subsystems introduce added time and cost for installation and commissioning. This complexity may also introduce troubleshooting challenges for end users who may have historically done some of their own maintenance and repair work. For nonpackaged products, the extra time required for piping runs, extra wiring, and more extensive commissioning will add time and cost and introduce opportunities for installation errors. Packaged products (e.g., built-in energy storage) will not have added installation complexity but will require extra effort and training for programming and commissioning. Products must seek to promote plug-and-play functionality that requires minimal effort by installers and reduces potential for incorrect scheduling.

Attribute	Consideration and Applicable Grid-interactive Technologies
	Equipment functionality disruption [All technologies]: Customers that want to provide grid services via their appliances may have to do so while sacrificing some level of functionality. Although consumers always have the chance to override these features, there will always be a trade-off for them; financial incentives, even big ones, are not always enough to promote participation. Disruptions may occur in various forms. For example, delaying the cycle on a dishwasher or clothes washer will result in a later completion time. Such interruptions can be mitigated through smart functionality, such as mobile notifications. This may be particularly disruptive for clothes washers if a wet load of clothes is left without transfer to the dryer. Similarly, running a clothes dryer on low power will result in a longer cycle time.
Human Health	**Increased food-related risks [APP#3 and APP#4]:** Failure or poor application of advanced refrigerator/freezer controls could result in improper temperature control and potential for reduced shelf life and/or increased risk of foodborne illness. These factors could further result in a financial burden that could potentially outstrip the financial value of using the appliance/equipment as a grid resource.
Environment	**Use of high-GWP refrigerants [APP#3 and APP#4]:** The majority of today's refrigeration products use high-GWP refrigerants to operate. These refrigerants can leak, which increases the direct GHG emissions of the product. Some advanced models use propane or CO_2 as the refrigerant, which dramatically reduces the impact. Large refrigeration systems, such as those in supermarkets, are much more prone to leaks than other system types, and often need refrigeration added every year because of small, continuous leaks.

4.4 Related Natural Gas Technologies

There are several issues to consider when discussing the medium- and high-priority natural gas technologies in the context of the natural gas and electric grids:

NG#1: Building-Scale CHP

NG#4: Water Heaters with Smart, Connected Controls

NG#2: Smart Thermostats

NG#6: Modulating, Advanced Clothes Dryers

These considerations are detailed in Table 19.

Table 19. Attributes of Grid-interactive Natural Gas Technologies

Attribute	Consideration and Applicable Technologies
Reliability	**No reliability impact from addition of grid interactivity [All technologies]:** The medium- and high-priority grid-interactive natural gas technologies do not suffer from any reliability degradation because of their grid interactivity. Curtailment and cycling of natural gas burners at the frequency expected for grid interactivity will not impact the lifetime of the product or impact day-to-day performance.
	Limited grid-reliability value of electric-to-gas fuel switching in some regions [All dual-fuel technologies]: In areas with high reliance on natural gas power generation and/or areas that are gas-supply-constrained, the interplay between electricity and gas markets is complex and may not provide expected value to either market. For example, during a cold snap in the northeast (gas-supply-constrained AND heavily reliant on gas generation), substantial amounts of generation must operate on fuel oil because home heating supply is prioritized, which leads to high electricity prices and simultaneously high gas prices. Switching between fuels in this situation can have complex implications on the markets and should be studied further. See Section 2.1.4 for additional discussion.
Resilience	**CHP backup power capabilities [NG#1]:** CHP is valuable for resilience and is often considered to be the central asset when designing a resilient emergency backup or microgrid project. Depending on system sizing, the CHP could provide full power to the building or campus or simply serve a subset of loads during islanded (grid-outage) operation. The increased resilience of the natural gas distribution network as compared to the electricity distribution network means that a natural gas CHP system almost always has access to natural gas and can run in the event of an electricity outage. When installed in strategic locations, such as emergency shelters, police departments, hospitals, etc., the CHP can enable important emergency capabilities for a community.
	Hot water during power outages [NG#5]: As with their electric counterparts, advanced water heater controllers can be used to preheat water in anticipation of a winter storm or hurricane when an outage may be possible. Assuming water pressure is still sufficient from the potable water supply (which may require on-site energy storage or backup generation), users could have some hot water available during the outage.[67]
	Grid-independent operation for self-powered equipment (NG#2): Furnaces and other self-powered gas equipment still require electrical input in order to operate auxiliary functions such as fans, ignitors, and controls. By generating electricity during the combustion process at the burner, self-powered equipment can produce enough electricity to operate independently of the electrical grid.[68]
Usability	**Increased convenience for end users [NG#5, NG#3, and NG#7]:** Connected systems, such as smart thermostats and advanced water heaters, give users the ability to control their units remotely, giving them better control to optimize their utility and comfort.

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[67] For example, in a house of people use about 10 gallons of hot water per shower, a 50-gallon water heater that is preheated to its normal set point could provide five showers during an outage (based on EERE estimate from: https://www.energy.gov/eere/femp/energy-cost-calculator-electric-and-gas-water-heaters-0).

[68] For more information see: https://www.energy.gov/eere/buildings/downloads/drop-retrofit-furnace-maximum-efficiency-self-powered-system.

4.5 Cross-Cutting Technologies

There are several issues to consider when discussing the medium- and high-priority cross-cutting technologies:

CC#1: Thermal Energy Storage

CC#3: Non-Vapor-Compression Materials/Systems

CC#2: Modulating Capacity Vapor Compression

These considerations are detailed in Table 20.

Table 20. Attributes of Grid-Interactive Cross-Cutting Technologies

Attribute	Consideration and Applicable Technologies
Reliability	**Extended product life [CC#2]:** Modulating vapor compression technology reduces the number of cycles that the compressor and other system components experience by modulating the output to better match the load at a low and continuous operating level. Reductions in cycles helps to increase product life by reducing the wear and tear of cycling, which puts the most stress on the vapor compression system.
Resilience	**Energy storage during power outages [CC#1]:** TES systems can increase the resilience of refrigeration or HVAC systems by enabling heating and/or cooling during electricity or gas outages. A small amount of power is still required, but that can be provided via battery backup or a generator. Storage capacity will dictate the duration that the system can operate without grid power, and resilience-focused systems would be sized much larger than systems that are strictly intended for intraday load shifting.[69] Maintaining refrigeration during outages is important, because temperatures need to be maintained to ensure food safety and preservation.
Usability	**Energy storage for renewables [CC#1]:** For sites that have PV panels but do not have on-site battery energy storage, TES will allow for the storage of excess generation output that is not being used on-site and might otherwise be curtailed.
	Increased space requirements [CC#1]: TES requires additional floorspace compared to traditional refrigeration or HVAC systems. In some existing buildings, this may be physically prohibitive; others who do have space (or for new construction) may opt to use the space for other purposes, particularly if there is an opportunity cost associated with lost leasing or retail revenue. Advanced TES, such as those using phase change materials, have high energy density, but nevertheless must still be designed with space limitations in mind. The floorspace should be specified via optimization of financial parameters; outdoor space (e.g., rooftop) may be the preferred option for some customers, but tradeoffs must still be considered for alternative uses of the space (e.g., PV panels). Architecture and engineering firms will need to be become comfortable with analysis of such tradeoffs.

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[69] As an example, a commercially available commercial forced air furnace has a storage capacity of 240 kWh (approximately 819,000 Btu); at full charge, this would provide 24 hours of heating at an average rate of 10 kW (approximately 30,000 Btu/h). For details, see: http://www.steffes.com/electric-thermal-storage/forced-air-furnace/.

Attribute	Consideration and Applicable Technologies
	Complex installation and troubleshooting [CC#1]: TES systems introduce additional components and subsystems that introduce added time and cost for installation and commissioning. This complexity may also introduce troubleshooting challenges for end users who may have historically done some of their own maintenance and repair work. For nonpackaged products, there is extra time required for piping runs, extra wiring, and more extensive commissioning. Packaged products (e.g., built-in energy storage) will not have added installation complexity but will require extra programming and commissioning of the grid-interactive components.
Human Health	**Improved air quality and indoor conditions [CC#2]:** Modulating vapor compression systems for HVAC can provide superior comfort via precise control over temperature and humidity, resulting in:[70] • Better optimization of temperature and humidity to increase occupant comfort • Avoided building maintenance associated with high indoor humidity (e.g., mold/mildew) • Improved ventilation and reduced contaminants. Modulating HVAC equipment can separately adjust airflow across the condenser and evaporator as well as the refrigerant flow through the compressor to better serve dehumidification loads versus single-speed systems.[71]
Environment	**Use of high-GWP refrigerants [CC#3]:** The majority of today's vapor compression products use high-GWP refrigerants to operate. These refrigerants can leak, which increases the direct GHG emissions of the product. Some models use CO_2 as the refrigerant, which dramatically reduces the impact.

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[70] For details, see: https://www.nrel.gov/docs/fy14osti/60655.pdf.

[71] Modulating A/Cs operate for longer runtimes but at reduced energy consumption and capacity. The longer runtimes allow more condensate to form on the evaporator coil, leading to superior dehumidification when compared to single-speed A/Cs. This effect is particularly pronounced in the shoulder seasons, when the cooling load is much smaller and a single-speed A/C would have to cycle on and off very often, with very reduced runtime.

5 R&D Challenges and Opportunities

Grid-interactive HVAC, water heating, appliances, and refrigeration is an area of growing interest. As discussed in Section 2.1.4, these types of equipment can provide great value to the grid, such as the ability to provide load shedding during peak times, load shifting via scheduling, and even some level of load modulation for frequency regulation. However, these technologies also face some important challenges that inhibit them from reaching their full potential, as discussed in Section 4. This section identifies R&D opportunities that can help these technologies overcome these challenges and achieve the level of adoption necessary to provide impactful grid services. R&D opportunities related to the interoperability and cybersecurity of GEBs are discussed in Section 5.1, with specific recommendations for HVAC, water heaters, appliances, and commercial refrigeration where applicable. Sections 5.2 to 5.7 describe specific challenges of HVAC, water heaters, appliances, and refrigeration, and present R&D opportunities that could help address those challenges. Section 5.9 summarizes those findings by technology. Many other R&D opportunities exist that are specific to improving efficiency and cost of these technologies and are not included here.

5.1 All Connected Technologies

All internet-connected technologies in buildings with data communication and control capabilities face common challenges, including interoperability, cybersecurity, and cost barriers. For more information on interoperability and cybersecurity challenges facing all connected technologies, refer to the *Whole-Building Controls, Sensors, Modeling, and Analytics* report.

5.1.1 Interoperability

Interoperability is the ability of devices or software systems to reliably and consistently exchange data. This is a key technical and market barrier to connected technologies providing grid services (DOE 2015). Interoperability relies heavily on communication within the building as well as between buildings and the grid (Hale et al. 2018). GEBs involve numerous previously separate industries—HVAC, lighting, envelope, electronics, water heating, major appliances, DERs, IT and network security, control vendors, and utilities—that have developed their own communication approaches and protocols. Accordingly, there is little incentive for competing device/system manufacturers to develop interoperable devices and systems because developing proprietary hardware/software forces consumers to purchase all products from a single vendor. Developing common interoperable platforms and communication protocols is critical to maximizing grid service provision and ensuring that vendor lock-in does not curtail consumer interest in connected technologies.

Electronic telecommunication is typically thought of as a hierarchy of protocols operating at different layers. Interoperability requires compatible protocols within a given layer and all of the layers below. At the bottom of the hierarchy are physical data layers, which define the physical medium and the properties of signals that are exchanged on it (e.g., ethernet, Wi-Fi, Bluetooth). Several industry organizations are working to support increased interoperability at this layer through common communication protocols and established standards, including the Open Connectivity Foundation, the TALQ Consortium, oneM2M, Bluetooth special interest group, the Industrial Internet Consortium, and the Zigbee Alliance. In the middle are network layers, which define the form, routing, and delivery of messages (e.g., Transmission Control Protocol/Internet Protocol , Secure Sockets Layer/Transport Layer Security). On top are application layers, which define the internal structure and semantics of the messages being sent (e.g., BACnet and Project Haystack, respectively).

GEB technology telecommunication protocols do not map cleanly to these layers, but most activity takes place at and above the application layers, leveraging common data and networking protocols like Wi-Fi, Transmission Control Protocol, and Transport Layer Security. Common data models are also critical to ensuring interoperability between devices; however, at the level of an individual device or technology, because it only needs to model itself, the common data model is less critical and therefore not discussed at length here. Research is needed to support the development and adoption of standardized semantic and syntactic specifications for connected devices and software systems. Standardized semantic and syntactic specifications have the potential to reduce deployment costs and increase adoption of connected technologies.

5.1.2 Cybersecurity

Cybersecurity is the process of enabling appropriate confidentiality of information, integrity of that information and the devices on which it resides, and availability of devices and information when needed. For an interaction between a building and grid, a cybersecure service would be delivered such that only the building and the service aggregator or utility would know (1) what service is being provided and when, (2) that the measurement and verification information is accurate, and (3) that devices that support service delivery and measurement and verification are available when needed. Cybersecurity is necessary for data privacy and critical for communication network reliability.

As more and more devices and software systems interconnect and interact, a vulnerability in one component can provide backdoor access or compromise other systems on the same network. Such vulnerabilities can even lead to impacts on corporate enterprise IT systems, slow digital business processes, or even cause them to cease operating altogether. In addition, connected, major end-use loads could provide access points to the greater electric grid. Previous cyberattacks have demonstrated the ability to damage or compromise targeted hardware equipment, though this requires significantly greater skills, time, and system knowledge (Langner 2011; Lika et al. 2018).

Cybersecurity must be implemented at multiple logical levels, from individual devices to systems, whole buildings, service aggregators, and the grid. As such, some system architectures are more compatible with cybersecurity than others. Further development is needed to integrate end-to-end data security. Research is needed to support the adoption of secure system architectures and cybersecurity best practices. Promoting cybersecurity reduces a major risk associated with digital automation and has the potential to increase adoption of connected technologies.

5.1.3 High Cost

Current high product and installation costs for many connected technologies represent a significant barrier to widespread adoption. Payback periods for additional sensors, controls, software, and commissioning may be too long to justify the added cost (without incentives). Further, additional communication components and software are needed to enable grid interactivity. Currently, grid-interactive systems are considered premium products with prohibitively high costs for many residential consumers and commercial building owners, though this is often a result of the inclusion of many high-cost features that are not required for grid interactivity.

Research is needed to develop manufacturing processes that have low capital costs or can use existing manufacturing equipment with minimal investment in tooling or reconfiguration. Further, there is a need to develop materials and technologies compatible with scalable manufacturing methods that enable increasing production volumes without incurring linearly increasing capital costs.

5.2 Reduce Product Costs

5.2.1 Challenge

The technologies considered in this report will generally cost more than their non-grid-interactive equivalents. The grid value that these technologies provide requires additional mechanical and electronic components, as well as additional software. Although much of the product cost premium can be addressed alongside similar efforts for cost reductions for high-efficiency equipment, grid-interactive technologies present some unique cost challenges because of inclusion of a different set of technology solutions and components (e.g., reducing costs for an advanced heat exchanger versus reducing cost for TES integration.) These costs are an important barrier to market adoption that needs to be addressed in research.

5.2.2 R&D Opportunities for Non-Vapor-Compression Technologies

Develop lower-cost NVC materials, systems, and components. With fewer established products on the market than vapor compression systems, NVC systems still have the opportunity for system configuration improvements. Optimal configuration may vary substantially by end-use application and by NVC solution (e.g., thermoelectric versus magnetocaloric). Many NVC solutions have been proven to have high efficiency, but bringing them to market at reasonable cost remains a hurdle.

5.2.3 R&D Opportunities for Modulating-Capacity Vapor Compression Technologies

Develop lower cost modulating-capacity systems, with a focus on heat exchangers and compressors. These two components are the two most costly in a typical vapor compression system. Modulating is typically restricted to premium tier products, so identifying opportunities for cost reduction can enable integration of modulating capacity on a broader range of products. Cost reductions on heat exchangers could be applied to all vapor compression systems and to other heat exchanger applications as well.

5.2.4 R&D Opportunities for Building-Scale CHP

Conduct cost-reduction R&D with a focus on smaller scale (e.g., <50 kW) systems. CHP systems for large customers have been attractive for decades in some places. However, smaller systems, which contain most of the same complexity of large systems, have not benefitted from sufficient cost reductions because their designs have been scaled down from their larger counterparts. Alternative system architectures and innovative approaches to system packaging could enable cost reductions to make smaller CHP (e.g., microCHP) more attractive to a broader market.

5.2.5 R&D Opportunities for Modulating, Advanced Clothes Dryers

Conduct cost-reduction R&D for heat pump clothes dryers. Despite being available in other countries, heat pump clothes dryers—which provide a substantial efficiency improvement over electric resistance clothes dryers—are not available in the United States, primarily due to high cost and longer drying times. Development of low-cost solutions to implement heat pumping technology could provide substantial efficiency grid value via clothes dryers. A potential solution area could include NVC technologies (see CC#3 for Non-Vapor-Compression Materials and Systems).

5.3 Reduce Installation and Commissioning Costs via Prepackaged Systems

5.3.1 Challenge

Beyond the added cost for installation and commissioning of grid-interactive system components, some systems, such as nonpackaged TES, will additionally require extra piping runs, extra roof penetrations (for some rooftop installations), and pumps/fan/compressor control integration. The process of installation, testing and verifying proper operation can add substantial cost to the installation. Lack of familiarity among contractors will also increase costs to customers, indicating a need for (non-R&D) quality installation and workforce programs to ensure that installation and maintenance is done correctly on grid-interactive systems. Enabling grid-interactive functionality requires advanced, complex commissioning steps for many technologies.

5.3.2 R&D Opportunities for Thermal Energy Storage, Liquid Desiccant Thermal Energy Storage for Dehumidification, and Separate Sensible and Latent Space Conditioning

Develop packaged systems to reduce installation and commissioning complexity. Development of prepackaged systems can provide value for TES on a wide array of residential and commercial HVAC and refrigeration technologies. Liquid desiccant TES for dehumidification, and separate sensible and latent space conditioning can also benefit from R&D and product development on simplified, prepackaged solutions that enable rapid, simple installation. Evaluation of the landscape of applications (product types and building types) would enable prioritization among the numerous potential solutions.

5.4 Enable Grid-interactive Appliance Retrofits

5.4.1 Challenge

Connectivity is often marketed as a premium feature in the appliance market. As a result, the first products to hit the market with connected, grid-interactive technology are generally high-cost premium products. In addition, appliances often have product lifetimes of more than 10 years, leading to slow adoption via natural turnover. To enable faster adoption of grid-interactive equipment, inexpensive interfaces should be considered. Existing appliance could be retrofit with a grid-interactive controller that can translate utility signals into commands that the appliance can understand. This has been done for water heaters and for some HVAC, but no commercial products exist for appliances.

5.4.2 R&D Opportunities for Grid-Interactive Appliances and Advanced Controls for HVAC Equipment with Embedded Thermostats[72]

Develop inexpensive retrofit grid-interactive packages for appliances. Rather than simply cutting off the power to the appliance (as a smart outlet would), this type of interface could be able to control the appliance in a more granular way to maximize customer functionality. This could include enabling low power modes, complex scheduling strategies, selective disabling of specific and noncritical components.[73] Given the large number of makes/models and variations between them, the expectation is that most would not have the capability to accommodate many of the more advanced features (beyond basic communications and on/off functionality), which would limit demand flexibility potential. R&D to help overcome this challenge would increase the potential grid value of this solution.

Develop inexpensive retrofit grid-interactive packages for HVAC equipment with embedded thermostats. Ductless products, window A/C, and portable A/C all have embedded thermostats and thus no ability to leverage a smart thermostat for grid interactivity. Many ductless heating/cooling products now have relatively expensive add-on controls packages that provide connectivity and could enable grid-interactive functionality, but none are known to currently have this technology. Further, manufacturers are commonly motivated to pack premium features together in their top-of-the-line products, which limits accessibility of grid-interactive functionality. A thorough evaluation of the available products could help identify gaps in functionality for various product types/configurations to understand where there is a need for added grid-interactive functionality. Supporting development of low-cost solutions would enable connectivity and grid interactivity without the added cost of other premium functionality that is typically packaged together.

5.5 Support Development of High-Density and Tunable Thermal Energy Storage

5.5.1 Challenge

One of the main hurdles for adoption of liquid desiccant TES and TES in general is the additional floorspace occupied by the energy storage system. Custom solutions designed to fit the building may be able to circumvent this issue, but they tend to be more expensive. Widely applicable solutions must include packaged or semipackaged products with limited increases in required floorspace versus conventional systems without energy storage. TES that can support both heating and cooling operations with the same footprint can also make equipment coupled TES more appealing.

5.5.2 R&D Opportunities for TES and Liquid Desiccant Thermal Energy Storage for Dehumidification

Develop novel TES materials with increased energy storage density and thus decreased space requirements. This may include phase change materials of various compositions, new ways to store thermal energy at higher or lower temperature (to maximize sensible heat), repurposed materials, and so on. The DOE

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[72] Similar devices already exist for water heaters (for example, see: https://aquanta.io/). For HVAC equipment, a smart thermostat would provide this functionality. Therefore, this technology applies specifically to appliances.

[73] Similar interfaces exist for water heaters and ductless minisplit heat pumps. For example, see: https://aquanta.io/ and https://sensibo.com/.

2019 BENEFIT FOA provided targets for such R&D, including: energy density greater than 100 kilowatt-hours [kWh]/m^3 and a price less than $15/kWh.[74]

Develop novel ways to package TES solutions. These packages should be designed to fit easily into the most common types of installation. Alternatively, these packages could be designed with flexible shapes so that the energy storage solution can be easily tailored to fit the available space at a low cost. For additional discussion of the value of prepackaged TES systems, see Section 5.3.

Develop novel ways to modify the properties of TES materials. The ability to control the charge/discharge rates and transition temperature of phase change thermal storage materials has the potential to increase the value of such storage media. Supporting research must be conducted to determine the desired or optimal active control capabilities for such thermal storage. This research would consider generic thermal storage and control capabilities to determine the performance requirements for thermal storage provision of a range of potentially feasible grid services. The findings from this work would help to define the minimum required performance for active control materials and systems and might also help establish the marginal benefit of further improvements to control performance beyond that minimum threshold.

5.6 Evaluate Duration, Temperature, and Humidity Limitations of Curtailment

5.6.1 Challenge

Demand flexibility strategies such as precooling and low-power operation would affect the temperature and humidity of the conditioned area in refrigeration and HVAC systems. To ensure product quality (refrigeration) and comfort (HVAC) during and after curtailment, grid-interactive system designers must understand and build in limits so that, without operator intervention, product quality and occupant comfort are sufficiently maintained at acceptable levels.

5.6.2 R&D Opportunities for Connected HVAC and Refrigeration

Model and test to characterize curtailment limitations. Modeling (i.e., building energy modeling) and validation testing will enable establishment of guidance and control parameters on acceptable limitations for curtailment of HVAC and refrigeration systems. Analysis should cover a wide array of system types and building types/vintages, including considerations for insulation levels and leakiness of the envelope. Analysis should cover systems with and without added TES, which could provide insights on appropriate energy storage sizing for these specific applications. Analysis should cover precooling and load shedding with postcooling. Both temperature and humidity should be evaluated, including for systems with separate sensible and latent cooling with the objective of understanding how the system controls could be optimized to minimize load while maintaining comfort. A set of guidelines for an array of applications could be developed to simplify adoption in various building sectors and equipment types.

5.7 Heat Pump Water Heaters for Demand Flexibility

5.7.1 Challenge

Today's HPWHs operate on a vapor compression cycle, with substantially higher efficiency than electric resistance water heaters.[75] However, the vapor compression cycle using today's common HFC refrigerants is not able to efficiently raise temperatures up as high as electric resistance water heaters can achieve. As a result, HPWHs, without the use of a supplemental electric coil, are not able to effectively store as much energy through preheating above the set point. HPWHs also face two additional issues:

- Leakage, albeit very infrequently, of high-GWP HFC refrigerants

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[74] 2019 BENEFIT FOA information available via press release at: https://www.energy.gov/articles/doe-announces-47-million-flexible-building-technologies-heating-ventilation-and-air; specific details of targets available within FOA documents at: https://eere-exchange.energy.gov/FileContent.aspx?FileID=39dac4e2-5f53-47ed-9b5a-6fffc2606173.

[75] Electric resistance water heaters are limited to a coefficient of performance of 100%; HPWH can reach coefficients of performance of 300% or even greater.

- Added load on the heating system during winter for systems installed indoors.

5.7.2 R&D Opportunities for Heat Pump Water Heaters to Enable Their Use with *Smart Connected Water Heater Controllers*

Evaluate the optimal approach for hybrid electric resistance/HPWHs to provide demand flexibility. Hybrid water heaters may be able to leverage the electric resistance's fast ramp up/down and high temperature capabilities along with the heat pump's superior efficiency. Additionally, use of advanced, low-cost insulation could extend the usability of stored water without the need to raise temperatures excessively high. With these features, hybrid water heaters may be able to provide fast curtailment or superior operating efficiency as needed by the grid. Hybrid HPWHs already exist in the market, but their ability to provide grid services has not been studied in detail.

Develop low-GWP refrigerant-based (e.g., CO_2) HPWHs for higher-temperature capabilities. Certain refrigerants, such as CO_2, can operate at higher temperatures than the more commonly used HFCs, while also being lower-GWP than HFCs. Implementing those refrigerants would extend the preheating range for HPWHs (without resorting to electric resistance heat) while also greatly reducing the issue of accidental leakage of greenhouse gases. These products are widely available as split-system HPWHs in Asian markets but are not yet widely available in the United States. Where they are available, they are still cost prohibitive. Split-system HPWHs would have the added benefit of not removing heat from the indoor air, thus reducing the impact of the HPWH on the space heating system.

5.8 Non-Vapor-Compression Technologies

5.8.1 Challenge

NVC technologies provide an avenue to increased operational flexibility to help provide grid services but are generally a very nascent group of technologies with high costs and are limited in the applications for which they can be deployed today. System-level engineering, testing, and architecture refinement are lacking, which prevents more rapid product development and deployment of the technologies in cost-competitive packages.

5.8.2 R&D Opportunities for Non-Vapor-Compression Materials and Systems

Expand development of NVC for a broad range of HVAC&R applications. Many opportunities exist to further develop NVC technologies, including[76]:

- Develop and test prototypes of membrane heat pumps and thermoelastic systems
- Develop preproduction designs and evaluate manufacturing cost of evaporative liquid desiccant A/C
- Develop and test demonstration prototype of Vuilleumier heat pump
- Develop cost-effective gas-fired heat pumps for heating-only or reversible operation, including integrating space-conditioning and water-heating capabilities
- Develop high-efficiency regenerating components for liquid desiccant A/Cs
- Develop cost-effective, compact heat exchangers to transfer heat to and from solid state modules without requiring large temperature differences.

In addition to these discrete R&D topics, there is additional work to introduce these fundamental concepts into products, develop prototypes, and validate performance and costs in new applications. To date, NVC has seen very limited deployment among the numerous applicable end uses, and significant research opportunities exist to understand the system architectures and configurations that could best suit each application.

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[76] Top 6 R&D initiatives identified in DOE's 2014 report: https://www.energy.gov/sites/prod/files/2014/03/f12/Non-Vapor%20Compression%20HVAC%20Report.pdf.

5.9 Summary of Findings

The technical challenges and their corresponding R&D opportunities are listed by technology (excluding MELs) in Table 21.

Table 21. Challenges and Opportunities by Technology

Technology		Challenges	R&D Opportunities
All	All Connected Technologies	Interoperability	• Support the development and adoption of standardized semantic and syntactic specifications for connected devices and software systems
		Cybersecurity	• Support the adoption of secure system architectures and cybersecurity best practices
		Cost	• Develop manufacturing processes that have low capital costs or can use existing manufacturing equipment with minimal investment • Develop materials and technologies compatible with scalable manufacturing methods that enable increasing production volumes
HVAC	All HVAC GEB Technologies	Limited understanding of duration, temperature, and humidity constraints for curtailment	• Model and test to characterize curtailment limitations
	HVAC#1: Smart Thermostats	None identified beyond sensors and controls content (refer to *Whole-Building Controls, Sensors, Modeling, and Analytics* report—see Section 1 for relevant links)	
	HVAC#2: Separate Sensible and Latent Space Conditioning	Complex installation and commissioning	• Develop packaged systems to reduce installation and commissioning complexity
	HVAC#3: Liquid Desiccant TES	Complex installation and commissioning	• Develop packaged systems to reduce installation and commissioning complexity
		Generally high floorspace needs	• Develop novel TES materials with increased energy storage density (volumetric and gravimetric) • Develop novel ways to package storage systems
	HVAC#4: Advanced Controls for HVAC Equipment with Embedded Thermostats	Lack of nonpremium products with grid-interactive functionality	• Develop inexpensive retrofit grid-interactive packages
Water Heating	WH#1: Water Heaters with Smart, Connected Controls	Lower preheat capabilities from HPWH (without heating element) vs. electric resistance	• Evaluate the optimal approach for hybrid electric resistance/HPWHs for curtailment • Develop low-GWP refrigerant-based (e.g., CO_2) HPWHs for higher-temperature capabilities
Appliances and Refrigeration	APP#6: MELs: Water Heating	Lack of nonpremium products with grid-interactive functionality	• Develop inexpensive retrofit grid-interactive packages
	APP#1: Modulating, Advanced Clothes Dryers	Lack of nonpremium products with grid-interactive functionality	• Develop inexpensive retrofit grid-interactive packages
		High product cost (heat pump models)	• Conduct cost-reduction R&D for heat pump clothes dryers
	APP#2: Advanced Dish and Clothes Washer Controls	Lack of nonpremium products with grid-interactive functionality	• Develop inexpensive retrofit grid-interactive packages
	APP#3: Connected Refrigerator/Freezer Advanced Controls	Lack of nonpremium products with grid-interactive functionality	• Develop inexpensive retrofit grid-interactive packages

Technology		Challenges	R&D Opportunities
	APP#4: Advanced Controls for Commercial Refrigeration	Lack of broad understanding of duration and temperature constraints for curtailment	- Model and test to characterize curtailment limitations
Natural Gas	**NG#1: Building-Scale CHP**	High product and installed costs	- Conduct cost-reduction R&D with a focus on smaller-scale (e.g., <50 kW) systems
	NG#4: Water Heaters with Smart, Connected Controls	None identified beyond sensors and controls content (refer to *Whole-Building Controls, Sensors, Modeling, and Analytics* report—see Section 1 for relevant links)	
	NG#2: Smart Thermostats	None identified beyond sensors and controls content (refer to *Whole-Building Controls, Sensors, Modeling, and Analytics* report—see Section 1 for relevant links)	
	NG#6: Modulating, Advanced Clothes Dryers	Lack of nonpremium products with grid-interactive functionality	- Develop inexpensive retrofit grid-interactive packages
Cross-Cutting	**CC#1: Thermal Energy Storage**	Complex installation and commissioning	- Develop packaged systems to reduce installation and commissioning complexity
		Large space requirements/footprint	- Develop novel TES materials with increased energy storage density - Develop novel ways to package storage systems
		Limited flexibility of thermal storage materials for year-round use	- Develop novel ways to modify TES materials to dynamically manipulate their transition temperature (e.g., for both heating and cooling energy storage) - Determine the conditions for thermal storage operation that offer the greatest GEB service provision potential and energy savings potential
	CC#3: Non-Vapor-Compression (NVC) Materials/Systems	High product costs	- Develop lower-cost NVC materials, systems, and components
		Nascent solutions have limited field validation of architectures and approaches	- Expand development of NVC for a broad range of HVAC&R applications
	CC#2: Modulating-Capacity Vapor Compression	High product costs	- Develop lower-cost modulating-capacity systems, with a focus on heat exchangers and compressors

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