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Emerging Technologies Research and Development

DRAFT Research and Development Opportunities Report for Opaque Building Envelopes

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DRAFT

Disclaimer

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List of Acronyms

ACH50	air changes per hour at an induced pressure differential of 50 Pa
BEM	building energy modeling
BIM	building information modeling
BTO	Building Technologies Office
CFM75	cubic feet per minute of air leakage per square foot building envelope surface area at an induced pressure differential of 75 Pa (sometimes denoted $CFM75/ft^2$)
ECM	energy conservation measure
HVAC	heating, ventilation, and air conditioning
IECC	International Energy Conservation Code
MPC	model-predictive control
ORNL	Oak Ridge National Laboratory
PACE	property-assessed clean energy programs
PCM	phase change materials
R&D	research and development
TAMs	thermally anisotropic materials
VIPs	vacuum-insulated panels
VOCs	volatile organic compounds

Executive Summary

BACKGROUND

The opaque envelope—the barrier that helps maintain comfortable indoor conditions irrespective of prevailing outdoor conditions—is the single largest contributor to primary energy use in residential and commercial buildings.

Residential and commercial buildings comprise 39% of total U.S. primary energy use [1]. The opaque envelope affects 25% of building energy use, or 10% of total U.S. primary energy use [2]. Improving the energy performance of the opaque envelope in U.S. buildings is critical to reducing total building energy use. Retrofits are crucial to realizing the energy savings potential of the opaque envelope because nearly 85% of residential and 55% of commercial buildings that exist today will still exist in 2050 [1]. Building envelope performance is also relevant to occupant comfort, productivity, health, and well-being.

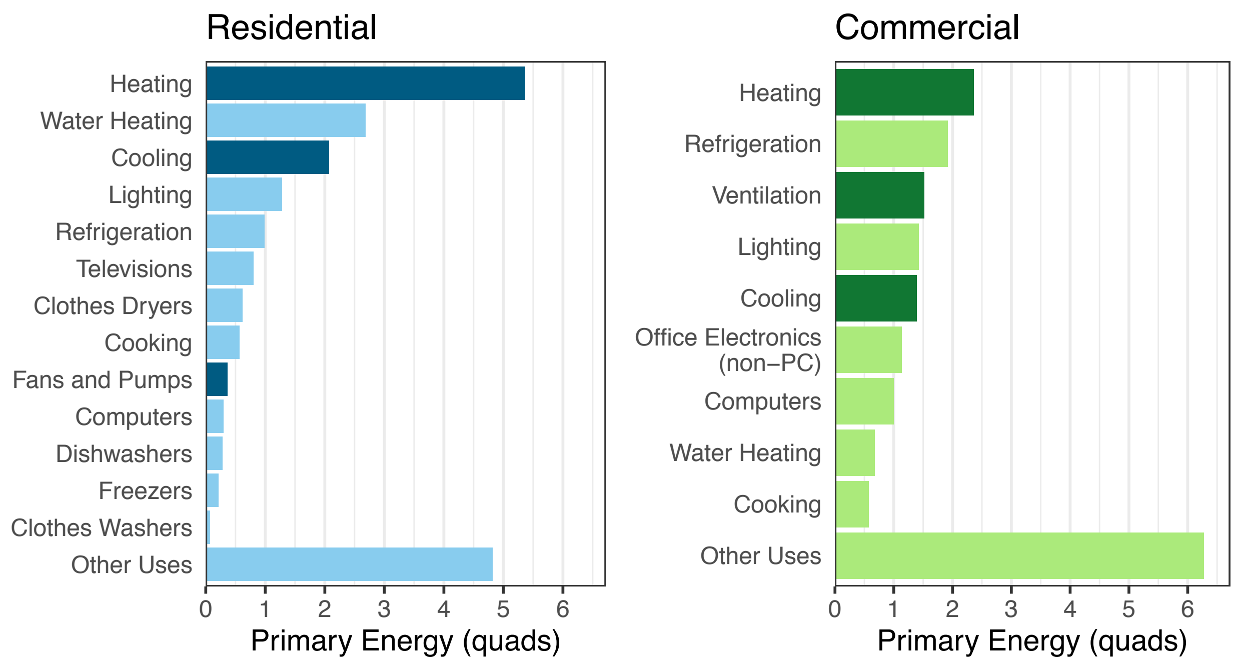

Figure ES-1: The opaque envelope affects heating, cooling, and ventilation (fans and pumps) energy use; these end uses are among the largest contributors to total primary energy use in U.S. buildings. Performance improvements in the opaque envelopes of new and existing buildings can reduce energy use in all three of these end uses. [1]

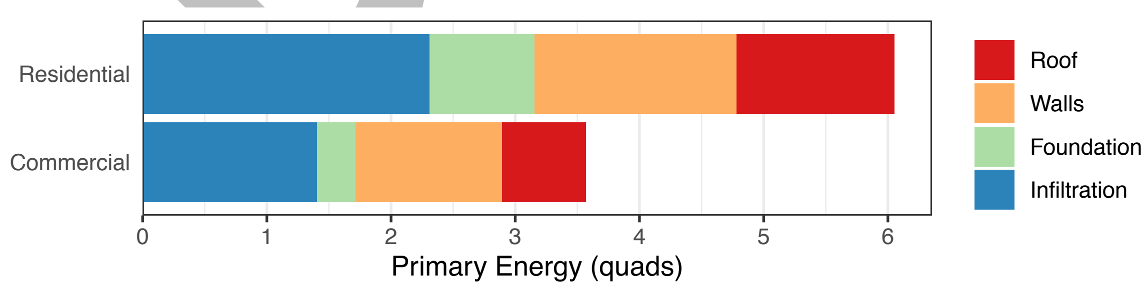

Figure ES-2: The breakdown of energy use by the components that comprise the opaque envelope shows that infiltration is the single largest contributor to total energy use, though all of the components represent a substantial contribution to energy use in buildings. [2]

TECHNOLOGY SOLUTIONS

Novel opaque envelope technologies could dramatically reduce building energy use while simultaneously delivering additional benefits—comfort, well-being, and productivity—for building owners and occupants. This research and development (R&D) opportunities report identifies technologies that have the greatest potential to transform opaque envelope performance in new and existing buildings. This report articulates critical technology improvement needs and the R&D actions to address those needs for each of five technology focus areas.

Needs

- Reduce Air Leakage
- Improve Moisture Management
- Increase R-Value
- Improve Constructability
- Increase Longevity
- Improve Affordability
- Enable Demand Flexibility

Technology Focus Areas	
Ultra-High R/in Insulation Materials	Materials with a high R-value per inch of thickness can enable higher insulation levels in new construction and reduce the cost and complexity of retrofits of existing buildings.
Envelope Diagnostic Technologies and Modeling Tools	Technologies that can characterize the key energy performance-related properties of existing opaque envelopes could facilitate retrofit adoption by quantifying the benefit of retrofits and verify post-retrofit performance.
Envelope Remediation Technologies	Once a building envelope is complete, it is difficult to improve performance without substantial teardown and reconstruction; novel remediation-specific technologies can resolve this challenge.
Tunable Transport Materials	Tunable transport materials promise new envelope functionality, adjusting envelope properties in response to electric grid needs and interior and exterior conditions to minimize energy use while maximizing occupant benefits.
Energy Storage Systems	Thermal and moisture storage can shift the timing of heating and cooling energy demand, improve thermal comfort by stabilizing indoor temperatures, and offset energy use by taking advantage of favorable ambient conditions.

Needs Addressed

Ultra-High R/in Insulation Materials

Technology Action Plan

- Develop materials and encapsulation methods that are durable and ensure long life with stable R-value
- Develop high-throughput, low-capital-cost manufacturing methods for relevant materials
- Develop materials and fabrication methods that yield convenient form factors for installation
- Develop materials that allow for on-site modification of the dimensions of the as-delivered product while maintaining R-value and durability
- Develop material formulations that achieve expected R-values at the macroscale
- Develop new metrology that offers accurate measurement at low thermal conductivities (<20 mW/m-K)
- Develop simulation methods that accurately represent thermal transport phenomena at multiple relevant length scales.

2040 Target (Walls)	Today	2040 Target (Walls)	Today
20 R/in	**<18** R/in	**0.64–1.91** $/ft² area	**14–17.25** $/ft² area

Envelope Diagnostic Technologies and Modeling Tools

Technology Action Plan

- Develop novel diagnostic metrology suitable for year-round buildings testing conditions
- Investigate virtual sensing to evaluate envelope performance and establish minimum requirements
- Develop diagnostic metrology for envelope moisture performance
- Develop low computational cost, accurate methods for modeling complex heat and mass transfer flows.

Envelope Remediation Technologies

Technology Action Plan

- Develop novel materials and methods for overcladding with reduced labor effort and complexity
- Investigate compatibility of high R/in insulation materials with remediation delivery systems
- Develop materials and installation methods that can yield air sealing in the climate-appropriate plane without significant teardown
- Develop autonomic self-healing air barrier films
- Develop one-step spray- or liquid-applied air and vapor control materials.

2040 Target	Today	2040 Target	Today	2040 Target	Today
1 ACH50 (residential)	**1–3** ACH50 (residential)	**0.2** CFM75/ft² (commercial)	–	**0.17–1.09** $/ft² area	**1.5–2.5** $/ft² area

Tunable Transport Materials

Technology Action Plan

- Establish fundamental physics underlying circuit element mechanics in solid-state materials in environmental conditions comparable to the opaque envelope
- Achieve dynamic resistive switching ratio (R_{off}/R_{on}) ≥ 10 with a high thermal resistance state ≥ R_{air}

- Evaluate cycling durability and develop materials with minimal performance degradation over thousands of cycles
- Establish viable heat sinks and sources for anisotropic systems and demonstrate operation.

2040 Target	Today	2040 Target	Today
50% energy savings	–	**0.93–1.28** $\$/\text{ft}^2$ area	–

Energy Storage Systems

Technology Action Plan

- Develop storage with sufficient thermal conductivity (>1 W/m-K) and energy density (>100 kWh/m^3) using low-cost materials
- Develop materials with transition temperature tunability in a buildings-appropriate regime (20°–25°C)
- Develop technologies that enable charge and discharge timing and rate control
- Develop active moisture storage materials with selective moisture extraction capability and charge and discharge control
- Determine storage form factors and control strategies to maximize benefits
- Explore value of coordination with other storage types and building energy end uses.

2040 Target	Today	2040 Target	Today	2040 Target	Today
100 kWh/m^3	**30–50** kWh/m^3	**1** W/m-K	**0.1–0.5** W/m-K	**15** $\$/\text{kWh}_{\text{thermal}}$	**>45** $\$/\text{kWh}_{\text{thermal}}$

ACCELERATING TECHNOLOGY ADOPTION

Beyond developing novel opaque envelope materials and systems as well as supporting tools and infrastructure, other actions can help broaden the value proposition and accelerate the adoption of next-generation, high-performance building envelopes. The building construction and products industry in the United States is mature and has been slow to change and adopt new practices and materials. Prevailing construction and building retrofit market conditions and adjacent factors can create significant barriers to technology uptake. These barriers can be financial, knowledge-related, or implementation-related. Approaches to addressing these barriers can include a range of voluntary actions, marketing and information sharing strategies, and policy interventions.

ADVANCED BUILDING CONSTRUCTION WITH A SYSTEMS-LEVEL APPROACH

High-performance opaque envelopes affect the heating, cooling, and ventilation requirements of a building. Taking a whole-building systems-level approach ensures that the interactions between these major building subsystems are reflected in decisions made throughout the design and construction process. Such an approach, in both new construction and retrofits, can maximize the energy savings delivered for a given project budget.

Although available retrofit technologies and approaches could cut building energy use in half, only a small portion of existing buildings undergo high-efficiency envelope retrofits. A major barrier to the adoption of these retrofits is that currently available envelope retrofit products and processes can be particularly disruptive in existing, occupied buildings. Furthermore, unlike other building equipment that is replaced periodically due to failure or obsolescence, building envelopes are much less frequently altered. More common changes, such as reroofing or residing, rarely result in improved energy performance. Existing retrofit approaches also rarely address moisture and vapor control layers, thus increasing the risk of moisture, comfort, and durability problems. To tap into the potential for substantial energy savings from opaque envelope retrofits while improving durability and occupant health and comfort, building owners need affordable, less-disruptive alternatives for improving building envelope performance.

Advanced building construction seeks to capitalize on these opportunities for substantial energy and cost savings that arise when taking a holistic perspective of building design, construction, and operation. With an advanced building construction approach, technology and business practice innovations throughout the building project life cycle can help reduce cost while increasing scalability and repeatability to drive technology adoption. This approach might lead to the development of novel envelope configurations that integrate multiple control layers for air, moisture, and heat, as well as structural functions, into fewer layers and components. Rethinking envelope assemblies to simplify effort and improve flexibility or adaptability could be particularly beneficial for retrofit applications, which tend to require a high degree of customization due to the enormous variation in existing buildings.

GRID-INTERACTIVE EFFICIENT BUILDINGS

Grid-interactive efficient buildings (GEBs) can dynamically manage their energy use to help integrate distributed energy resources, meet electric grid needs, and minimize electricity system costs, while meeting occupants' comfort and productivity requirements. Opaque envelope technologies have the potential to contribute to these building demand-side management strategies with passive and active responses. Opaque envelope technologies with static (non-time-varying) properties can provide grid benefits passively by increasing building shell thermal resistance to heat flow, reflecting solar energy, or increasing thermal mass. These performance improvements can benefit the grid by reducing peak period demand, thus potentially deferring generation, transmission, and distribution system expansion. Novel opaque envelope technologies that offer active modulation of their heat transfer characteristics or active control of thermal storage can provide grid benefits by reducing or shifting the timing of heating, cooling, and ventilation electricity demand.

Improving the grid-responsiveness of buildings through GEB envelope technologies has a major co-benefit of improving the resilience of buildings. Thermal shell improvements and proper management of building thermal mass through control strategies can help reduce the strain on the grid, and subsequently, the likelihood of a dangerous outage from occurring in the first place.

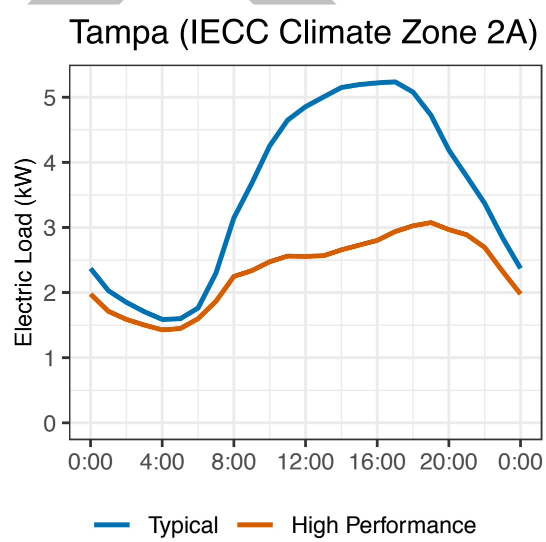

Figure ES-3: Average summer 24-hour load shapes for a residential single-family detached home show that improving opaque envelope (and window) performance from that of a typical existing home to slightly above new building code levels reduces peak electric load by 20%–47% depending on the climate zone; larger summer peak reductions are seen in hotter climate zones. These reductions are from passive opaque envelope technologies alone; active, dynamic technologies could provide further grid benefits.

IMPLEMENTATION

Once novel, high-performance opaque envelope technologies are made commercially available, market conditions can affect their adoption. Addressing financial-, information-, and implementation-related market barriers can facilitate the adoption of these technologies. Although changes to reduce these barriers might not explicitly incentivize investment in envelope energy efficiency, by creating conditions in which the building construction industry and building owners and tenants all perceive incentives or value in improving building energy performance, envelope upgrades are more likely to be adopted alongside other efficiency measures.

ABOUT THE BUILDING TECHNOLOGIES OFFICE

The mission of the Building Technologies Office (BTO) is to invest in R&D that enables industry to develop and deploy novel technologies that can improve the efficiency and reduce the energy costs of the nation's residential and commercial buildings, in both the new and existing buildings markets. Research supported by BTO is focused on reducing energy intensity and cost for technologies across the buildings sector, while maintaining or enhancing occupant comfort, productivity, and product performance. Progress toward achieving this goal will make building energy costs more affordable—especially beneficial to U.S. families and businesses.

ABOUT THE BTO EMERGING TECHNOLOGIES PROGRAM

The BTO Emerging Technologies program supports R&D for technologies, systems, and software tools that can contribute to reductions in building energy use. The Emerging Technologies program provides R&D support in five primary areas: solid-state lighting; heating, ventilation, air conditioning, and refrigeration (including water heating and appliances); sensors and controls; windows and envelope; and modeling and tools. The Emerging Technologies program contributes to BTO's energy use intensity reduction goal by supporting the development of cost-effective, energy-efficient technologies. Broadly, to make significant progress toward BTO's goals, any next-generation envelope technologies must achieve widespread adoption. As a result, specific emphasis is placed on developing technologies that will have market-acceptable characteristics, including payback period and total installed price, aesthetics, durability, and sustained energy performance over the lifetime of the technology.

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1. Introduction

1.1 Buildings and Their Contribution to U.S. Energy Use

Modern buildings require energy: to provide occupant comfort, operate appliances and devices, and illuminate interior and exterior spaces. The building services provided through energy use are central to the purposes that buildings serve in our society. In 2018, residential and commercial buildings in the United States used 20.4 and 18.3 quadrillion Btu (quads), or 20.6% and 18.5% of total U.S. primary energy use, respectively [1]. As shown in Figure 1-1, residential and commercial buildings together represent more domestic energy use than either the industrial or transportation sectors. On a primary energy basis, electricity comprises a majority of building energy use: 27.8 quads or 71.9% of all building energy use [1]. Direct natural gas use in buildings is limited to only a few end uses, such as heating, water heating, and cooking, but still represents 8.4 quads or 21.6% of primary energy use in buildings [1]. Other petroleum fuels and renewable generation[1] provide the remaining 6.5% (2.5 quads) [1].

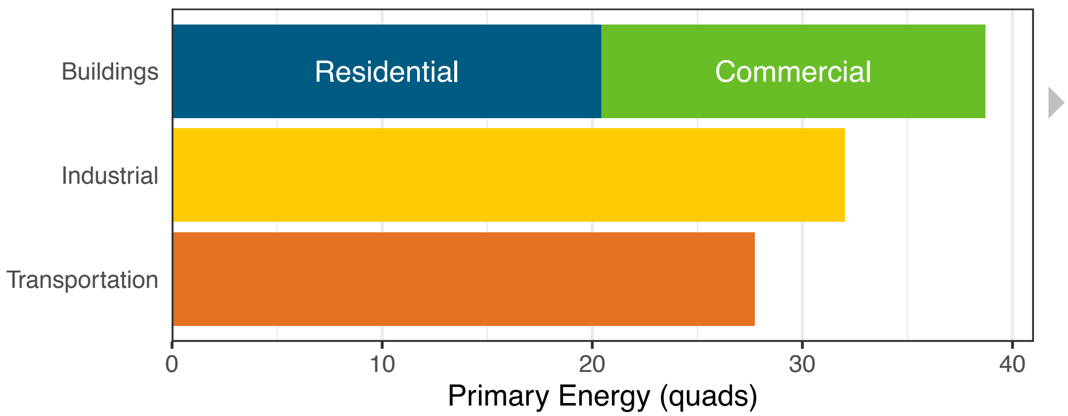

Figure 1-1: Residential and commercial buildings together are the largest single sector of U.S. primary energy use.

The breakdown of energy use among building services and devices (i.e., end uses) for an individual building can vary widely depending on the building type or function, square footage (size), local climate, and many other factors. More generally, the division of U.S. buildings' energy use among end uses differs between residential and commercial buildings, as shown in Figure 1-2. For residential buildings, energy use is dominated by space conditioning—heating and cooling—comprising 7.8 quads, or 38% of total residential energy use [1]. Water heating (2.7 quads, 13%) and lighting (1.3 quads, 6.3%) are also significant contributors, and together with space conditioning, represent more than half of total residential energy use [1]. In commercial buildings, space conditioning and mechanical ventilation together remain the dominant end use (5.3 quads, 29%) [1].

[1] Renewable generation in this context includes biomass, solar thermal, solar photovoltaic, and wind energy [1].

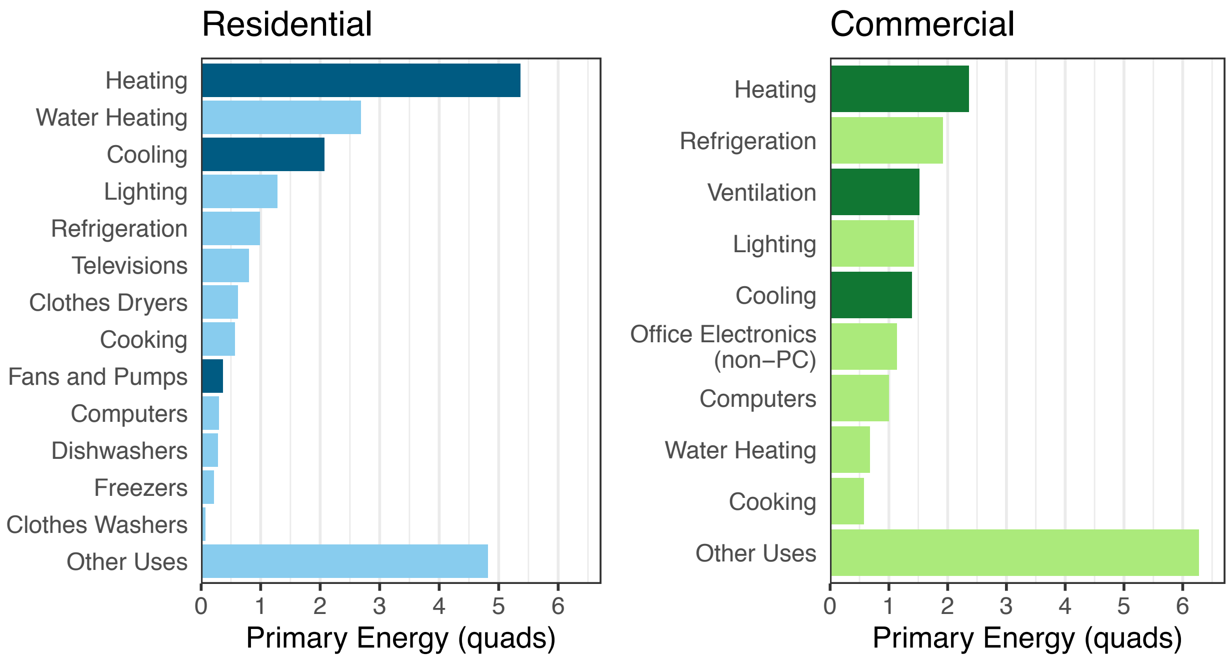

Figure 1-2: Apart from "other uses," heating is the largest single end-use contributor to total primary energy use in both residential and commercial buildings. When all space conditioning-related end uses—heating, cooling, fans and pumps, and ventilation—are taken together, they represent significantly more energy use than any other end use. These end uses (along with lighting, to a lesser degree), highlighted with darker bars, represent the energy use that can be reduced with performance improvements in opaque envelope components. These data are derived from the 2018 U.S. Energy Information Administration's Annual Energy Outlook [1].

1.2 Influence of Opaque Envelope Components on Building Energy Use

The building envelope protects building occupants from undesirable external environmental conditions. Some envelope elements can also be configured to take advantage of desirable external conditions by absorbing solar energy or allowing air to pass through at specific times. Both strategies—leveraging desirable external environmental conditions and mitigating the influence of undesirable conditions—can reduce the need for heating and cooling, and thus reduce energy use associated with heating, cooling, and ventilation equipment.

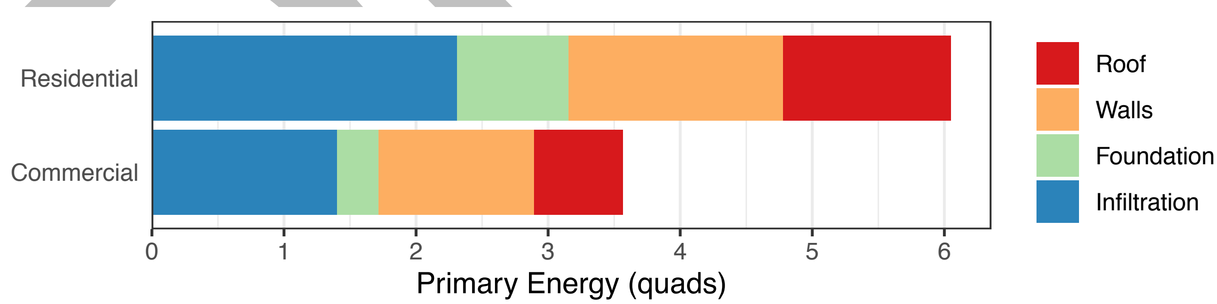

Figure 1-3: The breakdown of energy use by building envelope component in residential and commercial buildings during the heating and cooling seasons shows that the opaque envelope is the single largest contributor to envelope-related energy use, followed by infiltration (and exfiltration). Bars with negative values represent component contributions that reduce energy use. [2]

High-performance opaque envelope technologies have substantial potential to reduce energy use in buildings. Data in Figure 1-2 show that 34% of U.S. buildings' primary energy use is from space heating and cooling.

Figure 1-3 shows the breakdown of that energy use by envelope component.[2] The opaque envelope is represented by the major building elements where sensible heat transfer[3] occurs—the roof, walls, and foundation. Air and moisture flows that carry sensible and latent heat into or out of the building (denoted by “infiltration” in this report) pass primarily through interfaces between components, such as between window frames and rough openings, between the walls and the roof and foundation, and around miscellaneous penetrations through the opaque envelope (e.g., ducts and electrical outlets). Based on the data shown in Figure 1-3, for both residential and commercial buildings, the components that offer the greatest opportunity for energy savings (represent the largest contributors to energy use) are infiltration and walls. The data shown in Figure 1-3 represent U.S. totals, and the balance of energy use among envelope components varies by climate zone.

The composition of the building stock changes over time as new buildings are built and some old buildings are demolished, but the turnover rate (accounting for demolitions and new construction) of the U.S. building stock is relatively slow, particularly for residential buildings. Figure 1-4 shows the effect of building turnover rate on the prevalence of “existing” buildings (built before 2018) and “new” buildings (built in or after 2018); residential buildings are shown by housing unit and commercial buildings by available square footage. Because windows, air and water-resistive barriers, and insulation are built into the envelope at the time of construction, it is generally easiest to augment the energy performance of the envelope during initial construction.

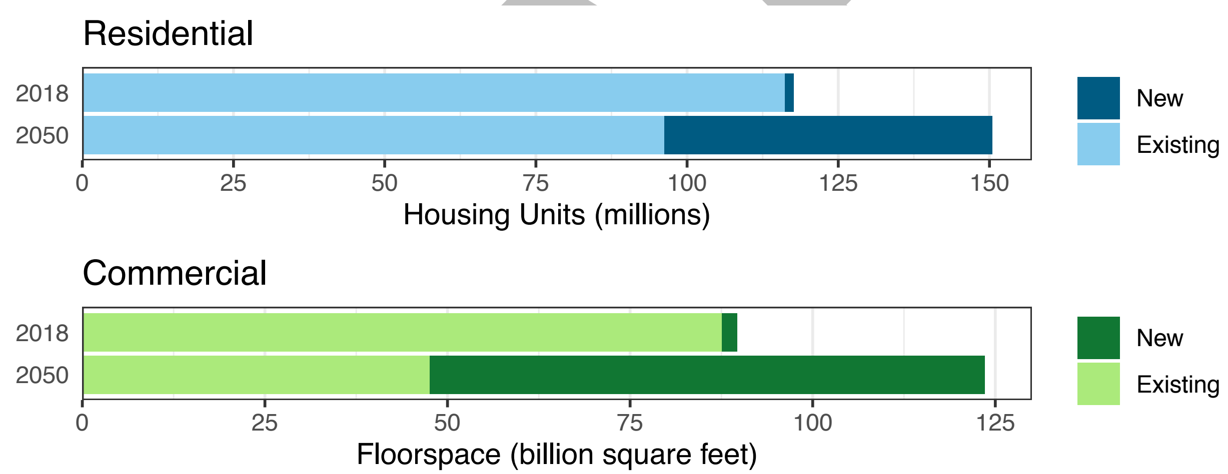

Figure 1-4: To maximize energy savings, new technologies must be suitable for retrofitting existing buildings, particularly in the residential sector, where by 2050, nearly two-thirds of the building stock will still be composed of “existing” buildings—those built before 2018. The remainder of the stock, represented as residential housing units and commercial square footage, will be buildings that were built after 2018. Commercial buildings turn over somewhat faster than residential buildings, but even then, in 2050, approximately 40% of square footage existing in 2018 will remain in the stock.

Though it might be easiest to incorporate high-performance envelope components in new construction, the data in Figure 1-4 highlight the importance of developing envelope technologies that are also suitable for retrofit of existing buildings. By 2050, these data indicate that slightly more than half of the commercial square footage existing today will have been replaced, while only one-third of residential units will have been replaced, and in the interim period, existing buildings will dominate the building stock. Moreover, these data do not account for which buildings are being replaced, so it is possible that the buildings being turned over are newer buildings and the data in Figure 1-4 underestimate the size of the existing stock.

[2] These data do not account for the potential for daylighting to reduce lighting loads.
[3] “Sensible heat” denotes heat transfer that causes the temperature of the system to be increased or decreased. “Latent heat” denotes heat transfer that occurs without a change in temperature; it relates to the difference in how a 90ºF day feels in Phoenix and Atlanta. In the context of the building envelope, this type of heat transfer is associated with the movement of water vapor (i.e., changes in humidity) through the opaque envelope.

Table 1-1: Residential retrofit projects undertaken in 2015 in owner-occupied units show replacement of windows and doors and roofs at rates comparable to HVAC systems, though with widely differing median project sizes. Siding projects can come with larger median expenditures, but are performed less frequently than other upgrades. Insulation projects are conducted somewhat more often, though both the number of projects and median expenditures lag other categories [3].

	Number of Projects (10^6)	Median Expenditure
HVAC	5.2	$3,150
Insulation	1.8	$750
Windows/Doors	4.3	$1,500
Roofing	4.0	$5,500
Siding	1.1	$3,000

While Figure 1-4 shows overall stock turnover, Table 1-1 shows the approximate number of retrofits of various envelope components in owner-occupied housing units in 2015. These data show that some retrofits, particularly those that involve key critical structural or life safety components (e.g., roofs) are pursued more frequently, in spite of their high prices, than retrofits to insulation or siding that might be principally to improve aesthetics or thermal comfort. HVAC systems are shown as a cost and scale point of comparison to underscore that although HVAC systems must often be replaced because of major mechanical faults, other envelope components are also regularly replaced. The replacement of envelope components at a rate that approaches or even exceeds the total number of new housing units built each year suggests that there might be meaningful opportunities for package retrofits that simultaneously repair or replace a major envelope component and improve energy performance. Table 1-2 shows renovation data for commercial buildings in 2012. These data show similar relationships between upgrade rates for different envelope components, where roof replacements occur at rates comparable to HVAC system upgrades and replacements, while insulation upgrades lag behind. Novel approaches discussed in this report have the potential to increase the retrofit rates or adoption of envelope energy performance upgrades for existing buildings by addressing the labor requirements (and concomitant price implications), disruption to building occupants, and other factors that currently limit the frequency with which envelope component replacements are considered.

Table 1-2: In 2012, among commercial buildings constructed before 2008 (as in residential buildings [Table 1-1]), roof replacement occurred at a rate nearly comparable to HVAC system upgrade or replacement. Other envelope upgrades were less prevalent, led by windows and followed by insulation upgrades and other exterior wall renovations. [4]

	Number of Buildings (10^6)	Percentage of Pre-2008 Buildings
HVAC	1.10	21.0%
Insulation	0.38	7.2%
Windows	0.56	10.7%
Roof	0.99	18.8%
Exterior Walls	0.19	3.7%

1.3 Building Technologies Office

Research supported by the Building Technologies Office (BTO) is focused on reducing energy intensity and cost for technologies across the buildings sector, while maintaining or enhancing occupant comfort, productivity, and product performance. In essence, a building must use energy more productively and efficiently, not only use less energy. Progress toward achieving this goal will make building energy costs more affordable—especially beneficial to U.S. families and businesses.

BTO's approach to improving energy productivity includes its grid-interactive efficient building (GEB)[4] strategy, which advances the role buildings can play in energy system operations and planning. This strategy includes both new and existing residential and commercial buildings, including their energy-consuming and labor-saving equipment. BTO's strategy will support greater affordability, resilience, environmental performance, reliability, and other goals, 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 like rooftop photovoltaics, electrochemical and thermal energy storage, combined heat and power, and other distributed energy resources (DERs) can be co-optimized with buildings to provide greater value and resiliency to both utility customers and the electricity system; and
- The value of energy efficiency, demand response, and other services provided by behind-the-meter DERs can vary by location, hour, season, and year.

Developing next-generation building technologies, including building materials, components, equipment, energy models, and systems, is critical to increasing energy productivity cost-effectively.

To achieve these objectives, BTO sponsors R&D efforts that target improving the largest energy users within buildings (shown in Figure 1-2): lighting, space conditioning, water heating, appliances, and miscellaneous electric loads, as well as the building envelopes themselves. BTO's R&D support also includes system-level efforts, including developing algorithms for improved energy modeling and system controls required to better predict and manage energy-efficient equipment and whole-building energy usage, particularly to enable grid-responsive operations.

BTO collaborates with industry, academia, and other leaders across the building sector to develop, validate, and verify solutions that help building owners and homeowners reduce energy use. Ultimately, design and decision tools developed with BTO support help building owners and operators apply efficient building operational practices and technologies through improved understanding of their costs and benefits, resulting in more cost-effective, comfortable, and healthy buildings.

Finally, BTO works with industry, professional societies, trade groups, and nonprofits such as ASTM and ASHRAE to develop and implement methods to evaluate and validate the energy performance of building components. BTO also evaluates changes to model building energy codes developed by ASHRAE and the International Code Council, which inform state and local building code processes.

1.4 BTO Emerging Technologies Program

The BTO Emerging Technologies program supports R&D for technologies, systems, and software tools that can contribute to improving energy efficiency and load flexibility. The Emerging Technologies program provides R&D support in five primary areas: solid-state lighting; HVAC and refrigeration (including water heating and appliances); sensors and controls; windows and envelope; and modeling and tools. The majority of Emerging Technologies funding is distributed competitively through solicitations (i.e., Funding Opportunity Announcements), which in general are open to applications from large industry, small businesses, academia, national laboratories, and other entities. BTO also invests in state-of-the-art capabilities at U.S. Department of Energy national laboratories that support its mission; these facilities are available to the buildings R&D community for cooperative research, component evaluation, and product performance validation.

The Emerging Technologies program contributes to BTO's energy use intensity reduction goal by supporting the development of cost-effective, energy-efficient technologies. Broadly, to make significant progress toward

[4] A grid-interactive efficient building is an energy-efficient building that uses smart technologies and on-site distributed energy resources to provide flexibility while co-optimizing for energy cost, grid services, and occupant needs and preferences, in a continuous and integrated way. For more information, see the recent *Grid-interactive Efficient Buildings Technical Report Series.* The *Overview of Research Challenges and Gaps* report can be found at https://www1.eere.energy.gov/buildings/pdfs/75470.pdf and contains introductory information as well as links to the other four technical reports in the series.

BTO's goals, any next-generation envelope technologies must achieve widespread adoption. As a result, specific emphasis is placed on developing technologies that will have market-acceptable characteristics, including payback period and total installed price, aesthetics, durability, and sustained energy performance over the lifetime of the technology.

1.5 Organization and Purpose of this Report

This report focuses on R&D for energy efficient opaque envelope technologies. It is the result of collaboration with prominent researchers and leaders in the field and aims to provide strategic guidance for BTO's investments in developing the next generation of high-performance, cost-competitive opaque envelope technologies.

The R&D opportunities identified in this report are predicated on an assessment of the need for improvements in the performance of opaque envelope components. An overview of thermal and mass transport in buildings, including state-of-the-art practices, is presented in Section 2, "Overview of Envelope Systems." This assessment provides the motivation for the fundamental and enabling research areas identified in Section 3, "Research Opportunity Areas." Section 3 includes a discussion of the current state of research, future research opportunities, technology-specific performance metrics, and the associated national energy savings potential. Technical, manufacturing, and market risks are also noted briefly in Section 3. The final two sections address topics that are important to the successful market entry of the technologies in Section 3. Section 4, "Integration," addresses two opportunities to fully realize a broader value proposition for envelope technologies: the adoption of a systems-level approach to new building design and deep retrofit planning, and the application of envelope technologies to benefit electric grid operations. Section 5, "Implementation," examines the technology transfer landscape as it relates to moving technologies from early-stage R&D to market-ready, commercially available products. Section 5 discusses the roles of industry, academia, national laboratories, and other public- and private-sector entities alongside BTO, with a particular focus on accelerating the handoff of technology R&D from BTO to its private-sector partners.

This report is a reconsideration of the technology R&D opportunities, technical risks, and deployment barriers presented in the 2014 roadmap [5]. Many of the technology R&D opportunities discussed in this report are also mentioned in that earlier document. This report seeks to build on the earlier efforts by broadening the discussion of technical needs and opportunities and moving that discussion forward to fully encapsulate the R&D technology opportunities detailed in Section 3.

This report does not provide an exhaustive presentation of all of the R&D opportunities related to opaque envelope technologies. The research opportunities presented in this report are seen as the most promising and impactful as they relate to national energy savings, consumer benefits, technical risk, and other factors that might affect the suitability of these R&D opportunities for future investment. This report includes some discussion of manufacturing risks, market barriers, and other concerns not directly tied to R&D, but it does not include an extensive treatment of these factors, only so much as is needed to provide context for and a robust appraisal of the various research directions presented. Similarly, because the focus in this document is on R&D program strategy, regulatory programs and incentive or rebate design are beyond our scope.

By articulating opportunities of particular importance and potential energy use impact, and the barriers inhibiting their progress, this report may help inform the strategic direction of BTO in soliciting and selecting innovative technology solutions to overcome technical barriers and ultimately help fulfill the BTO mission and goal.

Successful research, development, market entry, and widespread adoption of novel opaque envelope technologies requires sustained, long-term, high-risk research investment. Collaboration between academia, national laboratories, government, and private industry is critical to achieving these objectives. This report is intended to be a resource to assist in this process for the range of entities involved in the development and deployment of these technologies—state and local governments; utilities; academic, national laboratory, and private-sector researchers; international organizations; and others—and as such it will continue to be refined and updated as the market develops and as technology matures.

2 Overview of Envelope Systems

This section outlines the current state-of-the-art in existing opaque envelope technologies. This discussion includes not only technology characteristics that directly affect building energy use at the component level, such as thermal conductivity, but also attributes of those technologies that might influence total U.S. long-term energy savings potential by reducing or increasing technology adoption, such as installation price, quality control and repeatability, durability, and retrofit suitability, among others.

The building envelope is composed of the elements of the outer shell or enclosure of the building that maintain a dry, heated, or cooled indoor environment and facilitate its climate control. As described by Straube and Burnett [6], the many functions of the building envelope can be separated into three categories:

- Support (to resist and transfer structural and dynamic loads)
- Control (the flow of matter and energy of all types across the plane of the envelope)
- Finish (to provide the desired aesthetics on the inside and outside).

The control function of the envelope is central to energy efficiency, and in practice focuses on bulk water, water vapor, air, and heat flow control. This report overall focuses on the opaque portion of the envelope—that is, all of the building envelope other than windows and doors, although these three primary envelope functions also apply to those building elements.

Control of water is most fundamental, and there are numerous strategies that aim to facilitate this control, including ventilation air gaps, drainage planes, and weather-resistive barriers. These systems are employed to minimize the total amount of water—primarily as rainfall—that can penetrate into the building envelope system and also to facilitate the removal of any water that does gain access. Vapor control is required in climates where there is a significant portion of the year in which the vapor pressure gradient is in a singular direction across the envelope plane. As illustrated in Figure 2-1, the driving forces of vapor transport can change directions diurnally. Failure to adequately address liquid water and water vapor control can lead to reductions in energy efficiency, durability issues, or health issues for the building's occupants.

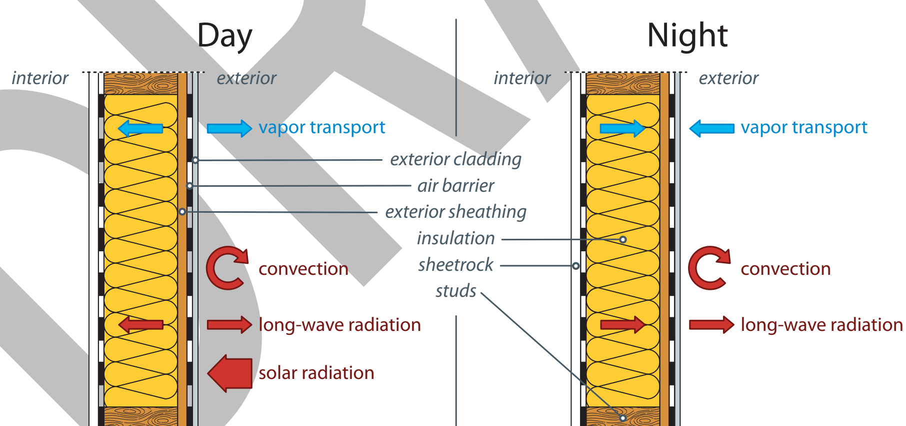

Figure 2-1: Within building envelopes, water vapor, liquid water (if present), and thermal energy (heat) have complex coupled transient transport, which is driven by time-varying interior and exterior ambient conditions. This illustration reflects a hot-dry climate during the summer. During the day, solar heating increases the exterior surface temperature, which creates a temperature differential that drives vapor transport. During cool nighttime conditions, a reversal in the temperature gradient thus reverses the vapor transport gradient. At all times, heat transfer from natural convection is present, driven by temperature differences between the exterior and interior surfaces and the surrounding air; additional forced convection from air circulation indoors and wind outdoors can accelerate heat transfer. In addition, at all times, the interior and exterior surfaces reject heat to the surroundings via long-wave radiation.

Control of airflow is important to ensure adequate indoor air quality, reduce energy use, avoid condensation (help ensure durability), and provide comfort. Air movements that need to be controlled include air that flows through the envelope, as well as air that flows into an envelope component and out of the same component (e.g., air that goes into and out of a roof plenum through the roof deck), which is referred to as "intrusion." Both of these scenarios can be mitigated with an air barrier system. Hence, air control includes minimizing the impact of windwashing—wind-driven air passing through insulation, which reduces its effectiveness—and convective loops, which are air movements within a wall or ceiling cavity.

Heat flow control is accomplished with a layer of thermal insulation between the conditioned space and the exterior climate. This layer should be continuous to minimize thermal bridges—conductive pathways that penetrate the insulation layer and facilitate heat transfer from the interior to the exterior (or vice versa). The performance of this layer is defined by its thermal resistance or R-value; recommended minimum R-value levels are climate specific and are tabulated in the building codes. Heat flow control can also be affected by the thermal mass of a building envelope component. Thermal mass or thermal inertia delays the transfer of heat flow through a building envelope component. In some specialized applications where large air spaces exist (such as attics), radiation heat transfer can be reduced through the use of low-emissivity surfaces. Finally, control of heat gain through solar radiation can be affected by the reflectivity of the exterior surface of the envelope.

These functions—support, control, and finish—are traditionally provided in constructed envelopes using components with static properties that resist time-varying internal and external thermal, moisture, and structural loads. An alternative approach, particularly with respect to energy performance, might be to employ components with dynamic properties. These novel dynamic envelope components could change their properties based on, or even autonomously in response to, interior and exterior conditions to take advantage of transient opportunities to minimize energy use. Dynamic envelope components also have the potential to enable coordination with the electric grid by changing their properties to strategically modify the timing of energy use. In this way, a dynamic envelope might be able to shift the timing of electricity demand to reduce peak load, reduce ramp rates, or take advantage of available distributed generation resources, such as rooftop solar. Static high-performance envelopes also have the potential to offer electric grid benefits, though the extent of these benefits might be more limited without dynamic capabilities.

2.1 Thermal Energy Management

Thermal energy management in typical building envelopes is primarily achieved with the use of insulation materials. Wall systems are typically constructed with nonstructural insulation installed in a structural frame (steel or wood) and sometimes supplemented by a continuous insulation layer applied to the exterior side of the structural frame. Foundations and low-slope commercial roofs typically employ a similar configuration, where a layer of continuous insulation is placed between the structural element (i.e., the foundation or roof deck) and the external environment. In steep-slope roofs, the large cavity between the occupied space and the roof deck allows for a variety of insulation options, from nonstructural insulation installed in the structural frame of the attic floor, to insulation sprayed or mechanically held between the rafters of the roof.

Other means for managing thermal loads include controlling their magnitude by adding thermal resistance and improving the airtightness of the envelope as well as blocking the load from being absorbed by the exterior and interior surfaces of the assembly.

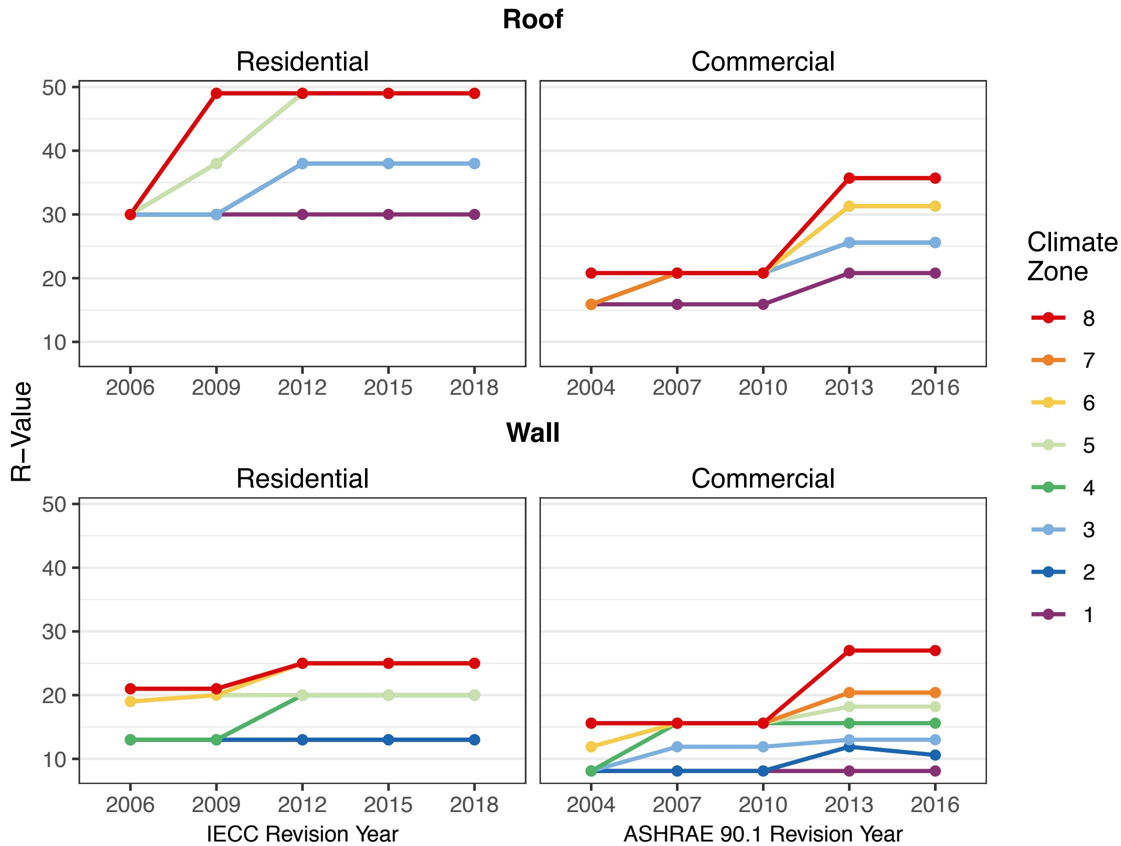

Figure 2-2: For both residential and commercial buildings, over the past five revisions, energy codes have been updated with incrementally increasing insulation levels in most climate zones. These increases, however, do not apply to existing buildings, and thus the products and assemblies that can be applied to achieve these performance levels in new construction might not be suitable for existing buildings.

Figure 2-2 shows the improvement in residential and commercial building energy codes for various opaque envelope components that influence thermal energy management. Although the data in Figure 2-2 show that insulation requirements in codes have steadily increased, these codes typically only affect new construction. As a result, these improvements do not carry over to existing buildings. In particular, the technologies and assemblies that can achieve the prescribed performance levels might not be compatible with existing buildings without radical or total reconstruction of the opaque envelope.

There are a few systems currently commercially available for envelope retrofits that do not require significant envelope demolition and reconstruction. To improve envelope R-value, wall cavities can be filled with blown-in loose insulation, so-called "drill and fill," illustrated in Figure 2-3a, and similar insulation materials can be blown into uninsulated or underinsulated open attic areas. There are similar products for filling wall cavities using foam, and recent improvements in installation methods have significantly reduced the potential for interior or exterior sheathing blowouts due to foam expansion in overfilled cavities. New methods can also inject foam into wall cavities with some types of existing insulation to further improve R-value. Overcladding systems—either built-up on-site (illustrated in Figure 2-3b) or using prefabricated insulated panels and installed on the exterior of an existing facade—have become popular in Europe but remain a relatively niche product in the United States. Currently available insulated siding offers a limited performance improvement due to the low R/in values of widely available, low-cost insulation materials. Continuous insulation, which is placed between the exterior sheathing and cladding in new buildings, can reduce the energy losses from thermal bridging through structural elements (e.g., studs, rafters) in the building shell. Overcladding systems can address thermal bridging for existing buildings because they add insulation on top of the existing facade, but these systems require extensive detail finishing work around windows and doors.

Figure 2-3: Drill-and-fill insulation (a) reduces heat transfer through walls by adding insulation to cavities between studs through small filling holes in each stud bay; overclad insulation retrofits (b) add one or more layers of insulation (typically rigid foam insulation) on top of the existing exterior facade; the layers are then covered by new exterior sheathing and finishing layers.

Insulation materials that comprise the typical state-of-practice—fiberglass batts, rigid foam boards, spray foams, and loose fill materials—typically do not exceed R-6/in and have not improved substantially in performance in decades [7]. Although these materials could theoretically be applied to new buildings in ever greater thicknesses to achieve higher overall levels of insulation, such an approach is generally impractical. Further, existing buildings could not accommodate thick insulation without a loss of floor space or reconstruction of the entire facade.

Materials that exceed the R/in values of typically available insulation are generally one of three types: aerogels, vacuum insulation, and nanostructured insulation. Each of these materials is composed of a porous solid that achieves a high R/in value (>10 R/in) by limiting conduction through the solid portion of the material and convection within the pores in the material (or in the case of vacuum insulation, eliminates most of the air). To control gas-phase conduction, pore size is critically important; pores must be on the order of or smaller than the mean free path of air[5] (30–60 nm). With that pore size achieved, strategies for controlling radiation and the solid phase conductivity become the critical challenges.

Aerogels, most commonly silica aerogels, have been investigated for several decades. They are traditionally fabricated by separating the liquid from a gel using supercritical drying [8], which ensures that the porous structure does not collapse as the liquid is extracted from the gel. This production method is time consuming, requires significant energy, and is an inherently batch process [8]. The resulting gel is hydrophilic, but its structure can be destroyed by liquid water and it is susceptible to crumbling, thus limiting durability in real-world applications. Recent research has found ways to improve the durability of traditional silica aerogels; results have shown significant improvement in mechanical properties, but with the trade-off of reduced insulating value [9].

Vacuum insulation is typically in the form of small panels (vacuum-insulated panels, or VIPs) with a porous core material sealed inside a multilayer enclosure that is evacuated to a very low pressure. Modified atmosphere insulation panels are similar to VIPs but are produced by drawing a moderate vacuum and then injecting the enclosure with steam. The condensation of the steam increases the vacuum to a level comparable with VIPs. A significant challenge for VIPs is maintaining the vacuum, and thus their insulating performance,

[5] The mean free path is the average distance traveled by a particle between collisions with another particle. Collisions between particles characterize gas-phase conduction heat transfer. When the pore size is reduced below the mean free path, collisions with the pore walls are more likely than with other particles, thus dramatically reducing the gas-phase conduction contribution to the total thermal conductivity of the bulk material.

during transportation, installation, and while in service. VIPs can achieve center of panel R-values from 25 to 50 depending on vacuum level, barrier film material, and panel thickness, but after accounting for thermal bridging and edge effects, overall R-values for VIPs are generally up to approximately 20 R/in; however, the R-value of the panel will decline as vacuum is lost over time, which is particularly problematic given the typically long lifetimes of building envelopes.

Nanostructured insulation or nano-insulation materials are low thermal conductivity materials composed of nanoparticles in a variety of form factors, including packed beds, foams, and sponges. These materials can achieve high R/in values by limiting phonon transport at the nanoscale and, as noted previously, controlling pore size to be below the mean free path of air to limit gas-phase conduction heat transfer [10], [11]. Depending on the approach, these nanoparticles might be filled with air or another gas or evacuated. There are a wide range of methods for producing nanoparticles for nano-insulation materials [12], [13].

2.2 Envelope Modeling

By providing design guidance and exposing potential durability risks prior to construction, building envelope component and system modeling is a key enabler of the adoption of energy-efficient, high-performance building envelopes. There are a wide variety of tools and software packages that have been developed to aid in the modeling of building envelopes.

Various stand-alone tools exist that are capable of evaluating specific building envelope components. WUFI is a tool developed by Oak Ridge National Laboratory (ORNL) and Fraunhofer IBP. It is a simulation package that allows for the realistic calculation of the transient coupled one-dimensional heat and moisture transport in multilayer building components exposed to natural weather. LBNL's THERM models two-dimensional heat transfer through envelope assemblies. A four-year project that is wrapping up in the summer of 2020 is adding dynamic moisture modeling to THERM, bringing its capabilities closer to that of WUFI. The Energy Savings and Moisture Transfer Calculator developed at ORNL was designed as a simple tool for building architects, designers, and owners, and allows them to estimate the energy savings that could be expected if an air barrier system was added to the building. Additionally, ORNL's Cool Roof Calculator and Lawrence Berkeley National Laboratory's Solar Reflective Index Calculator are both tools that can aid in the evaluation of alternative roofing technologies.

Another category of tools is whole-building energy modeling (BEM) engines. BEM engines simulate interactions between multiple building systems, including the envelope, and can translate envelope design decisions into overall building performance. BTO funds and manages the development of the open-source BEM engine EnergyPlus®. EnergyPlus models one-dimensional heat and moisture transfer through the envelope via a choice of transfer function or finite difference methods. A list of BEM tools can be found at the International Building Performance Simulation Association's Building Energy Software Tools directory.[6] Many BEM tools are capable of aiding in optimizing building envelopes for energy use reduction. The role of envelopes in buildings goes beyond energy usage and also impacts thermal and visual comfort. More efforts can be made toward multi-objective optimization for building envelope simulation for comfort and energy efficiency. [14]

Both moisture loads and infiltration loads are driven by climate attributes that are not easily captured by BEM tools. These important weather-related effects are difficult to incorporate into simulations because characterizing airtightness and infiltration in a bottom-up model is complex and difficult to do for even the most experienced BEM users. Although national energy estimates can be calculated using BEM tools like EnergyPlus with existing weather data, these analyses do not accurately capture moisture durability and infiltration effects related to ambient moisture and wind conditions. Work has begun to better understand how the U.S. climate varies as a function of moisture load and wind speed, but further study is needed to better generalize durability and air leakage phenomena.

[6] https://www.buildingenergysoftwaretools.com

Traditionally, envelopes have been modeled as static components, and as such modeling approaches generally do not need to take into account time-varying properties. Modeling transient heat/moisture transfers and storage capabilities require component properties to be modifiable during simulation run time. Additionally, controls of dynamic envelope components need to be developed, taking into account interactions with other building systems. To implement dynamic opaque envelope components in popular building simulation platforms, advanced or expert knowledge is typically required. [15]

Computational models gain much more value after they have been validated by real-world data. ANSI/ASHRAE Standard 140-2017 contains suites of tests that evaluate aspects of BEMs. Section 5.2 contains methods to test the ability of programs to model effects such specific heat transfer mechanisms, the combined effects of thermal mass and various heat gains, and other envelope characteristics. Currently, these test suites contain only analytical results and results generated by a range of simulation engines for comparison purposes. However, DOE has funded a number of empirical validation projects on well-controlled and highly instrumented test facilities such as LBNL's FLEXLAB (Facility for Low Energy Experiments) and ORNL's FRP (Flexible Research Platform) to create measured data sets that can be added to reference results. As dynamic envelope technology simulations see more development, tailored means of comparing and validating dynamic technology model representation will be needed. [16]

2.3 Air Leakage

As shown in Figure 1-3, infiltration and exfiltration accounts for greater energy losses than any other component of the building envelope and is responsible for more than 4% of all the energy used in the United States. Technologies and construction methods are readily available in the market to build new buildings that have minimal air leakage.

2.3.1 Air Sealing Technologies

According to the 2015 International Energy Conservation Code (IECC), technologies to control air leakage include:

- **Air barrier materials:** materials with an air permeability not greater than 0.02 L/s·m^2 under a pressure differential of 75 Pa when tested in accordance with ASTM E2178, which is a laboratory evaluation. Figure 2-4 (a) illustrates the configuration for ASTM E2178.
- **Air barrier assemblies:** air barrier materials and accessories that when combined provide a continuous plane with an air leakage rate not greater than 0.2 L/s·m^2 under a pressure differential of 75 Pa when tested in accordance with ASTM E2357, which is a laboratory evaluation, as shown in Figure 2-4 (b).
- **Air barrier systems:** a combination of air barrier assemblies that provide a continuous barrier to the movement of air through building enclosures, and have an air leakage rate not greater than 2 L/s·m^2 under a pressure differential of 75 Pa when tested in accordance with ASTM E779, which evaluates the airtightness of the building envelope through a blower door test. The setup for an ASTM E779 evaluation in a completed building is shown in Figure 2-4 (c) and (d).

The most commonly used air barrier materials are mechanically fastened membranes, self-adhered membranes, fluid-applied membranes, insulating sheathings, noninsulating sheathings, and spray-applied foams. Because these materials are designed to create a continuous wrapping layer around the entire opaque envelope, they are easier to install in new construction; their installation in existing buildings generally requires partial disassembly of the existing exterior sheathing or facade.

Air barrier materials commonly used in new construction to build up an air barrier system will yield widely varying performance depending on the complexity of the installation process for the materials used, installer expertise, extent of transition detailing work required, condition of the substrate to which the air barrier materials are applied, and weather conditions during installation. Some of these challenges have been addressed with newer technologies that have been commercialized, though these technologies are not necessarily widely adopted. Cohan et al. [17] presents data collected from newly constructed, single-family

Figure 2-4: (a) Experimental setup to measure the air permeability of a 1-m by 1-m air barrier material in accordance with ASTM E2178; (b) Experimental setup to measure the air leakage rate of a 2.4-m by 2.4-m air barrier assembly in accordance with ASTM E2357; (c and d) Experimental setup to measure the air leakage rate of a building envelope in accordance with ASTM E779.

homes as part of a study on building code compliance and energy savings. The measured data include air leakage rates or air changes per hour at a pressure differential of 50 Pa (ACH50). Figure 2-5 shows the leakage rates gathered in Alabama, Arkansas, Kentucky, Maryland, Michigan, North Carolina, Pennsylvania, and Texas; the number of homes tested in each state; and the ACH50 requirement that the homes were supposed to meet. In general, air leakage measurements spanned from 1 to 9 ACH50. This broad range in leakage rates suggests significant variability in construction quality, regardless of the air barrier system used and the code requirement for air sealing.

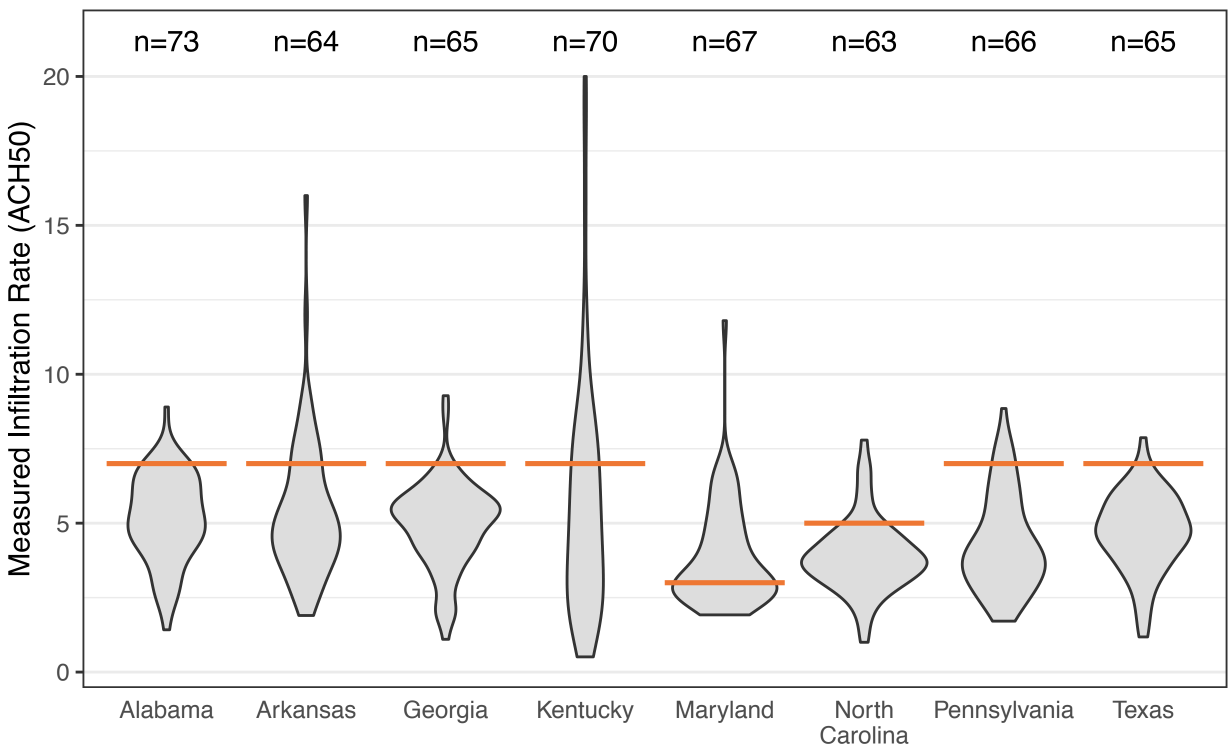

Figure 2-5: Blower door test measurements were collected in eight states from newly built single-family homes prior to occupancy. The distribution of measurements is indicated by the shape for each state. The number of samples collected is indicated above each state. The solid horizontal line through the distribution for each state shows the leakage requirement specified in the building energy code for that state at the time the data were collected. These results show that although most homes in most of the states studied met the code requirement, some far exceeded it. Additionally, in every state, at least a handful of homes in the sample did not meet code requirements. The airtightness of the most tightly sealed homes and the range of performance appear to have little to do with code requirements.

An evaluation conducted by Pallin et al. [18] reduces the number of variables that could affect air leakage measurements by focusing on a single air barrier system. In this study, blower door tests were performed in 19 homes that used noninsulating sheathings with a water-resistive overlay as the air barrier material on the exterior walls. All the homes were located in Tennessee and in climate zone 4; however, they were built by three different builders. Figure 2-6 shows how the measured leakage rates varied with each builder. Builder #1 had homes with leakage rates ranging from 2.1 to 5.3 ACH50, builder #2 ranged from 3.3 to 6.7 ACH50, and values from builder #3 ranged from 4.8 to 5.3 ACH50. The large spread in measurements clearly indicates inconsistencies in the installation of the air barrier system. Given that noninsulating sheathings with a water-resistive overlay will very likely have their joints taped to avoid water penetration, this indicates that the inconsistencies in installation likely occurred at the interfaces between the wall and foundation; roof, window, or miscellaneous penetrations; or at penetrations in the roof/ceiling plane.

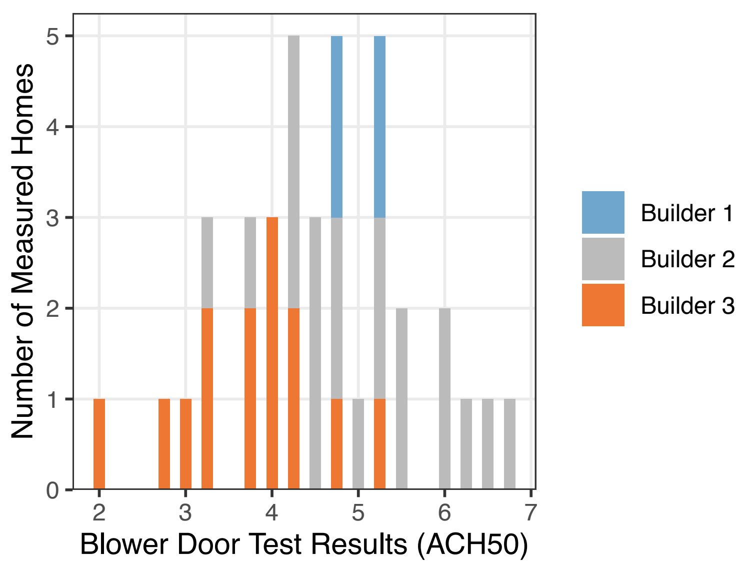

Figure 2-6: Results from blower door test measurements from 19 homes in Tennessee that had the same air barrier material on the exterior walls, but were constructed by three different builders [18].

2.3.2 Air Leakage Diagnostics

Although spec sheets from air barrier materials state that these materials have air leakage rates that comply with ASTM E2178 and and/or ASTM E2357, as shown in Figure 2-4, these test methods are laboratory evaluations of certain materials and accessories. Therefore, data from these tests do not guarantee that the entire building envelope will achieve a certain airtightness level; the only way to know the airtightness of a building is by conducting an in-situ evaluation, such as a blower door test, on that building.

The most common technique used to measure the air leakage rate of residential and commercial building envelopes is the blower door test. A blower door test uses fans to pressurize or depressurize a building over a range of pressures between 10 and 60 Pa below and/or above ambient pressure. The pressure difference across an orifice plate is then used to measure the total air volume entering or exiting the building per unit time, such as cubic feet per minute or air changes per hour. This evaluation method has been relatively successful in homes because it can be accomplished in less than half a day by energy raters who are commonly available throughout the country. As shown in Figure 2-8, blower door tests can also be performed in commercial buildings, but they typically require more equipment and longer setup and dismantling time than in houses because of the larger volume and more complex space layout.

Measurement tools for building envelope thermal performance rely primarily on infrared thermography. Current methods to locate air leaks are mostly coupled to blower door tests. The airflow that is created by the pressure differential from the blower fans amplifies any leaks, making them easier to identify with additional tools. For example, infrared thermography can reveal changes in the temperature of envelope materials because of airflow induced by the blower door. Alternately, smoke can be released indoors while the building is pressurized, and air leaks are identified as the locations where the smoke exits the building. This method is also not universally appropriate because building occupants can be sensitive to the smoke during its release as well as to its residue.

Figure 2-7: Guarded blower door tests, shown here set up in a single-family home, are similar to standard blower door tests, but use additional fans to isolate specific sections of a building's facade.

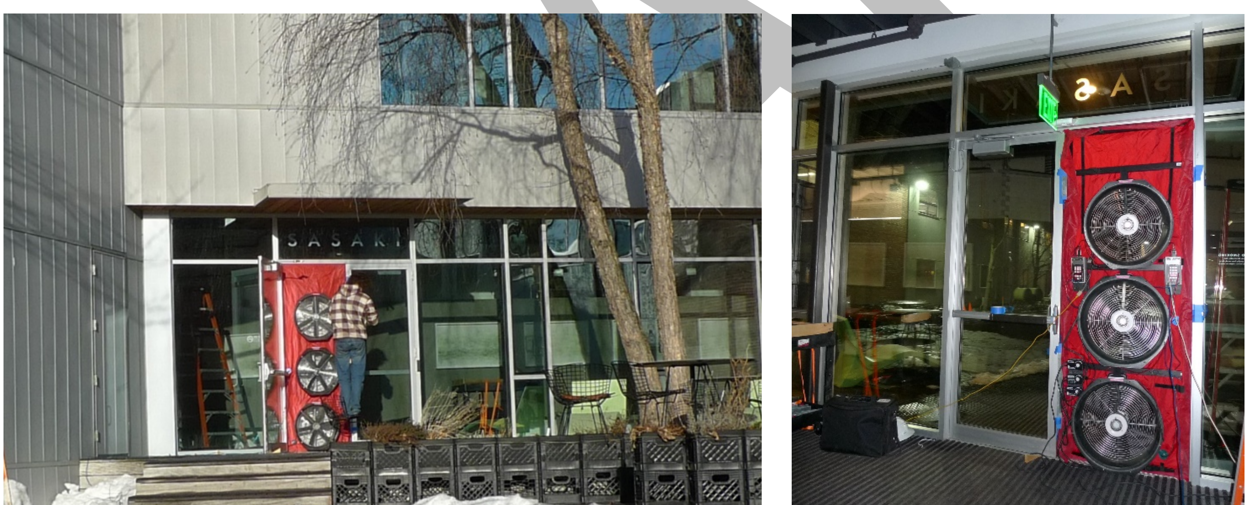

Figure 2-8: Blower door tests for commercial buildings can require much more equipment, which adds significantly to the setup and teardown time, as well as the complexity of performing the test itself.

2.4 Durability and Moisture Management

As buildings become more airtight and have higher insulation levels, the building envelope can be more easily damaged by moisture if it is not taken into account in the design [19]. Figure 2-9 illustrates the damaging effects that improperly managed moisture can have on the building envelope. Moisture can be introduced into the opaque envelope on the exterior side from ambient weather conditions—as bulk water from rain, snow, and condensation, and as water vapor from humidity—and on the interior side from moisture sources like cooking and bathing. Exhaust ventilation and air conditioning systems can remove moisture from the building interior. As illustrated in Figure 2-1, diurnal variations in ambient conditions change the driving forces influencing moisture in the envelope. Opaque envelope assemblies that are likely to be moisture durable are thus a function of climate zone, type of construction, and whether the building is new or existing. In new construction, hygrothermal simulations, field studies, and prior experience has enabled the development of best practices for ensuring durable enclosures that incorporate effective air sealing and high R values. For existing buildings, the wide range of construction materials and practices, which vary by building vintage, building type, and location, in addition to variation in current building envelope condition, internal moisture loads and control capability, climate zone, and other factors all make developing standard recommendations or guidance for highly insulating retrofits especially challenging. The literature is replete with case studies of individual building retrofits where no two retrofits have similar initial conditions, project budgets, and retrofit goals, and as a result, the specified retrofit and resulting envelope performance vary enormously. These varied results do not readily support the articulation of high-performance envelope insulation and air sealing retrofits as a function of initial building conditions that can promise long-term moisture durability.

Figure 2-9: Examples of building envelope problems associated with extensive moisture intrusion. Photos (a) and (b) show the consequences of moisture intrusion and insufficient drying that has led to decay affecting multiple layers of the opaque envelope assembly. Photos (c) and (d) show the effect of moisture intrusion on the interior side of the opaque envelope. (Photos (a) and (b) courtesy of André Desjarlais, ORNL; photo (c) from the Building America Solution Center; photo (d) from the National Institute for Occupational Safety and Health)

Besides the energy implications, uncontrolled air movement through the building envelope can have a significant impact on the amount of moisture transfer. It has been estimated that air leakage can transport more than 100 times more vapor than diffusion. Figure 2-10 shows results from a CONTAM [20] and EnergyPlus simulation exploring the effect of air leakage on moisture transfer through the building envelope. These results show that the addition of an air barrier to a building decreases the amount of water that will pass through the wall system by a factor of 10–20.

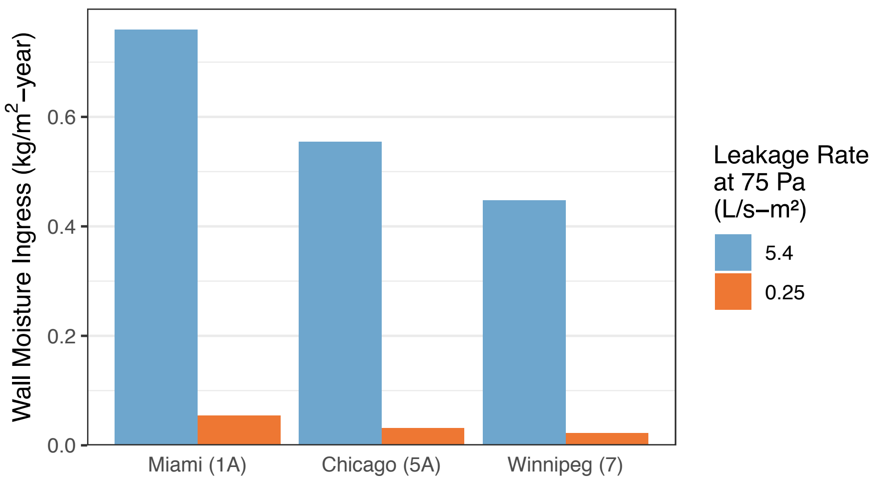

Figure 2-10: The amount of water in a year that will be transferred through the walls of a stand-alone retail building due to air leakage as a function of climate based on the combined CONTAM and EnergyPlus approach used by Shrestha et al. [27]. Illustrative cities in three different ASHRAE climates are shown—1A, hot-humid; 5A, cold-humid; and 7, very cold. Buildings with high air leakage rates will have substantially more moisture entering the walls, even in relatively dry climates.

3 Research Opportunity Areas

This section articulates the technology areas and the characteristics required in those technology areas to address the challenges faced by the current state-of-the-art. These novel technologies are generally expected to offer significant energy savings compared to current alternatives, and should be cost-effective, even if the current state-of-the-art technologies are not. In most cases, these novel, high-performance building envelope technologies have other energy benefits, particularly with respect to the timing of energy use—they might be able to reduce peak electricity demand, time-shift envelope-related thermal loads to match distributed renewable generation availability, or reduce ramp rates. These technologies also generally offer substantial nonenergy benefits to building owners and occupants—increased thermal comfort, improved building shell durability, and improved occupant well-being and productivity. These benefits can broaden the value proposition for these novel technologies and thus help drive early industry R&D offtake (see Section 5.1) and accelerate adoption (see Section 5.2). In addition, this section discusses future developments in opaque envelope component and system modeling and metrology as well as how these modeling tools and measurement capabilities can be used to accelerate R&D and commercialization, improve construction quality, and ensure that dynamic systems are configured as intended to maximize energy savings and nonenergy objectives.

We identify six main technology areas, corresponding to the subsections within this section and divided into two groups—technologies with static properties and those with dynamic properties:

Passive, Static Technologies

- Section 3.1 on ultra-high R/in insulation materials explores technology solutions for increasing the passive thermal resistance of building envelopes.
- Section 3.2 on envelope diagnostic technologies describes avenues for more convenient, accurate, and cost-effective methods to evaluate the in-situ performance of existing building envelopes and partially complete envelopes during construction.
- Section 3.3 on envelope remediation technologies presents means to effectively increase building envelope performance with minimum disruption to building occupants.

Active, Dynamic Technologies

- Section 3.4 discusses tunable transport materials, which offer a means of altering the properties of installed materials in-situ to allow the envelope to dynamically influence building heating or cooling loads.
- Section 3.5 expands on prospects for thermal and moisture storage in buildings.
- Finally, Section 3.6 discusses the opportunity for additional energy savings and potential for dynamic operation with novel combinations of the technologies described in one or more of the preceding sections.

Each of these subsections:

- Reviews the state of the relevant literature in comparison to the state-of-the-art currently commercially available;
- Specifies total installed price and energy performance-related metrics, future price and performance targets, and the corresponding U.S. primary energy savings if those targets are achieved;
- Describes the critical quantitative and qualitative characteristics for the technology to be acceptable to architects and engineers, building trades, and building owners; and

- Outlines the future work to address shortcomings in the current state-of-the-art and thus achieve the energy performance, total installed price, and nonenergy performance characteristics needed to be market acceptable and have the potential to achieve widespread adoption.

The technology solutions in this section address challenges with the current state-of-the-art articulated in Section 2. Many of these solutions might address multiple challenges; by doing so, these novel solutions might be able to provide multiplicative benefits when used in conjunction with each other. As technologies in each of these solution areas are developed, attention should be paid to these potential complementarities, as they might address shortcomings in coordinating technologies, reduce total installed prices, improve overall system performance and resulting energy savings, or enable or expand additional value streams that can help justify the installation of novel opaque envelope technologies.

Price and Performance Target Development

Total installed price and technology performance targets are specified for each technology area. This helps define the potential opportunity offered by substantial energy performance improvements and to suggest needed reductions in installed price for state-of-the-art high-performance windows to be cost-effective for a majority of the market. The price and performance targets were established using Scout, a model that estimates the energy use and cost impacts of the adoption of efficient technologies in residential and commercial buildings. Scout accounts for building and equipment stocks and flows out to 2050. Energy use reductions for a given technology estimated using Scout are based on the difference in performance—R-value in the case of insulation materials, for example—between the incumbent or “business as usual” and the more efficient technology. These energy savings are then converted to utility bill savings based on average retail energy prices. Annual utility bill savings can then be used with a desired or “acceptable” simple payback period to determine a target total installed price for the performance level specified.

The configuration of Scout influences the price and performance targets. For all of the targets in this report, a “technical potential” scenario that excludes competition between technologies is used in Scout. The technical potential scenario assumes immediate and universal national adoption of the technology being considered, and excluding competition ensures that for any given technology, none of its energy savings potential is diminished because of parallel adoption of other efficient technologies. These assumptions maximize the energy savings potential for a technology, thus increasing the total installed price target. The performance and associated price targets are based on a range of assumptions in Scout that represent climate zone or national stock-wide average characteristics, including retail energy prices, window-wall ratios, building facade areas, existing window performance, and other factors. As a result, these targets represent performance and acceptable installed price for an average building in the United States; individual buildings vary enormously, thus building-specific “acceptable” total installed prices for a given performance level might be much higher or lower than these targets. Further information about Scout and how it was used to develop the targets in this report is provided in Appendix A.

Passive, Static Technologies

Passive, static opaque envelope technologies have properties that are intended to be unchanging with time. These technologies include water resistive barriers, air barrier systems, and insulation materials. In general, there are multiple commercially available options for these technologies. Although these products might be widely available, there remain multiple opportunities for improvements in their energy performance and total installed price. The contribution of installation to total project price for these technologies is a particular challenge. Novel methods to improve constructability—reducing installation complexity, labor effort, potential for installation defects, and disruption to building occupants—are needed to address this challenge. It might be possible to develop new materials and systems that can deliver these improvements directly, as a result of attributes inherent to the products. An alternative, complementary approach considers new materials and systems alongside novel technologies that enable significant changes in current typical practices specifically targeting constructability challenges. This latter approach underpins BTO's Advanced Building Construction initiative.[7]

Though drop-in replacement envelope components and systems might offer the most obvious route to commercialization, because they simply improve upon the performance of the current typical or state-of-the-art product, technologies that involve or require more dramatic changes in the envelope assembly might have the potential to offer more substantial energy savings and other benefits. Using novel approaches to assemblies or combinations of multiple components might reduce costs, improve performance, and reduce errors by completing assembly in a controlled factory environment. Combining multiple control layers for air, moisture, and heat, as well as structural functions into fewer layers and components could reduce complexity in factory and on-site construction, thereby reducing cost and potentially improving performance, or providing an additional benefit that could justify incorporating a high-performance technology that is not otherwise required. Rethinking approaches for assemblies to simplify effort and improve flexibility or adaptability could be particularly beneficial for retrofit applications, which tend to require a high degree of customization because of the enormous variation in existing buildings; these variations add significant cost, quality, and performance challenges to retrofit projects, all of which inhibit envelope retrofit adoption.

3.1 Ultra-High R/In Insulation Materials

3.1.1 Overview

In general, the primary function of building insulation material is to limit the flow of heat through the opaque portions of the envelope and therefore limit the energy required to maintain the temperature difference between the heated or cooled indoor space and outdoor ambient conditions. As shown in Figure 1-3, energy use associated with roofs, walls, and foundations, which could be reduced with additional insulation, dominates total envelope energy use. As a result, materials that offer high thermal resistivity (high R-value per unit thickness) can offer significant potential heating and cooling energy savings in both the residential and commercial sectors.

Materials with a high R-value per inch of thickness can enable higher insulation levels in new construction and make feasible retrofits of existing buildings. Ranges of typical and future targets for insulation materials are shown in Figure 3.1. Research on vacuum insulation and aerogels is extensive, though technical hurdles remain that prevent their adoption; highly insulating (low thermal conductivity) nanostructured materials are a comparatively new area, with many remaining research avenues.

[7] See: https://www.energy.gov/eere/buildings/what-advanced-building-construction-initiative.

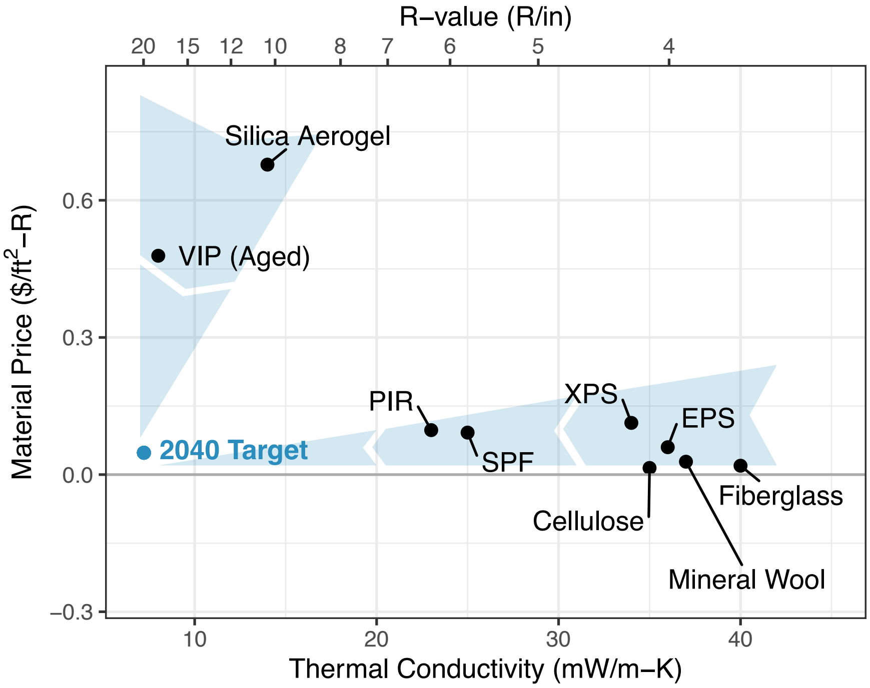

Figure 3-1: An area of opportunity exists between the current state-of-practice low-price, low-R-value per inch materials (lower right) and the high-price, high-R-value per inch materials (upper left) for the development of low-cost, highly insulating materials (lower left). The potential exists either by bending the cost curve on existing high-R/in materials or by developing novel materials with a ready pathway to very low-cost volume production. The 2040 installed price and R-value target for high R/in wall insulation materials is shown to highlight the goal of developing materials with these price and performance characteristics.

3.1.2 Technical Barriers and Challenges

Key barriers to the widespread adoption of aerogels as a building insulation material include high prices and durability challenges. Supercritical drying is the primary method by which crack-free monolithic aerogels are fabricated and it is an inherently batch process. As a result, aerogel manufacturing capital costs scale up in step with increasing production volume. Future work on aerogels should focus on production methods that have the potential to scale to typical insulation material production volumes by addressing the energy, time, and production cost implications of supercritical drying, either through improvements to that method or by improving alternative production methods, e.g., ambient pressure drying. In addition, durability is a significant challenge. Aerogels can be modified to be to be hydrophobic or otherwise strengthened to improve durability, but often at a loss of R-value. Further investigation of novel formulations is needed to achieve market-acceptable mechanical properties and durability while maximizing R-value per inch.

The biggest risk for VIPs is perforation damage that breaks the panel's vacuum, especially prior to completion of the building envelope. It is likely that damage could be unnoticeable, leading to the installation of failed or failing panels. Recent research has investigated a variety of VIP encapsulation methods to protect panels, though the risk of failure by perforation still exists for many of these approaches [21]. Improvements are needed for protecting the panel from damage, such as self-healing barrier films, as well as for clearly indicating failed panels, ideally by visual inspection. Moreover, methods for demonstrating the long-term performance of panel materials and production methods (e.g., accelerated aging) are critical to building confidence in the long-term durability of VIPs for building applications. Current VIPs cannot be cut or shaped at the construction site to accommodate variously shaped spaces—any perforation of the barrier film will cause loss of vacuum. Novel approaches that can 1) re-seal VIPs after perforation and 2) allow for on-site cutting of the panel into specific shapes would improve panel durability, and the latter would substantially simplify construction using VIPs for both retrofit projects and new buildings. Another approach to broaden the applicability of VIPs might be to develop them into a technology that offers variable R-value by dynamically changing the internal panel pressure.

For nano-insulation materials, appropriate production methods are a critical development step. These methods should be able to yield a finished product in a familiar form factor—such as batts, sheets, or boards—in sizes appropriate for buildings applications and at a rate appropriate for the quantity of material needed for buildings. Further investigation is also needed to identify the optimal material formulations for compatibility with the aforementioned manufacturing methods and R/in values consistent with preliminary results in the literature. In support of the development of these materials, further advancements are also needed in thermal conductivity measurement methods for small samples of low thermal conductivity materials [21]–[23].

For the development of novel ultra-low thermal conductivity materials for the opaque envelope that attempt to leverage nanoscale material properties or phenomena, new simulation tools for bulk materials that incorporate subcontinuum thermal transport principles are needed. Prior work to develop nano-insulation materials has primarily relied on first principle or theoretical models that have been developed to represent semiconductors or superconductors [24], [25] and assume ideal conditions (e.g., perfect construction, identical structures, and uniform surface contacts). Bulk insulation materials do not satisfy these ideal conditions. Furthermore, the first principle models used to develop nano-insulation materials are somewhat simplified because they focus on a subset of the phenomena operating at the nanoscale; in reality, there are numerous variables at the nano and macroscale that will influence of the performance of nano-insulation materials that are fabricated in bulk. Novel simulation tools that address these shortcomings will help researchers transition from trial-and-error passive screening for materials development to a more direct, materials-by-design approach.

As previously mentioned, conventional materials with high R/in values are typically aerogels, vacuum insulation, and nanostructured insulation. These three insulation types do not represent an exhaustive catalog of high R/in materials. Other novel approaches should be considered if they offer a credible pathway to achieving higher R/in levels than the current state-of-practice at competitive installed prices.

3.1.3 Market and Deployment

For retrofits of existing buildings, technologies for cost-effectively improving thermal performance of the opaque envelope are quite limited. Steep slope roofs with unoccupied attic spaces can usually have insulation added cost-effectively. Additionally, walls and roofs in stud-framed construction can have loose insulation added to their cavities, but these retrofits do not address the substantial thermal bridging from the structural elements. Exterior continuous insulation can be added, but to achieve meaningful improvements in R-value, at least two inches of insulation must be added on top of the existing sheathing; this then requires substantial reconstruction of corners, roof details, and other features to ensure a finished appearance and visually acceptable result, as illustrated in Figure 3-2. In addition, some buildings might not be able to have insulation added to the desired thickness and still remain in compliance with setback requirements and property boundaries. Systems that support retrofits with less intensive finishing work by incorporating less insulation might have lower overall R-value than a thicker, more labor-intensive retrofit, but developing these thin continuous insulation retrofit systems now would provide a ready pathway to commercialization for novel high R/in materials when they become available.

For existing buildings, the lower R-value of the walls means that greater energy savings is available from a wall insulation upgrade compared to adding insulation to code-compliant new construction. Higher R/in insulation materials can facilitate retrofits for a wide range of existing buildings. Particularly for buildings that are not candidates for drill-and-fill-style insulation retrofits, or where a reduction in thermal bridging is desired, high R/in materials can more easily be used to retrofit continuous insulation compared to currently available insulation materials, potentially through recladding or overcladding. Because insulation is rarely replaced or upgraded, the availability of high R/in materials and compatible installation methods does not mean that they will inevitably be adopted because of building or component turnover in the existing stock; high R/in materials must offer an extremely strong value proposition to induce adoption from building owners. Section 3.3 expands on the potential for high R/in insulation materials designed for the remediation of complete or partially complete building envelopes.

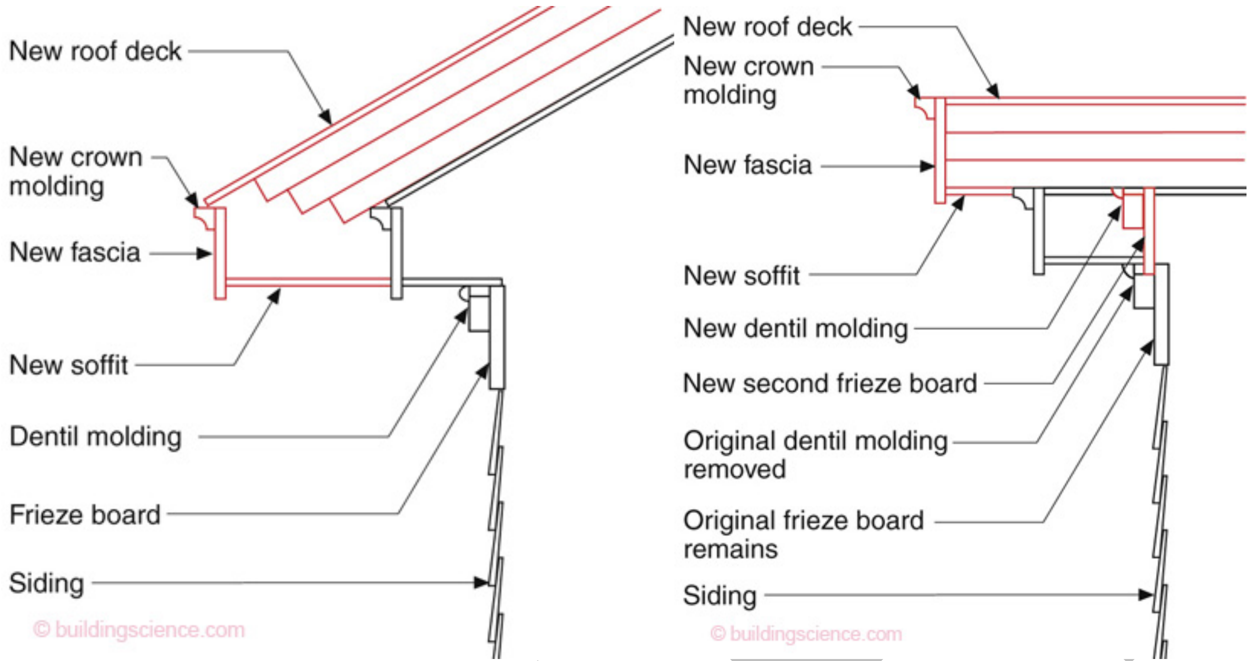

Figure 3-2: Adding above-deck roof insulation—shown as long red rectangles on top of the existing roof deck—to eliminate thermal bridging and improve the performance of the roof assembly results in substantial additional detailing work along the roof edge (left) and gable ends (right), which adds materials and substantial labor costs to the overall project.

Because of the long in-service period for building insulation, improvements in lifetime beyond the current state-of-practice are not generally needed, though many current insulation materials do experience some reduction in performance over time. Novel high R/in insulation materials must be able to offer long lifetimes without significant degradation in performance because of moisture, settling, or structural changes in the material.

3.1.4 Technology Action Plan

The installed price and performance targets for wall insulation, commercial roof insulation, and residential foundation insulation are shown in Table 3-1. These targets and the associated primary energy savings are based on a technical potential scenario, which assumes universal adoption overnight once the technology is available and assumes that the technology is commercially available before 2040. The installed price targets are based on a 10-year payback period. Payback calculations are based on utility bill savings from upgrades to the indicated performance levels, which are, in turn, based on energy savings.

Table 3-1: Performance and installed price targets for insulation available in 2040, evaluated separately for discrete opaque envelope components by building sector. Variation in the primary energy savings potential, shown for 2040, and associated energy costs between sectors, influences the installed price targets.

Wall Insulation (2040)					
Building Sector	Performance		Installed Price*		Primary Energy Savings (quads)
Residential	20	R-value/in	0.64	\$/ft² wall area	1.1
Commercial			1.91	\$/ft² wall area	0.77
Roof Insulation (2040)					
Commercial	2x	ASHRAE 90.1 2016	0.57	\$/ft² roof area	0.37
Foundation Insulation (2040					
Residential	15	R-value/in	0.7	\$/ft² footprint	0.5

* Installed price is additional to the installed price of the same assembly with code-minimum insulation.

These targets are based on an aggregation of energy savings across U.S. buildings, and thus represent an average target. Savings from any given building might be more or less than those suggested by these results. In general, energy savings potential is greater for existing buildings than new construction. There is a larger overall energy savings opportunity in residential buildings, because, as Figure 1-4 shows, they turn over more slowly than commercial buildings. As the stock turns over, however, new residential buildings are specified with much more insulated envelopes than new commercial buildings, thus the acceptable installed price is lower for residential buildings than for commercial buildings. Because of the higher wall insulation levels and different wall construction materials in newer residential buildings compared to commercial buildings, the per-building energy savings from further increases in residential wall insulation are more limited, so the indicated installed price is lower than for commercial buildings. Table 3-1 also shows that total technical potential primary energy savings in 2040 across both residential and commercial buildings for wall insulation alone is 1.9 quads. For the performance targets that are specified as R/in, the energy savings and the accompanying targets are based on an assumption that the material under consideration will be used in continuous insulation applications with a minimum of two inches of insulating material on the indicated opaque envelope surface. If a thinner layer is used, higher R/in values will be required to achieve the indicated energy savings.[8]

[8] Wall insulation and residential foundation insulation energy conservation measures were defined as total additional R-value (R-40 and R-30, respectively) and converted to R-value/in of thickness based on an assumption of two inches of continuous insulation in either application. If it is beneficial to further reduce the thickness of the insulation material used, for example to reduce installation costs associated with detailing rework, higher R-value/in insulation will be needed to deliver the energy savings indicated in Table 3-1.

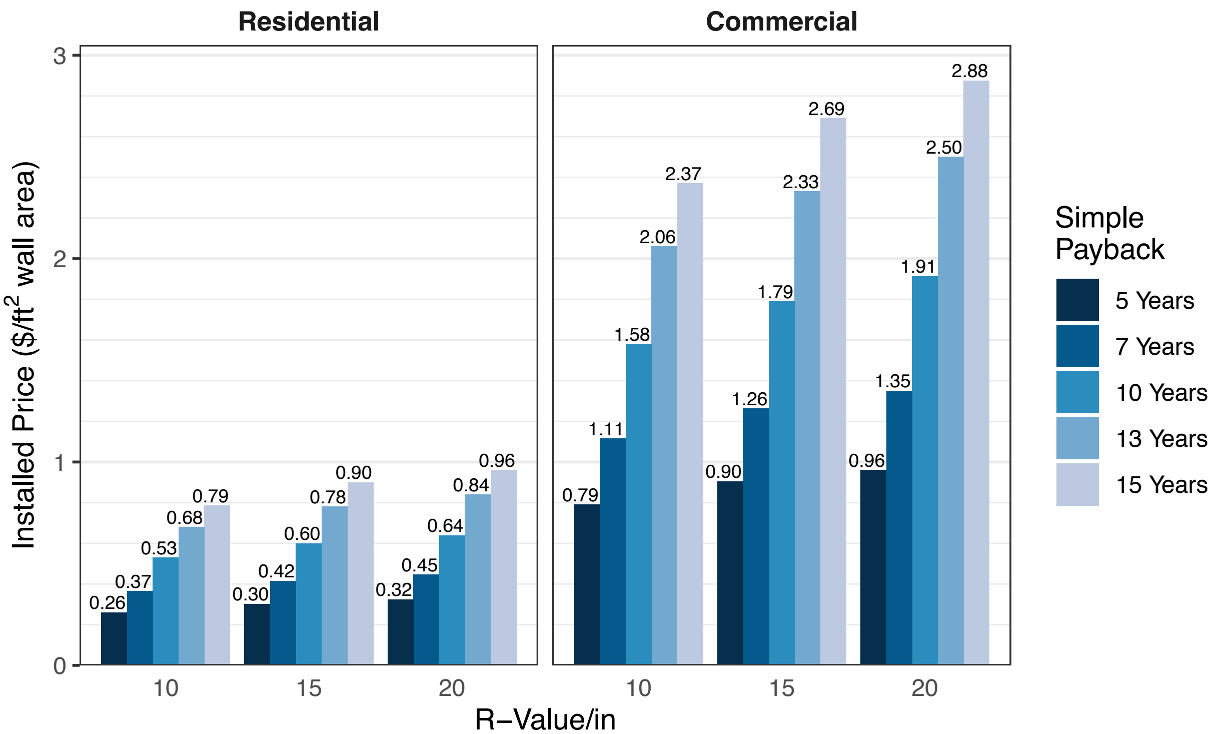

Figure 3-3: Installed prices shown for a range of payback periods and R/in values are somewhat dependent on payback period, and are more strongly dependent on payback period than insulating performance, especially for residential buildings. Because of the comparatively higher baseline performance of residential walls, the acceptable installed prices for the longest payback periods shown for residential buildings are comparable to those for the shortest payback periods for commercial buildings.

Figure 3-3 illustrates the differences in acceptable total installed prices for wall insulation for a range of payback periods. These results are presented in terms of $\$/ft^2$, as opposed to $\$/ft^2$-R, in order to isolate the impacts of installed price and performance. The results show that the market-acceptable installed price varies more with changes in payback period than with improvements in insulating performance. For residential insulation, doubling the payback period approximately doubles the acceptable installed price, but increasing the R/in value has a limited effect on the cost-effective installed price. Labor costs for traditional interior or exterior insulation is 0.4–0.5 $\$/ft^2$, depending on the insulation type, before accounting for associated construction such as moving windows or electrical outlets [26]. Therefore, in addition to reducing material costs, the R&D target cannot be achieved unless new insulation materials enable extremely low-cost, low-labor-effort installation methods. Particularly for the residential building sector, novel high R/in materials themselves must be very low cost and offer significant labor cost reductions to achieve a market-acceptable payback period. The results in Figure 3-3 suggest that commercial buildings might offer a better market entry point for novel high R/in materials, though application methods and appropriate form factors are not necessarily the same between commercial and residential buildings.

The Technology Action Plan table defines specific R&D activities to be pursued to facilitate the development and market introduction of technologies that can meet or exceed the technology price and performance targets in Table 3-1. The Enabling Technology Characteristics table lists additional properties required for high R/in materials to be acceptable for market adoption. The Technology Action Plan includes activities related to specific technologies that have shown promise as high R/in materials, but it is not exclusive of other possible avenues to develop high R/in materials; these approaches are valuable if they offer a pathway to the price and performance targets in Table 3-1.

Technology Action Plan		
Technology	**Objective**	**R&D Activity**
Aerogels	Reduce total installed price	Develop continuous-throughput ambient pressure drying processes
	Increase longevity; Improve constructability	Develop hydrophobic formulations with reduced friability
VIPs	Reduce total installed price	Develop high-throughput production methods for VIPs
	Increase longevity; Improve constructability	Develop self-healing and/or puncture-resistant encapsulation methods
	Improve constructability	Create new materials or designs that enable cutting and re-sealing or cutting without vacuum loss for on-site customization
	Increase longevity	Develop improved barrier films, desiccants, and getters
Nano-insulation materials	Reduce total installed price	Develop novel materials and fabrication methods that yield convenient form factors
	Improve R-value	Develop material formulations that achieve expected R-values at the macroscale
	Enable improved R-value	Develop new metrology that offers accurate measurement at low thermal conductivities (<20 mW/m-K)[a]
	Enable improved R-value	Develop simulation methods that accurately represent transport phenomena at multiple relevant length scales
Alternative Novel Approaches	High R-value; Superior longevity; Low total installed price	Develop novel highly insulating materials or technology approaches for retrofits and new construction

[a] This R&D activity might yield benefits for other insulation materials and systems.

Enabling Technology Characteristics
• Long-term retention of R-value • Stable size (minimal shrinking or settling) over typical lifetime • Moisture (liquid and vapor) tolerant • Stable properties under typical exposure conditions (-40°–60°C) • Chemical compatibility with other building envelope materials • Presents no hazards to human health • Compatible with existing tooling at the construction site *or* incorporating a substantial change in installation method that yields lower overall cost, labor effort, and installation time • Able to be cut, shaped, or otherwise customized on-site to fit site-specific dimensions without degrading insulating performance, durability, or lifetime • Available in traditional form-factors • Decreases labor effort for installation • Minimizes potential for installation errors • Fire and flame resistant, ideally without added retardants.

3.2 Envelope Diagnostic Technologies and Modeling Tools

3.2.1 Overview

Technologies that can characterize the existing opaque envelope—its energy performance, state of repair, dimensions, or other key properties—could help facilitate the adoption of envelope retrofits by quantifying their prospective (project-specific) value proposition, enabling the specification of appropriate retrofit interventions and verifying performance improvements following retrofits. These technologies might also be useful for building energy code compliance assessment in new construction, potentially offering rapid in-field validation of building construction and energy performance. Currently available technologies include blower door testing to measure air infiltration as well as infrared imaging to locate and estimate the extent of insulation inadequacies and air infiltration in the envelope. Novel nondestructive testing and sensing technologies; simplified, lower-cost physical testing platforms; and novel, low-computational expense data acquisition and synthesis software have the potential to significantly expand the impact and reach of envelope diagnostic technologies.

3.2.2 Technical Barriers and Challenges

3.2.2.1 Nondestructive Testing Methods

A significant barrier to the availability of envelope diagnostic technologies is a lack of nondestructive testing or evaluation technologies that can measure direct or indirect envelope performance parameters under the constraints applicable to building envelope testing. For example, evaluation methods are not currently available for detecting the location and extent of infiltration through the opaque envelope. Such sensors would need to be able to differentiate between defects (i.e., seams or cracks in the facade surface that do not contribute to infiltration) and sources of infiltration. Additional data on the leakage pathway would benefit decisions about whether to do remediation work from the interior or exterior. Sensors or other nondestructive testing methods also do not generally exist for the evaluation of partially complete envelopes.

Nondestructive testing methods used in other applications, such as magnetic resonance imaging or ultrasonic testing, might be adaptable to buildings applications. To satisfy the constraints faced by building raters who would operate the equipment, any nondestructive testing technologies must have low capital and per-test costs, have adequate durability for operation outdoors and at construction sites, and satisfy the other requirements identified in the Enabling Technology Characteristics table.

3.2.2.2 Virtual Sensing

Virtual sensing—using indirect measurements that can serve as proxy for the parameters of interest—might be a viable alternative or companion for dedicated testing methods. Particularly with the development and increasing adoption of a wide range of sensors for building control applications, data from these sensors could be used to evaluate building envelope properties, potentially in combination with specific building subsystem operations data. With adequate sensor resolution, this approach might even be able to provide location and extent data for air sealing and insulation defects or deficiencies. For example, operating a ventilation or forced air system to increase pressure differentials, or operating the heating or cooling system to increase temperature differentials between zones or between the building interior and exterior to detectable levels, could yield data on envelope performance, particularly when combined with additional simultaneous envelope diagnostic measurements from dedicated equipment. Using combined CO_2 and occupancy sensing with awareness of ventilation system operation to estimate the expected rate of change of CO_2 concentrations could provide measurements of infiltration and exfiltration from an interior space. With adequate sensor resolution, CO_2 diffusion to other interior spaces might be separable from infiltration through the building envelope. Although this approach cannot separate infiltration through windows and the opaque envelope, if the total infiltration detected is significant, separate targeted testing of windows can be conducted.

3.2.2.3 Diagnostic Equipment Platforms

Novel sensors for envelope diagnostic measurements must be used with an appropriate platform to be able to collect the requisite building envelope performance data for diagnostic applications. The platform used—hand-held or mounted on a self-propelled robot, vehicle, or unmanned aerial vehicle—could have a significant effect on test accuracy, duration, and cost, among other factors. The appropriate platform will also depend on the characteristics of the sensors; scan rate, field of view, minimum and maximum distance from the test article, vibration tolerance, power requirements, and other sensor characteristics will influence what platforms are both appropriate and viable to ensure that the tests yield usable data. The platform should also be able to cope with obstacles and requirements specific to the testing environment. For sensors designed to be used inside buildings, the platform should be able to navigate partitioned interior spaces (e.g., open doors, move from floor to floor, and avoid furniture and building occupants). For sensors to be used on the exterior facade, appropriate platforms should be able to provide adequate field of view for the full height of the building, either through the design of the sensor or the platform moving the sensor over the facade to provide complete coverage. Research on computer vision and autonomous navigation of 3D space for other applications might prove useful for self-guided testing platforms.

3.2.2.4 Diagnostic Data Acquisition and Processing

To be viable as a tool that can be used by building raters, the sensor(s) and platform must be supported by seamless data acquisition, processing, and synthesis software that converts sensor data and, if applicable, platform position data into actionable insights regarding the current state of the envelope, including the location and severity of any defects. It is possible that an envelope diagnostic system might involve multiple sensor data streams or test methods used simultaneously or in series; effective data integration software must be able to manage all of the applicable data streams, synthesize the data, and deliver human-readable, actionable results to testing personnel. To circumvent in-field accessibility constraints and the cost of high-performance computing resources, the software should employ computationally efficient methods. Critically, sophisticated data processing software that can efficiently deliver actionable insights to testers in the field is no more useful than sensors or a platform in isolation—testing equipment that produces accurate and relevant data about envelope performance as well as platforms that can enable the testing equipment to reach all parts of a building under test must be available off-the-shelf or developed in tandem with the required data acquisition, processing, and synthesis software tool(s).

When used to evaluate existing buildings, novel envelope diagnostic technologies might reveal a range of deficiencies—thermal bridging, unintended or unmanaged infiltration, or insulation that is inadequate or entirely absent. Without improvements to remediation technologies, discussed in Section 3.3, correcting these deficiencies can be costly and labor-intensive. Although there are some defect remediation options that involve limited teardown and reconstruction of the envelope, these technologies: might be limited to only certain climate zones, construction types, and/or building vintages; are not universally available for remediation of heat transfer and air and vapor transport mitigation; might not be able to achieve performance levels comparable to new construction because of limitations in the available materials; and can still be difficult and labor-intensive to install. Moreover, outside of these few technologies, improvements in the performance of the envelopes of existing buildings require high costs, high-labor-effort teardown, and reconstruction of major portions of the envelope. Existing buildings would therefore benefit from a wider range of remediation technologies that can correct deficiencies in the opaque envelope without such extensive effort. Deep retrofit projects can also have defects, so even when improving the envelope performance of existing buildings, the need remains for high-performance remediation options.

3.2.2.5 Component and Building Information Modeling

Modeling of heat, air, and moisture flows in the envelope is critical to understanding the effect of insulation, air sealing, and assembly construction on the energy performance of the envelope. Although a range of computational models exist that are capable of modeling heat, air, and moisture flows in buildings, they are not widely adopted for real-world building design and construction, and they suffer from a variety of shortcomings that limit their adoption. Heat, air, and moisture transport in building envelopes corresponds to a multitude of 3D processes governed by a range of physical phenomena—convection, radiation, diffusion, (de)sorption, and capillary action. These phenomena occur over multiple length and time scales relevant to the envelope. To reduce computational effort, most models do not attempt to represent flows for heat, air, and moisture simultaneously, or do not represent all of the transport mechanisms. Most also use 1D or 2D approximations. These 1D approximations impact the ability of BEM to capture critical transport effects. For example, because (almost all) BEM tools use 1D heat transfer representations, there is no way to calculate thermal bridging effects from first principles. Currently, the input complexity and solution time required for more sophisticated models restrict their applicability. Simplified high-level guidance tools that leverage envelope models—such as the Airtightness Savings Calculator [27] or Building Science Advisor [28]—can be used for customer acquisition or education purposes to demonstrate the value, in general, of high-performance opaque envelope materials and assemblies to building owners, suppliers, and designers. However, these tools lack the building geometry and characteristics required to accurately inform building- or project-specific decisions, where improvements to BEM tools to capture or represent 3D envelope characteristics in the underlying building energy models are required.

Existing BEM tools can adequately capture the effects of conduction and radiation heat transfer associated with insulation materials, but methods to evaluate air leakage and moisture effects need improvement. These methods require parametrization of the air and moisture flows that is difficult and time-consuming to configure correctly, even for expert users, and the resulting simulations are often computationally costly. Traditional methods for simulating air flows, such as computational fluid dynamics simulations, suffer from similar shortcomings with respect to ease-of-use and computational expense. Alternative models are needed that are appropriate for air and vapor transport regimes in buildings and compatible with widely adopted BEM tools. Developing software that integrates diffuse published and experiential knowledge about moisture performance for builders and designers will build confidence in the selection and construction of more energy-efficient wall systems and in the adoption of novel high-performance envelope technologies. By taking into account uncertainty in the parameters that influence air sealing and moisture performance, BEM tools could provide design-specific recommendations to ensure assembly durability while increasing energy savings.

To maximize the potential impact of advancements in opaque envelope energy performance modeling, capabilities should be integrated into the software tools and business workflows used by architects and engineers during the design and construction process. By elucidating potential risks and providing insight into the cost and performance tradeoffs between envelope configurations and HVAC system sizing and configurations, these decision makers can better understand the implications of particular envelope product specification and value engineering decisions. Integrating these data into their software workflows also has the potential to provide more detailed data to contractors and trades during construction to ensure appropriate staging of envelope components and completion of the envelope as specified. These changes have the potential to increase the specification and correct installation of high-performance envelope components.

For new construction and deep retrofit projects, integrating the results of heat, air, and moisture flows associated with the building envelope into existing design software workflows can help architects understand the effects of the building envelope assembly and components early in the design process. In particular, the integration of envelope component cost and performance data into building information modeling (BIM) can enable the integration of cost estimation, energy modeling, and operational cost estimation. In 6D BIM,[9] the inclusion of operational costs on the building design can help elucidate the relative effect on long-term operational cost of substituting long-life, high-performance envelope components with additional space-conditioning equipment that requires greater ongoing maintenance and more frequent overhauls. Architects and designers can thus see the downstream effects of changes in envelope performance on the design and operation of the building and can communicate that information to clients to enable more informed decision-making regarding envelope specification. To support this vision, widely adopted BIM tools must incorporate additional capabilities to represent the energy and maintenance costs associated with the operational phase of the building (i.e., BIM-to-BEM) and energy modeling features that represent envelope performance with adequate fidelity. BIM can already provide insight for designers into spatial conflicts between components—incorporating envelope performance could similarly reveal thermal bridges and other potential envelope assembly efficiency risks. Third-party BIM building materials databases must be updated to include the additional parameters needed to characterize the heat, air, and moisture performance of envelope materials with sufficient detail for energy modeling. With these data and capabilities, BIM can facilitate a holistic, systems-level approach to building design and operation that incorporates total lifetime cost-effective, energy-efficient envelope features.

[9] The 6th dimension in "6D" BIM relates to BIM data that describes and supports the operational phase of the building and is sometimes referred to as a separate component called an asset information model. Asset information models contain similar information to the operational phase in 6D BIM, but are not typically integrated in the overall BIM and BIM-to-BEM workflow that could be used to capture operational cost impacts that relate to up-front capital equipment and envelope performance specification decisions.

3.2.3 Market Challenges and Development

Multiple building types and applications are out of reach of current envelope diagnostic technologies because of gaps in capabilities. Currently available thermographic imaging technology requires an indoor-to-outdoor temperature differential of greater than 20°F for the leakage points to be visible in a thermal image. This required temperature differential for thermography limits ideal conditions to winter and summer months. Direct solar radiation on the surface being tested can also affect results from infrared thermography, which limits evaluations to nighttime and persistently cloudy days. If air leakage evaluation is desired, care must be exercised when using thermography, because there are numerous envelope features that can create a thermal anomaly unrelated to air leakage—lack of insulation, thermal bridging, shading, and thermal reflection. Thermography is not currently a feasible method to determine the R-value of insulation materials or whole wall systems or air sealing of whole envelope segments during construction, because the required temperature differential cannot be readily sustained with an incomplete building.

Blower door tests are a common method to evaluate the air sealing of the building envelope (both windows and the opaque envelope). One of the main drawbacks of the blower door test is disruption of building occupants. Although this requirement might not be significant for the majority of residential buildings, which are typically unoccupied during regular business hours, these tests generally need to be conducted after hours in commercial buildings. Furthermore, this test is difficult to execute for a single tenant of an existing building with several tenants. Although a guarded blower door test (shown in Figure 2-7)—where multiple blower doors are used to isolate a portion of a building for infiltration testing—could be conducted under these circumstances, cooperation and coordination of building occupants is needed, which adds effort and expense. Similarly, given that the blower door test relies on creating a pressure differential across the air barrier, it is nearly impossible to execute while the construction of a new building progresses, because a complete air barrier system must first be in place. Consultants who can conduct blower door tests of commercial buildings are not readily available around the country; the cost of the test can be significantly affected by equipment and staff transportation expenses.

Addressing these capability gaps, either through novel testing methods or improvements to the current state-of-the-art, has the potential to substantially broaden the reach of envelope diagnostics. Moreover, expanding the applicability of envelope diagnostics to a broader range of building types, building states of completion, and ambient conditions during testing could facilitate greater adoption of high-performance building envelope technologies by quantifying the benefits of those technologies. For example, an impediment to the wider adoption of air barrier systems into buildings is the lack of a simple, credible tool that can be employed by building architects, designers, and owners that accurately estimates the energy savings that could be expected if an air barrier system was added to the design and provides guidance on the potential moisture risks associated with the envelope assembly configuration when the air barrier is added. A tool that can evaluate the performance of high R-value walls under many different conditions, such as variations in material properties (increasing or decreasing transport properties), workmanship (accidentally creating transport paths around wall or roof components), as well as indoor and outdoor environments (temperature, relative humidity, solar radiation, wind, and rainfall), would have great value.

3.2.4 Technology Action Plan

The Technology Action Plan table summarizes R&D activities that have the potential to advance the current state-of-the-art with respect to envelope diagnostic technologies and modeling software and tools. These R&D activities can improve the performance of these technologies with respect to accuracy, precision, speed, flexibility, or applicability. In the case of diagnostic technologies, some of these R&D activities might also reduce equipment costs, which could be passed on to customers as reduced testing prices. The R&D activities listed might not be exhaustive; any R&D that targets improvement opportunities relative to the current state-of-the-art, as articulated in this section, have the potential to enable envelope performance improvements in new construction and existing buildings. The Enabling Technology Characteristics table summarizes the discussion in this section with regard to the additional characteristics that the technologies addressed in this section should have to be suitable for widespread adoption. R&D projects should be conducted with an eye toward incorporating these characteristics into technologies under development.

Technology Action Plan		
Technology	**Objective**	**R&D Activity**
Envelope Diagnostic Technologies	(Enabling) Improved R-value; Reduced air leakage; Improved moisture management	Develop novel diagnostic metrology suitable for buildings testing conditions
		Determine the potential for virtual sensing to evaluate envelope performance
		Identify the key attributes of a sensor system that are required for virtual sensing functionality
		Develop diagnostic metrology for envelope moisture performance
		Develop supporting data acquisition and processing software that delivers actionable insights to testing personnel
Envelope Modeling Software	(Enabling) improved R-value; Reduced air leakage; Improved moisture management	Incorporate support for modeling of materials with time-varying properties
		Improve accuracy of air and moisture transport modeling in existing tools
		Develop novel methods to reduce the computational cost of accurately modeling complex heat and mass transfer flows in the envelope

Enabling Technology Characteristics	
Envelope Diagnostic Technologies	• Provide location and quantified extent of the measured variable(s) • Yield results for the whole building or sections of the envelope • Require minimal setup and teardown effort and time • Deliver accurate results regardless of outdoor weather conditions • Avoid disruption to building operations or occupants.
Envelope Modeling Software	• Integrate into existing software workflows used in the architecture, engineering, and construction sector • Provide clear, simple, actionable guidance to users • Rapidly generate findings with computationally efficient methods to enable real-time or near-real-time iteration on design choices and tradeoffs between various envelope configurations.

3.3 Envelope Remediation Technologies

3.3.1 Overview

In both new construction and retrofits, improving building envelope performance presents a substantial opportunity for energy savings, as indicated by Figure 1-4. Once a building envelope is complete, however, it can be difficult or impossible to correct defects or improve its performance without substantial teardown and complex reconstruction. This rework has project cost and schedule impacts that are unacceptable for new construction, and high-performance envelope retrofit adoption is limited by the substantial labor effort and complexity of traditional retrofit methods. Technologies that can improve envelope performance by reducing unwanted air leakage and insufficiently controlled heat transfer in buildings with complete or nearly complete envelopes have the potential to substantially reduce building energy use and increase the adoption of envelope retrofits. These technologies can, in general, be referred to as "remediation" technologies, in that they remediate inadequacies or weaknesses in the energy performance of an as-built opaque envelope assembly without substantial rework or reconstruction. These technologies can also yield important nonenergy benefits, similar to more traditional energy-efficient envelope technologies, including improved indoor air quality, occupant comfort, and productivity.

For existing buildings, constructability is hampered principally by the complexity and associated effort in improving the performance of opaque envelopes with currently available technologies. Materials, assemblies, and construction practices that can deliver substantial energy savings in new construction relative to typical practice or the existing stock are typically not well-suited to retrofitting existing buildings. For example, data in Figure 2-5 show that currently available materials for new residential construction have the ability to yield envelopes with relatively low air leakage. These same materials cannot be readily employed in existing homes to improve air sealing without substantial demolition and reconstruction of the entire envelope, which includes not only the envelope assembly components that affect energy use but also the extensive finish work—trim, siding, soffits, etc. The same difficulty exists for thermal energy management improvements for existing buildings. The substantial construction effort to implement these retrofits adds enormous time and labor costs to projects. Novel materials are needed that can significantly reduce or eliminate the demolition and reconstruction required to improve the performance of existing buildings.

Although high-performance building envelopes can be readily incorporated into new construction, building envelope assemblies are complex structures typically constructed on-site and corresponding to the specific design of each individual building. This method of construction, combined with the multifarious layers and materials that are combined in the envelope, as well as the extensive detailing required at interfaces between facade elements (illustrated in Figure 3-4), make achieving design performance in as-built buildings extremely difficult. Manufacturers of building technologies have been working on making their products easier to install. The data collected by Cohan et al. [17] and Pallin et al. [18] suggest that further advances in installation practices or new methods/technologies are needed to improve the consistency of energy performance in new construction. These findings might also carry over to deep retrofits that involve major facade reconstruction with an effort devoted to improving performance.

Figure 3-4: The corner of a roughed-out opening for a window in new residential construction is an example of the complex detailing required at interfaces to provide for air and water sealing. In (a), the air/moisture barrier has been wrapped around the window opening, but the corners have not been properly flashed, while in (b) and (c) the corners have been neatly detailed to ensure proper drainage around the window opening. The custom work required to accommodate each penetration through the facade creates a significant opportunity for errors and defects, which leads to variability in envelope performance from building to building. (Source: (a) EPA, (b, c) NIST)

Novel envelope remediation materials could be fault-tolerant or self-correcting to reduce the potential for or impact of installation errors that lead to the variability in performance shown in Figure 2-5. These materials could be developed for stand-alone installation or for combination with other building envelope retrofit activities already undertaken, such as those indicated in Table 1-1, to reduce the incremental labor burden of the energy performance upgrade. Combining these technologies as a package with existing retrofits can broaden the value proposition for those upgrades. The appropriate approach for a given material or technology—stand-alone or as an upgrade package—should be tailored to the characteristics of the technology and frequency of upgrades for the other components in the package. Materials that are suitable for stand-alone installation could also be used in new buildings to remediate defects following construction.

3.3.2 Technical Barriers and Challenges

3.3.2.1 Air Sealing Remediation

In new construction, a shared difficulty among commonly used air barrier materials is that their performance as part of an air barrier system relies heavily on their installation: the installer, installation steps, transition details to other building components, substrate conditions, and ambient conditions during installation. Although many of these factors influencing performance have been addressed through incremental improvements in commercialized technologies, transition details remain a weakness of air barrier systems. Figure 3-5 illustrates a transition detail with significant infiltration problems. Technologies are needed that allow for simple and effective methods to seal interfaces between:

1. The wall and foundation (see Figure 3-5), roof, window, or miscellaneous penetrations;
2. The roof or ceiling and miscellaneous penetrations through them; and
3. The foundation and miscellaneous penetrations through it.

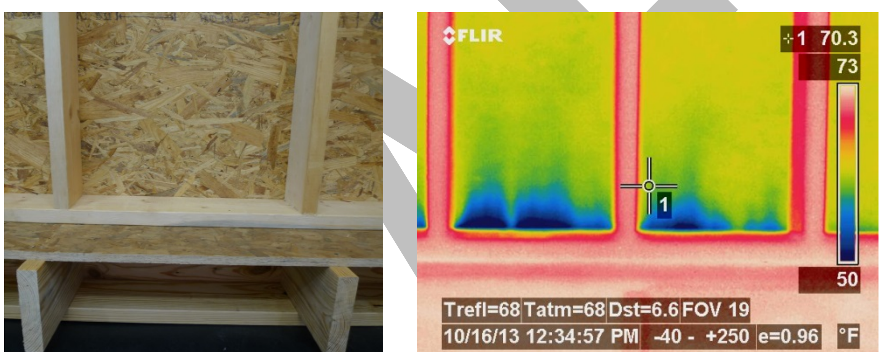

Figure 3-5: Interior side of wall-to-foundation joint (left) and corresponding infrared image (right) showing cold air infiltrating through the interface between the oriented strand board sheathing and the bottom plate [29]. The image shows a test wall that did not have an air barrier and was subjected to a pressure and temperature differential in a test chamber. (Source: ORNL)

Improving the airtightness of existing buildings or in new construction once the envelope is complete has proved to be mostly elusive without partial teardown of the facade. The exception has primarily been areas where leakage exists at gaps, seams, or joints in the facade that can be filled from the interior or exterior, such as those between the opaque envelope sheathing and window frames. A novel approach to air sealing that uses aerosolized adhesive distributed to infiltration sites using a blower door-induced pressure differential has shown promising results in new and existing residential buildings [30], [31]. A challenge with this technology is that the deposition of the adhesive particles to fill defects that are contributing to infiltration is not directly controlled. The positioning of the air barrier or water-resistive barrier within the layers in the envelope assembly can influence the moisture durability of the assembly, and appropriate positioning depends on both the other materials in the assembly and the climate zone [32]. With a pressure-driven aerosol air sealing system, it might be difficult to establish the final position of the air barrier and what effect, if any, it will have on moisture durability. Further work with this technology should explore the performance of the technology and any challenges specific to its use in occupied existing buildings, as well as the potential to reduce installation time.

Given the sensitivity of buildings with improved energy efficiency and air sealing to moisture problems, new materials could be developed to improve the hygrothermal resilience of building envelope systems. Maximizing the drying potential of wall systems while minimizing their wetting potential requires materials whose moisture transport properties are directional and vary as a function of relative humidity. In particular, materials are needed that can promote drying of walls and resist vapor ingress in climates with large seasonal changes in humidity. For existing buildings, materials that can promote wall cavity drying by driving water out to the exterior surface are particularly important, because insulation retrofits applied to the interior of existing buildings can otherwise create significant moisture damage risk, which can offset the potential energy savings and comfort benefits of an insulation retrofit.

For new construction, air barrier films could incorporate self-healing properties. These self-healing films could recover from punctures and small tears during installation, as well as tears that develop once the film is between envelope sheathing layers as a result of settling over time and differential thermal expansion of the sheathing elements. Autonomic self-healing materials—those that begin healing without external intervention or inputs—would be most appropriate for buildings applications. Extrinsic systems, which rely on microcapsules or a vascular network to facilitate healing [33], might be compatible with existing air barrier materials as an embedded interlayer, though selecting the appropriate healing compound and ensuring compatibility with air barrier film manufacturing, storage, and installation methods would be needed. Intrinsic systems, which are inherently autonomously self-healing, require application-specific material formulations [34], and it is possible that polymer families with intrinsic self-healing characteristics could not simultaneously offer appropriate mechanical and mass transfer properties for air barrier or water-resistive barrier applications.

For new construction and deep retrofits, zero- or low-VOC (volatile organic compound) spray-applied air barriers and water-resistive barriers might be highly resilient to installer error by adhering reliably to a wide range of substrates without fasteners or joint taping under a wide range of ambient conditions. Spray-applied technologies might also reduce labor effort compared to mechanically fastened membranes. Although there are some spray-applied products currently available, these products generally suffer from one or more shortcomings that limit their applicability—VOC content, overspray, dry times, substrate adhesion and compatibility, and high installer training requirements. For example, formulations that have high VOC contents are unsuitable for interior use at tenant fit-out in existing commercial buildings. Forthcoming spray-applied materials should seek to address these shortcomings to improve their applicability for new construction and retrofits for the widest possible array of substrates. Novel spray-applied membranes that can span small gaps, thus functioning as both membrane and liquid flashing, would eliminate the need for most detailing work around penetrations and floor-wall and wall-roof interfaces prior to applying the membrane, and would therefore significantly reduce the labor effort. By offering one-step installation that replaces caulking, joint taping, and liquid flashing, such a membrane material would also reduce the risk of installation defects. Self-leveling and self-healing formulations would further increase resilience to installer error and ensure long-term performance as buildings undergo thermal cycling and settling.

These new technologies also need to address special challenges in existing buildings; that is, owners typically require minimal teardown, disruption to occupants, and setup and dismantling time. In cases where building owners will not tolerate any teardown, technologies are needed that can locate leaks and seal them without damaging interior surfaces. Such technologies would also be valuable to new buildings with poor blower door test results that need a method for detecting and fixing leaks so the building can comply with an airtightness requirement. These technologies, by reducing setup, teardown, and reconstruction effort, can also substantially reduce air sealing retrofit costs.

3.3.2.2 Thermal Energy Management Remediation

The R-value of uninsulated or poorly insulated building envelopes can be increased without substantial teardown for some building types using a few commercially available systems, including drill-and-fill blown cellulose or foam for wall and ceiling stud cavities as well as loose insulation for unoccupied residential attics. Overcladding of existing buildings does not require substantial envelope teardown, though the labor effort to install an overcladding system is still significant. Also, although overcladding can substantially improve aesthetic appeal, it is not feasible in cases where preservation of the original appearance of the facade is required. Overcladding system performance can be improved through the development of higher R/in insulation materials, though the primary barrier to market impact is price. Where overcladding is commonplace outside of the United States, prices are also high, but have been reduced through increased demand, standardization of construction methods, and increased contractor familiarity with overcladding systems reducing risk and total project time.

For cavity-filling systems, compatibility with novel high-performance materials is possible; in forthcoming research on high R/in insulation materials, as described in Section 3.1, consideration should be given to compatibility with this type of delivery system for retrofit applications. In addition, higher R/in materials that can be delivered through smaller or fewer penetrations while still achieving complete cavity filling within a reasonable time would be beneficial, because that change would reduce the time required to patch entry holes. Cavity-filling systems that can prevent overfilling and materials compatible with adding insulation to partially insulated walls where the insulation material has settled or shrunk, or whose R-value could be improved by adding a higher-performance material, would also be valuable. Novel materials used for cavity insulation should not leak out through penetrations added later, should be low or zero VOC, and should not present other health hazards (e.g., particle sizes below 10 microns).

Beyond improving existing approaches, novel materials could be developed specifically for R-value improvement of existing envelopes. In particular, materials are needed for buildings where retaining the appearance of the existing facade is desirable, particularly stone and masonry facades. Highly insulating low-cost transparent materials that can be liquid- or spray-applied as a kind of "liquid overcladding" could be relevant for these buildings and could also be used with other facade types. These materials could also incorporate air or moisture control features. Materials developed for the ARPA-E SHIELD program to improve the R-value of single-pane glazing might be applicable, though additional work would be needed to determine material deposition and adhesion characteristics on typical opaque envelope substrates as well as permeability and the effect of the coating on envelope assembly drying. Any novel materials developed for this application should rely on low-cost precursors and feedstocks, use low-cost and low-labor effort installation methods, and incorporate features that improve resilience to installer error.

3.3.3 Market Barriers and Challenges

Despite their significant contribution to building energy use, as shown in Figure 1-3, Tables 1-1 and 1-2 show that opaque envelope components in existing buildings are rarely upgraded to reduce energy use, remedy performance problems or defects, or improve aesthetics. Barriers to envelope retrofits or improvements in existing buildings include the limited observability of performance degradation and component failures as well as the high perceived—and actual—price and complexity of envelope retrofits.

Although equipment in buildings, such as heating and cooling systems, water heaters, and light bulbs, is often replaced due to increasing maintenance costs or outright failures, the same does not hold true for building envelope components. The degradation of envelope components is often gradual and can typically be masked by additional heating and cooling. Given the relatively recent advent of high-performance building envelopes, people are likely accustomed to poorly insulated, leaky buildings, and might perceive those conditions as typical or characteristic of best-available envelope performance. In addition, some failure modes, such as the collapse of loose fill insulation in wall cavities, cannot be observed by a building occupant or owner. These types of failures are entirely different than a refrigerator that fails to keep food cold or a light bulb that burns out.

Some envelope upgrades are performed more frequently than others, such as window and siding replacements, blown-in ceiling insulation, and drill-and-fill wall cavity insulation. Table 1-1 shows the frequency of these retrofits by category. In general, these retrofits share the characteristic that they require minimal on-site labor effort and/or are critical to overall building integrity. For the insulation retrofits, in particular, there are also task-specific off-the-shelf tools that installers can use to simplify and expedite the job. Conversely, siding replacements provide an aesthetic upgrade in addition to improving energy efficiency (in the case of insulated siding retrofits). Additional value streams beyond energy savings, such as aesthetics, ease-of-use, or comfort, can help increase adoption. In particular, value streams that are readily observable, such as aesthetics or convenience features, can help broaden the appeal of envelope retrofits that also increase energy efficiency.

The cost of envelope retrofits is directly related to the disruption to building occupants as well as the scale and complexity of teardown and reconstruction of an entire building envelope. These factors contribute to the significant on-site labor effort that can be required to complete an envelope retrofit project, and thus the overall project cost. These issues are particularly applicable to opaque envelope retrofits, because the opaque envelope is generally composed of many separate layers and components, so improvements can require removing some layers or components to reach the elements of the envelope to be modified or improved. Moreover, the opaque envelope generally includes many detailed elements and interfaces, which require special attention that can add significantly to the cost and increase the probability of workmanship errors that lead to below-design performance. Among other approaches, these challenges might be addressed by developing ultra-low-cost approaches that incorporate robotics or other advanced manufacturing methods that are nondestructive or minimally invasive to eliminate disruption to occupants during the retrofit. Section 4.1.2 expands on the opportunity to adopt methods from other fields to address market and technical barriers to retrofit fabrication and installation. Systems or materials that integrate all needed control layers as-delivered—simultaneously addressing thermal insulation, air infiltration, bulk moisture control, and water vapor control, avoiding extensive on-site fabrication and assembly—could also help reduce cost and disruption to building occupants.

3.3.4 Technology Action Plan

The installed price and performance targets for air sealing remediation technologies available in 2040 are shown in Table 3-2. These installed prices correspond to the energy savings derived from the indicated performance levels to achieve a 10-year simple payback. Although these prices correspond to total installed prices, remediation expenses can also be folded into the budget for a larger project. When adding remediation to an existing project, if it can be done at a price at or below the target installed price, the expenses should accrue for only the remediation itself. Moreover, remediation technologies that can be used in furnished homes could incorporate those expenses into other retrofit activities, even those that might be unrelated to the opaque envelope.

Table 3-2: Energy performance and installed price targets for air sealing remediation technologies available in 2040, and the corresponding primary energy savings. Energy savings from existing buildings, particularly residential buildings, dominates total energy savings from air sealing improvements for these targets. As a result, for the selected payback period, installed prices are somewhat higher for existing buildings.

Air Sealing Remediation (2040)					
Building Sector	Performance		Installed Price		Primary Energy Savings (quads)
Residential (New)	1	ACH50	0.84	$/ft^2 envelope	0.4
Residential (Existing)			1.09	$/ft^2 envelope	1.36
Commercial (New)	0.2	CFM75/ft^2	0.17	$/ft^2 envelope	0.09
Commercial (Existing)			0.55	$/ft^2 envelope	0.29

A range of installed prices for various payback periods is shown in Figure 3-6; different building owners will likely find different payback periods acceptable depending on their effective discount rate and cost of capital. The targets are specified separately for new construction and existing buildings, because existing buildings in particular suffer from poor airtightness. This shortcoming of existing buildings is reflected in the primary energy savings shown in Table 3-2, where greater energy savings are available from existing residential and commercial buildings (at equivalent performance levels). The comparatively faster turnover in the commercial sector, as shown in Figure 1-4, also appears in the energy savings in Table 3-2.

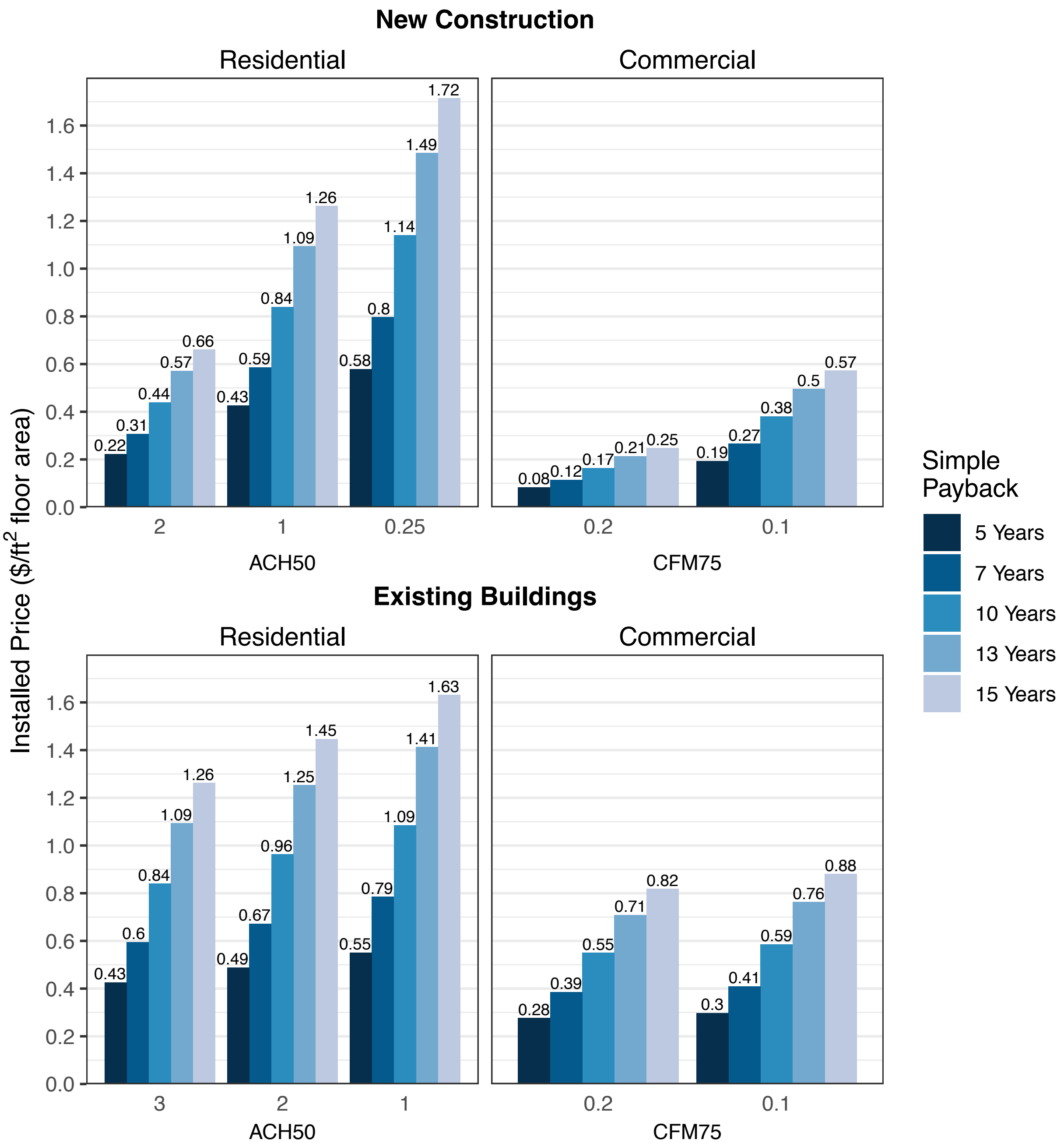

Figure 3-6: Installed prices are shown for a range of payback periods for existing and new residential and commercial buildings in 2040. Reducing the air infiltration rate increases the acceptable installed price across all buildings, with particularly significant savings in existing (as compared to new) commercial buildings. Conversely, the comparatively lower turnover rate in residential buildings, as shown in Figure 1-4, results in much larger total energy savings from residential building retrofits.

The Technology Action Plan table describes R&D activities that could help develop building envelope diagnostic technologies to ultimately achieve the targets outlined in Table 3-2. Each R&D activity is linked to the limitations of the current state-of-the-art that the activity will target or address. These R&D activities are not necessarily an exhaustive list, rather they represent some of the possible research directions that have the potential to improve currently available technologies or lead to the development of new approaches to envelope diagnostics. The Enabling Technology Characteristics table describes additional properties that envelope diagnostic technologies should have if they are to be useful for building energy assessment professionals.

<table>
<tr><th colspan="3">Technology Action Plan</th></tr>
<tr><th>Technology</th><th>Objective</th><th>R&D Activity</th></tr>
<tr><td rowspan="4">Insulation Remediation</td><td>Reduce total installed price;
Improve constructability;
Reduce air leakage;
Improve moisture management;
Improve R-value</td><td>Develop novel materials and approaches for overcladding without superstructures and opaque panels</td></tr>
<tr><td>Reduce total installed price;
Improve constructability;
Improve R-value</td><td>Develop materials for overcladding that do not obscure existing facade materials</td></tr>
<tr><td>Reduce total installed price;
Improve constructability;
Improve moisture management</td><td>Investigate compatibility of novel insulation materials with remediation delivery systems</td></tr>
<tr><td>Reduce total installed price;
Improve constructability</td><td>Develop materials with minimal expansion or settling over time, suitable for cavity insulation with small penetrations</td></tr>
<tr><td rowspan="4">Air Sealing Remediation</td><td>Reduce total installed price;
Improve constructability;
Reduce air leakage;
Improve moisture management</td><td>Develop materials that can yield air sealing in the climate-appropriate plane without significant teardown</td></tr>
<tr><td>Reduce total installed price;
Improve constructability;
Reduce air leakage;
Improve moisture management</td><td>Develop materials for air sealing at the external facade without obscuring the existing facade materials</td></tr>
<tr><td>Improve constructability;
Reduce air leakage;
Improve moisture management</td><td>Develop autonomic self-healing air barrier films</td></tr>
<tr><td>Reduce total installed price;
Improve constructability;
`Reduce air leakage;
Improve moisture management</td><td>Develop one-step spray- or liquid-applied air and vapor control materials</td></tr>
</table>

<table>
<tr><th colspan="2">Enabling Technology Characteristics</th></tr>
<tr><td>Insulation Remediation</td><td rowspan="2">• Minimal envelope teardown and reconstruction requirements
• Ability to direct remediation to affected areas with minimal manual intervention
• Suitable for use in occupied or soon-to-be-occupied buildings
• Minimal additional effort for project- or building-specific customization
• Fault-tolerant installation method(s).</td></tr>
<tr><td>Air Sealing Remediation</td></tr>
</table>

Active, Dynamic Technologies

Opaque envelope technologies are crucial to increasing building capacity to modify demand because they influence a substantial portion of building energy use, as shown in Figure 1-2. In reality, all opaque envelope technologies that improve energy performance are GEB-relevant. In this capacity, opaque envelope technologies would contribute to GEBs in a passive way, by improving the overall thermal performance of the building. In addition to these passive technologies, which have co-benefits for both energy efficiency and GEBs, dynamic opaque envelope technologies could change thermal capacitance or heat transfer through the envelope at critical times. The need for demand flexibility from buildings depends on the market and grid conditions at any given time. Requests for flexible operation could be on only a few days per year (e.g., reliability-based demand response), or on a daily, hourly, or even continuous basis. Typical grid services can be delivered by buildings via four different mechanisms: efficiency, load shedding, load shifting, and load modulation (i.e., frequency regulation or voltage support). The ability of opaque envelope technologies to deliver these services hinges on the existence of the necessary communications infrastructure to connect utilities directly to the end-use loads or the transparent facade's device-specific or whole-building energy control systems.

3.4 Tunable Transport Materials

3.4.1 Overview

In general, components that comprise the opaque envelope serve a single function—support, control, or finish—and have static properties. For windows, various operable attachments and more recently developed dynamic glazing facilitate the adjustment of window properties to minimize energy use. Mirroring this, there is an opportunity for the development of novel opaque envelope materials that also have dynamic or tunable properties. Such envelope materials can help reduce energy use by adjusting their characteristics in response to a control signal or changes in ambient conditions.

With the growth in variable renewable electricity generation (including distributed solar generation) alongside cities, states, and nations pursuing aggressive CO_2 emissions reduction programs, the timing of energy use and the ability to shift energy use to accommodate the availability of renewable generation is of increasing interest. In the future, it will be important for researchers developing novel envelope materials, particularly those with time-varying or dynamic properties, to be able to understand the effects of those technologies not only on total building energy use but also on the timing of energy use. Moreover, as these time-varying energy use control features become important to an increasing number of clients, architects and engineers will benefit from representation of these characteristics in their building information modeling (BIM) workflows. Section 4.2 elaborates on the opportunity for the building envelope to facilitate demand flexibility from buildings.

The development of novel dynamic and/or multifunctional materials that can reduce energy use and deliver additional benefits will require a first-principles, systems-level approach to manipulating heat and mass transfer within and through the opaque envelope. Depending on their configuration, these materials have the potential to deliver significant energy savings, as well as grid-related operational benefits such as load shifting or peak shaving, improved thermal comfort, and increased durability. In some cases, these materials might offer novel combinations of functionalities in form factors that are incompatible with existing construction practices for some or all applicable building types. However, as long as the materials offer sufficient building-level benefits to incentivize switching from current business-as-usual materials, assemblies, and practices, making fundamental changes in construction methods may be worth the cost and immediate inconvenience. Regardless, these novel materials must meet nonenergy performance requirements and standards that apply to the functions served by the incumbent materials and components, including mechanical properties, fire performance, moisture tolerance, materials compatibility, and durability under typical operating conditions (e.g., temperature, humidity, and solar irradiation).

3.4.2 Technical Barriers and Challenges

3.4.2.1 Variable Resistivity Materials

Materials could conceivably be developed that would function in the heat or mass transport domains in a manner analogous to common circuit elements—diodes, switches, and transistors—in the electrical domain. Wehmeyer et al. [35] explore a few potential circuit elements and their thermal analogues in general terms for a wide range of engineering applications. For building envelopes, these tunable or variable resistivity materials could operate to alternately restrict or promote thermal, air, or moisture transport through the envelope, either in response to a control signal or passively based on a switching condition related to temperature or vapor pressure, for example. Though their exact form factor is uncertain, these materials would likely be films or membranes applied across the surface(s) of interest (e.g., facade or roof sheathing), with positioning between the layers of the applicable surface(s) depending on the affected property (heat or moisture) and intended operation of the particular material. Regardless of the configuration, some of the critical parameters defining the performance of these materials are the on/off ratio and the rectification ratio [35]. In addition, if these materials are used as replacements for one or more existing envelope components (e.g., an air barrier), the dynamic transfer rate material must also replicate the performance required of the supplanted component, except in the case where the variable resistivity material is intended to manipulate one or more of the key performance characteristics of the supplanted component (e.g., replacing a static air barrier with a dynamic material that can intentionally allow airflow under certain circumstances to reduce energy use).

The multilayered nature of building envelopes has the potential to restrict the effectiveness of variable resistivity materials, because one of these layers might serve as a buffering or rate-limiting step in heat or mass transport that the variable resistivity material seeks to influence. Once a candidate envelope assembly configuration for a particular material and application is established, the properties of the other elements of the assembly and their interaction with the heat or mass transport circuit element should be established to determine the efficacy of the system.

One potential application for variable thermal resistivity materials is accessing free cooling or heating through the envelope during periods when outside conditions could reduce the need for mechanical heating or cooling. The energy savings potential of a hypothetical variable resistivity material would vary significantly based on a range of factors. Menyhart and Krarti [36] found an energy savings potential of 7%–42% for variable thermal resistivity insulation in the continental United States, with the largest savings in marine and cold climates and the lowest savings in hot-humid and hot-dry climates. Another study considered a different technology approach and found savings of 29%–32% in a cold climate [37]. The optimal minimum and maximum R-values to maximize energy savings depend on the climate zone. The effectiveness of these materials will likely also be affected by the surface area (on which the material is applied) to whole-building volume ratio, where buildings with low variable R-value surface area-to-volume ratios will see lower energy savings. Depending on the climate zone, performance might be improved with variable absorptivity and emissivity materials or surface treatments that respond to varying outdoor air temperatures, incident solar irradiation, or material temperatures to enhance the desired cooling or heating effect.

There are numerous material and system approaches that might yield variable thermal resistivity materials. VIPs achieve their low R-values through the evacuation of air and other gases from an insulating material. If this pressure is changed, the R-value of the panel will change. Methods that can affect active or passive control of the pressure inside a VIP once installed in the envelope could therefore yield a variable R-value insulation system. Shape memory polymers integrated into an insulation material might be able to modify the shape of the insulation material to reduce its effective R-value. Different shape memory polymers could likely be configured for passive operation in response to a temperature gradient or specific temperature conditions, or for active operation with electrical actuation. Active shape memory polymers should require very low power (less than 1 W/m^2) to maintain their switched state, or ideally, only require power to switch between states. Numerous approaches can also be investigated for variable resistivity materials targeting moisture transport. One such solution could consist of using membrane materials with variable permeability. Through passive control (like responding to humidity levels) or actively controlled though a signal, this type of system could meter moisture transport to help maintain comfortable indoor conditions and prevent mold formation.

The previous discussion has generally referred to variable resistivity materials as stand-alone elements of a multilayered building envelope. Depending on their configuration, these materials might yield increased performance improvements when combined with thermal/moisture storage mediums by increasing the amount of energy that can be offset by favorable ambient conditions. The potential for multicomponent assemblies is elaborated in Section 3.6.

3.4.2.2 Energy Redirection Materials

The typical paradigm for managing thermal losses and gains in buildings has focused on resisting heat transfer through the envelope. Alternatively, novel strategies including thermally anisotropic materials (TAMs)—

materials with directionally dependent properties—could reduce heating and cooling by redirecting conduction heat transfer through the envelope to or from a thermal reservoir or other external source or sink. TAMs are engineered multilayer structures with alternating high and low thermal conductivities. TAMs have been used for thermal management in electronics applications [38]–[40] to redirect heat away from sensitive components. As shown in Figure 3-3, multilayer carbon-carbon TAMs were also used on the Space Shuttle Orbiter to manage thermal loads. Investigations of anisotropic properties in building materials have previously focused on the effect of anisotropy on failure and fracture mechanics or wetting and absorption of liquid water in materials used for building structures (e.g., masonry [41], wood [42], or rammed earth [43]). TAMs to redirect heat flows in building envelopes have not been explored extensively in the literature. The critical parameters defining TAM performance are not fully established, but might include surface convection coefficients, conductivity of the anisotropic layers, contact resistance between layers in an anisotropic assembly, and heat sink or source characteristics.

Preliminary work has shown that thermally anisotropic composites—multilayered assemblies functionally comparable to TAMs—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.[10] Experiments using a large-scale climate simulation chamber have been conducted to compare wall assemblies with thermally anisotropic composites made of currently commercialized materials against continuous exterior insulation with equivalent R-value and thickness. Empirical results indicate that the thermally anisotropic composite led to heat gain reductions of up to 75% under simulated summer conditions. These results suggest U.S. technical potential energy savings of 0.6 quads per year in residential buildings. Additional investigation is needed to establish primary energy savings across building types and climate zones and to explore optimal TAM configurations and parameter values to maximize energy savings.

Figure 3-7: Reinforced carbon-carbon is a graphite-reinforced carbon composite matrix with thermal anisotropy used for the nose cap and wing leading edges of the Space Shuttle Orbiter. [44]

Technologies and/or materials that can efficiently redirect heat within buildings are key enablers of effective TAMs and other prospective thermal energy redirection methods. These materials would function as the thermal equivalents of wires in electrical distribution systems and could create more uniform temperatures between interior spaces, improve thermal comfort, and facilitate rejection of thermal energy to available sinks. Currently commercialized thermal energy redirection technologies include heat pipes and thermosyphons.

For TAMs, 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 [45]. These systems 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. TAMs might also have the

[10] 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%.

potential to be dynamically controlled by changing the heat transfer characteristics of the connection between the TAM and the heat sink or source. 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, especially when coupled to thermal redirection systems like TAMs. As an example, the narrow-band blackbody radiator developed by Raman and colleagues [46] could be coupled with an HVAC system, but as yet could not be readily coupled with a TAM or other thermal energy redirection technologies.

Recent research has yielded a variety of 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. 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 consideration for occupant visual comfort. These materials would likely perform best when paired with other dynamic envelope components, particularly thermally anisotropic systems, 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, but none are yet widely commercialized. Developing novel approaches or improvements to these technologies that reduce their cost and increase their flexibility in placement and form factor would make them suitable for a broader range of opaque envelope and interior thermal management applications.

3.4.3 Technology Action Plan

Achieving widespread adoption of tunable transport materials requires advancing the energy performance and nonenergy characteristics of these materials beyond the current state-of-the-art through R&D. The 2040 installed price and performance targets for multifunctional and dynamic opaque envelope materials are shown in Table 3-3. The target installed prices are based on materials that apply to the walls and roof of the opaque envelope and the energy savings that arise from a 50% reduction in heating and cooling energy use associated with losses and gains through the envelope. This energy savings target is intended to be generic to a wide range of technologies, given that different multifunctional materials might deliver energy savings in different ways that might not be directly comparable.

Table 3-3: Energy performance and installed price targets for multifunctional and dynamic materials in 2040, as well as corresponding primary energy savings. These targets were developed to be generic for any technology that can deliver the targeted reduction in heating and cooling energy use associated with losses through the wall and roof components of the opaque envelope.

Multifunctional Materials (2040)					
Building Sector	Performance		Installed Price		Primary Energy Savings (quads)
Residential	50%	Envelope energy savings	0.93	$/ft² envelope	1.2
Commercial	50%	Envelope energy savings	1.28	$/ft² envelope	0.68

The installed prices in Table 3-3 are determined for a 10-year simple payback. These installed prices correspond to total installed prices inclusive of any required controls if these materials are installed as a stand-alone retrofit, but are incremental prices if incorporated into a new construction project or included as part of a larger retrofit package, such as a recladding or overcladding system. For example, if a recladding project is being undertaken on a commercial building (in 2040) at $\$5/ft^2$, that price can increase to $\$6.28/ft^2$ to incorporate a multifunctional material, with an associated payback of 10 years for that component. Actual acceptable payback periods will vary by project and building owner; Figure 3-8 shows the acceptable installed prices for a range of payback periods for residential and commercial buildings. Notably, installed prices for commercial buildings are somewhat higher for equivalent energy savings and payback periods, which suggests that the commercial buildings sector might be a good opportunity for market entry for these materials. Subsequent price reductions enabled by manufacturing scale-up could then lead to a product suitable for the residential market.

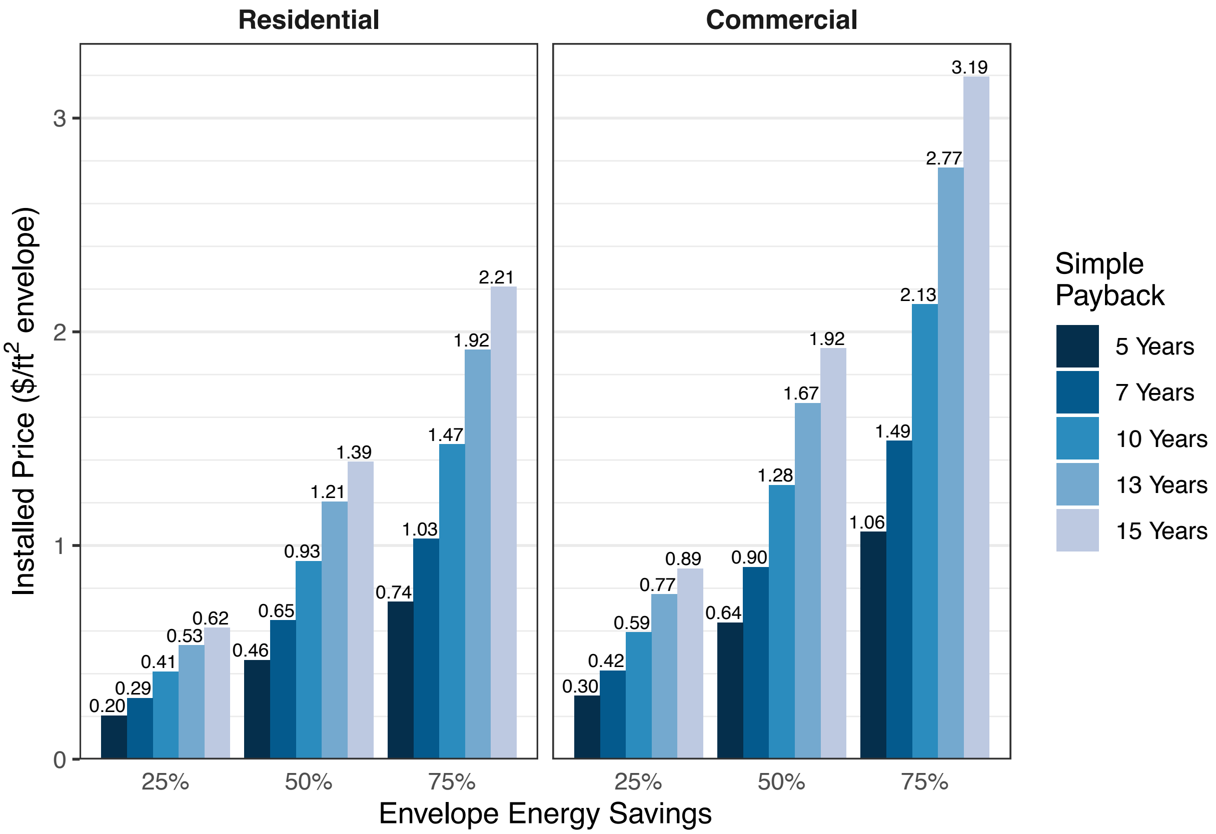

Figure 3-8: Total installed prices to achieve various payback periods are shown for three different energy savings percentages. These envelope energy savings are derived from reductions in heating and cooling energy lost through the walls and roof of the opaque envelope. Multifunctional and dynamic materials and technologies have the potential to improve the energy performance of the opaque envelope by an array of mechanisms; these results do not presume any particular method for achieving the indicated energy savings. For the same energy savings and payback period, commercial buildings have higher acceptable installed prices than residential buildings.

The Technology Action Plan table articulates R&D activities that can be pursued for dynamic and multifunctional materials to address critical needs related to cost-effectiveness, energy performance, and nonenergy attributes. These R&D activities can help to achieve the installed price and performance targets articulated in Table 3-3 for these materials. The Enabling Technology Characteristics table provides additional performance parameters or features these materials should have to be appropriate and market viable for buildings applications. These characteristics might not influence energy performance directly but should be kept in mind when pursuing materials R&D in this area, as technologies that are unable to provide these features might not readily transition to the private sector for commercialization.

Technology Action Plan		
Technology	**Objective**	**R&D Activity**
Variable Resistivity Materials	Improve (effective) R-value; Improve moisture management	Establish fundamental physics underlying circuit element mechanics in solid-state materials in environmental conditions comparable to the opaque envelope
	Improve R-value; Reduce air leakage; Improve moisture management	Investigate materials that can offer desirable control features for the opaque envelope
Energy Redirection Materials	Improve (effective) R-value	Investigate climate zones and system configurations that maximize energy savings
	Improve (effective) R-value	Establish viable heat sinks and sources and demonstrate operation
	Improve (effective) R-value	Determine potential benefits from enhanced directional control on energy savings

Enabling Technology Characteristics
• Dynamic resistive switch ratio (R_{off}/R_{on}) ≥ 10 • Offer high thermal resistance state ≥ R_{air} • Minimal degradation over thousands of cycles • Thickness ≤ 1 inch.

3.5 Energy Storage Materials and Strategies

3.5.1 Overview

Opaque-envelope-integrated thermal and/or moisture storage has the potential to offer multiple benefits in buildings. Thermal storage[11] can shift the timing of heating and/or cooling energy demand, improve thermal comfort by reducing the magnitude of temperature swings, and in some cases, offset energy use by recharging using nighttime air or solar heat gain and reduce the size or extent of space-conditioning equipment [47]. The annual energy savings potential of thermal storage varies widely as a function of climate (including available ambient recharging opportunities), storage system configuration (including the system size and switching temperature), building characteristics (including interior set points, internal heat loads, building size, and facade to floor plate area ratio), and other factors. As a result of these factors and the lack of real-world experiments with thermal storage systems, energy savings estimates in the literature vary widely and might not be representative of actual savings potential across the building stock [48]. Moisture storage[12] might also be able to provide substantial energy savings, especially given that moisture control in buildings is currently achieved primarily with cooling systems. The opaque envelope offers significant interior surface area for moisture absorption, though the ideal form factor for these materials is as yet unknown and might depend on their cost and particular performance characteristics. Moisture storage materials that have adequate properties for opaque envelope applications are currently elusive. Appropriate methods for moisture extraction and the potential for moisture redirection from these materials are also unclear, but will be critical to ensuring long-term moisture durability of the envelope.

[11] Thermal storage corresponds to systems that can store and discharge sensible heat—thermal energy that changes the temperature of the system. Thermal storage systems can store sensible heat as sensible heat (e.g., raising and lowering the temperature of a concrete slab) or latent heat (e.g., by driving a phase transition in a phase change material).

[12] Moisture storage corresponds to materials and systems that can store and discharge latent heat—thermal energy that does not change the temperature of the system. In practice, moisture storage changes the relative humidity of the system as the storage is charged or discharged.

Thermal and moisture storage has the potential to offer storage opportunities for extant thermal and moisture conditions in buildings that cannot be efficiently converted into a more readily stored form. Like existing electrochemical energy storage technologies, such as lithium-ion batteries and redox flow batteries, thermal and/or moisture storage does not itself offer energy savings unless it is coupled with a freely available charging source or improves the efficiency of an existing HVAC system. In the case of thermal storage, this free charging resource is generally in the form of solar radiation for heating or low nighttime temperatures for cooling. If these resources are inadequate for complete charging, the building HVAC system can be used to supplement. If the HVAC system is used exclusively for charging, thermal storage could boost the efficiency of the HVAC system, the effective round-trip efficiency of thermal storage might result in a net increase or decrease in total energy use compared to a system without storage depending on the building and equipment configuration and the local climate [47]. Coordinated HVAC and storage system design will be needed to maximize potential net energy savings from adding thermal or moisture storage when relying heavily on the HVAC system for charging. Depending on the sizing and configuration of the system, the load shifting from HVAC-charged thermal storage can also increase total emissions from electricity generation [49]. Moreover, depending on the discharge duration, if discharge control is not part of the thermal storage system, its operation can exacerbate the ramping demand in systems with high levels of solar PV generation (i.e., worsen the "duck curve") [50], [51].

3.5.2 Technical Barriers and Challenges

The extent of prior research in thermal storage and the maturity of thermal storage technologies, particularly for buildings applications, varies widely depending on the technology. Moreover, not all thermal storage technologies are suitable for integration into the building envelope. Domestic hot water tanks are thermal storage found in most buildings; they can be used for load shifting and shaping if sophisticated controls are added, but they are not suitable for envelope integration. Ice storage is another thermal storage technology sometimes used in commercial buildings; it requires large volumes to achieve useful total capacities. The combination of the volume change in transitioning between ice and liquid water, the significant weight of the water, and the water damage potential make it inappropriate for envelope integration. In general, thermal storage technologies that are suitable for building envelopes do not require a supporting mechanical system, have high volumetric capacity, and can be encapsulated with depth less than 2–3 cm. The incorporation of thermal storage materials has been investigated for multiple envelope components, including wallboards, concrete, floor slabs, and insulation material [48].

A significant shortcoming across most thermal storage technologies is a lack of methods to control the timing of charging and discharging. This problem is especially acute in systems that are intended to be envelope-integrated—prior research on these systems has typically focused on the development of materials that respond entirely passively once installed, storing or releasing heat when the surrounding environment reaches the temperature that triggers the storage or release mechanism. There are two types of control that would improve the energy savings potential and thermal comfort performance of envelope-integrated phase change materials (PCMs)—activation control and transition temperature tunability. Thermal storage systems with activation control would be able to selectively charge or discharge once the switching condition is reached, enabling delayed charging or discharging to time those events to maximize energy and/or cost savings. This capability would help ameliorate the coincident electricity demand ramping that can be caused by passive thermal storage technologies. Han et al. [52] demonstrate a possible approach to achieving this type of control with an organic PCM, but significant further work is needed to identify alternative approaches to achieving activation control over PCMs. Transition temperature tunability would improve the performance of PCMs subject to seasonal variations in interior set points and exterior temperatures. Figure 3.6 shows the results of an analysis of the effect of transition temperature tunability on energy storage in U.S. buildings. These results show that regardless of whether the thermal storage material is primarily intended for use during heating or cooling season, increasing tunability significantly increases the annual energy storage potential. More work is needed to better quantify the impact and energy savings potential of tunability [48].[13]

[13] A similar phenomenon has been observed with moisture buffering, where having a fixed charge and discharge state can reduce occupant comfort for some buildings in some climates [59].

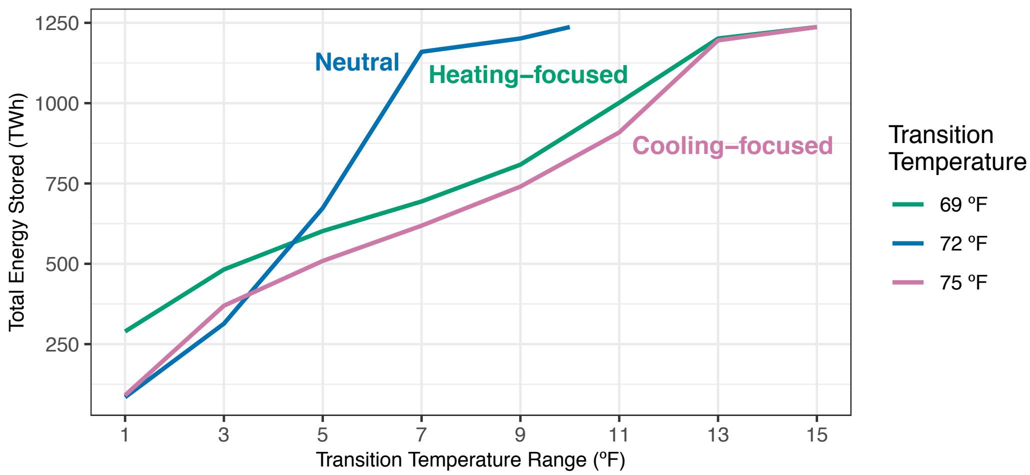

Figure 3-9: A parametric analysis of the effect of thermal storage transition temperature range on the total energy storage capacity shows that in all cases, but especially for heating-focused (69°F transition temperature) and cooling-focused (75°F transition temperature), increasing the range of possible 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.

3.5.2.1 Phase Change Materials

Perhaps the most thoroughly studied thermal storage technology for buildings applications are phase change materials (PCMs). These materials store thermal energy as latent heat through a phase change process, generally storing and releasing heat in the solid-liquid phase change regime. In addition to the features listed in the Critical Characteristics Table, PCMs applicable to buildings should have high latent heat of fusion, specific heat, and density. PCMs can be incorporated in construction materials using direct incorporation, immersion, encapsulation, micro-encapsulation, and shape-stabilization [53]. Materials with phase change properties that are suitable for buildings generally fall into one of three classes: organic, inorganic, and eutectic. Organic PCMs transition at appropriate temperatures for buildings but suffer from low thermal conductivity and are flammable [54]. Microencapsulation—placing the PCM inside a thin shell ~3 um in diameter—can help address the flammability and thermal conductivity concerns of organic PCMs, but it reduces the volumetric storage capacity and increases cost [48]. Inorganic PCMs are low cost and have good storage properties, but can suffer from high degradation under cycling and poor initial response when the transition temperature is reached [54]; successful approaches that address the long-term cycling stability of inorganic PCMs remain elusive. Eutectic PCMs are mixtures of multiple organic and/or inorganic PCMs; these PCMs tend to have higher costs and do not necessarily offer superior characteristics compared to their constituent PCMs, though eutectic PCMs have been the subject of fewer studies compared to single-compound PCMs. Kalnaes and Jelle [48] provide a good overview of the types of PCMs suitable for buildings, their characteristics, potential form factors, and future research directions.

3.5.2.2 Thermochemical Storage Materials

Thermal storage can also be affected using reversible thermochemical reactions. Thermal storage achieved using this mechanism is conceptually similar to electrochemical energy storage, but instead of converting chemical potential to electricity, it is converted to thermal energy. Thermochemical storage is achieved primarily through sorption processes [55]. Thermochemical storage systems typically have higher energy densities than sensible or latent thermal storage, which reduces the quantity of material required for an equivalent storage capacity and might therefore reduce costs. Many thermochemical couples require high charging temperatures [55], in some cases exceeding the auto-ignition temperature of building envelope materials; thus, the charging components for a thermochemical storage system would likely need to be separate from the envelope. Thermochemical storage could offer control over exothermic discharge timing, because the separation of the reactants can be readily maintained, precluding their exothermic synthesis, even at the switching temperature. As yet, building integration for thermochemical storage has not been studied extensively [56], and especially not for envelope applications, because the form factors for hypothesized systems are generally unwieldy. A pouch or thin rigid panel encapsulated system using a low charging temperature (< 80ºC) species and a selective membrane for species separation might be a viable path to an envelope-integrated thermochemical storage system, but future work should attempt to evaluate the viability of available thermochemical couples for form factors suitable for building envelopes. In addition, future work should consider the potential merit for building envelope applications of a combined sensible or latent and thermochemical storage system to capture the strengths of each system while mitigating some of their individual weaknesses.

3.5.2.3 Moisture Storage

Given that relative humidity can influence occupant comfort and affect the operation of cooling systems, moisture storage or buffering could affect energy use. Water vapor in buildings is stored in porous materials, such as upholstered furniture, wallboard, and some types of wall insulation. Adding materials with moisture storage capacity or enhancing the capacity of existing materials has been found to reduce cooling energy use in simulations [57], and limited research has investigated novel moisture capacity enhancement materials [58]. Significant energy savings are possible in temperate, arid, and semi-arid climates where there are sufficient swings in outdoor relative humidity to regenerate the moisture storage capacity of the building overnight without using the HVAC system [57]. When recharging cannot be performed using exterior ambient conditions, moisture storage might be able to provide load shifting, though the passive operation of these systems can limit the potential benefits of load shifting. Thermal comfort can also be improved, though Winkler et al. [59] find that in high humidity conditions, significant moisture storage can reduce occupant comfort. Passive moisture storage can be readily integrated into building envelope components, such as wallboards and wall cavity insulation [60], [61], but hygrothermal analysis is required to ensure that any particular building and moisture storage configuration in a given climate will not lead to condensation on surfaces, especially inside the wall, floor, or roof assemblies.

Materials that offer active control over the timing of moisture storage and release can reduce cooling energy use, mitigate occupant comfort risks, and might facilitate the application of moisture storage in a wider range of climates. Active control capabilities 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.

3.5.3 Market Challenges and Development

For envelope-integrated thermal and moisture storage to be commercially successful, it must be competitive with respect to its overall value proposition compared to other forms of stationary building-scale storage. Incumbent storage technologies for buildings are limited to thermal mass and passive thermal storage, ice storage, and—relatively recently—battery storage. Each of these technologies also faces barriers to adoption. Because thermal and moisture storage are not commonplace in buildings, there is limited expertise and experience in the field with respect to specifying and installing these storage systems. This lack of experience is particularly critical because thermal and moisture storage could create significant building performance problems if used improperly. Many of the novel functionalities and capabilities outlined in Section 3.5.2 are also critical to enabling adoption, as they widen the range of use cases and benefits of thermal and moisture storage. Even after commercialization of these new capabilities, poor awareness of the potential benefits of thermal and moisture storage might continue to limit adoption.

Both residential and commercial buildings can take advantage of design approaches that incorporate thermal mass for passive solar thermal management. Thermal mass can improve occupant comfort and reduce HVAC energy use, but it requires careful modeling during the design stage; improperly sized or configured thermal mass can cause severe thermal comfort problems manageable only with extensive heating and/or cooling system operation, which can increase total energy use compared to the same building without additional thermal mass. Other forms of envelope-integrated passive thermal storage can face similar challenges; improper system design can lead to increased, rather than reduced, HVAC energy use. Because of the extensive analysis and corresponding expertise needed to correctly specify passive thermal systems, they remain out of reach for most buildings.

The complexity and importance of accurately specifying a thermal storage system likely extends to thermal and moisture storage that integrates the novel functionalities discussed in Section 3.5.2. Novel design tools integrated into architecture, engineering, and construction software workflows that can simplify system specification during the design stage could help address this challenge. These tools must also be built to ensure that when changes are made later in the design and construction process, the system is re-specified to be compatible with those changes.

In commercial buildings, ice storage can reduce cooling energy use during periods of peak demand on the electric grid, thus reducing demand charges and total electricity expenditures. Ice storage can have high round-trip efficiencies compared to other storage types because it uses the cooling system to charge the storage at night, when cooling equipment efficiency is highest. Ice storage has low gravimetric and volumetric energy density, however, which makes it difficult to place in a building. And as with thermal mass and passive thermal storage, project-specific design requirements mean that ice storage cannot readily scale to a large number of commercial buildings. Ice storage systems are also not generally available for buildings that have noncentralized cooling systems, such as packaged terminal air conditioners (as in many hotels), or rooftop units (common in warehouses and retail buildings). Other thermal storage materials might be better suited for integration with a wider variety of HVAC systems, which might also compete with envelope-integrated thermal and moisture storage.

The eventual introduction of active control capability for thermal and moisture storage will substantially widen the applicability of these storage systems, but they will also require appropriate control algorithms. These controls must be readily adapted to a wide range of buildings with minimal configuration to reduce the installation and commissioning cost of thermal and moisture storage. These controls should also integrate with automated controls for HVAC systems, again with minimal configuration effort. Systems that can operate with minimal setup time and effort as well as minimal maintenance requirements will maximize adoption, as complexities at any stage in the installation and operation of these systems will discourage adoption. Harris [62] includes additional discussion of market barriers and technical challenges related to the introduction of envelope-integrated active thermal and moisture storage systems.

3.5.4 Technology Action Plan

Table 3-4 details the installed price and performance targets for thermal storage systems. The installed price includes any balance of system costs, if applicable. The performance targets are stated in terms of thermal conductivity and volumetric energy density. Other parameters that describe storage performance—such as gravimetric energy density, power density, charge/discharge rate, round-trip efficiency, or self-discharge—might also be important, but may not be the most critical parameters for defining viable envelope-integrated thermal storage performance. Additionally, thermal storage materials for other buildings-related applications, such as when integrated into an HVAC system, might have quite different performance requirements; these performance targets should not necessarily be applied to storage for those applications.

Table 3-4: Installed price and performance targets for thermal storage systems. The performance targets define thermal conductivity and volumetric energy density that are appropriate for envelope-integrated applications. These targets were developed based on a semiquantitative assessment of the price and performance of current state-of-the art thermal storage for buildings.

Thermal Storage (2040)				
Building Sector	Performance		Installed Price	
Residential, Commercial	100	kWh/m^3	15	$\$/kWh_{thermal}$
	1	W/m-K		

Storage is not readily modeled in Scout, described further in Appendix A, so these targets were developed using a different method than the other targets in this report. These targets are based on an assessment of the current price and performance of state-of-the-art thermal storage materials designed for building envelope applications, or more generically for buildings applications with respect to their transition temperature, durability, flammability, and other critical factors. The performance and operation of moisture storage technologies are less certain, so specific targets are not articulated. Although materials that offer direct latent heat management can certainly deliver energy savings, further fundamental development should precede market-specific price and performance targets.

The Technology Action Plan table articulates R&D activities and research directions that can help thermal storage achieve the targets articulated in Table 3-4 and advance moisture storage toward market-viable technologies. These activities include both R&D related to storage materials and encapsulation methods as well as balance of system R&D related to technologies that can control the operation of thermal storage and controls strategies themselves. The Enabling Technology Characteristics table details additional parameters and features that should be considered when developing thermal storage. These characteristics might not influence energy performance, but they are needed more generally for thermal storage to be suitable for buildings applications, affecting factors including material safety, fire performance, and durability.

Technology Action Plan		
Technology	**Objective**	**R&D Activity**
Thermal Storage	Improve constructability	Determine form factor requirements
	Improve operation range	Achieve switching temperatures appropriate for building interior environments (20°–25°C)
	Improve control of storage	Identify appropriate control strategies and physical configurations to maximize benefits (energy savings, load shifting, comfort improvement)
	Improve system integration	Explore value of coordination with other storage types
	Improve control of storage	Develop technologies that enable charge and discharge control, rate control, tunable transition temperatures in bulk thermal storage materials
	Improve (effective) R-value; Reduce total installed price	Investigate thermochemical couples with low charging temperatures and applicable encapsulation systems
	Improve (effective) R-value; Reduce total installed price	Identify critical envelope performance parameters for high-value (GEB-relevant) preconditioning system operations
Moisture Storage	Improve moisture management	Develop active moisture storage materials with charge and discharge control
	Improve moisture management	Develop materials with selective moisture extraction capability

Enabling Technology Characteristics (Thermal Storage)
• High thermal conductivity within the storage media/volume • Nonflammable or fire resistant up to 600°C • Noncorrosive and nontoxic, including products of combustion • Stable (chemistry and structure) over several thousand cycles, or the anticipated number of cycles for the lifetime of the host material for embedded storage • Switching temperatures appropriate for building interior environments (20°–25°C) and charging temperatures, if applicable, appropriate for available exterior ambient conditions • Minimal volume change between fully charged and discharged states • Response time of less than 15 minutes to a charge or discharge control signal (if applicable) and capacity to shift HVAC demand by on the order of one hour or more.

3.6 Dynamic Envelope Technology Assemblies

The solutions areas previously identified can each provide notable energy savings when applied individually. By combining multiple technology concepts, however, even larger energy savings might be possible. One such application of a crosscutting concept is the integration of energy storage with tunable transport materials. Energy storage materials can shift the heating and/or cooling loads, reduce the magnitude of temperature swings, and take advantage of favorable ambient conditions to reduce energy loads. Tight control over when the storage medium is charging and discharging is needed to fully maximize the potential of energy storage systems. Pairing energy storage systems with tunable transport materials can provide a convenient means of control to increase the energy savings potential of storage systems.

A simulation of three different wall configurations highlights the potential value of envelope assemblies that combine multiple dynamic elements [63]. The three configurations illustrated in Figure 3-10 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 3-11 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 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.

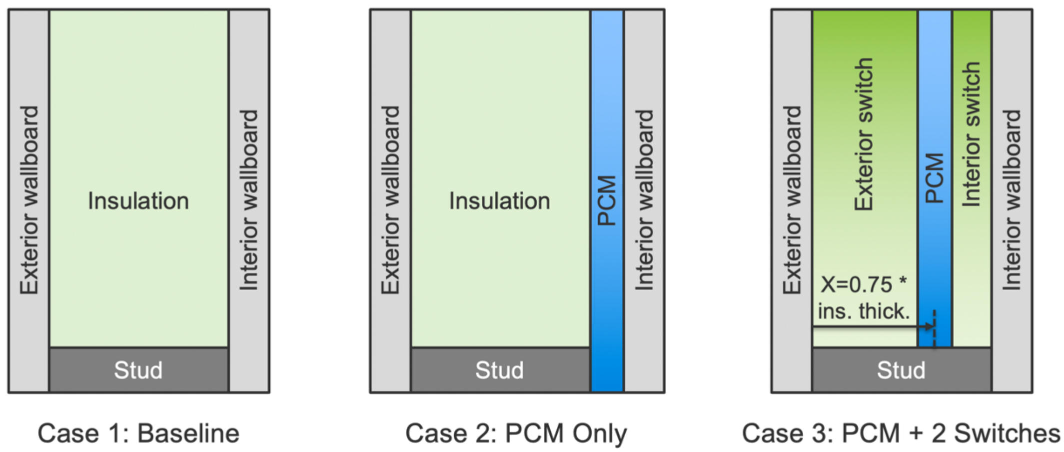

Figure 3-10: Wall assemblies with different configurations—insulation in a traditional configuration (Case 1), insulation with a PCM adjacent to the interior wallboard (Case 2), and PCM enclosed by thermal switches on both the interior and exterior side that can modulate heat transfer between the PCM and the exterior and interior environments.

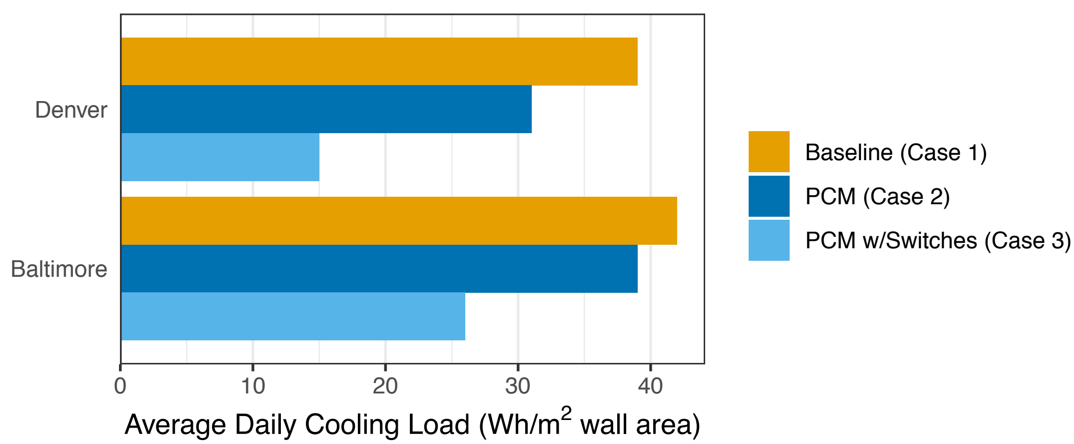

Figure 3-11: Simulation results for the three wall configurations shown in Figure 3-10, when applied to a 100 ft² wall during 1,000 hours in the cooling season (June 16–July 28), show that the average daily cooling load through the subject wall can be substantially reduced (in both climate zones shown) by adding thermal switches that enable active control of the charging and discharging of the PCM (Case 3).

With respect to dynamic insulation materials or systems, many different approaches have been proposed in the literature [64], but further work is needed to address existing shortcomings in these systems, which vary depending on the mechanism used to achieve variable thermal conductivity. Antretter et al. [64] simulated the load shifting capabilities of an active insulation system in a residential building over the course of a day. Figure 3-12 illustrates one possible configuration of a dynamic, switchable thermal mass system, that was used by Antretter et al. Simulation results for the illustrated configuration show the potential for almost 1.5 quads of U.S. annual energy savings. Moreover, the results in Figure 3-13 indicate that not only can total energy use be reduced compared to a typical building envelope, but energy use to control thermal loads during peak times can be shifted substantially. The wall configuration simulated was not optimized; additional energy savings and peak reduction capacity might be possible with further refinement of the system design. Ultimately, research will be needed to develop materials and systems with capabilities suitable for the desired envelope assembly implementations and most feasible grid services. For example, controls/optimization are needed to decide the optimal timing of when to turn various thermal switches on and off. Development of these materials and systems (and their integration into buildings) is an area of largely untapped potential for high-impact, early-stage R&D.

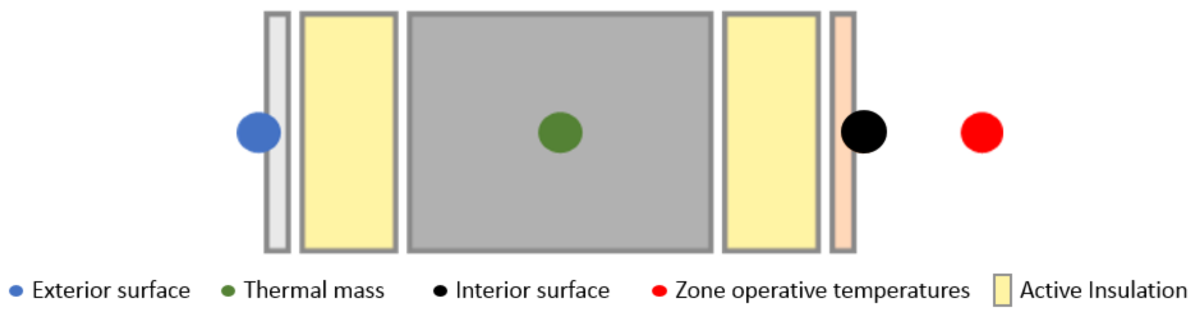

Figure 3-12: Structure of envelope in active insulation system analysis.

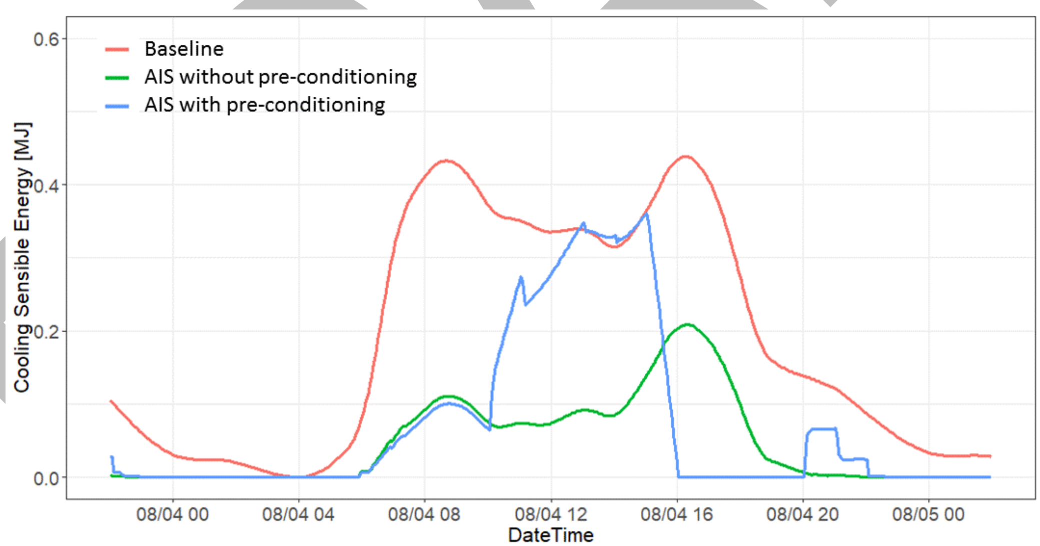

Figure 3-13: A simulation of an active insulation system in a residential building shows that electricity use for cooling, a major driver of peak electricity demand, can be reduced and shifted significantly with active insulation.

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. Further analysis is needed to quantify the potential benefits of a range of potential envelope configurations for a variety of building types.

4 Integration

Beyond developing novel opaque envelope materials, systems, and supporting tools and infrastructure, other actions can help broaden the value proposition for these materials and systems. Identifying, quantifying, and articulating the additional value streams or benefits associated with these technologies can help accelerate their adoption. Tweaking traditional approaches to building project procurement, design, and construction can help fully value the building end uses served with a high-performance building envelope, improving occupant comfort, increasing usable floor space, and reducing HVAC system costs. Building envelope components with dynamic or time-varying properties could enable the provision of electric grid services, which could lead to direct remuneration or be used as part of a strategy for increasing the value of variable renewable energy (VRE) generation. In addition to expanding the value proposition of building envelope materials and systems themselves, incorporating technologies, manufacturing methods, and engineering and business practices from other industries could represent innovations in the buildings industry that could be employed to improve performance or reduce total installed prices. These innovations, when brought to the buildings industry, could improve repeatability or precision in manufacturing or installation; reduce inventory, customer acquisition, or installation labor costs; or enable cheaper, simpler site-specific customization for high-performance building envelope retrofits.

4.1 Systems-Level Approach

4.1.1 Building Construction and Retrofit with a Systems-Level Approach

Opaque envelope features that can deliver energy savings also affect building occupants and the operation of major building subsystems, including space conditioning, ventilation, and lighting. Taking a whole-building, systems-level approach ensures that the interdependencies of these major building subsystems are reflected throughout a building's development, from design to occupancy, to ensure that tradeoffs in capital cost, operating cost, and other nonfinancial criteria are accurately accounted for in the specification of these systems to achieve the desired indoor environment. This approach should also capture differences in equipment and envelope component lifetimes in the operating costs. Using a systems-level approach could improve the adoption of energy-efficient envelope components and assemblies by showing early in the construction process the various impacts, cost and otherwise, of meeting building indoor environment targets with, for example, a code-minimum envelope and a large space-conditioning (heating, cooling, and ventilation) system compared to a high-performance envelope and a smaller space-conditioning system. Although the climate conditions in the United States make it more difficult than in Europe to completely eliminate space-conditioning equipment by specifying a high-performance envelope [65], such an envelope can still offer substantial co-benefits for building owners, tenants, and individual occupants by better managing factors that influence occupant comfort. As noted by Gladden [66], in commercial buildings, labor costs are typically two orders of magnitude larger than typical utility costs; so, even small or uncertain improvements in employee productivity from improved thermal comfort, adequate outdoor views, and access to natural light might offset high-performance envelope component costs. These factors can be incorporated into the systems-level process.

Software tools that can make clear the value proposition and tradeoffs in the specification of the building envelope and related building systems during the design phase can help communicate the value of high-performance envelopes to decision makers. These tools should be able to highlight these tradeoffs at-a-glance. Ideally, these tools could incorporate both quantitative factors, such as capital and operating costs, as well as semiquantitative or qualitative factors, such as construction budget and schedule risk as well as occupant comfort and productivity. These tools must fit into the existing workflows of architects, designers, and engineers such that the effort for them to obtain these systems-level insights is extremely low, and indeed, adds value to their workflow and provides insights that they can translate into value metrics for their clients. Critically, the software tools that are appropriate for the workflows employed by large firms for high-value, high-profile projects might be substantially different from the tools that are appropriate for smaller organizations that do not have the labor or overhead (room in their budget) to devote significant time to learning or using them. In these cases, tools that require less intervention or manual tuning to provide actionable insights, or even decision support tools that involve only simplified tradeoff calculations, might be appropriate.

Incorporating a systems-level approach into business processes for new construction and retrofits of existing buildings, particularly in the commercial sector, can accelerate adoption of high-performance opaque envelope upgrades. For new commercial buildings, in the current typical practice, energy-efficient features are often considered relatively late in the design process, which adds significant cost and risk to incorporating those features [67]. Energy efficiency objectives should be incorporated early in the project life cycle to minimize capital cost; using a holistic, systems-level design approach, these objectives can be met using an optimal combination of high-performance envelope technologies and upgrades to other building subsystems to maximize operating cost savings and other cost-adjacent factors such as employee productivity. In existing buildings, a similar focus on energy efficiency at the outset of retrofit projects can help ensure that energy efficiency is incorporated into buildings with the lowest possible capital cost and schedule risk, while ensuring that the value proposition provided by energy-efficient envelope technologies and other components is integral to the retrofit design.

In general, performance-based procurement—where performance requirements, including energy performance, are determined up-front and incorporated into the request for proposals and contract selection process—can achieve the objective of incorporating energy efficiency early in the design-build process, though there might be other strategies that achieve similar results and might be easier for some organizations to adopt [68]. Utilities can also use their incentive programs to promote the use of performance-based procurement by incorporating performance-based criteria into their programs, thus signaling to building owners that those criteria are central to receiving incentive funds [68]. Using this kind of incentive program structure also opens a performance-based pathway that encourages a systems-level approach to achieving utility program goals. These performance-based programs should also require post-occupancy measurement and verification, though different levels of measurement and verification will be appropriate depending on the size of the building and the value of the incentives offered.

4.1.2 Incorporating New Technologies with Advanced Building Construction Approaches

BTO's Advanced Building Construction initiative seeks to capitalize on opportunities for substantial energy and cost savings that arise when taking a holistic perspective of building design, construction, and operation.[14] There is substantial untapped potential to expand the market viability, scalability, and adoption of opaque envelope retrofits with new advanced building construction approaches. These approaches could build upon existing methods and knowledge in the buildings sector, or might borrow from diverse engineering disciplines and other technology sectors. In addition, these approaches need not be limited to retrofits; they might also enable higher performance opaque envelopes with lower project prices in new construction. Novel advanced building construction approaches should be developed with consideration for both traditional passive, static opaque envelope technologies, as well as forthcoming novel active, dynamic technologies, though these technology categories might benefit from different advanced building construction approaches given their differences in the level and type of required integration into the building.

Tools, materials, components, and platforms developed for other applications possibly could be directly applied to opaque envelope components, or they might offer insights into how challenges specific to the envelope can be addressed with new approaches. For example, minimally invasive surgical techniques have transformed the practice of surgery, reducing pain, scarring, recovery time, and other risks to patients. Minimally invasive methods could similarly transform the cost, market acceptability, quality, and performance of opaque envelope retrofits. A wide range of advanced manufacturing methods might be relevant to buildings, including advanced robotics, automation, and lean production methods. Manufacturing methods that reduce the complexity and cost of customization could be particularly relevant for retrofits because of the wide variation in facade configurations between buildings. Additive manufacturing ("3D printing") is a method well suited to customization for project-specific parts, unique geometries that are difficult to fabricate using traditional manufacturing methods, and components or molds that do not need to be replicated many times. Additive

[14] See: https://www.energy.gov/eere/buildings/what-advanced-building-construction-initiative.

manufacturing for buildings-related applications is often first thought to be a method for the direct deposition of material to build up whole envelopes, as in ORNL's Additive Manufacturing Integrated Energy (AMIE) technology [69]; however, additive manufacturing might have greater impact in envelope component applications, such as forms for precast concrete facade sections, as shown in Figure 4-1. These forms can increase the quality of facade sections [70], which could contribute to reducing infiltration for finished facades both in retrofits and new construction. Printed molds might also enable more complex form geometries, which could provide more effective passive shading to reduce solar heat gain through windows and increase the appeal of facade retrofits. Direct deposition of novel materials that incorporate multiple functionalities—such as low-thermal-conductivity structural materials that also manage air and moisture transport—could help justify the additional cost of additive manufacturing compared to traditional on-site construction methods while also offering the potential for higher dimensional precision than traditional methods.

The continued advancement of computer vision hardware and image processing algorithms for manufacturing and various software applications could be applied to data collection for retrofits by simplifying dimensioning for retrofit parts. There are likely many additional areas where computer vision, image processing, or additive manufacturing can be used, particularly for envelope retrofits where building-specific customization adds substantial cost and risk. Further work is needed to identify envelope energy savings opportunities that are feasible with currently available products as well as to identify areas where novel materials, software tools, or printing capabilities would facilitate additional energy efficiency improvements for building envelopes.

Figure 4-1: Additive manufacturing has been demonstrated successfully for precast concrete forms of building facades. Avenues to employ advanced manufacturing techniques, such as additive manufacturing, for energy-efficient building envelope components merit additional investigation. (ORNL/Diana Hun)

In addition to image processing, other software and computational methods used in other industries could enable component, subsystem, and whole-building designs that improve energy efficiency. At the component level, topology optimization could be applied to some envelope components [71]. In general, topology optimization describes a method used to identify the optimal geometry for a structural component subject to specific loads, while minimizing weight and/or the material required. Parts developed using topology optimization have found applications in high-value-added products where weight and structural performance are critical, such as aircraft and spacecraft. A similar approach could be used for factory-made envelope components that encounter high structural loads, where the geometry could be optimized to reduce thermal transport while meeting structural requirements, such as the work of Lee et al. [72] applying topology optimization for curtain wall mullions.

For whole-building and subsystem design, artificial intelligence—including machine learning—might find applications. Machine learning generally performs well when rigid heuristic-based approaches are inappropriate or intractable. Though machine learning can be extremely expensive to apply to any single project, high-volume decisions or design actions that are relatively repetitive but require extensive labor effort could be initial areas where machine learning might offer cost reduction opportunities. Machine learning might also be appropriate in providing actionable design decision guidance, particularly with respect to incorporating a systems-level approach into design workflows. Although the underlying building energy models determine the energy savings potential and thus the primary project tradeoffs between investing in energy-efficient envelope technologies versus larger HVAC systems, machine learning could provide users with information about novel technology options, including automatically investigating alternative envelope design approaches to improve efficiency and performance while simultaneously meeting other envelope performance requirements.

These capabilities would be particularly valuable for smaller firms that traditionally do not have adequate resources to adopt more sophisticated and novel high-performance materials by increasing awareness of these technologies while mitigating risk. Traditional optimization methods could conceivably be used to develop a multi-objective problem formulation for envelope and dependent subsystem design, but the scale of the problem makes an explicit formulation intractable and computational expense would likely be unacceptable. Throughout the project design process, there might be similar opportunities to increase the adoption of energy-efficient envelope components and designs using artificial intelligence methods. Applications of artificial intelligence in building design and construction are currently being explored, though not generally with the aim of increasing envelope performance or building energy efficiency more generally; further work is needed to identify these specific opportunities and evaluate their feasibility.

4.2 Grid-interactive Efficient Buildings

In line with BTO's focus on energy efficiency, goals for opaque envelope technologies have historically included aggregate metrics such as national energy savings, reducing end-use intensity, and driving down prices. A limitation of these energy savings metrics is that they do not distinguish the varying value of energy; energy used at different times and locations will vary in price and impacts according to the fuel used, market structures, and technological constraints. These differences are particularly pronounced in the electricity system, where supply must balance demand instantaneously at every moment in time. In order to better address this varying value of energy savings across time and space and to technologically prepare for a future of closely coordinated building and grid operations, BTO is developing a new strategy for GEBs, which complements the office's continuing focus on energy efficiency. The GEB strategy includes both connected and controllable technologies that might reduce electricity use at times when energy is more costly or impactful, as well nonconnected technologies that increase the capacity of the building to alter operations.

To help inform the building research community, BTO has published a series of technical reports that discuss its GEB strategy and evaluate opportunities for GEBs [62], [73]–[76]. The *Overview of Research Challenges and Gaps* report [73] serves as an introduction to these technical reports and is intended to provide background on core concepts related to GEBs. It addresses how flexible building loads can be integrated and controlled to benefit consumers, the electric grid, and society more broadly. The *Windows and Opaque Envelope* GEB report details the technology opportunities and R&D opportunities specifically relevant to providing demand-side flexibility with windows and opaque envelope technologies [62]. Complementing the GEB reports, the following subsections discuss the mechanisms by which buildings can provide demand flexibility that is beneficial to the electric grid and the relevance of passive and active opaque envelope technologies to electric grid operations.

4.2.1 Grid Operations and GEB Potential

Infrastructure in the United States related to electricity generation, transmission, and distribution is complex and requires engineers and managers to forecast, coordinate, plan, and communicate grid operations at all times throughout the year. In some areas of the country, variable renewable energy (VRE) sources have become a significant proportion of the generation mix. For example, in 2016 California produced nearly 17% of its utility-scale electricity from VRE [77], but it is estimated that when distributed VRE sources are included (such as rooftop solar PV), VRE actually accounted for 21% of the state's electricity production [78]. This scale of VRE creates additional complexities in managing the electrical grid, because now both electricity demand and VRE supply must be forecast and balanced. VRE output depends heavily upon weather conditions. Furthermore, when VRE sources are not owned by utilities, forecasting can be difficult, because the size, location, and even existence of these systems is not always known, although they will impact the demand profile seen by the grid operator.

With the complexity and uncertainty of VRE generation, grid operators need additional control options as well as improved forecasting capabilities. Traditionally, the electric grid has been built to handle the highest potential electricity demand that the system might experience, plus a factor of safety. In a high-VRE scenario, continuing to overbuild generation, transmission, and distribution infrastructure is one option for improving grid reliability, as is installing grid-scale energy storage. These infrastructure build-outs, however, are exorbitantly expensive. An alternate approach is to coordinate electricity demand to smooth peaks and align with available VRE, which would require less capital infrastructure investment. In this regard, buildings can potentially play a significant role. In the United States, the commercial and residential building sectors comprise approximately 75% of electricity demand [1], so changes to buildings' electricity demand characteristics are significant to the entire electricity demand profile.

Energy efficiency and demand response are the most mature and established demand flexibility programs for buildings. In addition to overall energy savings, efficiency plays an important role in supporting grid reliability by decreasing peak demand and easing strain on the transmission and distribution system. Demand response is the main form of demand flexibility used today, 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.

Beyond demand response, building envelope technologies are able to engage directly in electricity capacity markets. Two independent system operators (ISOs) that operate electricity capacity markets allow the bidding of energy efficiency measures into the market, including building shell upgrades such as improved insulation [79]. Capacity markets exist in some, but not all deregulated electricity markets as a contingency, so that grid operators can ensure that sufficient electrical generation capacity exists. For both ISO-NE and PJM, capacity resources bid three years in advance and can be either demand-side resources or electricity generators. In ISO-NE's auction for 2016, 4.25% of the total capacity market was energy efficiency, and another 3.3% of the capacity market was comprised of demand response and distributed generation. In PJM's 2016–2017 auction, energy efficiency was a much smaller contribution, comprising 0.64% of the capacity, with other demand-side resources comprising another 7.3% of the capacity market. Although the study reporting on these capacity market advancements [79] did not provide a breakdown of the specific energy efficiency measures being bid into the markets, it is likely that most of the demand response and a portion of the energy efficiency markets are dependent upon envelope upgrades. During an internal ISO-NE audit of energy efficiency capacity performance, energy efficiency savings were found to be much more reliable than any other capacity market product, providing 120% of what was bid in summer months (and even more in winter months). Demand response resources came in second with an availability 95.3% of what was bid. In contrast, supply-side generation is assumed to have 94.1% availability and peaking plants 80% availability [79]. With several years of participation in electricity markets, system operators are gaining confidence that energy efficiency and demand response resources are real and reliable for capacity markets. Because building envelope components can potentially bid as energy efficiency resources as well as enhance demand response capabilities when coupled with advanced HVAC control, remuneration from electricity markets provides an additional quantifiable value for opaque envelope retrofits.

4.2.2 Passive Opaque Envelope Technologies

In general, passive opaque envelope technologies increase building shell thermal resistance to heat flow, reflect solar energy, increase thermal mass, or shade building envelope components [80]. These passive technologies not only reduce the total energy demand of a building by reducing heating and cooling loads, but can also reduce daily and annual peak energy demand, because these peak periods typically coincide with the timing of peak thermal loads. These performance improvements can benefit the grid by potentially deferring generation, transmission, and distribution system expansion. Improving the thermal shell of the building might also increase the building's capacity to perform load shedding or shifting. As discussed in Section 4.2.4, improved opaque envelope performance can also increase the capacity of the building to respond to grid requests or periods of high electricity prices, because a well-insulated building can "coast" longer without running HVAC equipment and still maintain thermal comfort. In some areas of the country, electrification might shift annual peaks from summer to winter; passive envelope technologies improve performance in both cooling and heating seasons. Sections 3.1 and 3.3 discuss in detail novel technologies that can deliver these benefits.

Passive envelope technologies face a notable limitation in that the ambient and internal conditions under which they operate change continuously. Simply increasing the level of insulation around a building will not always lead to lower energy use at all points in time. Researchers at Oak Ridge National Laboratory performed an analysis on single-family detached homes in two climate zones for various levels of insulation.[15] The "typical" building had equipment upgraded to 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. The results for the average power consumption during a typical cooling season (June 12–September 17) are shown in Figure 4-2. The analysis showed that as the cooling demand peaked during the day, the power consumption for the high-performance house ranged from 20% to 43% below that of the typical house during peak hours.

Several other studies have estimated the impact of building envelope improvements on peak energy demand. Two simulations in Hong Kong, a notoriously hot and humid climate, estimate energy savings at the annual peak between 37% and 47% from passive envelope measures [81], [82]. In a study in Greece, external awnings shading the building were found to reduce the cooling load of the building by 30% [83]. Although such savings would not be replicable in all U.S. climate zones and would vary by building and based on the envelope measures selected, these studies illustrate the value from improving thermal shells, even in cases where HVAC controls are not grid-responsive.

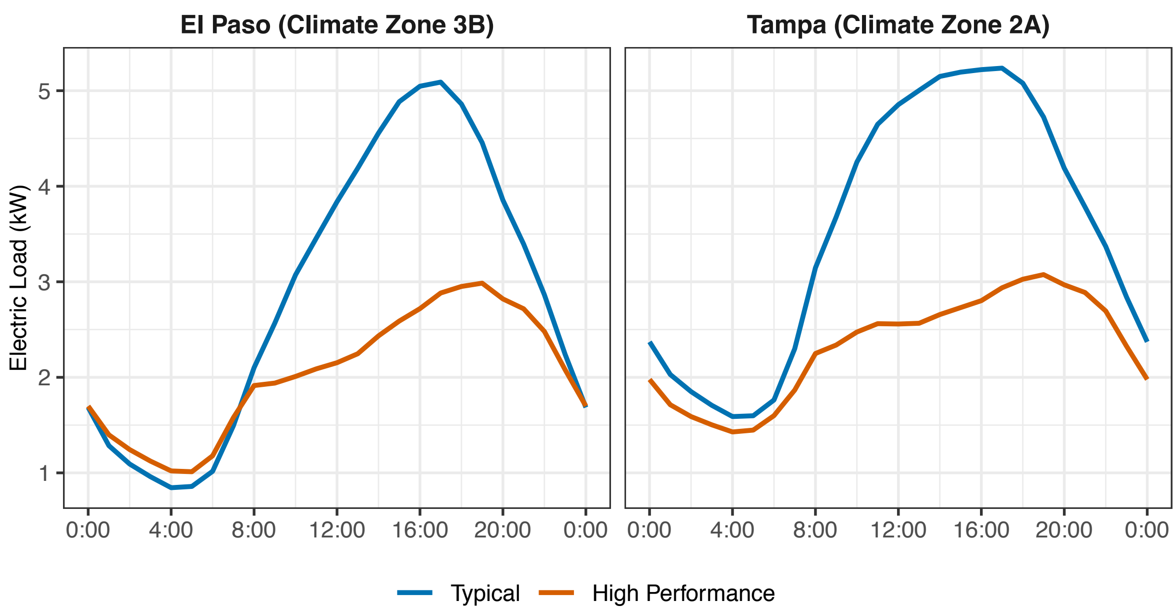

Figure 4-2: Simulation of a residential single-family detached home with varying levels of insulation reveals that increasing insulation (compared to IECC 2012 code levels) yields reductions in electricity demand throughout the peak period.

Although passive envelope measures can yield benefits for the grid without any alteration of building operation, coupling envelope improvements with control systems can further reduce grid impacts from the building and potentially decrease electricity costs by utilizing the building mass for thermal storage. Building thermal mass storage has the potential to provide significant flexibility to the electricity grid, because 63% of building energy demand and 39% of building electricity demand is for thermal end uses [84], [85].

[15] This Oak Ridge National Laboratory research was conducted for the purposes of this report, and the results are not currently published elsewhere.

Furthermore, active management of thermal energy in buildings is reported to be the most cost-effective form of demand-side management [86].

The best-known and most widely researched among thermal energy storage technologies that enhance or augment thermal mass are PCMs, which store energy as latent heat, often at rates many times greater than conventional materials. Currently, PCM transition temperatures are fixed, but thermal management techniques such as preheating or precooling can leverage the energy storage capabilities of PCMs. A study of using PCMs in combination with precooling in a hot desert climate found that energy costs were reduced by 29% by avoiding a peak time-of-use tariff by shifting 99% of cooling-related energy to off-peak times [87]. Another study found that enhancing insulation or gypsum board with PCMs could reduce cooling loads by 25% and 20%, respectively [88]. A study in the United Kingdom found that PCMs could reduce heating demand by 57% in the winter [89]. Another simulation study across three climate zones found that PCMs could reduce peak demand between 4% and 64%, depending on external weather conditions [90]. The high variability of these savings indicates the difficulty in estimating the value of envelope-related technologies at points of high demand; peak reduction and total energy savings are highly context-dependent. The International Energy Agency's Annex 23 developed a best practices guide for the incorporation of PCMs into buildings [91]. Section 3.5 discusses future research needs related to PCMs and other thermal storage materials.

4.2.3 Active, Dynamic Opaque Envelope Technologies

Dynamic envelope technologies could provide grid-responsive capability beyond that offered by passive technologies through active modification of the heat and mass transfer properties of the opaque envelope. 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 between the dynamic envelope components and the HVAC system is likely to yield the largest potential response and the greatest control over the response from any individual building. Multiple technologies could be developed to provide active heat and/or mass transport control through the building envelope. Extensive discussion of the R&D opportunities for these technologies can be found in Sections 3.4, 3.5, and 3.6 and in the *Windows and Opaque Envelope* GEB report [62].

While the development of novel dynamic opaque envelope technologies is key to the opaque envelope delivering the aforementioned benefits, other changes are needed to operate those technologies and maximize their benefits to the grid and building owner. Hardware and software that can deliver coordinated control of glazing systems and attachments, dynamic opaque envelope components, and HVAC systems, all of which influence heating and cooling energy use, should help maximize electricity use reductions at critical times. The hardware and software that control dynamic building technologies also require information from an external entity to determine how to operate those technologies. Although real-time electricity market prices could be used as a proxy for system needs, it is possible that other data streams would be better suited to indicating to building control systems the magnitude of electricity demand adjustment needed, the expected duration of the request, and the timing of the request (if in advance). Further, methods must be developed to determine the value of flexible operations from buildings, and infrastructure must be put in place to ensure that available remuneration is passed on to the building owner. Regulatory structures and requirements might require revisions to allow for buildings to deliver substantial flexibility that benefits utility and system operations, and receive corresponding remuneration. These enabling developments are discussed further in the *Overview of Research Challenges and Gaps* report [73] and the *Windows and Opaque Envelope* GEB report [62]. Forthcoming publications supported by BTO will also address valuation in greater detail.

4.2.4 Co-Benefit of High-Performance Opaque Envelope Technologies: Energy Resilience

Energy resilience describes the ability of building systems to predict and prepare for, withstand, recover rapidly from, and adapt to adverse events that effect the delivery of energy-based services such as heating, cooling, lighting, refrigeration and other energy-related systems. High-performance building envelopes reduce heating and cooling energy use, and thus can help reduce the strain on the grid and the likelihood of a dangerous outage. In the same way, efficient building envelopes can support microgrids by reducing heating and cooling requirements, thus providing increased flexibility in HVAC equipment operation. High-performance building envelopes can also increase the time from when an interruption occurs to when the building becomes uninhabitable because of temperature conditions. Figures 13 and 14 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 compared to a typical building, 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 impacts of static high-performance building envelopes on resilience can vary by climate zone and season. Energy efficiency and load flexibility can impact building energy resilience in both complementary and conflicting ways. As such, the interactions between efficiency, flexibility, and energy resilience must be considered holistically.

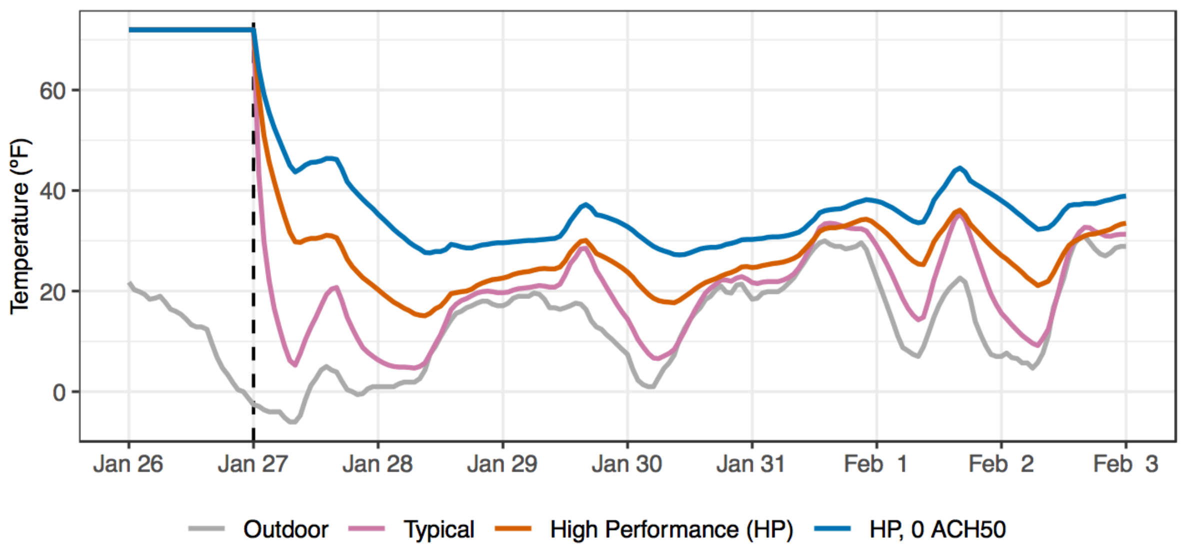

Figure 4-3: Indoor temperature trends compared to the ambient temperature for a single-family detached home with varying building envelope performance levels following a utility service outage modeled on January 27. As envelope performance increases, interior temperatures remain higher and more stable, even several days after service ceases. (Figure derived from Oak Ridge National Laboratory analysis [62].)

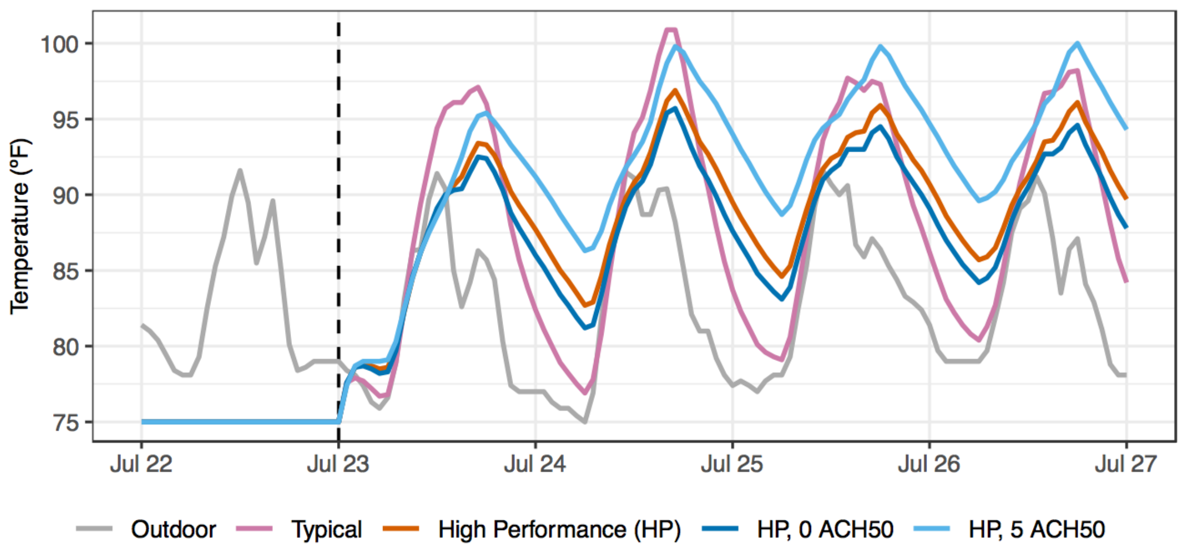

Figure 4-4: Indoor temperature trends compared to the ambient temperature for a single-family detached home with varying building envelope performance levels following a utility service outage modeled on July 23. As envelope performance increases, interior temperatures become somewhat more stable and peak temperatures are reduced, but minimum temperatures increase, because the building is less coupled with ambient temperature trends—both unfavorable and favorable. (Figure derived from Oak Ridge National Laboratory analysis [62].)

5 Implementation

To realize the energy savings potential of novel technologies developed for the opaque envelope, these technologies must be brought to market by companies that can market, sell, distribute, and support them. For technologies that involve fundamental changes in design or construction practices, even if those changes ultimately reduce labor effort, complexity, or total installed price, significant effort might be required to bring these changes to market. Technologies that can be used as drop-in replacements for existing components, materials, or systems might have a lower barrier to market entry, as they fit in an existing market segment; however, these technologies must still be taken from mid-stage development to a commercial product by resolving technical risks related to volume production, developing an appropriate go-to-market strategy, and investing in adequate marketing, sales, and distribution channels to reach the targeted market(s).

In general, DOE and BTO seek to invest in technologies that are early in their development and present technical or other risks that might preclude early private-sector investment, but have the potential to transition, as early as possible, to private-sector R&D funds and ultimately to commercialization by a private-sector entity. To that end, BTO seeks to lower barriers to and accelerate the timing of private sector investment, commercialization, and scale-up. There are two primary types of barriers to BTO's R&D transition and long-term energy savings objectives—technology development and commercialization barriers as well as market adoption barriers. Technology development and commercialization barriers can include access to appropriate technology testing, validation, and demonstration capabilities; the cost and structure of capital and access to capital; expertise in manufacturing, particularly when new techniques must be developed; and an adequate understanding of building industry and end customer needs, willingness to pay, and appropriate sales channels. Market adoption barriers include building owners' access to capital and awareness of novel technologies, market valuation of envelope upgrades and ease of capital recovery, confidence in energy savings estimates for envelope upgrades, and building construction industry practices that affect prices and installation quality. Many of these barriers are outside of BTO's purview, but might affect buildings technology adoption regardless. These barriers are collectively synergistic, because factors that act to inhibit market adoption of novel energy efficiency technologies create an environment in which equipment manufacturers are reluctant to pursue development of those novel technologies for fear that they will not be able to recover their costs through revenue from product sales.

5.1 Technology Development Pathway

To ultimately achieve the energy savings from novel opaque envelope component and system R&D discussed in this report, early-stage, high-risk projects must transition to private-sector R&D and ultimately to commercialization. R&D projects funded by BTO are structured to promote private-sector transitions as early as possible. In general, private-sector capital for R&D competes with other potential uses of that capital that can deliver shareholder value. Long-term potential market impact derived from R&D successes presents investment risk; therefore, the overall risk profile of any R&D project, as well as the risk presented by projects within a BTO subprogram research portfolio, should be minimized aggressively as early as is practicable. Projects should be designed particularly to reduce schedule and labor effort (time-to-market) and technical risks. Ideally, upon project completion or final investment from BTO, the remaining effort primarily involves scaling well-understood and well-characterized materials and underlying phenomena. Material synthesis and product form factors should be compatible with existing traditional manufacturing methods as much as is practicable—ideally relying on methods that have relatively low initial capital costs, which will reduce the total capital exposure (before first sale) for a private-sector entity. BTO-funded work might still involve some investigation of manufacturing methods or scale-up, where again the focus is on novel processes or practices, particularly where they have the potential to reduce the capital or operating costs of volume manufacturing.

Supporting systems (e.g., software; application programming interfaces, protocols and standards; modeling) can also be critical areas for BTO investment when they enable R&D, manufacturing, or adoption of novel opaque envelope technologies. Regardless of the scope, projects should incorporate industry engagement as much as possible to ensure private-sector relevance upon completion; this work might include input from product manufacturers as well as other building industry entities (e.g., component manufacturers, vendors and sales channel partners, architects, contractors, and installers). In some cases, input from these other entities might have greater impact on R&D project relevance than direct input from potential manufacturers. Input from these entities should flesh out the value proposition of the eventual functionalities or capabilities offered by a project to build the case for private-sector offtake.

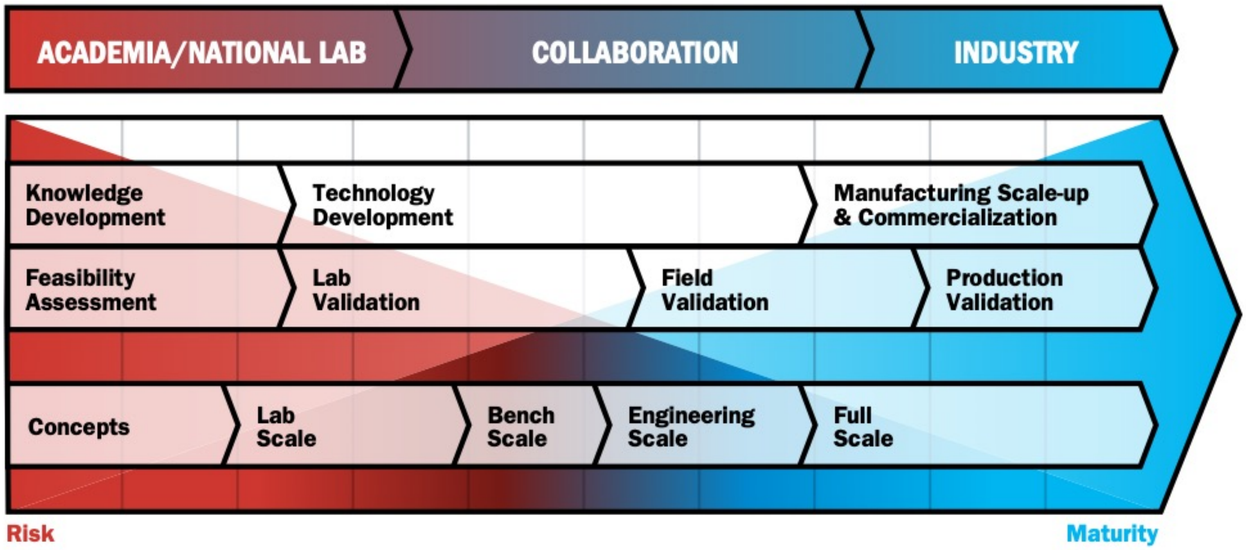

Figure 5-1: As R&D progresses from initial concepts and principles to development and ultimately to commercialization, risk decreases and technology maturity increases. In addition, the players involved in the work transition from academia and research labs toward increasing involvement and investment from industry. The smooth, linear representation of R&D and gradually decreasing risk shown in this figure belies the uncertainty and complexity inherent in high-impact R&D; novel technology development is highly nonlinear.

Researchers can leverage existing resources and industry knowledge to accelerate private-sector offtake of R&D efforts. Figure 5-1 illustrates the technology commercialization process; throughout this process, researchers can pursue actions to accelerate the transition to the private sector. For university and national lab researchers, institutional technology transfer offices or teams might offer resources for collaborating with industry or pursuing a spin-off as a new venture. These offices might also be able to connect researchers with nontraditional sources of capital to support R&D that can further de-risk technologies, amplifying federal investment and improving suitability for offtake by manufacturers. Researchers should investigate building industry pain points related to the envelope and seek to align their projects to strategies that can address those points. Researchers should also explore established sales channels and typical market dynamics for their targeted application areas such that they understand the value proposition of existing products and other product attributes that might be valued by customers and channel partners.

The building construction and products industry in the United States is a mature market that has been slow to change and adopt new practices and materials. Productivity in the buildings sector has remained persistently low, even as other industries have dramatically increased their productivity in the past few decades [92], [93]. Building construction sector R&D investment hovers around 0.5% of the total market [92], which lags behind typical investment rates in most other sectors, particularly those with high levels of innovation [92]. Even with increased federal R&D investment in building technologies in recent years, broader industry investment has remained low [92], [94]. Given these conditions, business model or business practice innovation—possibly in concert with the deployment of novel technology developments—might have a larger effect on market transformation than from the development of novel technologies alone. In the solar PV market, novel financing models enabled broader access to distributed rooftop solar, which when coupled with component and business practice innovations, significantly reduced the total installed price of distributed solar PV systems. Replicating this success might not be as readily achieved for building envelope improvements or upgrades, as these changes, even those that have an aesthetic element, are not perceived as "advanced technology" [95]. However, in general, the buildings industry presents significant low-hanging fruit with respect to driving novel technology adoption through system and business process and practice innovation.

5.2 Facilitating Technology Adoption with Market Transformation Partners

Once high-performance, energy-efficient opaque envelope technologies are made commercially available, they must generally achieve market adoption at scale to create sufficient demand to minimize production costs and maximize profitability. Prevailing construction and building retrofit market conditions and adjacent factors can create significant barriers to technology uptake. These barriers can be financial—such as adequate access to capital and appropriate financing mechanisms; knowledge-related—such as awareness of correct installation practices for novel technologies among contractors and installers; or implementation-related—including the extended disruption of the building and its occupants caused by many envelope upgrades. These barriers can be reduced or circumvented through a range of voluntary actions, marketing and information sharing strategies, and policy interventions, including many initiatives that are currently being explored or tested.

5.2.1 Financing

Product prices, available financing mechanisms and their costs, and an absence of appropriate market valuation for energy efficiency upgrades all present financial barriers to the adoption of high-performance opaque envelope technologies. As with most new technologies, new energy-efficient envelope technologies are likely to have high prices at market introduction. High capital costs might limit demand and thus hinder the business justification for manufacturing at scale, which is typically needed to reduce unit costs and therefore, in principle, the price faced by consumers.[16] For all building types, market valuation typically does not reflect energy efficiency-related upgrades. The appraisal process generally does not capture energy performance or efficiency upgrades, which has a downstream effect on building valuation and therefore mortgage lending and capital recovery from upgrades [96], [97]. This problem might be compounded for opaque envelope upgrades, which are often not observable by visual inspection and can only be accounted for with pre- and post-upgrade utility bills, energy audit results, or documentation of the work as it was being performed.

Today, these connections to real estate market value improvements have not been established. On top of the limited valuation of these upgrades, in the residential sector, consumers face comparatively high interest rates for energy efficiency improvement loans [95]. Consumers might be unable or unwilling to take on moderate-interest debt to finance energy efficiency upgrades, particularly because they are often dubious about the true energy savings potential of upgrades, and thus are unsure whether they can expect to be net cash positive following upgrades [95], [98]. In spite of these financing challenges, residential [95] and commercial [96] properties with higher energy performance have lower default rates. Though these data show that energy performance can reduce risks for private capital, accounting for these efficiency upgrades does not appear to be widespread among lenders.

The significant recent developments in business models and associated financing mechanisms for residential rooftop solar have increased interest in developing novel financing mechanisms for building energy efficiency investments—particularly in the retrofit market. These novel financing mechanisms reduce customer acquisition costs, increase quality and customer confidence in the finished product, and lower capital barriers—particularly for residential customers. Across both residential and commercial sectors, many of these financing mechanisms can also provide an avenue for cost recovery from tenants, thus addressing split incentives (i.e., the "landlord-tenant problem"). Property-assessed clean energy (PACE) programs were developed to alleviate the capital burden of energy efficiency retrofits. PACE ties financing for retrofits to the property, which can then be transferred to subsequent owners if the upgrading owner does not retain the property long enough to repay the loan [99]. Recent challenges with the execution of residential PACE programs can be remedied in part through careful program design and oversight [99]. Commercial PACE programs can also benefit from thoughtful program structure and lessons learned from residential PACE programs [100].

[16] For envelope-related upgrades, it is not clear if project prices faced by consumers, especially in the residential sector, are consistent with costs.

Direct and indirect financial incentives available from municipalities and utilities can be incorporated as part of the valuation of prospective upgrades. In many cases, these programs offer incentives for specific upgrades based on the total energy savings or emissions reduction impact of individual upgrades across a region or operating territory. More comprehensive upgrades appropriate for an individual building, particularly envelope component upgrades, often have limited overlap with available incentives. As a result, building owners frequently eschew the systems-level retrofit strategy discussed in Section 4.1 in favor of approaches that minimize capital costs and only include individual upgrades that align with available incentives.

Building-specific retrofit solutions supported by detailed energy models can benefit the residential and commercial markets, where the modeling results are used to determine guaranteed energy savings, and financing can be developed around those savings [95]. This approach is similar to that used in residential rooftop solar financing. Particularly for the residential sector, these packages can also incorporate warranties and maintenance contracts that help engender homeowner confidence in installation quality and reduce the maintenance effort for the homeowner [95]. Third-party entities might emerge to execute *and* finance these packages, as has occurred in the solar industry, because the guaranteed energy savings derived from the energy modeling used for project selection and customization might enable securitization, creating new energy efficiency investment vehicles. These upgrades could also be financed through an energy savings performance contract executed by an energy service company, where the energy service company amortizes the efficiency upgrades against the anticipated energy savings [101]. Regardless of the financing instrument, incorporating energy efficiency upgrades into property appraisals would ensure that those upgrades are perceived by buyers as comparable to aesthetic upgrades, and would enable efficiency upgrades with long payback periods to be explicitly captured in the value of the property, thus enabling capital recovery at the time of sale. Incorporating energy expenditure risk assessment into mortgage underwriting could also help improve the ability of owners to absorb the cost of efficiency upgrades.

5.2.2 Buildings Market Awareness

For novel high-performance envelope technologies, particularly those that are not drop-in replacements for existing envelope components or technologies and are identical in both function *and* form, lack of awareness and understanding of new technologies can lead to additional barriers to market uptake. If building owners are to pursue energy-efficient envelope components and assemblies, they must be aware of the relevant technologies and knowledgeable about the energy benefits available from those technologies. When high-performance envelope technologies are new to the market, the potential information gap among building owners is particularly acute. Excluding large real estate holding companies that have staff who can remain abreast of newly commercialized advanced building technologies, building owners are likely unable to invest the requisite time to fully understand high-performance enclosure elements and how any novel technologies might further improve energy performance.

Information asymmetry faced by building owners/consumers and by architects, engineers, contractors, and installers can be addressed by several means, including enhanced labeling and recognition programs, readily accessible data resources, and enhanced training programs for contractors and code enforcement officials. Labeling and recognition programs such as ENERGY STAR® have been shown to affect consumer decisions with regard to product energy efficiency [102]. Labels that use familiar schemes for indicating product energy performance—number of stars out of five, A–F letter grades—have been shown to increase the number of consumers who would select a more efficient product option, even when faced with a price premium for that option [102], [103]. Modifying existing labeling schemes for opaque envelope products might have a similar effect. Labeling and recognition schemes for opaque envelope components and, in particular, assemblies, would also be beneficial for consumers, because these materials and assemblies do not currently have any systematic and objective means by which consumers can compare their performance. Section 5.2.3 discusses the many sources of installation quality variation that make the development of objective and accurate rating schemes for opaque envelope technologies uniquely challenging. Whole-building energy performance evaluated through, for example, Home Energy Score (shown in Figure 5-2), might also provide valuable comparative information for consumers, though these scores do not separately capture window or opaque envelope performance. These scoring systems also do not capture the nonenergy benefits of a high-performance envelope, which might be critical to creating market pull for envelope upgrades.

Energy auditing and disclosure measures enacted in several municipalities can provide information to buyers and prospective tenants regarding energy performance of properties, and therefore might have the potential to influence the resale or rental value of otherwise comparable properties [104]. Providing these data in a form that is readily understood by prospects and in a location that minimizes or eliminates prospects required effort to obtain the data are critical to achieving the desired effect [104]. For commercial buildings, these factors could be addressed by prominently displaying whole-building performance grades based on audit data near the building entrance or, for all building types, providing the relevant score in property search tools [96].

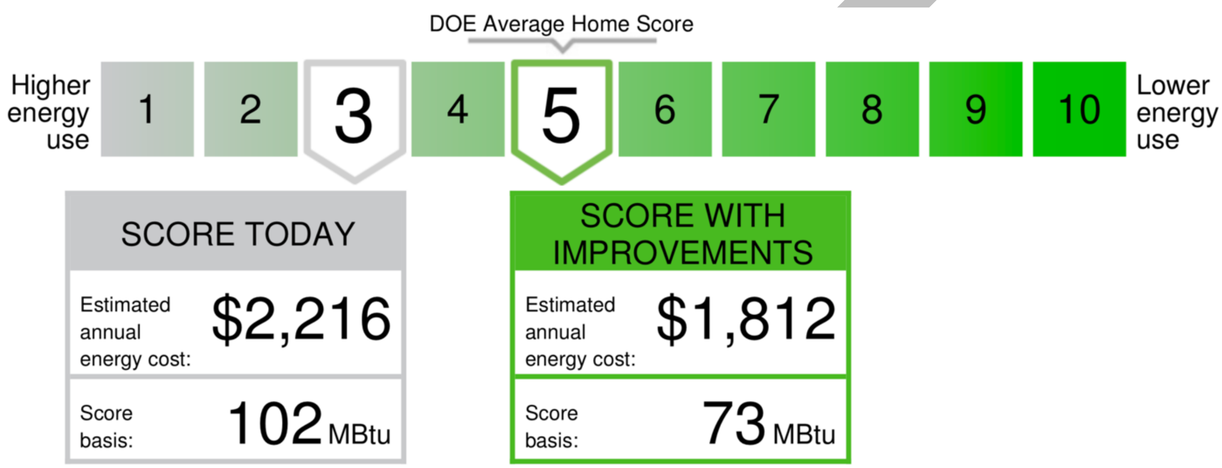

Figure 5-2: Home Energy Score reports can be used to highlight improvement opportunities for homeowners with specific actionable feedback on what retrofits can deliver energy savings, including envelope performance improvements. Similar building performance evaluations for commercial buildings can provide valuable insights to building owners, and disclosure of these data or similar information about building energy performance can also provide useful information to prospective tenants in both the residential and commercial sectors.

In typical retrofits—especially for the opaque envelope—the required teardown and reconstruction of the facade is disruptive for building occupants and might even preclude occupancy, thereby adding significant costs (e.g., lost rents, relocation) for occupants or building owners. Conversely, window and opaque envelope retrofits often provide multiple nonenergy benefits, including improved aesthetics, improved occupant comfort and productivity, and reduced ambient noise intrusion. Although these nonenergy benefits can be accrued with any type of opaque envelope retrofit to some extent, both the energy and nonenergy benefits are larger for higher efficiency retrofits, while the incremental cost of choosing high-performance products is often minimal compared to the overall project cost. Therefore, although nonenergy benefits might drive the building owner to pursue the upgrade, it is critical to inform the owner of the efficiency benefits that will be lost (and likely never regained) by choosing code-minimum materials. The importance of capturing these benefits from specifying a high-performance envelope early in the project decision timeline also applies to new construction.

5.2.3 Buildings Practitioner Awareness

For the building construction industry, improving awareness of novel envelope building technologies could come through a variety of channels. Existing mechanisms for publicizing new products—trade shows and publications, social media, and company websites—continue to be relevant. Additional opportunities to expose building owners and, indirectly, the construction industry, to new technologies might be through energy audits, which could be accompanied by upgrade suggestions that incorporate novel materials and methods when envelope upgrades are appropriate. BTO's integration teams support field studies to validate the performance of innovative opaque envelope products. However, utility and energy efficiency nonprofit case studies might benefit from incorporating nonenergy benefits such as comfort, aesthetics, and effect on property valuation.

These studies could also be used to build confidence among the architecture, engineering, and construction industry in specifying and installing novel products. Field and validation study results will be most impactful if they are made available through channels already regularly accessed by the industry and should be presented such that the results are easily interpreted. These results can also be further supported by simultaneously providing guidance on how to incorporate novel materials into typical construction practices.

Once building owners and building construction industry members are aware of novel, high-performance opaque envelope products, and if they have access to appropriate and acceptable mechanisms for financing potential envelope upgrades, there remain additional practical barriers to the implementation of these novel envelope technologies and assemblies. Because of the complexity and assembled-on-site nature of the opaque envelope, in particular, component manufacturers generally do not provide performance guarantees or otherwise make claims regarding the performance of finished building envelopes that incorporate their products. Different installers might be responsible for different stages of facade assembly and window installation, so no single entity among product manufacturers, contractors, or installers generally takes responsibility for the energy performance of the finished facade. As a result, there can be a significant difference between the specified and as-built performance of the envelope, and at no point during construction will defects that affect energy performance be intentionally identified and corrected.

For contractors and installers to be comfortable with the specification and subsequent installation of novel envelope technologies, they must be aware of the purpose and function of the technology. If the technology must be installed a certain way to achieve its rated performance, additional education of contractors and installers will be required to ensure proper installation. The difficulty of ensuring correct installation, even when manufacturers invest extensively in education, is compounded by the diffuse structure of the construction industry [93]. Labor turnover and variable labor demand for envelope installers also increases the burden for manufacturers attempting to spread information about installation practices for a new technology with requirements that differ from current practice with typical materials [93]. This challenge is an area where modular or factory construction of envelope assemblies, discussed in Section 4.1.2, might reduce the education effort required and thus generally improve in-field performance [93]. Finally, for novel technologies to be specified and installed, code officials and code development bodies must be aware of these technologies, particularly for prescriptive codes that might otherwise exclude technologies that provide envelope functions in novel or nonstandard configurations.

Installation quality can also be improved by incorporating fault-tolerant characteristics into novel opaque envelope technologies, protecting against improper installation and possibly improper system assembly configuration. Although these changes might not explicitly incentivize investment in envelope energy efficiency, by creating conditions by which the building construction industry and building owners and tenants all perceive incentives or value in improving building energy performance, envelope upgrades will be adopted alongside other efficiency measures.

5.3 Stakeholder Engagement in Market Transformation and Technology Transitions

BTO is interested in working with any and all stakeholder organizations and entities that can help accelerate the research, development, deployment, and widespread adoption of novel, high-impact opaque envelope technologies. Different stakeholders can serve different roles in the technology development and market transformation process depending on their constituencies, access to capital, and ability to convene other stakeholders, coordinate with other stakeholders, and directly conduct technology R&D. Table 5-1 includes an array of possible supporting activities for stakeholders.

Table 5-1: Stakeholders that interface with energy efficiency and buildings can help accelerate R&D and the widespread market adoption of innovative, high-performance opaque envelope technologies outlined in this report. Opaque envelope technologies have not always gained attention from energy efficiency advocates; these possible activities are based on general energy efficiency policy strategies and the IEA Envelope Roadmap [105]

Stakeholder	Suggested Supporting Activities
Governments	• Invest in and manage a portfolio of R&D projects composed of the high-priority technology areas identified in Section 3 • Conduct field validation studies of high-performance opaque envelope technologies and validate electric grid economic benefits and remuneration opportunities • Enable energy audit and disclosure ordinances that provide quantitative envelope performance insights to building owners, renters, and lessees • Develop system-level tools that increase the benefit and value of high-performance opaque envelope technologies, possibly including nonenergy benefits • Demonstrate potential by implementing high-performance technologies into their own facilities.
Nonprofits/ nongovernmental organizations	• Convene state and local partners to build knowledge infrastructure around the value of high-performance envelopes • Demonstrate novel building envelope technologies to build manufacturer and consumer awareness of energy savings potential and other benefits • Investigate actions that could increase market demand for innovative opaque envelope technologies.
Manufacturers	• Pursue investment in earlier-stage R&D with federal risk sharing and low TRL offtake • Work with researchers and academia to build capacity around R&D program structure to manage risk and maximize project spinoff or offtake • Establish, in collaboration with partners, system-level benefit sales tools.
Researchers/ academia	• Pursue novel technology and material research in the areas described in Section 3 • Collaborate with manufacturers and industry partners on transitioning research successes from lab-scale to production-ready • Leverage professional societies, trade associations, and nongovernmental organizations to share research findings and follow-on development opportunities.
National laboratories	• Provide advanced component evaluation equipment and facilities that provide enabling capabilities to the opaque envelope industries • Pursue novel technology and material research in the areas described in Section 3 • Collaborate with manufacturers and industry partners on transitioning research successes from lab-scale to production-ready technologies • Conduct comprehensive research on the energy performance and durability of novel high-performance envelope materials and assemblies to build industry confidence • Support nongovernmental organizations, utilities, manufacturers, and others to ensure scientifically rigorous methods are employed in system-level tools and serve as neutral third party for the consumer's interest.
Architects, engineers, and builders	• Expand use of life-cycle costing and work with clients to promote life-cycle costing when evaluating new construction and deep retrofit projects to fully assess system-level benefits • Develop full-value assessments including energy and nonenergy benefits to reduce the likelihood of "value engineering" that results in the downgrading of opaque envelope performance.
Utilities	• Work with local and state partners to identify opportunities for energy efficiency and peak demand reduction • Offer broad-based programs for envelope retrofits (i.e., inclusive of climate-appropriate opaque envelope technologies) • Investigate actions that could increase market demand for innovative opaque envelope technologies.

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Appendix A. Establishing Technology Performance and Price Targets

This appendix outlines the methodology by which technology price and performance targets are established for the opaque envelope technology categories in Section 3. Price and performance targets are based on future impacts calculated using Scout, a software tool that estimates U.S. energy use, carbon dioxide emissions, and operating cost impacts of building energy conservation measures (ECMs).

Approach for Establishing Technology-Level Targets

Prospective technology targets are limited to unit-level total installed price and energy performance. Lifetime, a third key technology parameter, is kept consistent with comparable baseline technologies. In the context of defining these goals, "baseline" refers to the business-as-usual scenario or characteristics of the typical incumbent technology or product. Goals for technology cost and performance at market entry are set through the following process:

- Set the desired market entry year
- Set the segment(s) of baseline energy use to which the technology applies[17]
- Set a desired energy performance value or range for the technology at market entry
- Set a cost-effectiveness threshold for the technology at market entry
- Determine the unit-level installed cost that satisfies the cost-effectiveness threshold, given the above parameter values.

In this report we use total installed price instead of cost (which is used in some other BTO R&D opportunity reports), because of the substantial contribution of installation labor and other costs to the price of opaque envelope technologies experienced by building owners. Given that project price is often identified as a barrier to adoption of high-performance opaque envelope technologies and envelope retrofits more generally, we emphasize the importance of price, not cost, to realizing widespread market adoption.

Scout

Prospective technology definitions corresponding to the technology areas identified in Section 3 were created and assessed using Scout[18], an open-source software tool developed by BTO for estimating the national energy use, carbon dioxide emissions, and operating cost impacts of building-related ECMs [2]. Scout simulates the impact of one or more ECMs on baseline case projections of national building energy use through 2050. Baseline case data are drawn from the EIA Annual Energy Outlook (https://www.eia.gov/outlooks/aeo). ECMs are defined primarily by the segment of baseline energy use they apply to, their market entry and exit years, and their installed price (or cost), energy performance, and lifetime.

Individual ECM energy savings impacts are derived from a unit-level comparison of the ECM's energy performance with that of a comparable baseline case technology. Scout estimates ECM impacts under two different technology adoption scenarios: 1) a technical potential scenario, where an ECM captures its entire applicable baseline energy use segment(s) on market entry and retains a complete sales monopoly in subsequent years, and 2) a maximum adoption potential scenario, where an ECM only captures the portion of its baseline energy segment associated with new construction, equipment replacement/retrofit at end of life or wear out, and a small fraction of elective replacements in advance of end of life. Given a portfolio of ECMs that apply to the same baseline energy use segments, Scout can apportion overlapping segments across

[17] Although goals are communicated at the sector level (residential versus commercial), sector-level goals combine outcomes from all of the major building types that comprise each sector.
[18] Scout is available online at: https://scout.energy.gov.

competing ECMs [106], [107].[19] In addition to overall energy impact, Scout also assesses the cost-effectiveness of individual ECMs under multiple financial metrics.

Baseline data in Scout include energy use, equipment/technology installed stock size, building stock size and growth, and technology cost, performance, and lifetime. These data are mostly derived from the EIA's Annual Energy Outlook. The Annual Energy Outlook data are, in turn, derived from the National Energy Modeling System. For this report, the 2018 Annual Energy Outlook provided most of the required input data apart from technology price and performance.

Baseline technology definitions for the building envelope are derived from a combination of sources. The baseline technology represents the incumbent that would be adopted in the absence of higher-performing alternatives. Total installed prices are derived from RSMeans building construction databases (https://www.rsmeans.com). Technology performance is based on current International Energy Conservation Code and ASHRAE building codes adopted in various regions, accounting for lag in code adoption by state [108] and with a projection applied to future improvements in codes based on trends in technology performance improvements in past code revisions and expert judgment regarding the potential for further technology performance improvements along the current trajectory in the codes.

Opaque Envelope Technology Goal Definitions

Technologies included in the opaque envelope ECM definitions encompass the major technology categories that can be readily captured in Scout—high R/in insulation, air sealing remediation, and dynamic tunable transport materials. The ECMs were applied to both residential and commercial buildings. These ECMs are intentionally defined generically to encompass a wide range of potential technology approaches to achieving the performance and installed price targets for that technology type. Product lifetimes were set equal to the baseline or typical existing technologies for each ECM. Because dynamic tunable transport materials are not currently commercially available, an estimated lifetime of 30 years was selected.

The high R/in insulation targets are separated by major building envelope component—roof, walls, and foundation—because the R/in and overall R-value of these components is not equal in typical buildings. Moreover, different levels of insulation maximize energy savings for different components and in different climate zones. The targets specified are intended to be technology agnostic. One or more approaches might be able to successfully achieve the specified price and performance targets. Other requirements, depending on the application, might impact what technologies are ultimately appropriate. Some of these requirements are described in the Critical Characteristics table in Section 3.1.4.

Air sealing remediation impacts are characterized with four separate ECMs—for new construction and retrofits of residential and commercial buildings. Because air sealing in new buildings is better, in general, than existing buildings, ECMs set up to represent both applications simultaneously will yield price targets that are too high for new construction and lower than necessary for existing buildings (for a given performance level and payback period). It is possible that the same technology might be able to address new and existing buildings, or residential and commercial buildings. Even in these cases, air sealing performance improvements from that technology might vary by application, pre-remediation air leakage, and other factors.

Dynamic, tunable transport materials are a category of technologies that have time-varying energy use-related properties. The time-varying features of these technologies might be able to deliver both peak electricity use reductions and total annual energy use reductions. Peak electricity use reductions, or more generally the ability to modify electricity demand in response to local and regional electric system conditions, could be quite beneficial for utilities and electric system operators. In the absence of a clear mechanism for the valuation of those electric system benefits and evidence that any available value will be passed on as remuneration to the ratepayer, the ECM for these technologies is limited to quantifying total annual envelope energy use reductions. Given that this category encompasses a wide range of technologies, and that ultimately

[19] Based on the technology choice models for residential and commercial buildings used in the National Energy Modeling System.

commercialized systems might incorporate multiple functionalities into a system, the operation of these systems could yield substantial annual energy savings.

Total installed price targets were developed for each ECM based on the performance targets previously articulated. Simple payback was used as the financial metric for this report to establish the goals for each individual technology area, corresponding to a particular ECM. Total installed prices are evaluated for payback periods ranging from 5 to 15 years. These payback periods are significantly shorter than the typical lifetimes of opaque envelope components, but using payback periods comparable to the typical in-service life of opaque envelope components could lead to excessively high prices, which can inhibit adoption. The goals defined for this report are based on the technical potential scenario and do not account for competition between ECMs. As a result, the energy savings are maximized for each ECM, and thus the installed price or installed price premium is maximized, because simple payback is based on operating energy cost savings. These assumptions are consistent with a future in which the technologies articulated in this report are widely adopted. Energy savings from these opaque envelope technologies might be reduced if next-generation, high-performance HVAC technologies are aggressively adopted, because those technologies would reduce heating and cooling energy use that could otherwise be offset by high-performance envelopes. Regardless, advanced opaque envelope technologies will still enable long-term reductions in energy use for existing buildings while improving occupant comfort, health, and productivity.

Limitations

An important limitation of this goal-setting methodology is its reliance on a limited valuation of ECM costs and benefits that is based only on installed price and operating energy cost savings from performance gains. This valuation excludes potential changes in nonenergy operating costs, which are difficult to assess for new-to-market or future technologies. Moreover, this approach excludes other potentially important benefits that are challenging to assess quantitatively, such as improved occupant comfort, employee productivity, or occupant health. In a strictly payback-focused decision frame, these factors cannot be readily included. It is also not clear whether consumers can readily incorporate these nonquantitative factors into their decisions, and without that information, any additional benefits might not merit inclusion in a goal-setting context.

Among the various opaque envelope technologies reflected in this report, many must meet various other performance requirements that might affect or be affected by their energy performance but are not directly captured in Scout ECM definitions. These factors can include code-mandated requirements (e.g., fire performance) or relate to consumer acceptance or market viability (e.g., installation complexity). Though these factors might not directly influence energy performance, they nonetheless remain important to incorporate into a complete assessment of the viability and relevance of novel technology R&D.

The representation of operating cost savings arising from opaque envelope performance improvements in Scout necessarily pools savings across wide swaths of the existing and projected future building stock. As a result, the total installed price or price premium targets reflect a stock-wide average. Although this target is appropriate given BTO's focus on national energy savings (not savings within individual buildings), it obscures the potential for higher-priced technologies to enter the market in existing buildings that have poorly performing envelopes. These buildings could see much larger energy savings than are reflected in the Scout analysis, and if simple payback is an appropriate metric for a given project, the total installed price for envelope retrofits could be much higher than this report's target while still realizing a customer-acceptable payback period.

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