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Windows and Opaque Envelope

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Disclaimer

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List of Acronyms and Abbreviations

AIA	American Institute of Architects
BIPV	building-integrated photovoltaics
BTO	Building Technologies Office
DER	distributed energy resource
DOE	U.S. Department of Energy
GEB	grid-interactive efficient building
HVAC	heating, ventilation, and air conditioning (also heating, *ventilating*, and air conditioning)
IECC	International Energy Conservation Code
IGU	insulating glass unit
PCM	phase change materials
R&D	research and development
TASs	thermally anisotropic systems
TOU	time-of-use
TWh	terawatt hours
T&D	transmission and distribution

Glossary

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

Grid services	Services that support the generation, transmission, and distribution of electricity and provide value through avoided electricity 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, focusing on windows and opaque envelope technologies only. It should be noted that the scope of this report and the *GEB Technical Report Series* is intentionally focused on technological capabilities and 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 major end uses for both residential and commercial buildings. End uses associated with windows and the opaque envelope comprise approximately 56% and 38% of residential and commercial electricity use annually from major end uses.[1]

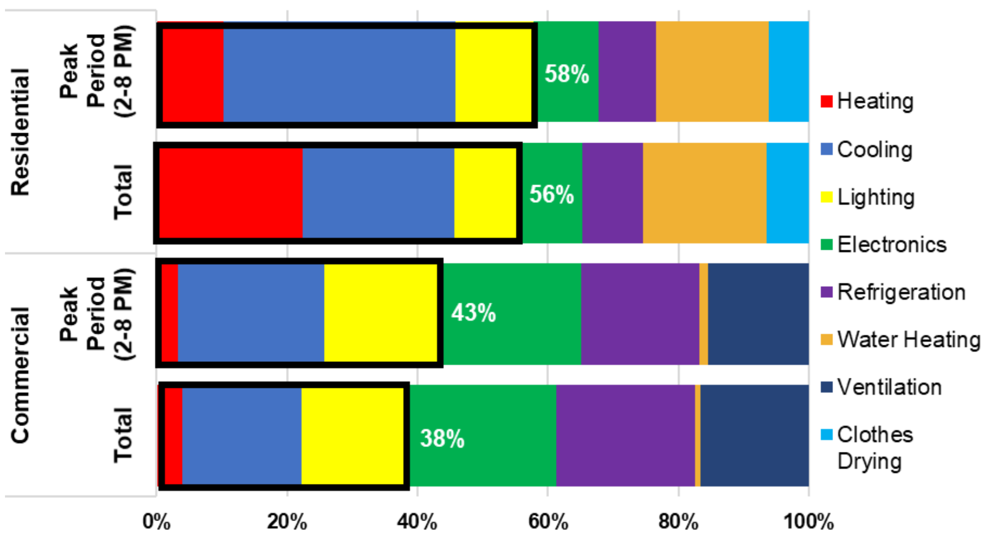

Figure ES-1. Total and peak period 2018 electricity use by major end use and building type[1]

Each colored bar represents a single end use and the end uses affected by technologies described in this report are outlined in black; the percentage contributions of the affected end uses to total and peak period electricity use are also shown.

[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.

This report focuses on dynamic window and opaque envelope technologies, as shown in Table ES-1. Dynamic building envelope technologies include, for example, electrochromic glazing, automated attachments, and thermal storage. These technologies are in contrast to static high-performance building envelope technologies, such as highly insulating windows.

Table ES-1. Dynamic Window and Opaque Envelope Technologies

Technologies		Description
Windows	**Dynamic Glazing**	Dynamic glazing includes a range of chromodynamic coatings applied to glazing that can switch between two or more states that block portions of the wavelengths that lead to solar heat gain in buildings.
	Automated Attachments	Automated attachments include interior devices, such as blinds, shades, and drapes, and exterior devices, including awnings and shutters, that can be adjusted automatically to reduce solar heat gain.
	Photovoltaic Glazing	Photovoltaic (PV) glazing describes a class of PV systems that can be installed in windows. Transparent and semitransparent PV glazing selectively absorbs a portion of the visible light wavelengths, allowing the remainder to pass through the glass and thus maintaining some visible transmittance. Switchable PV darkens in response to heating, thus activating the absorber layer.
Opaque Envelope	**Tunable Thermal Conductivity Materials**	Tunable thermal conductivity materials can dynamically adjust their thermophysical properties. The methods by which these materials change their properties vary widely, but the ultimate objective is to enable dynamic control over the operation of the envelope assembly in a manner that yields energy savings and has the potential to provide grid benefits as well.
	Thermally Anisotropic Systems	Thermally anisotropic systems (TASs) consist of materials or assemblies that have engineered layer(s) with alternating high and low thermal conductivities, thus yielding an anisotropic bulk material or assembly.
	Thermal Storage	Thermal storage materials store and release heat when charging and discharging, respectively. These materials can thus reduce and shift the timing of heating or cooling energy demand.
	Moisture Storage and Extraction	Moisture storage and extraction systems can actively remove moisture from the indoor environment and, with adjacent systems, reject it to the outside.
	Variable Radiative Technologies	Variable radiative technologies are a class of materials with radiation heat transfer properties that facilitate heat rejection and reflection from the exterior opaque envelope to the surroundings in a controlled manner, operating only when such operation is beneficial.
	Building-Integrated Photovoltaics	Building-integrated photovoltaics (BIPV) supplants or supplements opaque building facade materials with materials that incorporate PV cells for power generation. In this report, BIPV is distinct from traditional PV panels in that BIPV is designed to integrate into the aesthetic of the building, generally finished flush with the surrounding roof or facade, and sometimes mimicking the appearance of roof shingles, cladding panels, or siding.

The building technologies in Table ES-1 were evaluated based on their ability to provide value to the grid as well as 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.[2]
- **Load Shed**: the ability to reduce electricity use for a short time period and typically on short notice. Shedding is typically dispatched during peak demand periods and during emergencies.
- **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.

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

High Potential	Medium Potential	Low Potential
• Dynamic Glazing • Automated Attachments • Thermally Anisotropic Materials • Thermal Storage • Tunable Thermal Conductivity Materials	• Photovoltaic Glazing • Moisture Storage and Extraction • Variable Radiative Technologies	• Building-Integrated Photovoltaics

In Section 4, the window and opaque envelope technologies considered to have medium or high grid service potential are evaluated according to their attributes, including energy savings, resilience, system readiness, usability, cost, and human health impacts. Each of these technologies was analyzed with respect to these attributes, but not all attribute-technology combinations were found to have significant benefits or challenges. This exercise led to a list of relevant benefits and challenges that helped frame the R&D opportunities. The R&D opportunities articulated in Section 5 were developed based on the benefits and challenges of each technology and input from researchers and laboratories. The R&D opportunities identified in this report are summarized in Table ES-3.

[2] In general, efficiency has the greatest impact on the grid during high-cost periods by minimizing utilization of costly generation resources.

Table ES-3. Summary of Dynamic Window and Opaque Envelope Technology R&D Opportunities

Technology	Challenges	R&D Opportunities
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
All Dynamic Windows and Opaque Envelope Technologies	Grid service-specific control strategies that can balance occupant needs and grid benefits	• Determine quantitative measures for occupant comfort • Identify appropriate approaches for in-situ, real-time measurement of occupant comfort • Develop acceptable out-of-the-box defaults for controls that balance demand flexibility, building owner cost benefits (if any), and occupant comfort • Develop adaptive control systems that achieve improved multiobjective outcomes (e.g., comfort, cost, productivity, grid services) and minimize user overrides • Characterize conditions that lead to occupant overrides and develop strategies to minimize the probability of overrides
	Parameterization of grid response capability	• For technologies under development, employ preliminary multiphysics simulations of each GEB-relevant technology to explore the key figures of merit that influence demand flexibility ○ Quantify the influence of identified figures of merit on time to initial response, response (ramp) rate, total capacity, and other characteristics relevant to providing the grid services outlined in Table 4 ○ Determine the appropriate value or range of values for each of the key parameters identified for a given technology to provide the various grid services that can be provided by that technology • Develop deterministic quantitative methods for the design of sensors and control systems specific to each GEB-relevant window and opaque envelope technology
	Methods to quantify building-specific response characteristics	• Parametric study of the thermal response of residential and commercial buildings • Multiphysics simulation of the time-series interaction between GEB-relevant window and opaque envelope technologies and a range of residential and commercial buildings (prototypes or archetypes) • Easy-to-use design guidance for architects and engineers to specify and position sensors and control hardware so that the dynamic window and envelope components can deliver the expected grid services

Technology	Challenges	R&D Opportunities
Dynamic Glazing and Automated Attachments	Off-the-shelf controls with GEB functionality Complexity of sensor system configuration and commissioning	• Develop novel building controls strategies that incorporate dynamic glazing and automated attachment functionality into their core capabilities, alongside HVAC systems and other building components • Develop software tools for simple, low-effort sensor configuration planning and to verify installation and rapidly diagnose in-field faults • Determine whether GEB operation introduces additional commissioning or sensor system requirements and adapt tools accordingly
Tunable Thermal Conductivity Materials	Breadth of potential operations and the relative demand flexibility potential of various materials and configurations System physical and thermal response times Effect of assembly on operational performance	• Identify placement, applications, and types of tunable thermal conductivity materials or “circuit elements” that maximize demand flexibility • Investigate the energy savings, cost benefits, and demand flexibility potential of coupled systems (i.e., tunable thermal conductivity materials designed for use as a package with other dynamic envelope technologies) • Quantify the value of increasing the response speed of tunable thermal conductivity materials • Investigate the potential for more extensive changes in the envelope assembly to improve demand flexibility and energy savings • If valuable, design novel assemblies that use tunable thermal conductivity materials to enhance the performance of other dynamic and tunable components for demand flexibility and overall energy savings
Thermally Anisotropic Systems	Components or technologies that enable switching (on/off) of connection to sink/source Components or technologies that enable rate control with connection to source/sink Technologies that facilitate effective access to potential sources and sinks Effect of assembly on operational performance	• Develop novel materials or system designs that can effectively access thermal sinks and sources with minimal installation effort • Develop thermal switch materials or mechanical devices that can control the connection between the anisotropic material and a related source/sink • Investigate the potential for novel assemblies to improve performance, including coupling with other technologies • Determine ideal envelope assembly characteristics to maximize GEB capability • Design novel envelope assemblies that have improved compatibility with thermally anisotropic materials and composites

Technology	Challenges	R&D Opportunities
Thermal Storage	Active control of storage media Understanding of the desired or optimal capabilities for active control systems	• Develop materials or assemblies that can control the timing of charge and discharge cycles • Develop materials that can be dynamically manipulated to change their transition temperature • Develop materials or assemblies that enable control over charge and discharge rates/speeds • Determine the conditions for thermal storage operation that offer the greatest potential for demand flexibility and energy savings, independent of storage system characteristics, to establish requirements for active control capabilities (in addition to R&D conducted in response to "parameterization of grid response capacity or capability" in Table 9) • If indicated, develop control systems that minimize self-discharge
Moisture Storage and Extraction	Active control of storage media Understanding of the desired or optimal capabilities for active control systems	• Develop materials or assemblies that can control the timing of charge and discharge cycles • Develop materials or assemblies that can extract moisture in liquid form • Develop materials or assemblies that enable control over charge and discharge rates/speeds • Determine the conditions for moisture storage operation that offer the greatest potential for demand flexibility and energy savings, independent of storage system characteristics, to establish requirements for active control capabilities (in addition to R&D conducted in response to "parameterization of grid response capacity or capability" in Table 9)
Variable Radiative Technologies	Active control of operation Fouling, condensation effects on performance	• Develop materials that can alter key performance parameters in response to a control signal • Develop thermal switch materials for heat conduction control with daytime radiative coolers.

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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)[3] research and development (R&D) portfolio, BTO has published a series of technical reports that evaluate the opportunities for grid-interactive efficient buildings (GEBs)[4]. In addition to this report on windows and opaque envelope technologies, an overview report and three other GEB 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*[5]
- *Heating, Ventilation, and Air Conditioning (HVAC); Water Heating; Appliances; and Refrigeration*[6]
- *Lighting and Electronics*[7]
- *Windows and Opaque Envelope* (this report)
- *Whole-Building Controls, Sensors, Modeling, and Analytics*[8]

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, 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

[3] For more information, see: https://www.energy.gov/eere/buildings/building-technologies-office.
[4] For more information, see: https://www.energy.gov/eere/buildings/grid-interactive-efficient-buildings.
[5] Available online here: https://www.nrel.gov/docs/fy20osti/75470.pdf.
[6] Available online here: https://www.nrel.gov/docs/fy20osti/75473.pdf.
[7] Available online here: https://www.nrel.gov/docs/fy20osti/75475.pdf.
[8] 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 use 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, state-of-the-art sensors and controls can curtail or temporarily manage 10%–20% of commercial building peak load (Kiliccote et al. 2016; Piette et al. 2007). Accordingly, these strategies are available and necessary for implementing flexible, grid-interactive strategies to optimize building loads within productivity or comfort requirements.

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

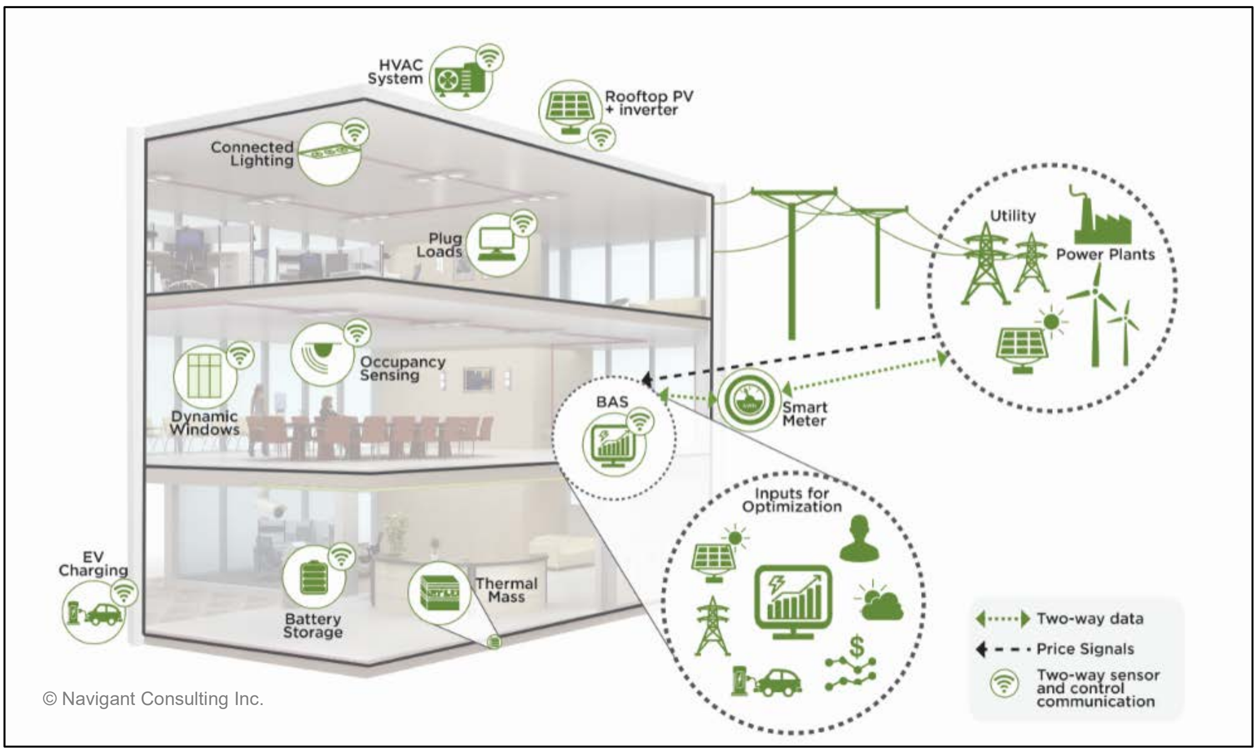

Figure 1. Example grid-interactive efficient commercial building

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

1.2 Report Approach and Scope

This report focuses on the building envelope, which comprises windows and the opaque envelope. The report approach is summarized in Figure 2. First, a list of current state-of-the-art and prospective future building envelope technologies that might have GEB technical potential are identified. Then, these technologies are evaluated according to their potential ability to provide seven grid services through four demand-side management strategies: energy efficiency, load shed, load shift, and modulating load. The grid services are elaborated in Table 1 in Section 1.3. Based on the potential to provide these grid services, each building envelope technology is classified as low, medium, or high potential. Then, technology attributes are discussed for each identified GEB technology, including energy efficiency, reliability, resilience, system readiness, usability, manufacturability, and health and environmental emissions. Finally, R&D activities and opportunities are identified based on current technical challenges facing the identified high- and medium-potential GEB technologies.

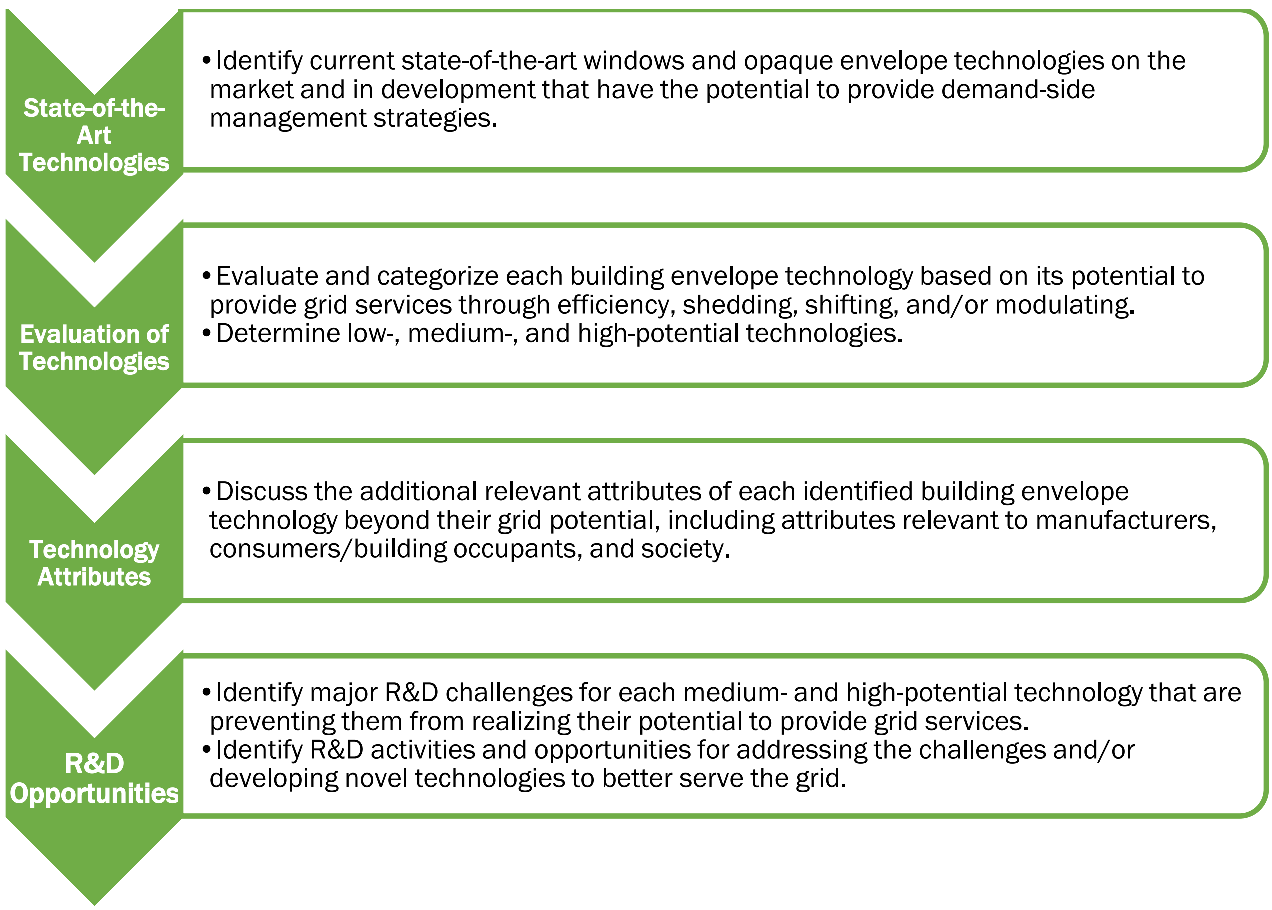

Figure 2. Windows and opaque envelope report approach

1.3 Grid Services Provided by Buildings

This report characterizes grid-interactive windows and opaque envelope technologies to help identify R&D opportunities to improve the demand flexibility for these technologies and the associated ability to provide grid services. Traditionally, a high-performance building envelope would be considered a key enabler for other end uses to provide grid services; this report considers the potential for the building envelope to itself provide grid services, in addition to the grid service potential that comes from coordination between a static or novel dynamic building envelope and other building end uses. 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 Service Benefits to Electric Utilities

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

Grid Services		Potential Avoided Cost
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[9]	Power plant fuel, operation, maintenance, and opportunity costs associated with providing contingency reserves
	Frequency Regulation	Power plant fuel, operation, maintenance, and opportunity costs[10] associated with providing frequency regulation
	Ramping	Power plant fuel, operation, maintenance, and startup and shutdown costs
Delivery Services	Non-Wires Alternatives[11]	Capital costs for transmission and distribution (T&D) 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. The ability of building envelope technologies to deliver value hinges on the existence of the necessary communications infrastructure to connect utilities directly to the end-use loads or to the building envelope's device-specific or whole-building energy control systems.

[9] This includes reserves products with various timescales, including spinning reserves, nonspinning reserves, and other particular reserves products that exist in some regions.
[10] For example, not selling power in order to be ready for up-regulation.
[11] Also referred to as deferred transmission and distribution (T&D) upgrades.

2 State-of-the-Art Technologies

The technologies covered in this report affect heating, cooling, and lighting energy use. These loads correspond to 511 and 338 terawatt hours (TWh) of site electricity use annually in residential and commercial buildings (Figure 3), comprising 56% and 38% of total residential and commercial electricity use from major loads (Figure 4). During the peak period of 2–8 p.m., the loads addressed by this report use 157 and 115 TWh of site electricity annually in residential and commercial buildings, comprising 58% and 43% of residential and commercial electricity use from major loads during this peak period.

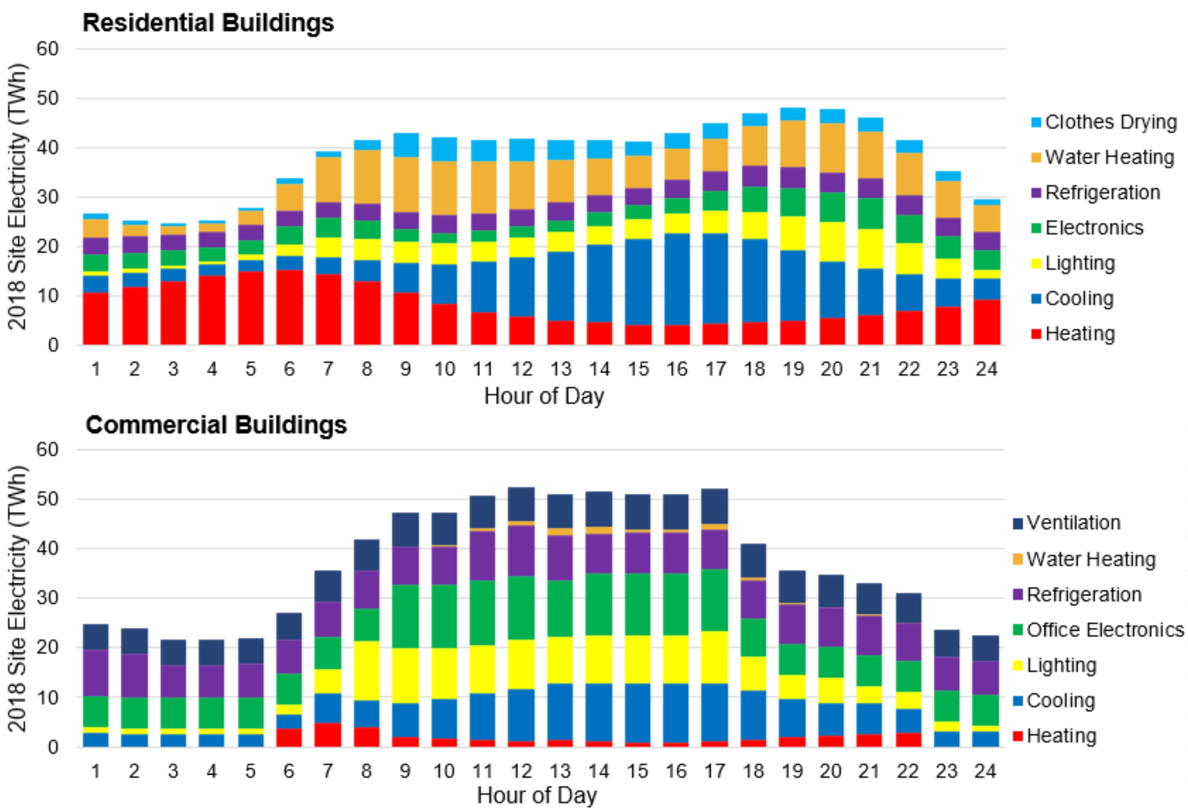

Figure 3. Hourly electricity use in residential and commercial buildings[12]

Total hourly electricity use in terawatt hours in U.S. residential buildings (top) and commercial buildings (bottom), broken out by major electric end use for 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.

[12] 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.

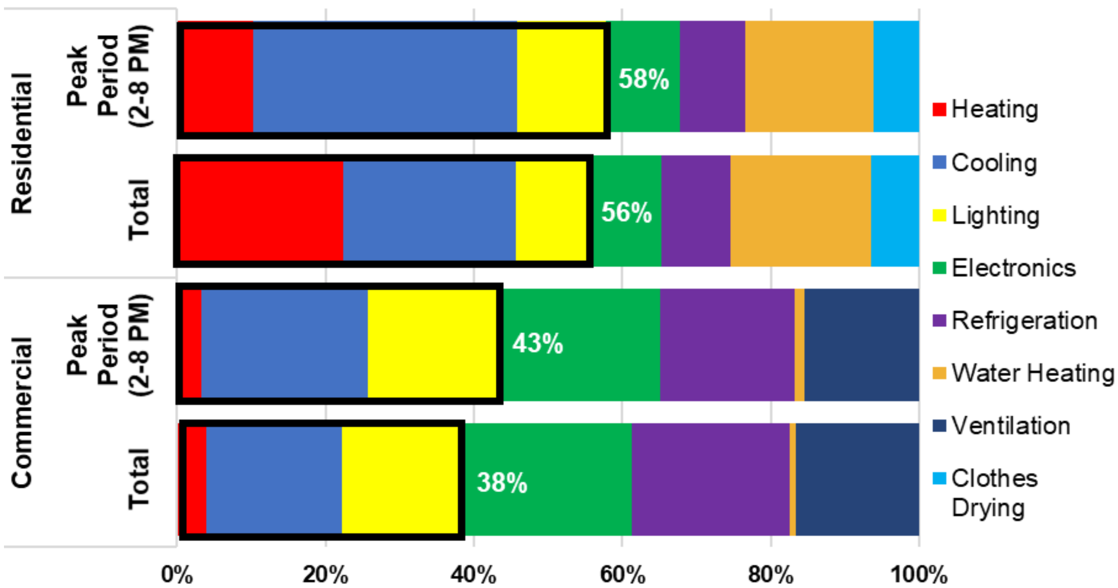

Figure 4. Total and peak electricity use by major end use and building type[13]

Total and peak period (2–8 p.m.) electricity use broken out by major electric end use in residential buildings (top) and commercial buildings (bottom) for 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; 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 56% and 38% of total residential and commercial electricity use from major loads and 58% and 43% 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 5, top image), comprising 43% of total residential summer cooling. In the commercial sector, these numbers are 40 TWh of electricity and 37% of total commercial summer cooling. Cooling electricity use in Figure 5 is driven by the Southeast region; the bottom image of Figure 5 shows that the Southeast also drives winter (December–February) heating electricity use, reflecting the large installed base of heat pumps and resistance heating in southern regions. Looking ahead, electrification of heating in northern regions, with their large heating demands, would grow the overall potential of the electric heating load substantially.

[13] 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.

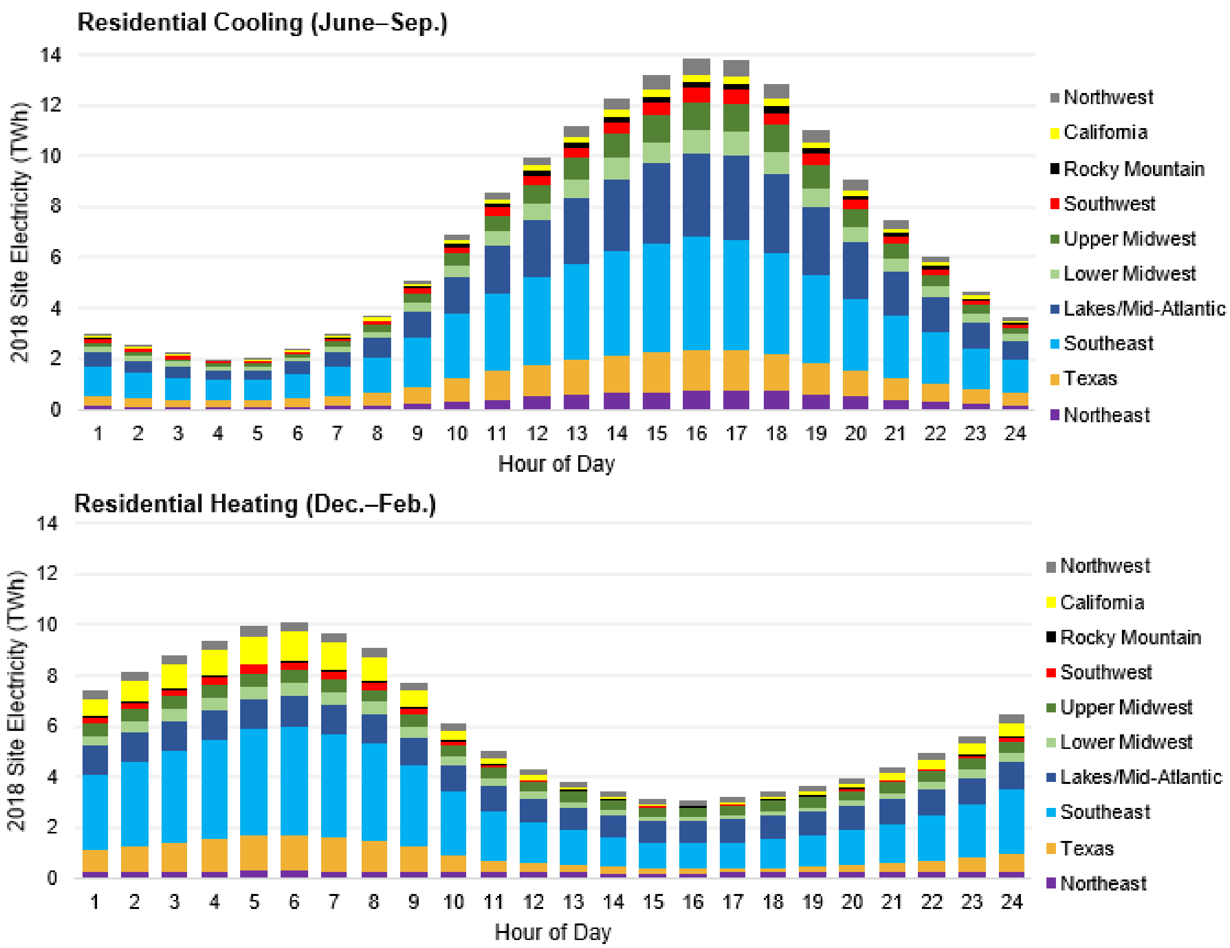

Figure 5. Residential cooling and heating hourly load profiles[14]

Total hourly summer cooling electricity use (top) and winter heating electricity use (bottom) in residential buildings, broken out by region for 2018. Each colored bar represents 1 of 10 regions in the United States and bar labels indicate the total site electricity use that occurs during each hour. Cooling peaks by the early evening (~4 p.m.) and has the largest diurnal changes in the Southeast and Great Lakes/Mid-Atlantic regions. The Southeast region also sees the largest hourly changes in winter heating, which peaks in the morning (~6 a.m.), reflecting the large installed base of heat pumps and resistance heating in that region.

2.1 High-Performance Dynamic Windows and Opaque Envelope Potential

The building envelope, which includes both windows and the opaque portions of the envelope, is the assembly that separates the conditioned indoor environment from prevailing outdoor ambient conditions. High-performance building envelopes more effectively control the influence of outdoor conditions on the interior environment than typical existing buildings and code-minimum new construction, reducing the heating, cooling, and lighting requirements to maintain the desired indoor conditions. Building envelopes do not use energy themselves, but they influence light, heat, and moisture conditions within the building, which directly impact lighting, heating, and cooling needs and corresponding energy use. Windows and window attachments also affect lighting energy use by admitting or blocking daylight. High-performance envelopes can improve

[14] 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.

occupant comfort while reducing the need for heating and cooling. As a result, both high-performance and dynamic building envelopes can provide benefits to the grid. The development of novel technologies that further advance the state-of-the-art in window and opaque envelope performance and functionality—whether through static or dynamic operation—are discussed at length in the forthcoming windows and opaque envelope Research and Development Opportunity publications.

2.1.1 Static High-Performance Building Envelopes

High-performance windows and opaque envelope assemblies can deliver substantial total energy savings and grid peak period demand reduction (load shedding) from both residential and commercial buildings while offering significant additional nonenergy benefits. In general, a building envelope that effectively manages heat transfer through high thermal resistance, minimal thermal bridging, effective air sealing, and appropriate windows for the climate will reduce energy use, including peak electricity demand. This peak-period demand reduction capability does not require dynamic or time-varying operation and is an inherent feature of a high-performance building envelope. The effect of a high-performance building envelope on summer electricity demand was recently quantified by researchers at Oak Ridge National Laboratory using a building physics simulation of two different single-family detached homes.[15] The "typical" building had equipment upgraded to the International Energy Conservation Code (IECC) 2012 code, but with duct leakage and an envelope and windows representative of typical existing homes. The "high-performance" building had similar equipment, reduced duct leakage compared to the "typical" home, and better-than-code envelope and windows. Average cooling season (June 12–September 17) electricity demand results for two IECC climate zones are illustrated in Figure 6. These results show that demand is similar during the early morning hours for both the typical and high-performance homes, but throughout the peak period, increased insulation and improved solar control reduces electricity demand dramatically. Average cooling season peak period (2–8 p.m.) energy use reductions observed across modeled climate zones[16] ranged from 20% to 43%.

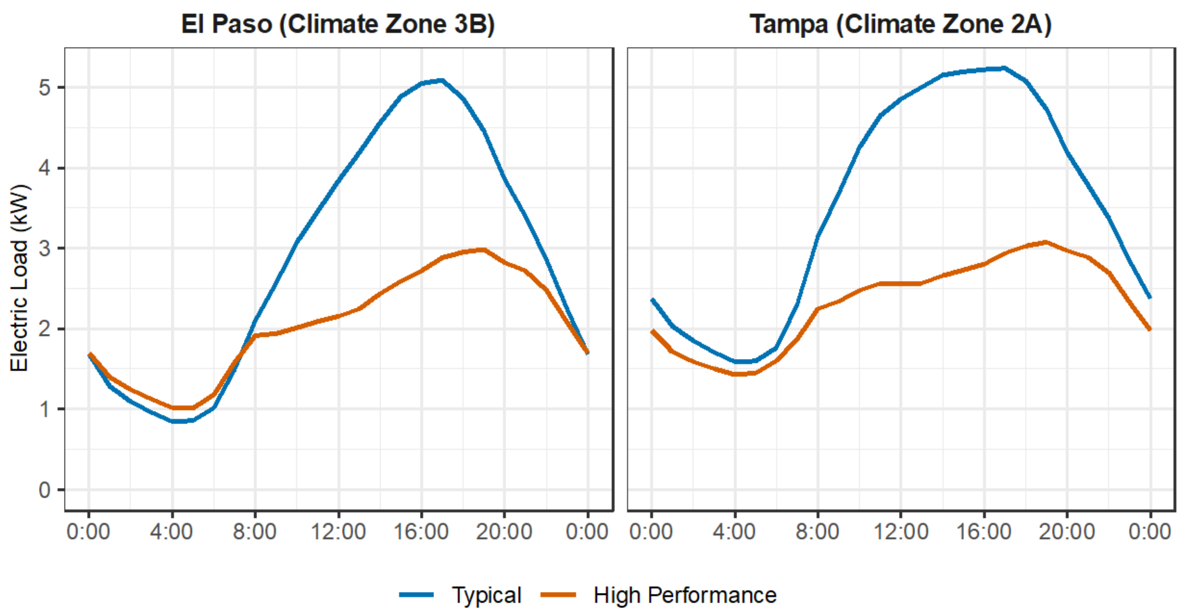

Figure 6. Simulation of a residential single-family detached home with varying levels of insulation

This simulation reveals that improved windows and increased insulation from current typical to slightly above current code levels yields dramatic reductions in electricity demand throughout the peak period during the cooling season.

[15] This Oak Ridge National Laboratory research was conducted for the purposes of this report, and the results are not currently published elsewhere.
[16] The analysis included single-family detached homes simulated in all major IECC climate zones.

Building envelope technologies can influence both summer and winter peak demand. Some building envelope technologies principally have a beneficial effect on peak electricity demand for cooling, such as thermal mass that increases inertia, and awnings, solar shades, exterior louvers, and other exterior-mounted devices that can shade windows from the afternoon sun. Interior shades can also reduce peak cooling loads, though somewhat less effectively than exterior window attachments (Curcija et al. 2013). Cool (reflective) roof surfaces and cool wall coatings are also demonstrably effective at reducing total and peak cooling energy use in cooling-dominated climates (Levinson and Akbari 2010). In regions with substantial winter heating loads and widespread electric heat, low U-factor (high R-value) windows and appropriately deployed insulating window attachments, in addition to a well-insulated and effectively air-sealed envelope, can help reduce winter heating peak electricity demand. A high-performance building envelope might facilitate peak shifting and overall peak reduction by enabling preconditioning (preheating or precooling); typical building envelopes fail to maintain a preconditioned environment for extended periods of time because of the lack of high thermal resistance (akin to trying to maintain food temperature in a refrigerator with the door ajar).

2.1.2 Dynamic Building Envelopes

In addition to windows and opaque envelope technologies with nominally static[17] performance properties, there are materials and technologies—both prospective and currently commercialized—that can dynamically modify their properties to improve envelope performance under varying interior and ambient conditions. Dynamic operation of the envelope could be triggered in response to immediate or forecast need for reserve capacity, changes in renewable generation output, or actual reductions or increases in electricity demand. A response to these grid service requests that is coordinated[18] between the dynamic envelope components and both the HVAC and lighting systems is likely to yield the largest potential response and the greatest control over the response from any individual building. In some climate zones, it is conceivable that a building envelope with a wide dynamic range and active thermal storage control could operate without an HVAC system, thus eliminating the coordinated HVAC and envelope control benefits, though this will require the development and commercialization of multiple active envelope technologies.

Dynamic envelope technologies that are widely commercially available include dynamic glazing—particularly electrochromic glazing—and automated attachments. Both technologies operate by switching their properties to either block or admit portions of the solar spectrum that come through windows. Automated attachments physically open or close to achieve this effect, while dynamic glazing switches the configuration of a coating on the glass. These technologies can reduce peak cooling loads by reducing unwanted solar heat gain and might be able to decrease peak heating loads by taking advantage of available solar heat gain blocked by windows with fixed solar heat gain coefficients and by attachments that are not adjusted to maximize energy benefits. Future R&D could yield additional technologies with dynamic capabilities, particularly for the opaque envelope. Table 3 describes a range of prospective dynamic technologies and materials for the opaque envelope. These materials could be developed to be actively controllable, likely with a meaningful response in the range of minutes to hours. Again, the speed and magnitude of the response will depend on the capability of the correlated building systems that use energy—HVAC and lighting—to respond in a coordinated fashion with the building envelope; for example, it might be possible for the HVAC system to turn off for the time that it takes the dynamic envelope component to respond appropriately. Tables 2 and 3 describe in further detail the dynamic window and opaque envelope technologies that are currently commercialized and still under R&D.

The development of novel dynamic and/or multifunctional materials that can reduce energy use and deliver grid services should be accompanied by a reconsideration of the design principles and typical assemblies used in buildings. In some cases, these new envelope assemblies might be incompatible with existing building envelopes and construction practices; fundamental changes in this regard might be worth the risk and complexity, as long as the materials offer sufficient building-level benefits to incentivize switching from

[17] The stated performance properties for envelope materials might vary as a function of ambient temperature or other ambient conditions, but this variation is a natural property of those materials and they are not considered dynamic materials.
[18] The technologies described in this report are most effective when operated in coordination with other building subsystems.

current business-as-usual materials, assemblies, and practices. Critically, these novel materials must meet nonenergy performance requirements and standards that apply to the functions served by incumbent building envelopes, including mechanical properties, fire performance, moisture tolerance, materials compatibility, and durability under typical operating conditions.

2.2 Current State-of-the-Art

This section summarizes the characteristics and current status of each state-of-the-art GEB technology, including a description of the technology and its interaction with the grid, its current performance level, its maturity (between early-stage research and fully commercialized), the applicable building sector and market, and the growth potential and projections. In Section 3, each of these technologies is evaluated by their ability to provide grid services. In general, the technologies in Tables 2 and 3 are active technologies, though a few passive versions of technologies are briefly mentioned. Static technologies that can provide GEB benefits are addressed in Section 2.1.1. Tables 2 and 3 present each technology in a separate section. Though these technologies are articulated separately, it is conceivable that they could be combined in a building envelope system, and such systems might yield greater energy savings or grid service capacity than the technologies when employed separately.

For windows, the current static state-of-the-art is characterized by a low U-factor (lower heat transfer between the building interior and exterior ambient conditions) and a fixed solar heat gain coefficient appropriate for a given climate zone. Northern regions that have large heating loads generally benefit from a somewhat higher solar heat gain coefficient to capture passive solar heating in the winter months. In most regions, the static solar heat gain coefficient is a tradeoff between blocking unwanted solar heating in the summer and allowing solar heating that offsets heating energy use in the winter. U-factors are affected by both the window frame and glazing, though recent developments in glazing technology appear poised to deliver larger near-term performance improvements compared to the current state-of-the-art (Hart, Selkowitz, and Curcija 2019). In particular, thin-triple insulating glass units (IGUs), which add a suspended center lite to a double-pane IGU, show promise as a route to reduced U-factors for both new and retrofit windows. In the future, durability and performance improvements in vacuum-insulated glazing might also lead to more mainstream availability and adoption. Table 2 describes the state-of-the-art for dynamic and actively controllable window technologies.

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

<table>
<tr><th colspan="2">GEB Window Technologies</th></tr>
<tr><th colspan="2">Dynamic Glazing</th></tr>
<tr><td>Overview</td><td>Dynamic glazing includes a range of chromodynamic coatings applied to glazing that can switch between two or more states that block portions of the wavelengths that lead to solar heat gain in buildings.
• Thermochromic glazing changes its state passively in response to temperature.
• Electrochromic glazing switches its state in response to a change in the applied voltage. It offers grid-integrated operational potential because it can be actively adjusted in response to a control signal to reduce energy use or provide grid services, though the response time of the electrochromic glazing might be faster than the correlated reduction in electricity demand.
These systems can modulate 75%–90% of visible and near-infrared wavelengths, thus yielding “light” and “dark” states when fully inactive and active, respectively. Three manufacturers currently offer electrochromic glazing, primarily targeted at the commercial buildings market. A third company passed industry-standard durability tests (ASTM 2141) in early 2019 on its way toward commercialization. DOE investment in electrochromic glazing R&D led to $2 billion in private-sector investment that brought these products to market.[19] Recent and ongoing research has investigated the potential for electrochromic glazing to offer decoupled control of visible and near-infrared wavelengths and to deliver “fully” darkened states that block all or almost all visible light for privacy purposes (DeForest et al. 2017). There is also the potential for largely transparent systems that reduce solar heat gain by selectively reducing some near-infrared wavelengths while maximizing visible transmittance (Garcia et al. 2011). Recent work by DeForest et al. (2017) has shown, however, that for at least one configuration of an electrochromic that has semicoupled switching of visible and near-infrared wavelengths, the additional energy savings are highly dependent on climate zone and building type. Increases in the dynamic range (effective solar heat gain coefficient) of electrochromic glazing beyond the current state-of-the-art could yield additional energy savings and might also improve demand flexibility (DeForest et al. 2017).</td></tr>
<tr><td>Applicable Market</td><td>Dynamic glazing can be installed in new construction and deep building retrofits, though the additional effort to provide an electrical connection is mitigated during new construction or a deep retrofit while the walls are open and both electrical and glazing trades will be on-site. Dynamic windows have generally been marketed toward and adopted in commercial buildings. In all application areas, the additional sensors, controls, and commissioning effort to ensure operation to deliver energy savings and flexibility adds to the total installed price of the system, though without this investment, the systems are unlikely to deliver any energy savings and might be subject to regular occupant overrides (Fernandes et al. 2018).</td></tr>
<tr><td>Growth Potential</td><td>Electrochromic windows are currently a small portion of the commercial windows market. Both reduced prices and improved formulations with neutral (gray) coloration in the darkened state would help accelerate adoption. In addition, improvements to and reductions in the cost of sensors and control systems that coordinate dynamic glazing operation with lighting and HVAC systems would reduce overrides and improve occupant comfort, thus improving the value proposition of dynamic glazing (U.S. General Services Administration 2014). Simplifying the commissioning process would also reduce prices and improve occupant satisfaction with the systems (Fernandes et al. 2018). Large commercial buildings, particularly those with glass curtain wall facades, present an especially significant opportunity for growth given that other technologies that enable envelope flexibility are not suitable for facades dominated by glazing.</td></tr>
</table>

[19] https://www.greentechmedia.com/articles/read/view-gets-massive-1-1-billion-investment-from-softbank#gs.7ldisj.

Automated Attachments	
Overview	Window attachments include interior devices, such as blinds, shades, and drapes, and exterior devices, such as awnings and shutters. In some cases, these attachments are operable so that they can be repositioned to control glare and perimeter zone heating and also provide privacy. Motorized attachments incorporate electric motors that provide remote control of attachment positioning. Adding network connectivity, light sensors, and control software to electrically actuated attachments allows the attachments to minimize HVAC and lighting energy use while maximizing occupant comfort. These automated attachments can offer benefits to the grid by reducing peak demand with improved control over solar heat gain and reduced lighting energy use during peak hours. Automated attachment systems are available today, though systems that have energy or grid-optimized operation are not commonplace. Automated attachments comprised approximately 10% of the window attachments market in 2018, and that figure is expected to rise to 12% by 2023 (Sundale Research 2019). Fixed attachments, such as exterior shades or awnings, can also reduce unwanted solar heat gains during periods of peak cooling demand but might be avoided for aesthetic reasons.
Applicable Market	Most buildings can accommodate automated attachments, though certain exterior attachment technologies might not be compatible with some facade types. The energy savings potential and associated GEB operational strategies will differ between commercial buildings (typically occupied during daylight hours) and residential buildings (with varying occupancy depending on the day of the week, but generally unoccupied during daylight hours). Automated attachments require an electricity supply, which can come from an integrated battery and small solar PV panel or from a connection to the building's electrical system. Wiring into the building's electrical system can add to the cost and complexity of retrofits (compared to manually operated attachments) and all automated systems will likely require some commissioning costs for optimal operation.
Growth Potential	Automated attachments have seen some adoption in commercial buildings, particularly in institutional settings where windows are out of easy reach for manual adjustment or where automatic adjustment is integrated into a lighting control system. These systems are generally designed to offer occupants convenient control of overall space illumination as well as glare and thermal comfort control, and do not have any energy savings objectives or operational capability. Systems that are designed to offer energy savings via autonomous operation are not widely available. If these systems are installed, adding passive or active coordination with the HVAC system, alongside lighting, could deliver further energy savings and improved grid responsive capability. Ensuring occupant satisfaction and minimizing the probability of overrides because of undesirable operation will be important to maximize energy savings and the potential for deployment in response to grid signals. Integration with home automation systems might drive adoption in the residential market. Newly introduced energy performance labeling might also help build consumer confidence in the energy savings potential of these products. For all building types, aesthetic considerations—such as having a consistent, uniform facade appearance—should be addressed, because "unattractive" technologies will not be adopted even if they offer proven comfort benefits or energy savings.

Photovoltaic Glazing	
Overview	PV glazing and traditional PV generate electricity in the same basic way. However, in the case of transparent and semitransparent PV glazing, the active material selectively absorbs a portion of the visible light wavelengths, allowing the remainder to pass through the glass, maintaining some visible transmittance. Some semitransparent PV glazing products are commercially available today. Switchable PV darkens in response to heating, thus activating the absorber layer. A range of material formulations for switchable PV has been demonstrated at the lab scale. In general, these technologies have not been demonstrated for the glazing sizes typical of residential or commercial windows, and research efforts continue in many areas, including efforts to increase efficiency and durability. Because these PV systems are mounted on surfaces that might be intermittently shaded, and are at a different angle and orientation from optimally positioned PV, the timing of their power generation will be different, which might reduce the aggregate ramp rate from changes in the solar resource (Rhodes et al. 2014). Moreover, the timing of power generation will likely be directly correlated to building HVAC demand driven by solar heat gain, though time-shifted because of the lag arising from building thermal mass. In addition to PV glazing, power generation at the facade can be achieved with traditional PV panels mounted on shading louvers or as awnings. These systems also provide passive shading from unwanted solar heat gains during summer peak periods.
Applicable Market	PV glazing is best suited to buildings that have a large glazed area with good solar access and limited roof area, such as high-rises. PV glazing is also most easily integrated into new construction. As a component that enables a self-powered dynamic window, PV glazing could improve the retrofit suitability of electrochromic windows. PV glazing could similarly be used to power automated attachments, which might also reduce the installation cost of these components at the facade in existing buildings. For power generation at the facade, existing buildings would require substantial additional infrastructure to support grid connection of the windows. In new construction, for buildings with substantial glazed area and limited available roof area, the additional cost might be acceptable if on-site power generation is strongly desired by the customer.
Growth Potential	PV glazing has very limited commercial availability currently. Because glass is a major contributor to the overall cost of PV panels (Wheeler et al. 2017), the incremental additional cost for transparent or switchable PV in glazing applications at scale will likely come mostly from additional balance-of-system or installation costs—innovative approaches that have successfully reduced the balance-of-system and installation costs for traditional rack-mounted PV might be applicable to PV glazing as well. Other glazing applications (e.g., automotive) might also be an early market entry point for this technology. Traditional PV at the facade in an awning-type configuration can be built today. Although these systems are immediately available at lower prices ($/W installed) than PV glazing and likely will be for the foreseeable future, the specific aesthetic and limited glazing accessibility from the outside that these panels create limits design options for architects and might be rejected by either the architect or the customer. Wind loads might also preclude their installation as a retrofit to existing buildings.

The current state-of-the-art in static opaque envelope technologies corresponds to materials that offer a high R-value per inch of insulation material thickness. The best materials include vacuum-insulated panels (VIPs) and fiber-reinforced aerogels, though these have seen limited application in buildings because of high costs as well as durability and product availability challenges. More typically, high-performance insulation is represented by a range of polymer foam materials. Durable, low-price, and low-production-cost materials that substantially exceed the performance (R/in) of current polymer foams are presently being researched, but none have yet been commercialized at scale. Technologies that are suitable for low-cost, low-intrusion, high-performance retrofits also remain elusive. Although "drill-and-fill" retrofits that fill uninsulated wall cavities with fibrous insulation materials are cost-effective for older homes, they have not found widespread adoption. Envelopes can also be reconstructed or overclad to add further insulation, but these retrofits typically involve substantial installation labor and associated costs. Table 3 expands upon the current and potential future dynamic and actively controllable opaque envelope technologies.

Table 3. State-of-the-Art GEB Envelope Technologies

GEB Opaque Envelope Technologies	
Tunable Thermal Conductivity Materials	
Overview	Tunable thermal conductivity materials can dynamically adjust their thermophysical properties. The methods for this functionality vary widely, but for buildings applications, the ultimate objective is to enable dynamic control over the operation of the envelope assembly in a manner that yields energy savings and also has the potential to provide grid benefits. As an example, in the cooling season, a tunable thermal material would have high thermal conductivity (low R-value) when ambient temperatures are lower than the indoor temperature, thereby providing cooling without the HVAC system. Similarly, this material would have low thermal conductivity (high R-value) when relative indoor and outdoor temperatures are reversed, minimizing thermal losses to the exterior. The result would be like night flushing,[20] but would not require extended ventilation system operation or automated operable windows, which can increase latent loads. Tunable thermal conductivity materials could also be combined in assemblies with other envelope materials (e.g., thermal storage) to create a system that can actively store and release thermal energy. In this configuration, the tunable thermal material would be adjusted to high or low thermal conductivity to control when energy is stored and released from the thermal storage material (Antretter et al. 2019). Depending on the specific configuration and characteristics of the thermal mass and tunable thermal material(s), the assembly could shift all peak period heating or cooling energy use for a building to off-peak hours (Antretter et al. 2019). Energy savings estimates for dynamic insulation—a specific tunable thermal system concept—range from 7%–42% compared to an R-30 wall, with the greatest savings in marine and colder dry climate zones (Menyhart and Krarti 2017). Using dynamic insulation in an envelope assembly that incorporates thermal mass yields energy savings of 5%–70% compared to a code-compliant wall (Antretter et al. 2019) and estimated total U.S. technical potential energy savings of 1.5 quads. Energy savings from dynamic insulation are the largest in moderate and hot climates (AIA climate zones 3–5).
Applicable Market	Tunable thermal conductivity materials are likely well suited to new construction, because the configuration of the envelope assembly, interior structural elements, and interior partitions can be optimized to maximize the energy savings and demand flexibility potential of these materials. These materials could be integrated into existing buildings, though their effectiveness might be limited by the characteristics of the existing envelope and interior components. Compared with traditional, static envelope retrofits, more extensive reconstruction might be required, thus leading to substantially increased costs. Buildings with highly insulated facades would likely be poor candidates for a retrofit with tunable thermal conductivity materials unless the existing insulation is removed and possibly replaced with other materials that enhance the

[20] Increased air movement at night—through open windows or driven by ventilation fans—to cool the interior of a building using cool outdoor air.

	operation of the tunable elements (e.g., thermal mass). Commercial buildings with high window-wall ratios also might not see meaningful benefits because of their limited opaque facade area. If these materials are developed and commercialized, additional work would be needed to evaluate the energy savings implications of installing the system with different existing building facade configurations and to identify the most cost-effective strategies for retrofitting existing buildings and yielding reasonable energy savings.
Growth Potential	Tunable thermal conductivity materials appear to deliver the greatest energy savings potential in specific climates in the United States, though in all climates some energy savings should be possible. Enabling demand flexibility might encourage installation in a wider range of locations than just those with large energy savings. Given that these materials are not currently commercially available or in active development, it is difficult to assess their growth potential. If these materials can be developed and commercialized, diagnostic technologies that better characterize the energy performance-relevant properties of the envelopes of existing buildings might be helpful in identifying buildings that are good retrofit candidates. Continuous growth of the PV market and other renewable sources of energy could make the use of interior walls or elevated floors with dedicated charging systems attractive.

Thermally Anisotropic Systems	
Overview	Thermally anisotropic systems (TASs) describe materials with carefully designed intrinsic thermal anisotropy (“thermally anisotropic materials”) as well as composites specifically assembled to have thermal anisotropy (“thermally anisotropic composites”). Regardless of the formulation, TASs consist of engineered layer(s) with alternating high and low thermal conductivities. The high conductivity layer(s) must be connected to a heat sink or source; for example, a heat sink could be a plumbing loop with circulating water (Biswas et al. 2019). TASs have anisotropic thermal transport properties, because the high conductivity layer(s) are the least resistive paths for heat transfer, thus helping reroute heat flow through the envelope to the connected heat sink or source. TASs also might have the potential to be dynamically controlled by changing the heat transfer characteristics of the connection between the TAS and the heat sink or source. Preliminary finite element model results validated against lab experiments on a large-scale prototype show that TASs could reduce peak cooling and heating energy demand associated with heat transfer through residential building envelopes by more than 60% compared to walls with R-13 cavity insulation and 1.5-inch continuous exterior insulation (Shrestha 2019). Total U.S. technical potential energy savings are an estimated 0.6 quads for the residential sector. Additional investigation is needed to establish energy savings and demand flexibility potential across building types and climate zones and to explore optimal TAS configurations and parameter values to maximize energy savings and demand flexibility. Laboratory evaluation of full-scale TAS panels is ongoing and field evaluation is planned. This technology still requires early-stage research on building integration, heat harvesting, form factor, and appropriate configuration for grid-interactive operation.
Applicable Market	TASs could be incorporated into an existing building retrofit, but they will likely incur minimal marginal materials or installation costs in new construction. Both residential and commercial buildings could benefit from TASs, though the energy savings and grid-interactive potential has not yet been established for commercial buildings.
Growth Potential	To reap substantial energy savings or grid-responsive capability, these materials would have to be applied over a substantial portion of the opaque facade. TASs require some supporting infrastructure (i.e., heat sinks or heat sources) not required for typical envelope insulation, but they should otherwise be compatible with typical overcladding and recladding envelope retrofits. The existing envelope retrofit market is small, but grid-interactive benefits could broaden the market uptake of these retrofits. Utility incentives, particularly to reduce capital costs, might also help market uptake of TASs as an alternative to traditional envelope retrofits.

Thermal Storage	
Overview	Thermal storage materials store and release heat when charging and discharging, respectively. These materials can thus reduce and shift the timing of heating or cooling energy demand. Thermal storage behaves similar to thermal mass, which is a well-established passive method for storing and releasing heat. When designed appropriately, high-thermal-mass buildings can maintain a comfortable interior temperature with reduced HVAC energy use despite outdoor temperature diurnal variations. Thermal storage enables thermal mass to be added to buildings with less weight and volume for equivalent storage capacity; thus, it is feasible for building retrofits and allows for greater design flexibility in new construction. Phase change materials (PCMs) are a class of thermal storage materials that are currently commercially available and can be concentrated or integrated into the building structure or envelope as well as HVAC equipment. With respect to grid-interactive operation, existing PCMs charge and discharge passively in response to ambient temperatures. Depending on the PCM formulation, they can shift either peak heating or cooling to off-peak hours, but they cannot control the timing of charging or discharging to maximize grid benefits. Depending on the placement and total capacity of a thermal storage system, it might improve occupant thermal comfort (particularly in perimeter zones) in addition to providing GEB benefits. Developing materials or packaging that enable control of charging and discharging is a key enabler for using this technology to offer grid benefits. Materials that can modify their switching temperature or characteristics to operate in both the summer and winter would significantly increase the total energy savings and grid-relevant benefits, particularly in regions with substantial electric heating/winter peak electricity demand. Additionally, novel materials and approaches are needed to address the major current shortcomings, such as subcooling and superheating (charging and discharging only start at temperatures far above or below the material's nominal transition temperature), leakage, phase segregation (for some PCM formulations), low lifetimes because of a wide range of failure modes, and high prices.
Applicable Market	Envelope-integrated thermal storage can be installed in a range of building types. Thermal storage might be more readily integrated as part of envelope specification for new construction, but attempts in existing buildings exist (Heier, Bales, and Martin 2015). Whether thermal storage is cost-effective for individual buildings will vary based on a variety of factors, such as climate zone, building size, HVAC system configuration, occupancy levels, and the total installed cost of the thermal storage system. Thermal storage could be suitable for both residential and commercial buildings, although more research is needed to establish the specific storage system parameters that will affect the energy savings and load shifting potential of thermal storage.
Growth Potential	Envelope-integrated thermal storage competes with other types of energy storage. For example, ice storage is relatively simple and inexpensive, but suffers from low gravimetric and volumetric energy density, and is thus suitable only for larger commercial buildings. Ice storage is also limited to only offering cooling energy savings and cooling energy demand-shifting. Because of the large surface area of the building envelope, envelope-integrated thermal storage does not require particularly high volumetric and gravimetric energy density to be suitable for a range of buildings. There are thermal storage materials that are currently commercially available, but price, performance, and durability limitations with these materials have limited their market acceptance, so the existing installed stock of thermal storage systems in U.S. buildings is quite small. If novel thermal storage materials are developed that address these price and performance challenges, substantial untapped market potential remains.

Moisture Storage and Extraction	
Overview	Moisture control is a significant contributor to cooling energy use in buildings, and cooling energy is a major driver of peak electricity demand. Envelope components, particularly those with surfaces exposed to indoor air, can be significant contributors to the moisture storage capacity of a building; moisture storage enables buildings to better tolerate moisture introduced from internal loads and from weather. Materials that can not only store water temporarily, but actively extract moisture from the indoor environment and—with adjacent systems—reject it to the surroundings, would complement existing moisture storage and reduce cooling energy use. Operating these materials on-demand might also enable time-shifting of cooling energy use while maintaining thermal comfort for building occupants by first storing moisture and then later using electricity to remove the moisture from the storage medium. The sizeable surface area available from the building envelope and internal walls could lead to substantial moisture removal capability when needed. Ideally, moisture stored from the building interior could be rejected to the exterior in liquid or vapor form; in either form, careful engineering will be required to ensure that the materials do not discharge moisture into envelope cavities. Stored moisture could also be returned to the interior and extracted from the air, if necessary, using the cooling system; this operational approach would still deliver some time shifting of cooling energy demand. These materials are currently at the laboratory scale, with significant fundamental materials research needed to identify potential physical mechanisms by which the previously described operation could be achieved.
Applicable Market	These systems would likely be suitable for both new construction and existing buildings, though additional preparatory work might be needed for existing buildings to ensure that the envelope is not damaged by improperly redirected moisture. In new construction, wall and ceiling assemblies can be designed intentionally to accommodate this functionality where it is cost-effective or desirable from the perspective of the building owner or utility.
Growth Potential	The energy savings derived from these systems will be highly climate dependent. Regions with long hot and humid summers will see the greatest total energy savings and peak period demand reductions, though climate zones that are humid but experience shorter periods of hot weather might also see substantial peak demand reductions and thus might see significant growth, particularly subject to available purchase or operational incentives. Preventing mold that arises from moisture trapped in the envelope is a significant concern for building occupants and ensuring that envelope assemblies are “moisture safe” is a significant focus for builders (LePage, Schumacher, and Lukachko 2013; Lstiburek and Carmody 1991); as a result, these materials might be of interest even in applications where the potential for demand flexibility is not substantial.

Variable Radiative Technologies	
Overview	Cool roofs and cool surfaces are well-established products that can deliver proven cooling energy savings, have good long-term durability, and are cost-effective. They are best suited to warm, sunny climates, and will not offer substantial annual energy savings in other regions. These materials are inherently passive; although they will reduce peak electricity demand during the cooling season, they cannot shift electricity use in a scheduled manner or in response to a specific request for operation or deployment. Materials that operate more like dynamic (particularly electrochromic) glazing, changing their radiation heat transfer properties in response to a control signal, could facilitate demand flexibility by reducing both peak heating and cooling loads. Moreover, unlike dynamic glazing, these materials do not suffer from tradeoffs that are imposed by the requirements of maintaining visible transmittance or controlling glare; these materials can operate in their full dynamic range without consequences for occupant comfort. Recent research has yielded photonic and plasmonic radiative cooling materials that can reject heat during the daytime, even in direct sun. Daytime radiative cooling materials can also operate in a manner similar to cool roofs and surfaces, rejecting excess heat to the ambient. These materials would likely perform best when paired with other dynamic envelope components, particularly TASs, whose demand flexibility potential hinges on having access to a thermal source and/or sink. For these materials, dynamic control is again important—overcooling is a significant consideration in climates with large seasonal temperature changes. The maturity of these materials varies. Some startups are seeking to commercialize material formulations already developed, while work continues to develop novel materials that perform well in a wider range of climates (especially in hot-humid climates).
Applicable Market	These materials could likely be developed to be usable for both new construction and retrofits. New construction might allow for other improvements in the opaque envelope assembly design that enhance their performance. However, because these materials are externally applied or mounted, they are far more likely to be easily applied as a retrofit solution compared to technologies that require changes within wall cavities or that the building's exterior sheathing be removed to allow for their installation. Because they operate on the opaque envelope, their demand flexibility potential and total energy savings will be greatest for buildings with lower window-wall ratios.
Growth Potential	These materials have substantial growth potential, though that might depend somewhat on the concurrent development and commercialization of other dynamic opaque envelope technologies. In some climates, these materials will have substantial energy savings potential alone that might justify their adoption, while in other climates, more complex operating capabilities might be needed before their adoption makes sense for a diverse set of buildings.

Building-Integrated Photovoltaics	
Overview	Building-integrated photovoltaics (BIPV)[21] supplants or supplements exterior building facade materials with materials that incorporate PV cells for power generation. In this report, BIPV is distinct from PV glazing in that BIPV applies to the opaque portion of the envelope—exterior cladding or sheathing and roofing materials. BIPV is also distinct from traditional off-the-shelf PV panels mounted to the roof or facade using a racking system because BIPV is designed to integrate into the aesthetic of the building, generally finished flush with the surrounding roof or facade, and sometimes mimicking the appearance of roof shingles, cladding panels, or siding. BIPV generally uses commercially available PV cell chemistries, and principally differs from traditional rack-mounted PV in its form factor, not the way it generates electricity. BIPV does not interact with building energy end uses directly like other building envelope technologies discussed in this report; it only uses the opaque envelope as a mounting location.
Applicable Market	BIPV can be used on a wide range of buildings and is generally mounted flush with the roof or facade surface. Panel orientation (direction the panel faces) and tilt (angle from horizontal) have a substantial effect on PV power output; thus, BIPV will not generally maximize total electricity generation potential for a given building, even if more total area can be covered with PV modules when using BIPV compared to traditional rack-mounted PV panels. In general, however, there is substantial roof area among both residential and commercial buildings that do not yet have PV, and BIPV is an option for many of those buildings. BIPV also opens up the potential to add PV to building facades with a product that is more visually appealing than adapting traditional PV panels for that application.
Growth Potential	In the residential sector, BIPV might offer an alternative to traditional rack-mounted solar for customers that would like rooftop PV but have an aesthetic objection to traditional systems, or in areas where covenants or codes restrict the installation of PV visible from the street. The reduction in power output resulting from nonoptimal panel orientation and tilt, when combined with much higher total installed prices, currently limit the appeal of residential BIPV to the aforementioned cases. For buildings that have limited roof area and low window-wall ratios (low fraction of glazed area on the facade), BIPV could provide an option for on-site power generation. For commercial and large residential buildings, like PV glazing, facade-mounted BIPV does not compete for roof space with other equipment, such as rooftop units, condensers, or elevator machine rooms. High-rise buildings could also take advantage of BIPV given their substantial facade area, though in areas with densely packed high-rises, shading from adjacent buildings significantly reduces the power-generating potential of BIPV.

[21] BIPV is sometimes referred to as building-applied PV (BAPV).

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).[22] 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.[23]
2. **Load Shed:** the ability to reduce electricity use for a short time period and typically on short notice. Shedding is typically dispatched during peak demand periods and during emergencies.
3. **Load Shift:** the ability to change the timing of electricity use. In some situations, a shift may lead to changing the amount of electricity that is consumed. Load shift in the *GEB Technical Report Series* focuses on intentional, planned shifting for reasons such as minimizing demand during peak periods, taking advantage of the cheapest electricity prices, or reducing the need for renewable curtailment. For some technologies, there are times when a load shed can lead to some level of load shifting.
4. **Modulate:** the ability to balance power supply/demand or reactive power draw/supply autonomously (within seconds to subseconds) in response to a signal from the grid operator during the dispatch period.

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 T&D system. Demand response is the main form of demand flexibility used today, though it is fairly limited in scope. The majority of demand response programs are generally focused on reducing peak demand through shedding or shifting, through direct load control (by utilities/demand aggregators), or behavioral load control programs in which utility customers make a decision to reduce their load in response to price signals.

In addition to peak demand reductions, a GEB may also be able help regulate power quality, provide contingency reserves, provide ramping services, or help avoid renewable energy curtailment. Table 4 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 window and opaque envelope technologies in Section 3.2.

[22] Voltage support is not included here because building envelopes are unlikely to provide this service.
[23] In general, efficiency has the greatest impact on the grid during high-cost periods by minimizing utilization of costly generation resources.

Table 4. 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 T&D: 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 T&D: Non-Wires Solutions	Load reduction during peak periods in response to grid constraints or based on time-of-use (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 T&D: Non-Wires Solutions	Load shifting from peak to off-peak periods in response to grid constraints or based on TOU pricing structures.	Typical duration	30 mins to 4 hrs
			Load change	Short-term shift
			Response time	<1 hour
			Event frequency	<100 hrs per yr/seasonal
	Contingency Reserves	Load shift for a short time to make up for a shortfall in generation.	Typical duration	Up to 1 hr
			Load change	Short-term shift
			Response time	<15 min
			Event frequency	20 times per year
	Avoid Renewable Curtailment	Load shifting to increase energy use at times of excess renewable generation output. This type of load shifting is not a dispatchable service but can be indicated through TOU pricing.[24]	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.[25]	Typical duration	Seconds to minutes
			Load change	Rapid increase/decrease
			Response time	Seconds to minutes
			Event frequency	Continuous

[24] TOU pricing that specifically incentivizes energy use times when renewable generation output is high and electricity prices are low.
[25] This is not currently offered as a grid service by any RTOs/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 4. 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.[26] 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 strategy (efficiency/shedding/shifting weighted higher than modulating), each technology is determined to have low, medium, or high potential to provide grid services in GEBs. Table 5 provides a summary of this evaluation, including the capabilities to perform the demand-side management strategies and the overall potential rating.

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

Table 5. Evaluation of Technology Capabilities

	Technologies	Efficiency	Load Shed	Load Shift	Modulate	Overall Potential
Windows	**Dynamic Glazing**	●	●	◑	○	High
	• Reduces cooling load by controlling solar heat gain • Might be able to provide some faster-responding service by modifying perimeter zone conditions if HVAC operation can be controlled independently in perimeter and core zones • Coordinated controls with HVAC calibrated to the building are needed to minimize response time and maximize response magnitude • Capability assumes response is triggered by automated demand response or another utility-generated control signal • Very fast responses (“Modulate Load”) are not possible due to the thermal inertia of the building and slow switching speeds of dynamic glazing compared to required response times and durations					
	Automated Attachments	●	●	◑	○	High
	• Similar functionality to dynamic glazing, though effectiveness depends on attachment material and interior or exterior placement • Supplemental lighting might be required when attachments are deployed • In residential applications, opening attachments during non-occupied daytime hours can capture beneficial winter solar heat gains					
	Photovoltaic Glazing	◑	◐	○	◐	Medium
	• Some load shedding might be possible for PV glazing formulations that also offer solar control • Power generation and grid objectives might sometimes be in conflict; controls will need to strategically coordinate automated demand response and grid services responses with other operational objectives • Voltage support and frequency regulation (“Modulate Load”) services will depend on inverter configuration, IEEE standards governing reactive power from inverters, and, likely, system size					
Opaque Envelope	**Tunable Thermal Conductivity Materials**	◐	◐	○	○	High
	• These materials might enable faster response, shorter duration load shedding by supplanting HVAC operation for brief periods • Coordinated controls with HVAC calibrated to the building are needed to minimize response time and maximize response magnitude • Load shifting and shedding potential could be increased substantially by combining tunable thermal conductivity materials with complementary materials (e.g., thermal mass) in the envelope assembly; a connected thermal mass could be “overcharged” (heated or cooled far beyond the interior set point) to increase shifting/shedding capacity • Interconnected thermal systems have time constants (thermal inertia) that exceed the required response time and expected duration for frequency regulation and voltage support • Heat transfer characteristics and switching speed will affect grid response times, though overall building response times will lag the switching of the dynamic insulation due to building thermal inertia unless other changes are made to the opaque envelope • Building thermal inertia likely prevents the provision of services requiring fast responses (subminute scale) unless an active charging system is incorporated; the limited remuneration available for fast response services suggests that active charging systems would not be justified for grid service provision alone					

Opaque Envelope

Technology					
Thermally Anisotropic Systems	●	●	◐	○	High

- Depending on the characteristics of available thermal sinks and/or sources for a given building, these systems could offset HVAC energy use, reduce peak electricity demand, and shift the timing of HVAC operation to periods when the system is more efficient
- Capacity for load shifting and shedding will also be affected by several building characteristics, including orientation, shading, thermal mass, and wall-to-floor area ratio
- Coordinated controls with HVAC calibrated to the building are needed to minimize response time and maximize response magnitude
- Fast response services ("Modulate Load") are likely out of reach due to buildings' thermal inertia

Technology					
Thermal Storage [27]	◐	◐	●	◐	High

- Primary mode of operation for thermal storage is load shifting by supplanting HVAC system operation during peak hours and using the HVAC system to recharge the storage during off-peak hours
- Support for faster responses—on the order of seconds to minutes—will depend on both storage and HVAC system configuration allowing rapid shutdown of HVAC loads and substitution of thermal storage
- An embedded electric charging system might enable the provision of fast-response services without coordinated operation of an existing HVAC system
- Efficiency benefits come from shifting HVAC system operation to periods when the system can operate more efficiently (due to ambient conditions and/or thermostat set point)
- Storage charging using ambient conditions (similar to free cooling) could yield additional eficiency gains, but this potential is dependent on building location (climate zone) and season
- Capacity will depend on critical thermal storage performance characteristics, e.g., surface area, thermal conductivity, energy density, etc.
- Tunable set point of PCMs could increase their potential for both energy savings and load shifting.

Technology					
Moisture Storage and Extraction	●	◐	◐	○	Medium

- Load shedding might be less attractive than load shifting since shifted load implies rejecting moisture back into the building interior during discharge cycles
- Active moisture storage could complement HVAC operation to achieve comfort targets, and might reduce HVAC energy use
- Coordinated operation with the HVAC system is likely not required to achieve energy savings or load shedding, though response times might be improved with coordination

Technology					
Variable Radiative Technologies	◐	◐	○	○	Medium

- If these materials are applied or mounted on the exterior of an existing building, the time required to begin affecting heating or cooling energy use might be lengthened if a high-performance envelope is already installed, since the bulk of the envelope is intended to mediate heat transfer between the interior and exterior
- Combining these materials with other variable opaque envelope technologies would likely increase their ability to shift or shed load—both response time and magnitude—by adjusting the heat transfer properties of the envelope to increase or decrease the rate at which the exterior surface influences interior conditions
- Given the potentially slow system-level responses resulting from the use of these materials, even if these materials can change their properties in minutes or seconds, they might perform best when operated using an hour-ahead or day-ahead forecast instead of in response to real-time grid service requests
- Surface heat transfer characteristics willl depend heavily on their cleanliness

[27] The capability ratings shown for thermal storage apply specifically to thermal storage when used in building envelope applications.

	Building-Integrated Photovoltaics	○	○	○	◐	Low
	• In general, BIPV does not directly influence building energy use, thus it cannot provide efficiency or load shedding or shifting • Voltage support and frequency regulation ("Modulate Load") services are possible if building net load (inclusive of power generation) is considered, but will depend on inverter configuration, IEEE standards governing reactive power from inverters, and, likely, system size.					

○ **Not Applicable** ◐ **Low Capability** ◐ **Medium Capability** ● **High Capability**

3.3 Evaluation Results

Table 6. Technology Priority Levels

High Potential	Medium Potential	Low Potential
• Dynamic Glazing • Automated Attachments • Thermally Anisotropic Materials • Thermal Storage* • Tunable Thermal Conductivity Materials*	• Photovoltaic Glazing • Moisture Storage and Extraction • Variable Radiative Technologies*	• Building-Integrated Photovoltaics

In some cases, integrating multiple dynamic opaque envelope technologies into assemblies might increase the grid response potential of the envelope system compared to any of those technologies operating by themselves. While any of the opaque envelope technologies might have expanded flexibility when packaged with others, systems involving the technologies indicated by asterisks in Table 6 are of particular interest. Combining tunable thermal conductivity materials and variable radiative technologies with thermal storage is of particular interest, because those technologies could enhance the operating range, response time, and response duration of thermal storage in envelope applications. Section 5 discusses additional approaches to assembly- and system-level design that might enhance the demand flexibility potential of all the technologies considered, as well as any additional supporting research required to develop these approaches. Section 5.7 focuses on the opportunities and demand flexibility potential that might exist specifically from these novel opaque envelope technology assemblies.

4 Technology Attributes

This section provides a brief discussion of the general characteristics of the technologies for which further R&D is discussed in Section 5, particularly those characteristics that might be relevant to market adoption or performance but that are not directly related to their ability to provide grid services. Table 7 outlines a range of system attributes that might apply to dynamic building envelope technologies and their impact on building occupants and operations.

Table 7. 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.
Lifetime	The total average operational lifetime of the technology.

All Dynamic Window and Opaque Envelope Technologies

Resilience is a system attribute that the building envelope is particularly well suited to provide. Resilience includes the ability of a building to supply needed services to occupants following a utility outage; given the long life of building envelope components, resilience should also include building envelopes designed to account for future changes in weather conditions. The building envelope technologies described in this report can improve the resilience of buildings to interruptions in utility service. High-performance windows and opaque envelopes generally reduce heating and cooling energy use, and thus increase the time from when an interruption occurs to when the building becomes uninhabitable because of temperature conditions. Figures 7 and 8 illustrate the effect of a high-performance building envelope (higher insulation, lower air infiltration, and improved windows) on occupant protection following a utility service interruption in the winter and summer, respectively. In the winter, increased envelope performance beneficially increases indoor temperatures and reduces temperature variations, maintaining a temperature difference of up to 30ºF. During a summer interruption, a high-performance envelope again reduces temperature variations, which reduces peak temperatures compared to a typical building, but peak outdoor temperatures are generally lower than peak indoor temperatures in all four building envelope cases considered. These results show that the resilience improvements offered by static high-performance building envelopes vary by climate zone and season when resilience is most needed. These benefits carry over to sizing of backup power systems; less backup power is needed to maintain safe indoor temperatures in buildings with a high-performance envelope. There are some tradeoffs for these resilience benefits; for example, currently available high-R insulation is often made from flammable materials. Energy-efficient and flexible technologies must be evaluated in a holistic manner to determine how best to deploy solutions while ensuring that buildings are resilient to future hazards.

Dynamic building technologies can deliver substantial load shifting or shedding capability, thus their operation during peak periods can improve thermal comfort. Dynamic technologies also help improve flexibility with respect to long-term changes in climate conditions, because they can adjust their operating ranges to reflect actual conditions, rather than design conditions when the building envelope was specified. Dynamic functionality could enable passive recharging or energy scavenging during off-peak hours to restore partial or full heating or cooling service provision. Switching or state changes for these systems will generally require some minimal power, thus systems that are self-powered have a greater potential to increase resilience. These systems should be designed to minimize power requirements for dynamic operation in the absence of supply disruptions, thus even small PV arrays and batteries should be sufficient for at least a few days of operation, perhaps more if there is adequate solar resource available. Because self-powered systems eliminate the need for a connection between the dynamic envelope technology and the electrical system in the building, they can also reduce total installed prices and broaden the potential customer base to buildings—especially retrofits—where these connections might be labor-intensive.

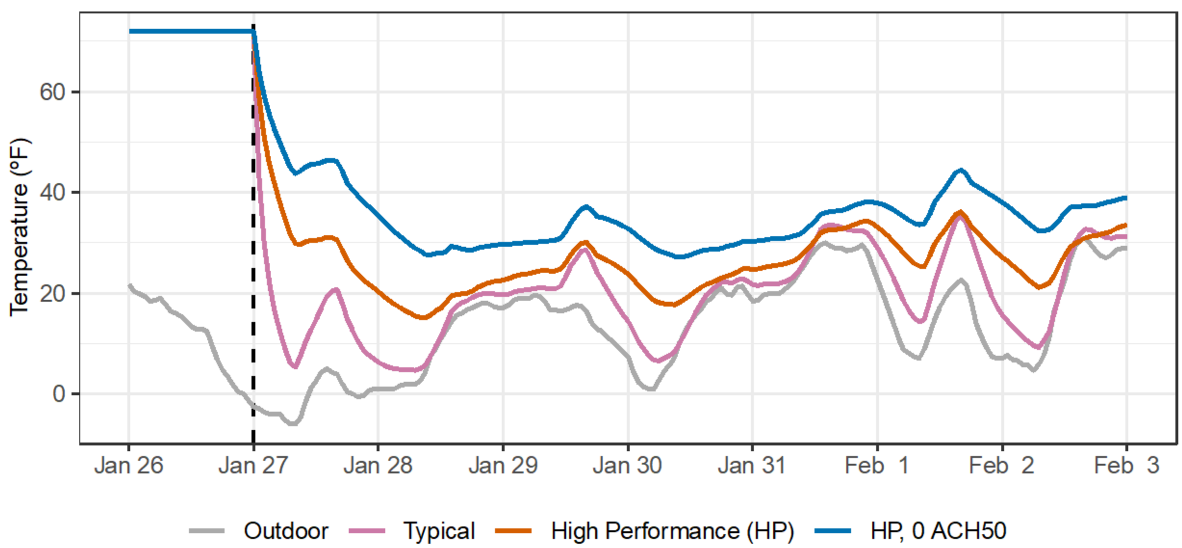

Figure 7. Indoor temperature trends compared to the ambient temperature for single-family detached home with varying building envelope performance levels following a utility service outage modeled on January 27.

As envelope performance increases, interior temperatures remain higher and more stable, even several days after service ceases.

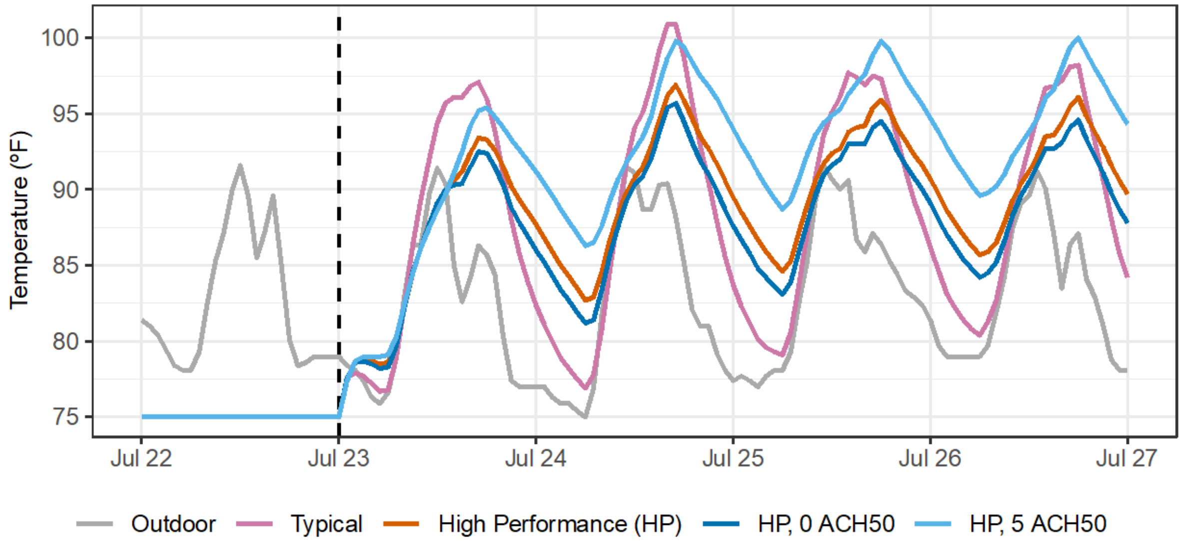

Figure 8. Indoor temperature trends compared to the ambient temperature for a single-family detached home with varying building envelope performance levels following a utility service outage modeled on July 23.

As envelope performance increases, interior temperatures become somewhat more stable and peak temperatures are reduced, but minimum temperatures increase, because the building is less coupled with ambient temperature trends—both unfavorable and favorable.

Dynamic building envelope technologies can also generally improve occupant comfort, health, and productivity. Variation of solar intensity and its spectral composition from daylighting has been correlated with improved health and performance in building occupants (Figueiro et al. 2017; Alrubaih et al. 2013). Opaque envelope components can increase the habitable floor area in buildings by increasing the temperature in the perimeter zone, and improvements in air sealing and moisture control can improve comfort and reduce the risk of mold growth and decay that can lead to respiratory problems (Treschel and Bomberg 2009).

Additional system attributes, potential benefits to building owners and occupants, and remaining challenges that might be best resolved with R&D that are applicable to individual technologies are discussed in Sections 4.1–4.8.

4.1 Dynamic Glazing

Electrochromic glazing that actively modulates visible light and near-infrared transmission has been commercially available for more than five years and has achieved a modest level of adoption in high-end, niche applications. However, market adoption has been slow because of concerns about color, switching speed, complex yet inadequate automated control, and total installed price. Dynamic glazing can reduce peak electricity demand for heating and cooling by modulating solar heat gain. The magnitude of the change in electricity demand will vary as a function of the solar irradiance and attenuation capabilities of the particular dynamic glazing material.

4.1.1 Reliability

The reduction of heating and cooling loads and associated electricity demand can reduce total energy use, while load shedding can reduce generation capital costs, generation operating costs, and T&D infrastructure expansion costs, and also potentially support the alignment of demand to renewable generation availability. There will be a time lag between switching of the dynamic glazing and changes in heating or cooling energy requirements; thus, contingency reserve provision might be possible, but frequency regulation and voltage support are not. The response time and available capacity for contingency reserve and other load shedding operations will need to be calibrated to each individual installation, and the critical parameters that might vary from day to day that influence response time and capacity will need to be determined and their effects quantified to be able to send accurate contingency reserve bids to the grid operator. Model predictive control methods, particularly those that incorporate data on real-time interior and exterior conditions, have the potential to reduce system response time lag and improve the accuracy of the delivered response compared to the requested response (Gehbauer et al. 2019; Lee et al. 2019).

4.1.2 System Readiness

Realizing these potential benefits will require dynamic glazing control algorithms that facilitate an optimal balance of energy savings, grid service response capabilities, and occupant comfort and satisfaction given a range of dynamic facade components that might be in simultaneous use. These controls will also need to allow for updates to support new dynamic facade technologies that are introduced. Switching some dynamic glazing technologies might lead to additional electric lighting demand, and the timing of the response from the dynamic glazing system is inherently dependent on HVAC equipment operation. Therefore, the control system should have access to all of the interdependent building systems to maximize the potential for serving all of the system's objectives. Sophisticated model predictive control methods can incorporate controls for these other systems and balance operational (energy) goals with occupant comfort objectives (Gehbauer et al. 2019; Lee et al. 2019). The proprietary nature of the building control systems on which these technologies depend can create concerns regarding vendor lock-in and resulting high long-term system operation and maintenance costs, particularly in commercial buildings, where the systems can be quite capital intensive. This concern is particularly critical for dynamic glazing and other facade systems because they tend to be much longer lived than other building systems. Control solutions that employ open-source interfaces or building-block-style models could provide solutions that enable long-term energy savings and reduce adoption risks for consumers.

4.1.3 Usability

Additional control options could be enabled with novel chromodynamic formulations that can independently attenuate visible and near-infrared light. Decoupled switching in the visible and near-infrared ranges would allow greater control over the tradeoff between daylighting and solar heat gain, which could be helpful as part of a load shedding or shifting strategy for buildings that are occupied during daylight hours (DeForest et al. 2017). This feature would be particularly beneficial in commercial buildings with high internal loads where electrochromic windows might otherwise remain in a switched (darkened) state in the winter months. Climate zones with large seasonal temperature changes will have the largest energy savings benefit from decoupled near-infrared switching (DeForest et al. 2017), but it is unknown whether some climates would benefit more than others with respect to grid service capability. High-performing lab-scale electrochromic devices have been developed with decoupled switching capability, but formulations that are suitable for high-volume, low-cost manufacturing remain elusive (Wang, Runnerstrom, and Milliron 2016).

Aesthetic considerations are also critical to widespread adoption of electrochromic and other actively controllable dynamic glazing. Uniform facade appearance, desired by some in the architecture and real estate industries, can limit long-term energy savings and control options for grid service provision. In addition, many electrochromic glazing formulations have a distinct color in their darkened state, again seen as aesthetically unacceptable for many applications. Slow switching speeds (10–30 minutes) sometimes lead to the installation of supplemental shades to satisfy occupant comfort, which eliminates the aesthetic benefits and potential cost savings from avoiding interior shades. These slow switching speeds might also limit the grid services that can be provided with dynamic glazing and could require grid-coordinated operation based on day-ahead or hour-ahead forecasts, instead of in response to real-time or near-real-time signals.

4.2 Automated Attachments

In general, some automated attachment systems are commercially available for both residential and commercial building applications. Although still somewhat of a niche product, these systems have seen adoption in an array of institutional settings, particularly in spaces where manual control of the attachments is not feasible and for exterior attachments where manual adjustment would be inconvenient. For automated shading systems to achieve widespread adoption, precision actuation, improved aesthetics, low power requirements, ease of installation, and low maintenance requirements are needed. Technology solutions at lower installation costs and initial configuration complexity of automated systems (as compared to static and manually operated systems) are now commercially available, including self-contained power supplies and wireless internet-protocol-based control connectivity.

4.2.1 Reliability

Automated attachments have the potential to deliver, in particular, on-peak energy savings by being deployed to reduce and delay heating and cooling demand, thus reducing generation capital and operating costs and delaying T&D infrastructure upgrades. These savings assume the attachment controls are configured with, at a minimum, an energy savings program or are controlled as part of an automated demand response scheme. User or facility control of automated attachments via mobile app interfaces has increased the transparency of system operation and facilitated troubleshooting in residential and small commercial applications. A critical shortcoming, however, is the general lack of knowledge on how best to control attachments for energy savings, occupant thermal and visual comfort, and user satisfaction, let alone provision of grid services. Because changes in the state of the attachment system might lead to changes in lighting energy use, the control system should incorporate lighting and use a combined objective for control. Like dynamic glazing, the electricity demand reductions from automated attachments come from offsetting HVAC energy use, and there will be a lag between any change in the attachment system and the heating or cooling demand subject to the thermal mass influenced by shading. Some contingency reserves might be possible from some buildings, though their response time would need to be autonomously evaluated by the control system or intentionally determined when commissioning the system. The characteristics of the response capability for the system installed in a particular building are critical to be able to appropriately respond to requests sent by the utility or grid operator. Currently commercialized control systems use building simulations to design rule-based controls for large-scale applications; to accommodate the continuing changes in utility operations and electricity markets in response to evolving demand- and supply-side conditions, more flexible approaches to controls design are needed.

4.2.2 Usability

With respect to adoption by architects and designers, automated attachments suffer from aesthetic problems related to their often uneven deployment across the facade—control systems that can balance occupant comfort, energy goals, and reliably deliver aesthetic control solutions might find greater acceptance, particularly in new construction and deep retrofits in commercial buildings. Greater acceptance of operable exterior attachments would increase energy savings and likely GEB performance potential, but aesthetic considerations must be addressed; sleek, unobtrusive designs that integrate well with a wide variety of facade materials common in the target building sector are critical. Technologies that can reduce occupant disruption from the operation of automated attachments would be valuable as a means to reduce occupant overrides and complaints; quiet actuators and motors and operations that minimize perceptible changes in lighting levels would all be beneficial. Integration with smart home systems might increase the appeal of automated attachments in the residential market. Retrofittable wireless self-powered actuators for existing manual attachments could further broaden the potential market, including to renter-occupied households. Reliable operation of these systems is critical, because faults that prevent the operation of these systems might impact building energy use and GEB performance, but might not be perceived by building occupants as significant issues because window attachments are not a primary component of the building.

4.3 Photovoltaic Glazing

For self-powered dynamic facade systems, or even to generate surplus electricity, PV can be integrated into windows with novel approaches. The most expensive components of PV panels are the glass and the transparent conductors (tantamount to low-emissivity layers, also known as "low-e") that already compose IGUs (Song et al. 2017). There are three types of PV glazing: static transparent, static semitransparent, and switchable; each has different strengths and weaknesses (Traverse et al. 2017; Sun and Jasieniak 2017; Wheeler et al. 2017; and Lin et al. 2018).

4.3.1 Reliability and System Readiness

Durability, integration, and efficiency remain challenging and are the focus of current research efforts. In general, grid-connected PV glazing can interact with the grid in a manner identical to dedicated PV panels. Subject to IEEE standards regarding the use of residential grid-tied PV to provide voltage support and reactive power injection, PV glazing can provide the same services as rooftop PV. With an automated control system that links to the utility or another supervisory operator, the PV system could also be curtailed as needed, following the same generation control strategies that would likely be applied to other distributed variable renewable generation. PV glazing that alters visible transmittance depending on its operating state would require more complex controls to balance power generation, visible light transmission, and solar-heat-gain-related objectives.

4.3.2 Usability

Transparent PV glazing converts only nonvisible solar energy (ultraviolet and infrared) to maintain maximum visible transmittance but suffers from low power conversion efficiency—the ratio of electrical power out to solar power in (Traverse et al. 2017). To increase power conversion efficiency and capture some of the energy available in visible light, IGU-integrated designs are typically semitransparent. The amount of light absorbed and converted to electricity is limited by the need to maintain adequate visible transmittance. Current semitransparent PV designs thus suffer from the fundamental trade-off between power conversion efficiency and visible transmittance. Switchable PV windows circumvent this fundamental trade-off by switching from a visibly transparent state (high visible transmittance) to a darkened (low visible transmittance) state in a manner similar to thermochromic glazing. Dynamic PV glazing allows for increased power conversion efficiency in the colored state without sacrificing visible transmittance during off-hours. This approach uniquely combines higher power conversion efficiency PV with the energy-saving benefits of dynamic glazing in a single system. Dynamic PV glazing development is still in its early stages and durability and switching temperature must be optimized before commercialization of switchable designs will be realized. Novel dynamic PV glazing formulations that can be actively switched might also enable improved grid responsive capability, because curtailment would be accompanied by additional flexibility in visible transmittance. More generally, operation of the dynamic PV glazing could be coordinated to balance the potentially competing objectives of modulating visible light, managing solar heat gains, and generating electricity.

4.4 Tunable Thermal Conductivity Materials

Tunable thermal conductivity materials can modify their thermal transport properties, thus changing the overall heat transfer through the opaque envelope component (roof, walls, foundation) in which it is installed. As a category, tunable thermal conductivity materials have the potential to enable dramatic new functionalities in the opaque envelope. These materials can enable or expand active control capabilities that completely alter the paradigm for opaque envelope design, associated energy use, and GEB performance.

4.4.1 Reliability

These durability considerations also extend to the provision of grid services. It is important that these systems are able to deliver promised responses reliably, and their response capability can be affected by both profound failures and more gradual capacity decay. Both failure characteristics should be detectable by the control system that operates the envelope assembly and reported accordingly to whatever infrastructure coordinates building operations or building-grid interactions. Capacity decay is particularly important, because it suggests that requested services might be possible, but at a diminished level that might be less easily detected than a nonresponsive system. Depending on how long the dynamic envelope assembly takes to reach its target or maximum response level, it might take tens of minutes before the decay is detectable, and given the numerous other factors that influence overall building response (including weather and building occupancy levels), slow degradation might be difficult to separate from changes in these other factors. Some consideration should be given to how to design control systems that can detect multiple fault types at varying rates of failure and, for buildings that have multiple dynamic systems, whether those systems can be used to compensate temporarily.

4.4.2 Usability

In the past, new opaque envelope materials have occasionally required changes in design practices, but those materials have not generally changed the underlying behaviors of the opaque envelope. To maximize the potential benefits for building owners and occupants, additional research is needed at the system level to rethink the design of the opaque envelope to fully leverage the potential of these dynamic features. Envelopes that fully leverage the benefits of tunable thermal conductivity materials might incorporate materials and technologies that have historically not been part of the opaque envelope, and research is needed to establish how these envelope assemblies should be designed. This research might include changes to the way that components are put together in the envelope, but might also require the development of new materials with different properties—higher or lower thermal mass; shear, tensile, or compressive strength; thermal conductivity; or other characteristics—than materials typically employed in today's buildings. In this research, avenues that facilitate high-performance building envelope retrofits that allow for the incorporation of tunable thermal conductivity materials should be investigated where possible. In addition, consideration should be given in later R&D stages to collecting any data needed to facilitate the revision of building construction and building energy codes to allow these new materials and assembly techniques.

For tunable thermal conductivity materials to find market traction, significant supporting work will be needed to enable architects, engineers, and others who specify building envelopes to confidently use these new materials. Design tools and software will need to be developed or updated to reflect the capabilities of these new technologies and provide climate-specific guidance, including the specification and configuration of required sensors and controls systems. Product packaging improvements and installer education will be needed to ensure that these materials are installed correctly and perform as intended, particularly in cases where improper operation might have substantial energy or durability consequences. It is possible that these materials will only be used as part of prepackaged assemblies, in which case some of this effort might not be needed, but it seems as likely that buildings that integrate these materials will perform best when they are installed as part of semicustom systems that are tailored to the building. Customized design might increase energy savings and/or demand flexibility, and the additional design effort and potential installation complexity might be justified by the additional energy benefits, though again, appropriate knowledge and tools to properly deploy these technologies will be needed throughout the building design and construction industry.

4.4.3 Lifetime

Most components of the opaque envelope are embedded within an assembly and are difficult to access after construction, and the components in building envelopes that influence energy use, such as insulation and air barriers, tend to be replaced infrequently if at all during a building's lifetime. Given these characteristics, it is important that tunable thermal conductivity materials and the assemblies in which they are packaged employ designs where any components that might require service during the life of the envelope are easily accessed. Moreover, these systems should be designed to minimize installation effort and complexity and the potential for defects or faults introduced during installation. Ideally, novel tunable thermal conductivity materials and systems would be developed to offer simple, straightforward installation and long life by mitigating potential failure modes and reducing dependence on complex or field-assembled components. These materials should also be developed to avoid poor reversibility and susceptibility to side reactions, if applicable.

4.5 Thermally Anisotropic Systems

Thermally anisotropic systems (TASs) are materials or composites that consist of engineered layer(s) with alternating high and low thermal conductivities. TASs have anisotropic thermal transport properties; the high conductivity layer(s) are the less resistive paths for heat transfer, thus helping reroute heat flow that would otherwise pass through the envelope to the connected heat sink or source instead. TASs also might have the potential to be dynamically controlled by changing the heat transfer characteristics of the connection between the TAS and the heat sink or source.

4.5.1 Usability

TASs can reduce energy use—including at peak times—during both the heating and cooling season. TASs employed in building envelopes for energy performance purposes have not been explored extensively in the literature. The critical parameters defining TAS energy performance are not fully established, but might include thermal conductivity and thickness of the anisotropic layers, contact resistance between layers in an anisotropic composite, heat transfer efficiency with the heat sink or source, and other heat sink or source characteristics. Preliminary work has shown that thermally anisotropic composites can yield primary energy savings of approximately 5% compared to continuous exterior insulation using currently commercialized materials of equivalent R-value and thickness, and 15%–20% compared to a residential building compliant with IECC 2006 specifications (Biswas et al. 2019).[28]

Technologies that can efficiently manage heat flows within buildings, reject heat to the surroundings, or store it for miscellaneous usage (e.g., water heating) are key enablers of effective TASs. Dynamic, controllable thermal energy materials could create more uniform temperatures between interior spaces, improve thermal comfort, and facilitate rejection of thermal energy to available sinks/sources. Technologies that enable thermal energy transfer between TASs and heat sinks and sources could include methods that are already used for ground-source heat pumps, but research on daytime radiative cooling materials suggests that these novel materials might offer substantial heat rejection potential when coupled with TASs. These materials are discussed further in Sections 4.8 and 5.6.

4.6 Thermal Storage

Thermal storage materials store and release heat when charging and discharging, respectively. These materials can thus shift the timing of heating or cooling energy demand. In general, currently available thermal storage materials for buildings can only charge and discharge passively in response to indoor temperatures; they cannot control the timing of charging or discharging to intentionally deliver grid services. Developing thermal storage materials or packaging for thermal storage that enables control of charging and discharging is a key enabler for using envelope-integrated thermal storage to offer grid benefits. Materials that can modify their switching temperature (tunable transition temperature) to operate in both the summer and winter would significantly increase the total energy savings and grid-relevant benefits of thermal storage. In addition, thermal storage might also be able to improve occupant thermal comfort, particularly in perimeter zones, depending on the configuration (placement within a building, total capacity) of the thermal storage system.

4.6.1 Reliability

For materials that undergo a state or conformation change at a specific temperature as their mechanism of thermal energy storage, that temperature is typically fixed, defined by the material formulation. In some cases, these materials do not transition fully or sharply at that that temperature, which can reduce total storage capacity and lead to poor thermal comfort. For materials that have switching temperatures and other properties that make them suitable for buildings applications, additional work might be needed to improve transition performance and ensure reliable transition at the design temperature. Ambient conditions and set points change

[28] These results showed site energy savings of 15%–26% for cooling and -5%–13% for heating compared to an envelope that meets IECC 2006 specifications. Compared to a wall system with equivalent R-value exterior continuous insulation, cooling energy use was reduced by 9%–16% and heating energy use increased by 2%–40%.

between the heating and cooling seasons; thus, because current thermal storage materials have a fixed transition temperature, they are usually designed to operate in a particular season for the targeted building type(s) and climate zone(s). New thermal storage materials or modifiers that can change their transition temperature would substantially increase their potential energy savings and GEB performance by enabling year-round operation.

4.6.2 System Readiness

Other forms of electrical storage might soon be available off-the-shelf for buildings. These systems might be able to provide grid services and might even yield modest annual energy savings, but they cannot directly influence the operation of other building systems by changing the underlying demand for the services (e.g., heating, cooling, lighting) that those systems satisfy. Utilities might have greater confidence in operating energy storage as a behind-the-meter source of system flexibility, so it might be advantageous to explore whether thermal storage should operate in coordination with electrical energy storage. Research should establish whether there are any potential benefits of coordinated operation and, if there are, the optimal characteristics of electrical energy storage and thermal storage or any other dynamic building envelope components when operating as a system.

4.6.3 Usability

Thermal storage materials used in the opaque envelope could have a variety of form factors. The design of the form factor would likely depend on the building type, performance parameters for the storage material, HVAC system configuration, and other factors. For a given thermal storage material, its form factor might substantially affect its performance. The critical performance parameters for thermal storage need to be identified, and might vary by application (e.g., diurnal storage, long-term storage, load shifting). These performance parameters for each viable application will likely then inform the form factors that are suitable. For example, materials with high volumetric energy density intended for short response services might benefit from high surface area to volume ratio form factors and might benefit from installation over a large number of surfaces. Effectively quantifying the relationships between these design and performance parameters will aid significantly in efforts to develop novel storage materials, determine energy savings potential, and viable grid services.

4.7 Moisture Storage and Extraction

Indoor relative humidity affects occupant comfort and the operation of cooling systems, particularly in hot-humid climates. Moisture storage technologies could be used to help enhance moisture control in buildings, which could improve occupant comfort, reduce energy use, and provide grid services. Porous materials present in buildings, including upholstered furniture, drywall, and some types of wall insulation, already store moisture passively. Active control over moisture storage in buildings could facilitate curtailment of cooling system electricity use and improve occupant comfort. Active moisture storage control could also be used in place of reheat, particularly in hot-humid climates and in buildings where substantial fresh air or make-up air is required.

4.7.1 Reliability

Methods for recharging actively controlled moisture storage media should be considered carefully; coordinated recharging with cooling system operation at off-peak times will be critical to minimizing energy costs and should be planned to avoid increasing demand charges. Recharge strategies will likely also depend on climate conditions—temperate, arid, and semiarid climates might use substantially different control approaches compared to hot-humid climates. Control systems designed to operate moisture storage systems will need to be able to take these various factors into account. Moisture storage materials that can recharge by draining moisture out as liquid water would prove advantageous, particularly in humid climates, where recharging will otherwise involve substantial cooling system energy use.

4.7.2 Human Health and Lifetime

Moisture management in the opaque envelope has been the subject of significant past research because both water vapor and liquid water can cause substantial and costly damage to buildings, potentially threatening occupant health and life safety. Extensive empirical work has been done to establish appropriate strategies for controlling moisture ingress and ensuring adequate drying for a wide range of building materials and in all U.S. climate zones. Although some commonly used materials in the opaque envelope have moisture storage properties, those properties have been accounted for in prior research. Introducing new materials into the building envelope that can extract moisture from the indoor environment, particularly if those materials have the ability to redirect that moisture to another location, will require new research to ensure that those materials do not cause moisture damage in their intended application and configuration within the envelope assembly. Materials that can extract water vapor and convert it into condensed liquid water that can be drained away might offer the largest energy savings and load shedding potential, but the production of liquid water might require particularly careful management in the envelope assembly.

4.8 Variable Radiative Technologies

Variable radiative surfaces include materials and surface coatings that can vary their reflectivity and/or emissivity in a manner conceptually similar to electrochromic glazing, as well as radiative cooling materials that have carefully tailored emissivity. Materials that change their radiation heat transfer properties—reflectivity and/or emissivity—in response to a control signal could facilitate demand flexibility by reducing both peak heating and cooling loads.

Photonic and plasmonic radiative cooling materials can reject heat during the daytime, even in direct sun. Radiative cooling materials would likely perform best when paired with other dynamic envelope components, particularly TASs, whose demand flexibility potential hinges on having access to a thermal source and/or sink. For these materials, dynamic control is again important to yield both energy savings and the potential to provide grid services.

4.8.1 Lifetime

Unlike most of the opaque envelope technologies discussed in this report, variable thermal property coatings and surfaces are fully exposed to different conditions. As a result, these materials must be designed to cope with environmental factors while maintaining their performance. Fouling from airborne contaminants might substantially diminish efficiency or dynamic range. Materials should be designed to be self-cleaning, if possible, and to minimize the consequences of long-term exposure on overall performance. These surfaces and coatings should also be resistant to long-term degradation from ultraviolet and infrared radiation to which they will be continually subject, and to the drying, cracking, peeling, and other surface defects that can arise in coatings exposed to solar radiation. Light abrasion or impact from plants and debris should have no effect on the coating. If a continuous coating or surface is required, the material should be able to accommodate thermal expansion and contraction of the building, as well as settling, shifting, and other motion of the facade as a result of internal and external forces. These materials, particularly if field-applied and used in retrofit applications, will need to adhere well to a wide range of substrate materials. Although some surface preparation can be required, such as using a surface primer or removing and repairing loose or damaged facade materials, multistage or particularly painstaking preparatory requirements should be avoided to reduce installation prices and total installer time on-site.

4.8.2 Usability

The performance of variable radiative technologies, because they are applied to or mounted on the exterior surface of the opaque envelope, is particularly sensitive to the configuration of the envelope assembly. In general, the opaque envelope is designed to blunt thermal transport from the exterior to the interior, which thus substantially limits the potential benefits of variable surface properties. Research that explores the effect of alternative assembly designs that can yield overall energy savings with these surfaces when compared to traditional envelope assemblies is critically important and will also affect the demand flexibility potential of these technologies. Radical redesign of the envelope assembly introduces other challenges with respect to commercialization, because it represents a much larger change in typical construction practices, processes, supply chains, and design tools, but might enable materially larger energy savings. Research should be performed to quantify the difference in demand flexibility potential and energy savings potential of these materials, both with traditional or typical opaque envelopes, as well as candidate novel assembly designs.

4.8.3 Reliability

For daytime radiative cooling materials, technologies or materials that can either stop cooling or even provide beneficial heating in the heating season are needed. Existing daytime radiative cooling materials will operate continuously, which could lead to undesirable cooling during the heating and shoulder seasons. Developing materials with temperature-dependent emissivity might help reduce excess cooling. Another viable approach might involve thermal circuit technologies that can stop or significantly restrict heat conduction between the radiative cooler and the envelope system during the heating season while offering high conductivity in the cooling season. The annual energy savings and grid service potential of radiative coolers could be expanded outside the cooling season if materials could be developed with the ability to switch to passive heating from solar radiation at cold temperatures when exposed to sunlight. Further work is also needed to improve the performance of these materials in humid conditions. Santamouris (2018) articulates a range of other areas where additional research could improve the performance of these systems, reduce their manufacturing costs, or expand their range of viable applications.

5 R&D Challenges and Opportunities

All Connected Technologies

All internet-connected technologies in buildings with data communication and control capabilities face common challenges, including interoperability, cybersecurity, and cost barriers. Many of the challenges identified here apply to dynamic window and opaque envelope technologies. For more information on interoperability and cybersecurity challenges facing all connected technologies, refer to the *Whole-Building Controls, Sensors, Modeling, and Analytics* report.[29]

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, controls 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 demand flexibility 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. 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.

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.

[29] See Section 1 for relevant report links.

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.

Manufacturers of window and opaque envelope products have not generally had to face cybersecurity challenges with respect to their product offerings, as their existing products are not generally internet-connected or otherwise networked. As a result, addressing this challenge might prove particularly difficult. The difficulty of ensuring security is made more challenging by the long lifetime (> 25 years) of typical envelope components; OEMs will need to continue to support and patch legacy connected equipment much longer than manufacturers of other building subsystems, and might need to offer software and hardware upgrade packages to upgrade networking and control capabilities to modern standards. Moreover, the high capital cost and extensive installation effort for most building envelope technologies make more frequent replacement an unattractive route to ensuring regular updates.

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. Research to develop technologies that are easier and faster to install can also help reduce capital costs for dynamic building envelope technologies in particular, because installation comprises a significant portion of the total cost.

Table 8. Challenges and Opportunities for All Connected Technologies

Technology	Challenges	R&D Opportunities
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

All Dynamic Window and Opaque Envelope Technologies

In addition to the R&D challenges and opportunities that cut across internet-connected technologies for buildings, there are additional challenges specific to dynamic windows and opaque envelope technologies. These challenges are principally related to the complex interactions between the building envelope and the HVAC and lighting systems as well as the substantial influence that the building envelope has on occupant comfort.

Grid Service-Specific Control Strategies That Can Balance Occupant Needs and Grid Benefits. Although dynamic window and opaque envelope technologies might be able to support flexibility, control strategies are needed to be able to provide that flexibility while balancing other building operational objectives, particularly occupant thermal and optical (glare) comfort. There might be operating conditions where it is not possible to simultaneously deliver ideal conditions for occupant comfort and satisfy grid requirements. In addition, if operating in a manner that maximizes grid benefits is not cost-minimizing for the building owner, the control system should balance building operating costs, providing grid services, and ensuring occupant comfort. Control systems for grid-interactive window and opaque envelope technologies should be able to balance these potentially competing objectives, particularly ensuring that occupant comfort is not reduced substantially below the baseline. For residential and small commercial buildings that do not have a dedicated building or facility energy manager, these systems must also be adaptive to a wide range of settings and operate right out of the box without substantial configuration.

Research is needed to develop control systems and strategies that can manage these competing objectives, balancing grid objectives with occupant needs, adapting to occupant overrides, and incorporating user preferences. These control systems will require inputs regarding occupant comfort to balance comfort with other objectives; thus, methods to parameterize occupant comfort and perform in-situ, real-time measurement and feedback regarding occupant comfort are critical. Research to identify the primary conditions or drivers of occupant overrides and strategies that minimize overrides would also be valuable.

Parameterization of Grid Response Capability. To maximize the impact of R&D on the GEB capability of the technologies discussed in this report, the fundamental physical processes and mechanisms that deliver the desired grid-interactive operational characteristics from a given technology must be identified. With this information, materials that incorporate or enable the desired GEB functionality can be selected and pursued. In addition, packaging for these materials and technologies can be developed to be complementary or to enhance the intended functionality. Research can quantify the influence of key figures of merit for an individual technology to grid-relevant response characteristics such as those outlined in the "Key Characteristics" column of Table 4. Further work should determine the required values for those figures of merit to achieve particular grid-response capacity from a given material or technology. In parallel, simulation capabilities should be developed to represent these technologies such that building envelope design and specification decisions can be made with specific emphasis on grid interactivity.

Methods to Quantify Building-Specific Response Characteristics. To be able to operate a control system that provides grid services using a GEB-capable building envelope technology requires a quantitative understanding of the key characteristics of building components and subsystems that affect the time-series interior environmental response of buildings. This information is needed to successfully deliver GEB-responsive capabilities from the envelope, because the grid service ultimately comes from changes in HVAC and lighting requirements, and the responses from those building subsystems from changes in the envelope system configuration must be known a priori to deliver the intended grid response from any dynamic envelope component.

Research is needed to parameterize the thermal and moisture response of a wide range of building types, and these data could then be translated into simulations of the time-series interaction between dynamic building envelope technologies and the rest of the building. Ultimately, this research could be used to develop design guidance for the architecture, engineering, and construction industry to correctly specify and position sensor hardware.

Table 9. Challenges and Opportunities for All Dynamic Window and Opaque Envelope Technologies

Technology	Technical Challenges	R&D Opportunities
All Dynamic Window and Opaque Envelope Technologies	Grid Service-Specific Control Strategies That Can Balance Occupant Needs and Grid Benefits	• Determine quantitative measures for occupant comfort • Identify appropriate approaches for in-situ, real-time measurement of occupant comfort • Develop acceptable out-of-the-box defaults for controls that balance demand flexibility, building owner cost benefits (if any), and occupant comfort • Develop adaptive control systems that achieve improved multiobjective outcomes (e.g., comfort, cost, productivity, grid services) and minimize user overrides • Characterize conditions that lead to occupant overrides and develop strategies to minimize the probability of overrides

	Parameterization of Grid Response Capability	• For technologies under development, employ preliminary multiphysics simulations of each GEB-relevant technology to explore the key figures of merit that influence demand flexibility
		  ○ Quantify the influence of identified figures of merit on time to initial response, response (ramp) rate, total capacity, and other characteristics relevant to providing the grid services outlined in Table 4
		  ○ Determine the appropriate value or range of values for each of the key parameters identified for a given technology to provide the various grid services that can be provided by that technology
		• Develop deterministic quantitative methods for the design of sensors and control systems specific to each GEB-relevant window and opaque envelope technology

	Methods to Quantify Building-Specific Response Characteristics	• Parametric study of the thermal response of residential and commercial buildings • Multiphysics simulation of the time-series interaction between GEB-relevant window and opaque envelope technologies and a range of residential and commercial buildings (prototypes or archetypes) • Easy-to-use design guidance for architects and engineers (specifiers) to specify and position sensors and control hardware so that the dynamic window and envelope components can deliver the expected grid services.

While research proceeds to address the challenges articulated in Table 9 and Sections 5.1–5.6, high-performance static building envelopes can provide tremendous energy and nonenergy benefits for building owners and occupants. As discussed in Section 2.1.1, high-performance building envelopes can deliver substantial energy savings and peak period load reductions in both the summer and winter seasons. High-performance passive envelopes also enable improved grid responsiveness from HVAC systems, which might provide a more immediate path to GEB-capable buildings.

5.1 Dynamic Glazing and Automated Attachments

Dynamic glazing and automated attachments are currently commercially available, but they lack the ability to provide grid services. Beyond the need for supporting infrastructure that enables grid service requests to be sent to buildings, automated attachment and dynamic glazing controls must include grid service provision functionality. Control algorithms, particularly for dynamic glazing, are becoming increasingly sophisticated. Building energy simulations can be used to support model-predictive controls, but this approach is not yet widely adopted, and requires additional one-off effort for each building. Most controls continue to be set conservatively and tuned over time to minimize complaints. Research is needed to develop controls that can reliably ensure occupant comfort to minimize complaints and overrides in a manner that builds confidence among building energy management staff, includes sufficient awareness of system response characteristics to provide grid services when requested by grid operators, and offers these capabilities off-the-shelf with minimal building-specific setup requirements.

Appropriate grid service responses, in addition to dynamic adjustments to maintain occupant comfort, require adequate sensor data for the control system. Sensors that are improperly installed and sensor systems that provide insufficient information to the control system will limit the capability of the dynamic glazing to respond appropriately to grid service requests, while also balancing occupant comfort and other objectives. Because automated attachments can have a reduced dynamic range compared to dynamic glazing (i.e., intermediate settings are achieved with partially open shades), they might have less flexibility in modulating daylight, managing glare, and controlling solar heat gain. This reduced flexibility might mean that sensor infrastructure and control sophistication requirements are lower than for dynamic glazing. Research is needed to determine the requirements from a sensor system for dynamic glazing or automated attachments to deliver grid services, and in particular, to establish whether the requirements differ from systems that do not incorporate GEB functionality. This research should also assess whether any other sensors, controls, or other system elements require changes to enable GEB functionality. The effort required for one-off sensor system design for each installation adds to the total installed price of the system and can lead to improperly designed and installed systems. To simplify sensor system design and installation, R&D to develop software tools that can provide design guidance and educational resources to ensure installer adherence to sensor system designs would be beneficial. Research is also needed to establish the fundamental sensor configuration requirements that can underpin these software design tools.

5.2 Tunable Thermal Conductivity Materials

As a category, tunable thermal conductivity materials could be key enablers of active control capabilities for novel opaque envelope assemblies that incorporate the technologies discussed in Sections 5.3–5.5. They could also be used independently, leveraging existing building envelope elements to modulate the timing and magnitude of heating and cooling energy requirements. These materials might also find applications in other building end uses (e.g., to enhance the performance of thermal storage built into HVAC systems). The demand flexibility potential of tunable thermal conductivity materials is influenced not only by the operating characteristics of the materials themselves but also by the characteristics of the rest of the assembly in which they are installed. Basic research is needed to develop these tunable materials and to determine their effectiveness in providing grid services in a wide range of potential configurations. This work should include varying physical configurations, performance characteristics, types of tunable materials or "circuit elements," and building types. This research should reveal both the key characteristics of tunable materials to maximize demand flexibility, as well as the best applications of those materials in various building types and when operating independently or in combination with other novel dynamic opaque envelope materials.

In addition to examining the effect of the envelope assembly on the performance of tunable thermal conductivity materials, research is also needed to understand the temporal relationship between the response time of envelope assemblies with tunable elements and corresponding HVAC system load, as indicated in Table 9 ("Methods to quantify building-specific response characteristics"). Even if the tunable materials can change their properties quickly, it is expected that the heating or cooling demand for the building will change more slowly. The occupancy level, internal thermal loads, shading, thermal mass, and wall-to-floor area ratio of the building will influence the lag in the response of the building. These items also influence, therefore, how far the indoor temperature will deviate from the desired set point temperature in response to a grid event, even if the adjustment of the tunable thermal material will eventually offset HVAC system operation. These two response relationships—tunable thermal material to complete envelope and complete envelope to HVAC system—will thus begin to establish the grid service potential of tunable thermal conductivity materials. These relationships will also help determine which system performance parameters are most critical to grid service provision and what performance levels need to be achieved for each of those performance parameters to reliably deliver the most viable grid services (potentially inclusive of those services suggested in Table 5).

The interactive effects between tunable thermal conductivity materials and the rest of the envelope assembly revealed by this research might indicate that demand flexibility would benefit from improvements in the characteristics of the envelope assembly. It is possible that these improvements can be readily achieved with slight modifications to construction methods or assembly configurations, but if not, as noted in Section 4.4, research should be conducted to develop novel envelope assemblies that enable improved demand flexibility from envelopes with tunable thermal conductivity materials.

Research to develop materials with dynamically tunable thermal transport features has mostly focused on applications where only a small amount of the material is needed. Further research is needed to develop materials suitable for the heat transfer conditions faced by buildings, and eventually, to identify low-capital-intensity production methods that are appropriate for the volumes required for building envelopes. Materials with variable thermal conductivity might benefit from research to broaden their dynamic range, particularly in the regime where thermal conductivity is low enough for building insulation. Some preliminary research on tunable thermal conductivity materials for buildings applications suggests that even at a switching ratio of 10:1, there is already some benefit available (Prasher, Dames, and Jackson 2019).

5.3 Thermally Anisotropic Systems

TASs connected to a thermal sink or source with active control capabilities could deliver grid services. Although not required, research to develop materials or assemblies that facilitate dynamic (on/off) connections between TASs and thermal sinks and sources could improve their performance. These materials or components should offer the ability to connect and disconnect the TAS from the sink/source. Beyond on/off control, methods to modulate the thermal energy flow rate between the TAS and the sink/source would improve control of cooling and heating loads through the envelope. Approaches to be investigated by future research could include mechanical systems or thermal circuit technologies, such as the directional heat transfer materials discussed in Section 5.2.

More generally, technologies and materials that can efficiently redirect heat within buildings have the potential to expand the grid service response potential of TASs. These materials would function as the thermal equivalents of wires in electrical distribution systems. For HVAC systems, hot water or refrigerant can be pumped to distribute heating and cooling throughout a building, but there are no equivalent methods for direct redistribution of existing thermal energy in building interiors. Thermal energy redistribution materials could create more uniform temperatures between interior spaces, improve thermal comfort, and efficiently redirect thermal energy to and from TASs that have access to an external sink or source. Currently commercialized thermal energy redirection technologies include heat pipes and thermosyphons. Developing novel approaches or improvements to these technologies that reduce their cost and increase their flexibility in placement and form factor could enhance the GEB performance of TASs.

To fully realize the potential for demand flexibility with TASs using thermal sinks and sources, research is also needed to develop materials or components that can effectively access thermal sinks or sources with performance properties that yield the desired GEB benefits. The materials discussed in Section 5.6 might offer a potential sink for excess thermal energy, though they might only be suitable for some climates. Further work is needed to establish appropriate sink and source characteristics as a function of climate and other system attributes, including system size and anisotropy.

As with other dynamic opaque envelope technologies, a TAS is only a component within an envelope assembly that serves multiple simultaneous functions, including providing structural strength, separation between indoor and outdoor conditions, and a visually appealing finished interior and exterior appearance. The resulting multielement, multilayered assembly has the potential to restrict the effectiveness of TASs, because one of these layers might buffer the influence of the TAS on heat transfer. The interaction of the other assembly components with the TAS should be established to determine the ability of the finished envelope assembly to provide grid services. Further research might be needed to develop substitute materials that replace the buffering element in the envelope assembly. Depending on which envelope component(s) interfere the most with TAS performance, research might also need to extend to novel envelope assembly designs that enhance TAS operation. This R&D opportunity applies to other technologies that provide active heat transfer management functionality in the opaque envelope and is also discussed in Section 5.2.

5.4 Thermal Storage

Demand flexibility from a building component or technology requires control over the timing of the operation of that system and the magnitude of its electricity demand. There are no methods currently available to independently control the timing or rate of charging or discharging of opaque envelope thermal storage technologies (such as PCMs). Existing opaque envelope thermal storage technologies can shift HVAC load, but only by reacting passively to the temperature of the environment where they are installed, and not in response to commands from a utility or system operator or even requests based on forward-looking (e.g., day-ahead, hour-ahead) forecasts. Research to develop materials that can be added to existing thermal storage materials or technologies, or novel thermal storage materials that have inherent charge, discharge, and rate control capabilities, is critical to the potential for building envelope thermal storage technologies to provide grid services. Charge and discharge event control is most critical; being able to stop and start charging and discharging is a minimum requirement for GEB operation with thermal storage. Conversely, rate control could enable more sophisticated responses, where, for example, both the duration and magnitude of the requested response might vary. Some grid conditions might call for a larger response, but over a shorter or longer period of time—having charge and discharge rate control would enable thermal storage to more closely match the requested response.

To facilitate research on materials that enable active control capabilities for opaque envelope thermal storage, supporting research must be conducted to determine the desired or optimal active control capabilities for 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, as identified in Table 5. 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. Further, this research would help determine whether additional capabilities are needed, such as whether there is value in developing thermal storage control capability to minimize self-discharge for longer-term (multiday) storage. This research would need to include both the response capabilities for an individual building's thermal storage system as well as groups of buildings (e.g., a single feeder). The latter can help inform the design of control signals sent by utilities or system operators to request a particular grid service, such as load shifting, and might also influence the desired control capabilities for an individual building. For example, rate control capability might change how an individual building's controls respond to deliver a requested service using thermal storage; the response request strategy from the utility might change if the desired response can be achieved through two homes each delivering half of the response, potentially enabling more flexibility later as compared to having one home not respond and the other respond in full.

The ability to control the transition temperature of phase change thermal storage materials could also increase the value of such storage media. Figure 9 shows the results of an analysis of the effect of transition temperature tunability on energy storage in U.S. buildings (Mumme et al. 2019). These results show that regardless of whether the thermal storage material is primarily intended for use during heating or cooling season, the addition of tunability to the transition temperature of the medium significantly increases the annual energy storage potential. Further work is needed to better quantify the additional demand flexibility available from tunable transition temperature thermal storage materials.

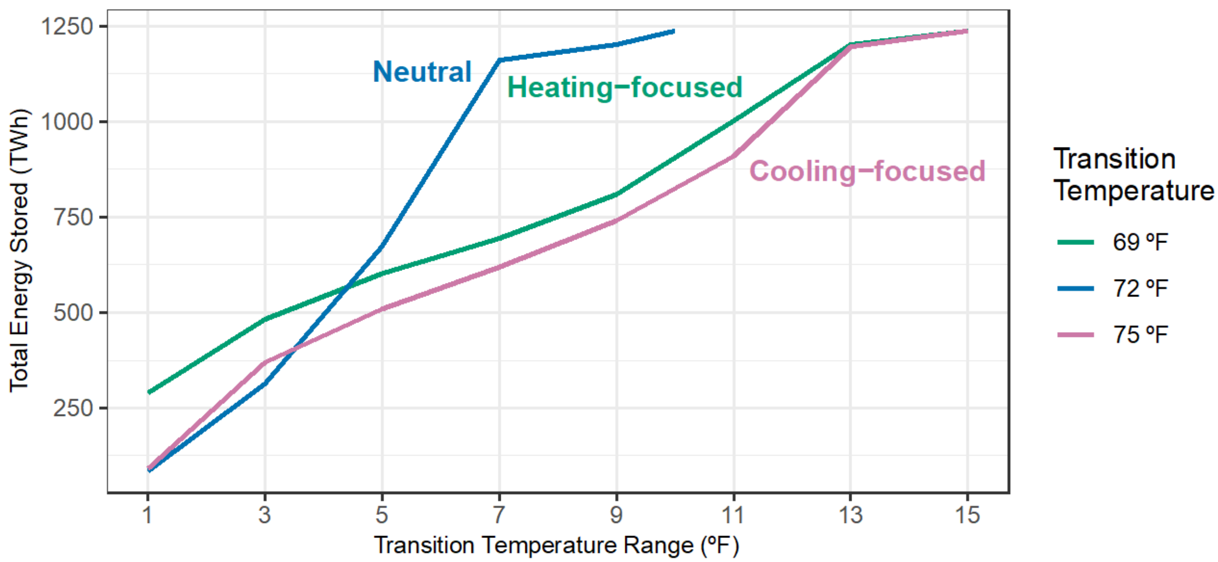

Figure 9. A parametric analysis of the effect of thermal storage transition temperature range on energy storage capacity

In all cases shown, but especially for heating-focused (69°F transition temperature) and cooling-focused (75°F transition temperature) thermal storage, increasing the range of possible transition temperatures substantially increases the total annual energy storage potential. Thermal storage materials with tunable transition temperatures thus have the potential to support demand flexibility over a wider range of weather and building operating conditions.

5.5 Moisture Storage and Extraction

As with thermal storage, materials that can store moisture, including materials in the building envelope, cannot currently have their storage behavior controlled based on desired operation; these materials respond passively to ambient relative humidity and store or discharge moisture accordingly. Novel materials with controllable moisture storage properties are needed to be able to provide grid services by reducing or shifting cooling system electricity demand through the manipulation of relative humidity levels in buildings. The introduction of moisture storage control capabilities might be facilitated through the development of control materials or technologies that can be applied to existing elements of the building envelope that can store moisture from the interior environment (principally drywall, but also suspended ceilings) or materials that have moisture storage capacity and intrinsic or embedded control features. With the advent of these materials, as noted in Table 9 (“Grid service-specific control strategies that can balance occupant needs and grid benefits”), control systems that can operate them to provide the desired grid services will be needed.

Moisture storage and extraction technologies that have substantial humidity control capabilities have not been extensively identified in the literature. Research is needed to establish the performance characteristics required of an active control system to maximize the potential to provide grid services from a given moisture storage system and to maximize, where possible, total energy savings potential. Results from this research will help define the minimum performance characteristics and critical control parameters for a moisture storage control system to deliver the intended performance. This research can also help establish which grid services are most viable and which services will require the highest levels of performance from the control system, which might help researchers develop initial go-to-market strategies. The specific grid services that can be provided using controllable moisture storage and extraction materials are currently unknown and will be determined through this research, though Table 5 provides an indication of what grid services might be possible.

5.6 Variable Radiative Technologies

In general, active control capability is needed for variable radiative technologies. Although passive single-state materials (e.g., cool roofs and surfaces) can deliver proven energy savings in some climates, active control over the radiation heat transfer properties of building envelopes will enable them to provide demand flexibility. Active control will require a quantitative understanding of the building-specific response that can be expected from changing the surface properties; the response characteristics of the building will vary widely as a function of shading, orientation, window-wall ratios, opaque envelope assembly design, and other factors. This information could be used in a model predictive control system, or a machine learning approach could be used to deduce building response characteristics and other critical parameters (such as weather) that should inform the control strategy for the surface(s).

For daytime radiative cooling materials, thermal circuit technologies that can control the connection between the surface material and the associated envelope system or assembly are a key enabler of grid service capability. Current advanced daytime radiative cooling materials will operate continuously, which will yield energy savings, but not load control abilities. A thermal circuit element that can connect or disconnect the radiative cooler from the rest of the envelope assembly will enable load shifting or shedding in response to a control signal. This circuit element might operate in a manner more akin to a potentiometer, allowing varying levels of heat conduction between the radiative cooler and the opaque envelope, which would enable more flexible control of the effect of the radiative cooler. Depending on the responsiveness of the cooling load of the building to changes in the configuration of the thermal switch or potentiometer, this variable thermal conductivity property might also allow for some ramp rate mitigation with the radiative cooling system when used on a building with a multizone, variable speed, or variable air volume cooling system.

Daytime radiative coolers might be able to be used as a heat sink for TASs (discussed in Section 5.3). In this manner, the high thermal conductivity layers of the TAS would be linked to a radiative cooler panel or network to reject excess heat in the cooling season. This system configuration might be easier to install and maintain than systems using the ground as a thermal sink/source and could facilitate the use of TASs on a wider range of buildings. In particular, this could facilitate TASs for tall buildings, where long conduction paths to a ground thermal sink/source might diminish performance. Thermal circuit control would be especially important in this application to avoid unwanted or excess cooling. Alternatively, a reversible radiative cooler that can provide passive heating in the heating season, as mentioned in Section 4.8, would expand the functional capability of the radiative cooling system and might entirely obviate a ground heat source or sink.

5.7 Dynamic Envelope Technology Assemblies

As noted in Table 5, it is likely that maximizing the demand flexibility—response speed, magnitude, and reliability—available from dynamic building envelope technologies will require coordinated control of the envelope components, HVAC systems, and in some cases, lighting systems. These interactions affect the performance of both static and dynamic envelope technologies, and although relatively well known in a research context, the practical implications of these interactions are not always reflected in the construction and operation of buildings. With dynamic envelope components, these interactive effects, and how they influence building responsiveness and interior conditions, become more critical. Research should be conducted to establish the importance of interlinked responses from various dynamic building envelope components, both as individual technologies and as part of integrated opaque envelope assemblies and upgrade packages, along with other impacted building end uses—HVAC and lighting. Results from that work would guide the development of controls that enable interlinked operation to maximize grid service provision and avoid unexpected feedback loops or interference from technologies delivering competing responses.

Dynamic building envelope assemblies comprising the technologies discussed in Sections 5.2–5.6 could deliver greater demand flexibility than their constituent components. For example, envelope-integrated energy storage materials can shift heating and/or cooling loads, reduce the magnitude of temperature swings, and take advantage of favorable ambient conditions to reduce energy use, but their operation cannot be readily controlled, thereby limiting their ability to provide demand flexibility. Tunable thermal conductivity materials can provide control over when the storage medium charges and discharges, thus substantially increasing the potential for thermal storage systems to deliver grid services.

A simulation of three different wall configurations highlights the potential value of envelope assemblies that combine multiple dynamic elements (Prasher, Dames, and Jackson 2019). The three configurations illustrated in Figure 10 consist of a traditional wood stud wall with cavity insulation (Case 1), a wood stud wall with cavity insulation with a layer of PCM added behind the interior wallboard (Case 2), and a wood stud wall with a PCM similar to that in Case 2, but surrounded on the interior and exterior sides with thermal switch materials (Case 3). Figure 11 shows the average daily cooling load results for 1,000 hours during the cooling season (June 16–July 28); cooling energy use is reduced dramatically in both climate zones considered when the PCM is controlled with thermal switches (Case 3) as compared to a current typical PCM configuration that lacks active control (Case 2). Although these results do not directly demonstrate the potential for a combined thermal storage and tunable thermal conductivity material combination to provide grid services, they highlight the influence of these dynamic material assemblies on the operation of and energy use associated with the building envelope and therefore suggest the potential additional demand flexibility enabled by dynamic envelope assemblies.

Further incorporation of advanced retrofit strategies into envelope assembly designs could accelerate adoption of novel systems and increase both energy savings and demand flexibility benefits. The proposed configurations discussed in this report should not be considered an exhaustive representation of dynamic envelope technology assemblies.

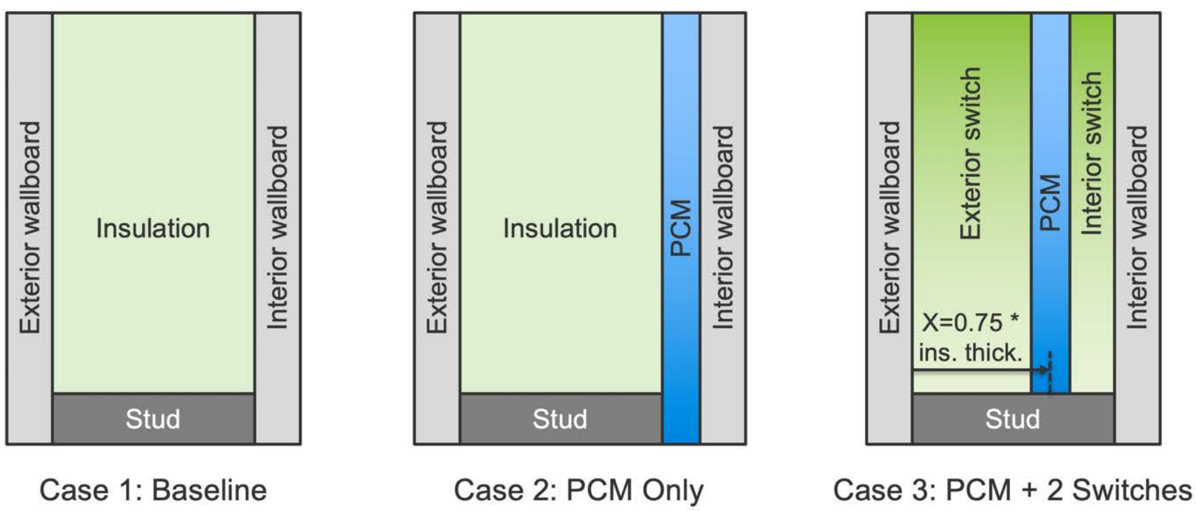

Figure 10. Wall assemblies with different configurations

Case 1 shows insulation in a traditional configuration, Case 2 shows insulation with a PCM adjacent to the interior wallboard, and Case 3 shows PCM enclosed by thermal switches on both the interior and exterior side that can modulate heat transfer between the PCM and the exterior and interior environments.

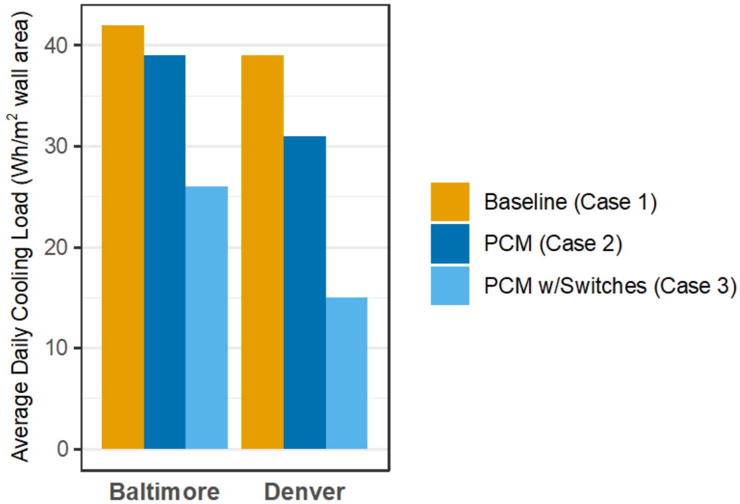

Figure 11. Simulation results for the three wall configurations shown in Figure 10

When applied to a 100 ft^2 wall during 1,000 hours in the cooling season (June 16–July 28), simulation results show that the average daily cooling load through the subject wall can be substantially reduced (in both climate zones shown) by adding thermal switches that enable active control of the charging and discharging of the PCM (Case 3).

5.8 Summary of Technology-Specific Challenges and R&D Opportunities

Table 10. Window and Opaque Envelope Technology Challenges and Opportunities

Technology	Challenges	R&D Opportunities
Dynamic Glazing and Automated Attachments	Off-the-shelf controls with GEB functionality Complexity of sensor system configuration and commissioning	• Novel building controls strategies that incorporate dynamic glazing and automated attachment functionality into their core capabilities, alongside HVAC systems and other building components • Develop software tools for simple, low-effort sensor configuration planning and to verify installation and rapidly diagnose in-field faults • Determine whether GEB operation introduces additional commissioning or sensor system requirements and adapt tools accordingly
Tunable Thermal Conductivity Materials	Breadth of potential operations and the relative demand flexibility potential of various materials and configurations System physical and thermal response times Effect of assembly on operational performance	• Identify placement or applications, types of tunable thermal conductivity materials or "circuit elements" that maximize demand flexibility • Investigate the energy savings, cost benefits, and demand flexibility potential of coupled systems (i.e., tunable thermal conductivity materials designed for use as a package with other dynamic envelope technologies) • Quantify the value of increasing the response speed of tunable thermal conductivity materials • Investigate the potential for more extensive changes in the envelope assembly to improve demand flexibility and energy savings • If valuable, design novel assemblies that use tunable thermal conductivity materials to enhance the performance of other dynamic and tunable components for demand flexibility and overall energy savings
Thermally Anisotropic Systems	Components or technologies that enable switching (on/off) of connection to sink/source Components or technologies that enable rate control with connection to source/sink Technologies that facilitate effective access to potential sources and sinks Effect of assembly on operational performance	• Develop novel materials or system designs that can effectively access thermal sinks and sources with minimal installation effort • Develop thermal switch materials or mechanical devices that can control the connection between the anisotropic material and a related source/sink • Investigate the potential for novel assemblies to improve performance, including coupling with other technologies • Determine ideal envelope assembly characteristics to maximize GEB capability • Design novel envelope assemblies that have improved compatibility with thermally anisotropic materials and composites

Technology	Challenges	R&D Opportunities
Thermal Storage	Active control of storage media Understanding of the desired or optimal capabilities for active control systems	• Develop materials or assemblies that can control the timing of charge and discharge cycles • Develop materials that can be dynamically manipulated to change their transition temperature • Develop materials or assemblies that enable control over charge and discharge rates/speeds • Determine the conditions for thermal storage operation that offer the greatest potential for demand flexibility and energy savings, independent of storage system characteristics, to establish requirements for active control capabilities (in addition to R&D conducted in response to "parameterization of grid response capacity or capability" in Table 9) • If indicated, develop control systems that minimize self-discharge
Moisture Storage and Extraction	Active control of storage media Understanding of the desired or optimal capabilities for active control systems	• Develop materials or assemblies that can control the timing of charge and discharge cycles • Develop materials or assemblies that can extract moisture in liquid form • Develop materials or assemblies that enable control over charge and discharge rates/speeds • Determine the conditions for moisture storage operation that offer the greatest potential for demand flexibility and energy savings, independent of storage system characteristics, to establish requirements for active control capabilities (in addition to R&D conducted in response to "parameterization of grid response capacity or capability" in Table 9)
Variable Radiative Technologies	Active control of operation Fouling, condensation effects on performance	• Develop materials that can alter key performance parameters in response to a control signal • Develop thermal switch materials for heat conduction control with daytime radiative coolers.

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