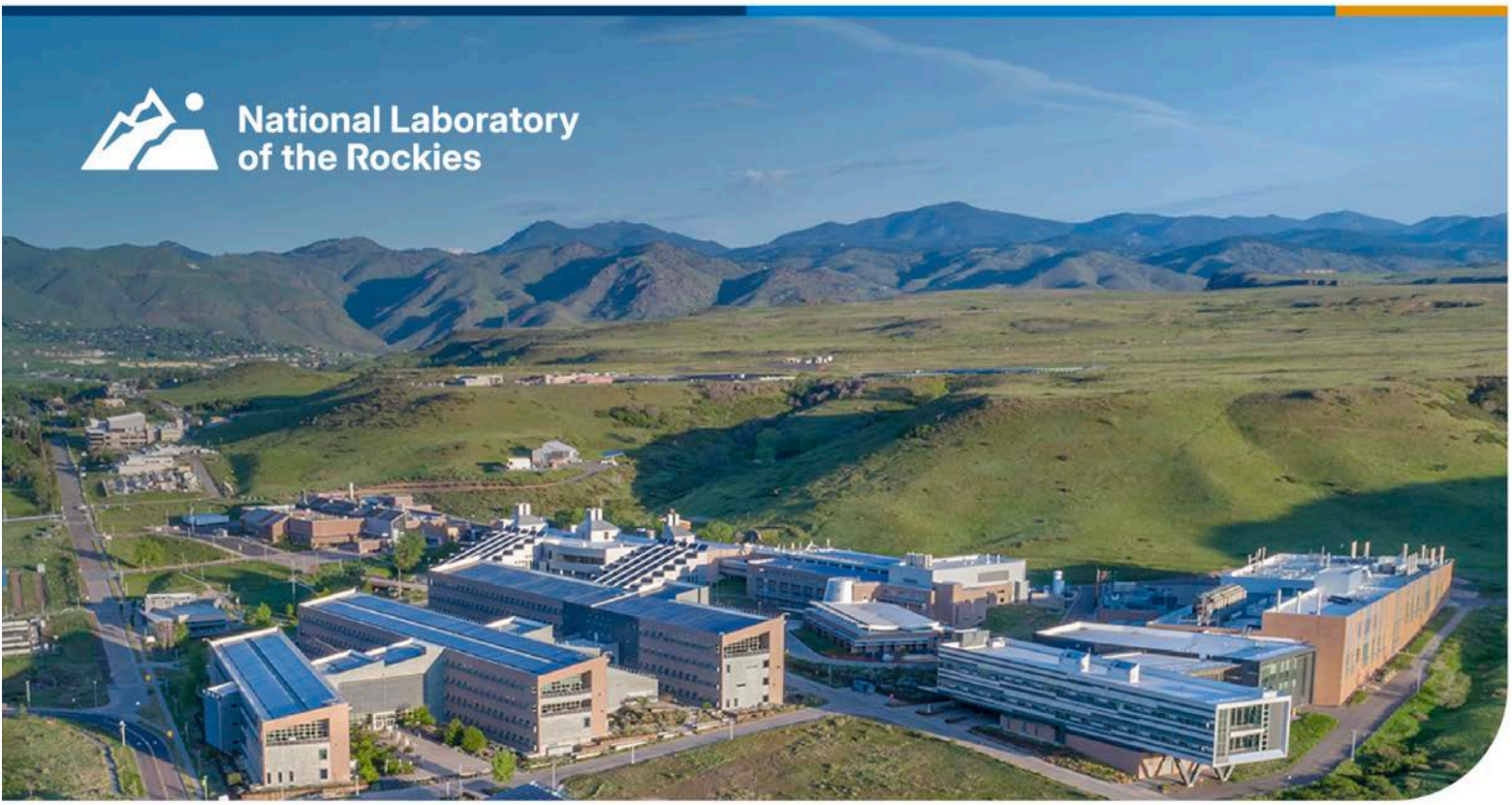

Market Analysis of Technology Development Trends for Building Envelope Retrofits

Katie McMahon, and Jack Mayernik

National Laboratory of the Rockies

The National Laboratory of the Rockies is a national laboratory of the U.S. Department of Energy, Office of Critical Minerals and Energy Innovation, operated under Contract No. DE-AC36-08GO28308.

This report is available at no cost from the National Laboratory of the Rockies (NLR) at www.nlr.gov/publications.

Technical Report
NLR/TP-6A20-97680
September 2026

National Laboratory of the Rockies

Market Analysis of Technology Development Trends for Building Envelope Retrofits

Katie McMahon, and Jack Mayernik

Suggested Citation
McMahon, Katie and Jack Mayernik. 2026. *Market Analysis of Technology Development Trends for Building Envelope Retrofits*. Golden, CO: National Laboratory of the Rockies. NLR/TP-6A20-97680. https://www.nlr.gov/docs/fy26osti/97680.pdf.

The National Laboratory of the Rockies is a national laboratory of the U.S. Department of Energy, Office of Critical Minerals and Energy Innovation, operated under Contract No. DE-AC36-08GO28308.

This report is available at no cost from the National Laboratory of the Rockies (NLR) at www.nlr.gov/publications.

Technical Report
NLR/TP-6A20-97680
September 2026

National Laboratory of the Rockies
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nlr.gov

NOTICE

This work was authored in part by the National Laboratory of the Rockies for the U.S. Department of Energy (DOE), operated under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Critical Minerals and Energy Innovation Building Technologies Office. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government.

This report is available at no cost from the National Laboratory of the Rockies (NLR) at www.nlr.gov/publications.

U.S. Department of Energy (DOE) reports produced after 1991 and a growing number of pre-1991 documents are available free via www.OSTI.gov.

Cover photo: Josh Bauer, National Laboratory of the Rockies 061725.

The National Laboratory of the Rockies prints on paper that contains recycled content.

Acknowledgments

The authors of this report are grateful for funding from the U.S. Department of Energy's Building Technologies Office. The authors specifically thank the following for their support, expertise and contributions: Nicholas Ryan & Cecilia Johnson. We also thank the following National Laboratory of the Rockies staff for their review and edits: Daniel Bilello, Chuck Booten, Jaquelin Cochran, Jeff Cook, Michael Deneen, Patrick Gibbs, Achilles Karagiozis, Stacey Rothgeb, Robert Tenent & Judith Vidal.

This report is available at no cost from the National Laboratory of the Rockies (NLR) at www.nlr.gov/publications.

List of Acronyms

ACH-50	air changes per hour at 50 pascals
ETCB	Emerging Technologies Collaborative for Buildings
HVAC	heating, ventilating, and air conditioning
IECC	International Energy Conservation Code
PCM	phase change material
TRL	technology readiness level

This report is available at no cost from the National Laboratory of the Rockies (NLR) at www.nlr.gov/publications.

Executive Summary

This report provides an assessment of the current state of building envelope retrofit technology development. A wholistic market overview examining workforce, technology, and economic trends—as well as technical, social, and financial barriers—is bolstered by a survey of past, present, and future trends related to specific technologies, as well as overall trends in the retrofit market. We present long-term market outcome metrics, which capture changes in the effectiveness and efficacy of research and development investments, along with estimates of historic rates of change. Finally, we present the current outlook for the building retrofit market, technology development, and workforce.

This report is available at no cost from the National Laboratory of the Rockies (NLR) at www.nlr.gov/publications.

Table of Contents

Executive Summary ..... **v**
1 Overview **1**
2 Market Landscape: Building Envelope Retrofits for Existing Buildings **2**
2.1 Current Market Outlook 2
2.1.1 Structural Definition 2
2.1.2 Workforce 3
2.1.3 Technology Trends 4
2.1.4 Economics of Residential Retrofits 5
2.1.5 Economics of Commercial Retrofits 5
2.2 Key Barriers 5
2.2.1 Technical 5
2.2.2 Social 6
2.2.3 Workforce 6
2.2.4 Financial 8
2.3 Key Approaches 8
2.4 Assessment of Current Status of Key Long-Term Outcome Metrics 13
2.5 Future Outlook 17
2.5.1 Market Outlook 17
2.5.2 Technology 18
2.5.3 Workforce 18
References **20**

This report is available at no cost from the National Laboratory of the Rockies (NLR) at www.nlr.gov/publications.

1 Overview

This report examines the current market, key barriers, case studies, and quantitative long-term outcome metrics for envelope technologies used during the building retrofit process. The market baseline draws on research about the current workforce, roles of key technology areas, recent technology trends, and relevant economic conditions. For each technology we identify and discuss technical, social, workforce, financial, and regulatory/policy barriers. Case studies contextualize how technologies have been developed and applied.

We present long-term outcome metrics to assess market transformation, including increases in R&D efficiency and efficacy. Finally, we summarize expert projections for each technology area, covering economic outlook, expected rates of technological advancement, and future workforce needs.

This report is available at no cost from the National Laboratory of the Rockies (NLR) at www.nlr.gov/publications.

2 Market Landscape: Building Envelope Retrofits for Existing Buildings

A building's envelope is a major driver of overall building energy efficiency. The building envelope comprises the physical components that separate the building's interior from the exterior—including the building's foundation, roof, walls, windows, and doors. A building's envelope is vital for the comfort, health, and safety of the occupants, as well as the building's structural integrity, energy efficiency, and aesthetics. When developing a building envelope, four key principles are usually considered for energy efficiency: thermal control, air control, solar radiation control, and moisture control (Davis and Bastian 2023).

Retrofits play a key role in improving the housing stock because older housing stock comprises a majority of U.S. buildings. Older buildings generally suffer from higher infiltration due to age-related issues such as settling and poor window sealing and insulation that was common practice in older homes. Over a building's lifetime, it is not uncommon for its envelope to be updated several times—including replacing windows, adding insulation, or improving the air sealing. Taking advantage of building envelope retrofits to improve the building's energy efficiency can have long-term benefits, including lower utility bills and greater occupant comfort. However, building envelope retrofits pose many cost and technical challenges (Aldykiewicz Jr, Desjarlais, Antunes da Silva, and Pallin 2022)

This section explores the current state of building envelope retrofits, highlights critical barriers and challenges facing this market, addresses key approaches to advancing energy efficiency, and discusses several long-term outcome metrics that can serve as indicators of the impact the Emerging Technologies Collaborative for Buildings (ETCB) is having on advancing the building envelope retrofit market.

2.1 Current Market Outlook

2.1.1 Structural Definition

The efficiency of a building's envelope is a major determinant in the overall efficiency of that building's heating, ventilating, and air-conditioning (HVAC) system, which represents 12% of overall energy use (González-Torres et al. 2022). Building envelopes, excluding windows, impact 20% of building energy use and 11% of total U.S. primary energy use. (Harris 2020) Building envelope retrofits are especially vital because it is estimated that 93% of residential and 60% of commercial buildings in existence will still be in use in 2050 (Harris 2022).

The key structural components of the building envelope are cladding and siding, roofing, windows and doors, sheathing and wraps, and insulation and sealing (Hayes, Hoyes, and Tao 2023). The building envelope can help determine the overall comfort of a building, including the ventilation, natural lighting, and heating and cooling (U.S. Department of Energy 2016). The materials used for new construction overlap significantly with those for retrofitting existing buildings.

Cladding and siding are both used to create an exterior-facing barrier for a building. Roofing structures are vital in protecting the building structure from harm caused by the elements, such as rain, hail, and snow. The roof can account for up to 40% of the building's exterior and generally

This report is available at no cost from the National Laboratory of the Rockies (NLR) at www.nlr.gov/publications.

comprises shingles, sheathing, trim, rafters, underlayment, flashing, and drainage. Common roofing materials include asphalt, clay tiles, metal, slate, shake, and/or synthetic products (McDonald 2023).

Windows and doors, also referred to as fenestrations, are openings in a building. By their nature, these openings are vital components for the building envelope to allow natural ventilation and air circulation within buildings; they let in air and light and serve as an entry point for people and goods to enter buildings. However, they also allow conditioned air to escape, contributing to energy waste (Window World 2023).

Sheathing and wrapping both provide further protection to the building and are typically applied underneath the cladding or siding that acts as the exterior layer. Sheathing creates a physical layer and surface on which the wrap can be applied, which protects the building from water and moisture. Sheathing generally comprises wood, fiberboard, cement, gypsum, and/or glass mat. The wrap is often made of asphalt-saturated felt or kraft paper, woven or nonwoven polymeric, and/or liquid-applied polymer-asphalt membranes (Roberts 2019).

The purpose of insulation is to reduce heat flow and help reduce heating and cooling losses; insulation generally comprises fiberglass, rockwool, cellulose, natural fibers, rigid foam boards, and/or sleek foils (U. S. Department of Energy n.d.-e). Sealing prevents air leaks by closing any gaps between the outside and inside (Wallin 2023). This process usually uses caulk, gaskets, tape, and foam sealants (U.S. Department of Energy n.d.-f).

2.1.2 Workforce

Understanding the current state of the building envelope workforce is vital to understanding the rate of improvements that technologies under research, development, and demonstration can translate to real-world applications. The building envelope retrofits workforce encompasses the primary installers through the researchers studying more efficient technologies—and every role in between. Each worker is an essential component for either enhancing or hindering the rate at which new technologies can be accepted and implemented.

Professions focused on or related to building envelopes include jobs that help provide or improve insulation, windows, air sealing, and other methods to improve energy efficiency via the building envelope. The *U.S. Energy & Employment Jobs Report* classifies building envelope professions under the category of "energy efficiency jobs," which have increased 7.4% since 2020 and are projected to continue growing (Keyser et al. 2023). The building workforce contains a wide range of skills and qualifications, but statistics exclusively on the building envelope profession are not currently maintained.

The building efficiency workforce divides commercial building envelope occupations into the following three primary categories: (1) general construction; (2) architecture, engineering, and other professional services; and (3) energy services (Brown et al. 2023). Careers within general construction include positions such as carpenters, construction managers, and roofers. Positions in architecture include architectural engineers and draftspeople, and careers in energy services include positions such as energy auditors. In addition, the upstream workforce includes a variety of positions, including those in research, trade, distribution, and manufacturing of building envelope retrofit components. This workforce includes manufacturing engineers, production

This report is available at no cost from the National Laboratory of the Rockies (NLR) at www.nlr.gov/publications.

workers, assembly workers, and operators. It is worth noting that the new construction workforce for building envelopes significantly overlaps with that of the retrofitting sector.

Advanced Degree Required

Many of these careers in architecture and engineering require an advanced degree in architecture, civil engineering, structural engineering, or mechanical engineering or an advanced degree in a related field. The minimum experience typically required for these positions ranges from 0 to 15 years.

Additional certifications such as Engineer in Training, licensed architect certification, and International Institute of Building Enclosure Consultants professional registrations such as Registered Roof Observer, Registered Roof Consultant, and Registered Waterproofing Consultant are also required for some positions. Experience with specific software tools such as AutoCAD, THERM, or WUFI may be required for some positions.

No Advanced Degree Required

Many careers focused on manufacturing building envelope components do not require advanced degrees, but rather emphasize experience and competence with mechanical tools and equipment, as well as specific physical requirements.

Careers focused on installing building envelope components generally require employees to be able to read construction drawings and have knowledge of the materials being used, competency with hand tools, and the ability to work long hours.

General Considerations

It can be challenging to identify the demographics of workers within building-envelope-focused careers, or any energy efficiency jobs for that matter. One reason is that energy efficiency is often just one component of a worker's responsibilities. The U.S. Bureau of Labor Statistics does not track careers within efficient building technologies, which can make it more challenging to paint a clear picture of the individuals who make up this workforce. However, when looking at energy efficiency workers across industry, it can be estimated that approximately 54% of workers work in construction, 22% in manufacturing and trade, and 24% in professional services and "other" (Brown et al. 2023). When divided by technology rather than industry, workers in building materials and insulation make up approximately 15% compared to other energy efficiency technologies (Brown et al. 2023). These statistics represent the overall picture because they address energy efficiency as a whole rather than building envelope retrofits.

2.1.3 Technology Trends

Current building envelope technology trends focus on a few key areas, including smart envelope systems, advanced insulation materials such as aerogels, prefabricated building envelopes, and cladding other than vinyl siding (Tao et al. 2024; Bejamin Obdyke n.d.; TechGolly 2025). New technologies, research, and innovation in building envelope materials have also shown promise, focusing on ways to create more efficient insulation by reducing its thickness. Superinsulating materials such as vacuum insulation materials and silica aerogel can be used to free up space and increase the value of the building. Supercool and smart materials also show promise for improving building cooling (Lim 2020; Ricci et al. 2019).

This report is available at no cost from the National Laboratory of the Rockies (NLR) at www.nlr.gov/publications.

2.1.4 Economics of Residential Retrofits

The costs for upgrading a building envelope can vary widely, but it is estimated that window installation is the most expensive component and air sealing is generally the least expensive. One study investigated the cost of residential project upgrades and found the median cost for full-frame window installations to be $6,464, wall insulations $2,106, attic and roof insulation $2,016, and sealing the house envelope $730 (Walker et al. 2021). Of these calculated costs, window installation had the greatest range. Although these numbers can help estimate which components are more costly, overall costs vary depending on the building. Note that this study observed residential buildings and did not include large commercial buildings (Walker et al. 2021).

2.1.5 Economics of Commercial Retrofits

In the case of commercial buildings, roofs are the most common component retrofitted, followed by windows and then walls. Retrofits contribute the most to revenue growth for window and roof insulation (Davis and Bastian 2023). Economic considerations for tenant relocation comprise several strategies but generally require owners to financially support tenant relocation costs including storage, movers, and rent increases. Split incentives between the tenants and landlords also contribute to this dynamic because whole building retrofits can have a longer payback period—that is, shorter-term tenants may not see the benefits (Mooney 2023; Rocky Mountain Institute n.d.; U.S. Department of Energy 2020). Due to these considerations, major retrofits often wait until tenants vacate voluntarily or until the sale of the property. Although these factors certainly contribute to the overall cost of commercial building envelope retrofits, studies comparing the costs of envelope components are lacking and difficult to compare because of the wide variety of commercial buildings in existence.

2.2 Key Barriers

2.2.1 Technical

Building envelopes can fail for many reasons, including poor design, improper materials, low-quality workmanship, weather, end of useful life of materials, and natural disasters. Careful planning and material selection for building envelopes is key. Therefore, the use of more resource-efficient materials and designs that are more durable to extreme events will become more desirable for building envelope retrofits. Although these adaptations are necessary to improve resource efficiency and durability against extreme weather events, they can pose daunting challenges—including the increase in time and cost needed for testing, research, and development of these new technologies.

When a new technology is transitioned out of the laboratory research phase, the product development process begins. Envelope technologies require real-world testing because buildings are traditionally assembled on-site, with various experts working on different elements of the envelope. In addition, the assembly of envelopes can be unique because buildings are often designed for a specific purpose, for example when transitioning an old warehouse into apartments. This may mean longer timelines and pose challenges to the deployment of new technologies at scale. Further barriers identified in one study include shortcomings in technical solutions, safety risk to homes during the construction process, and the end users' lack of technical expertise (D'Oca et al. 2018).

This report is available at no cost from the National Laboratory of the Rockies (NLR) at www.nlr.gov/publications.

2.2.2 Social

Social factors may prevent building owners from pursuing building envelope retrofits, which can disrupt tenants or other building uses, often prove costly for the owner, and are not always visible. In addition, details on building envelope retrofits and savings from energy efficiency measures can be confusing to building owners. These barriers can combine to make energy efficiency upgrades a low priority for many building owners.

Timing and awareness pose some of the key social barriers. A study of the psychological barriers to energy upgrades found that upgrades often are not implemented because building owners believe it is not the right time for an upgrade and are unsure about the economic savings potential (Klöckner and Nayum 2017). Access to information for consumers is a key social barrier to energy efficiency upgrades along with the energy savings being low (Klöckner and Nayum 2017). In addition to being expensive, the process of retrofitting a building envelope can be complex and time-consuming, further deterring building envelope upgrades (Davis and Bastian 2023).

Building owner motivation for building envelope upgrades—and energy efficiency upgrades in general—depend on many factors. Saving energy through building envelope upgrades is often low on a building owner's priorities list, if on the list at all. Building owners desire upgrades that are visible to guests and neighbors. In addition, building envelope information—which can be challenging to locate—can be confusing and overwhelming to a building owner. Energy audits that document and quantify key energy performance metrics can also be confusing to building owners, who often lack understanding of various energy efficiency metrics (U.S. Department of Energy 2010).

A similar set of social pressures exists for owners of commercial buildings. The fragmentation within and between relevant stakeholders, including tenants, owners, and agents can act as key social barrier (Janda 2014). In many cases, tenants are responsible for utility bills and building owners have little motivation to pursue envelope retrofits unless to make the building more modern and attractive to new tenants. In this case, the retrofits may or may not include efficiency upgrades and usually must be conducted once the building is free of tenants.

Corporate office building occupants have demonstrated an increasing demand for resource-efficient offices. This increasing demand is motivated by the apparent cost that results from energy-efficient buildings, including increased rents for landlords. Corporations aiming for resource efficiency can pursue labels such as Leadership in Energy and Environmental Design (LEED) or ENERGY STAR® certifications to promote and highlight the building's energy efficiency, making the building more attractive to tenants (Jones, Zamora-Duran, and Lipman 2024; Frazier 2023; Davis and Bastian 2023). As of 2018, one survey found that nearly half of U.S. building professionals expected 60% or more of 2021 projects to be focused on resource efficiency. (World Green Building Council 2018)

2.2.3 Workforce

The lack of a qualified workforce is a major barrier to envelope upgrades. Approximately 88% of firms in energy efficiency report at least "some difficulty" hiring professionals, generally due to insufficient skill and training (Jones, Zamora-Duran, and Lipman 2024; Frazier 2023). A 2023 estimate of worker shortfalls in the construction industry estimated 650,000 extra workers were

This report is available at no cost from the National Laboratory of the Rockies (NLR) at www.nlr.gov/publications.

needed to fully fill all positions for 2022 (Davis and Bastian 2023). These positions remained unfilled as of 2023, resulting in 4.6% of positions unfilled (Rafter 2024).

No Advanced Degree Required

The workforce shortage in jobs that do not require advanced degrees is the result of multiple contributing factors, including the negative perception and low interest in the building industry. Students are often unaware of the benefits of an energy efficiency career, and jobs in construction have a reputation of being "dull" compared to other career choices available (Truitt et al. 2022). High schools also play a part because counselors aim to get students into a 4-year college program over trade schools and apprenticeships (Truitt et al. 2022).

Other components also contribute to dissuading individuals who may be interested in the energy efficiency workforce. When benefits such as child care and health care are not provided, workers will look elsewhere for employment (Martinez 2023). Other soft skills such as communication, time management, and teamwork are often needed for successful energy efficiency careers and can, in some cases, create a barrier to employment for workers (Miniard et al. n.d.).

Advanced Degree Required

One of the largest contributing factors preventing the fulfilment of all advanced degree positions in energy efficiency is the educational requirements. Many high-paying jobs in this sector require a 4-year degree at minimum (Scott, Axelrod, and D'Elia 2024). Another contributing factor to this workforce shortage is the lack of technical skills and industry-specific knowledge. Although there are many options for workers to obtain the necessary credentials, the programs can be difficult to locate because no single location can be accessed online with all the options. Combine this with the difference in requirements by state, and the educational landscape for building envelope workforce becomes daunting, confusing, and unappealing to workers (Truitt, Williams, and Salzman 2020).

General Considerations

A key barrier for energy efficiency professions both with and without advanced degrees is the small applicant pool resulting from the decline in the number of young workers (MacPherson and Kadoch n.d.). Combined with the high rates of retirement among older workers, this contributes to an increasing workforce shortage in energy efficiency and construction occupations as a whole (Rafter 2024; Davis and Bastian 2023).

Building codes can further contribute time and cost barriers for new technologies. There is no single uniform building code at the national level, and building codes often vary by jurisdictions and tend to have differing licensing requirements. The learning curve needed for the successful adoption of new technologies is present at all levels of the building envelope workforce, not just R&D. The entire workforce—all the way to the end user—is impacted when any retrofit is implemented. For example, a smart envelope may require a specialized workforce for installation, with electricians or similar. Specialty materials may require different installation or safety measures not required for a traditional building envelope, in turn requiring training for workers. These components can add up to a steep learning curve.

Licensing requirements can also pose a barrier in some cases. For example, in cases in which a jurisdiction or law requires certifications, training, licensing or similar, the labor pool may

This report is available at no cost from the National Laboratory of the Rockies (NLR) at www.nlr.gov/publications.

become reduced as a side effect. This may also increase the costs to the end user as well (Srivastava, Ayalam, and Aquino 2025).

2.2.4 Financial

Pursuing building envelope upgrades for the sole purpose of increased energy efficiency is rare, generally because of the high upfront cost of a building envelope retrofit compared to other energy efficiency and renewable energy solutions. This high cost is a primary financial barrier that deters building owners (Fiscal, Vandevyvere, and Peeters 2023). If a building envelope already requires a retrofit as part of a planned renovation, energy efficiency options are more likely to be considered. The building envelope expenses are determined by material cost and include factors such as energy savings, potential for increased rent charges, and overall payback period.

Energy-efficient building envelope materials may comprise higher-quality insulation materials, more advanced sealing or fastening techniques, and possibly the additions of newer technologies required for smart envelopes. The cost of these solutions depends on factors such as the local climate, building type, and contractor rates. Building owners that undergo envelope retrofits that prioritize energy efficiency are likely to see the energy savings accumulate over time and must have confidence that the overall savings and ROI will cover the costs of the upgrades.

Unfortunately, the upfront energy savings projections can be unreliable. In addition, other costly factors such as a long payback time frame and associated costs of renovation (e.g., permitting fees, temporary living fees, waste removal, and homeowners association fees), can also dissuade owners from pursuing building envelope upgrades (Ma and Vandevyvere 2020; Dadzie et al. 2018). Combine these factors with recent low energy costs, and there is little motivation to implement building envelope upgrades.

Supply chain challenges can impact components of the building envelope and lead to delays in implementing upgrades, increasing costs faced by building owners. Many factors impact the supply chain, including weather, global emergencies (e.g., COVID-19), and shipping delays. Materials such as roof membranes, silicones, aluminum, and steel commonly have delays or shortages. Supply shortages not only cause delays, but they can also directly influence the end price consumers face; recent analysis has shown these shortages can increase prices by up to 300% (Smalley 2022).

2.3 Key Approaches

Air Sealing

Air leaking into and out of a building often leads to more expensive heating and cooling bills, as well as poor occupant comfort. Sealing gaps and openings in a building can improve comfort, savings, and air quality, as well as reduce humidity. Reducing external air infiltration also blocks outside pollutants and contaminants. In properly sealed buildings, air is forced to enter through a filter, leading to healthier indoor air quality. During extreme heat or cold, drafty buildings require much more energy to heat or cool, leading to less comfortable temperatures and higher energy bills. Air sealing blocks these gaps and openings to eliminate the flow of outside air within the building (U.S. Department of Energy n.d.-c).

This report is available at no cost from the National Laboratory of the Rockies (NLR) at www.nlr.gov/publications.

Traditional air sealing techniques include caulking, weatherstripping, and house wrapping (U.S. Department of Energy n.d.-b). Caulk can be a highly effective method for air sealing, but there are some possible drawbacks of this technique. Caulk can become less durable over time, crack, shrink, and sometimes fail if exposed to ultraviolet rays, certain cleaners, and materials, as well as constant exposure to water. Caulk can also require frequent maintenance and reapplication and requires a long curing time. Finally, it can be difficult to sand or paint caulk, making it less visually appealing (U.S. Department of Energy n.d.-d). Weatherstripping is an effective air sealing technique, but drawbacks include the visibility of some forms of weatherstripping such as door sweeps, the need for replacement over time, and susceptibility to water and cold, particularly in coastal and storm-prone areas (U.S. Department of Energy n.d.-g). Spray foam is another common and effective air sealing technique. However, drawbacks of not only spray foam air sealant retrofits, but air sealing retrofits in general, include the potential need to remove and replace insulation and to access inconvenient locations such as storage areas (Bohac 2024).

Newer techniques can help avoid some of the drawbacks of common air sealing techniques. One of the most promising new air sealing methods is atomized envelope sealant. This technology seals with a nontoxic water-based sealant that is automatically drawn to leaks and gaps. This technology is especially useful for reaching inaccessible areas and reducing human error. The sealant is composed of ultra-low-volatile organic compounds and builds on itself in increments. Software controls the degree to which the sealant is applied and monitors the temperature, air pressure, and humidity. Models have predicted this technology would result in higher energy savings in buildings with large exterior exposed areas and in colder and more humid locations. The technology has been shown to reduce air flow by more than 50%, even for buildings with an already airtight envelope (General Services Administration Public Buildings Service 2023). Atomized sealant is highly effective but can cost up to four times more than traditional methods and is limited on the size of the holes it can fill. Atomized sealant may require more work if there are leaks larger than 5/8 inch; in addition, the seals may deteriorate over time if exposed to standing water (Green ID n.d.).

Smart Envelopes

Adaptive building envelope technologies, or smart building envelopes, can address these issues. Unlike traditional building envelopes, adaptive building envelopes perceive and adapt to external environmental changes. Some of the most promising adaptive building envelope technologies include radiation-cooled façades, phase change materials (PCMs), and smart windows (Narbuts and Vanaga 2023).

Traditionally, building envelope retrofits include various measures to improve envelope features such as double-glazing windows; optimizing insulation in external walls, roofs, and floors; and improving air sealing and gaps—especially around doors and windows (Ingy El-Darwish and Gomaa 2017; Ashton 2024; Becqué, Allard, and Frischmann 2024). Although traditional materials and methods have been efficient enough historically, extreme weather will highlight the shortcomings of traditional building envelope techniques. This means traditional techniques may act as a barrier to sustainable energy consumption and result in drastic energy losses, especially during peak loads (Narbut and Vanaga 2023).

Double-glazed windows have two panes of glass with a gap between the two panes that is typically filled with an inert gas. This window design can improve insulation and energy

This report is available at no cost from the National Laboratory of the Rockies (NLR) at www.nlr.gov/publications.

efficiency, as well as reduce noise (Tsoy 2023). However, disadvantages include the inability for repair, heat trapping, and higher costs. Double-pane windows cannot be repaired; rather, the entire window must be replaced because of its unique design. These windows can hold excess heat, which can be beneficial during colder months but less helpful during warmer seasons. These windows also have a higher overall cost compared to single-pane windows (True Blue Glass 2022).

Insulation that can be sprayed or blown in is generally best for existing wall retrofits, primarily sprayed foam and foamed-in-place insulation, as well as loose-fill and blown-in (Types of Insulation 2025). Insulation retrofits can be targeted to areas where previous insulation is thinning, weak, or nonexistent such as floors. However, this process can be intrusive, depending on the number of locations in which added insulation is required. Panelized façades are another popular strategy for traditional building envelopes, especially for commercial buildings. Prefabricated panels can improve energy efficiency and offer quicker installation but can have drawbacks such as a potential higher initial cost depending on material type; they may also require maintenance (Studios 2021).

Radiation-cooled façades can decrease the surface temperature of a façade or roof by rejecting heat as thermal radiation. This technology works best at night, but ongoing research into daytime application has shown promise. One radiation-cooling roof design has been shown to reduce energy consumption by 16.9%–21.8% compared to traditional roof designs (Chen et al. 2022). These energy savings depend on many factors, such as the climate of the building's location. A study examining buildings with radiation-cooled façades in the United States found more significant savings for locations in hot, dry climates such as Arizona, whereas buildings in northern climates faced net electricity penalties (Wijesuriya et al. 2022). This pattern is also true of nonadaptive building envelopes. Overall, radiative cooling coatings result in substantial energy savings for most locations, even in areas of higher heating demand (Wang, J. et al. 2024). The façade's location on the building—that is, roof only or roof and walls—can also have an impact because radiative cooling coatings on east-facing walls were shown to double energy savings compared to roof-only buildings (Wijesuriya et al. 2022). Many factors must be considered to maximize savings when adopting radiative cooling façades, making the added complexity a potential deterrent to adoption.

Another approach to smart building envelopes is phase change walls, which use PCM within the building envelope to better increase the heat storage capacity of the walls and protect against external temperature changes. (Kishore et al. 2022) The PCM can be embedded into the bricks, mixed into the mortar, or form a specific layer. For retrofits, PCM can be especially successful if applied as tiles into the interior drywall or into prefabricated panels (Imafidon and Ting 2023; Pistochini et al. 2024). However, this limits the use of PCM for retrofits, especially in commercial buildings.

Smart windows can use various technologies to incorporate an adaptive component. Smart glass, encompassing electrochromic and thermochromic technologies, has been undergoing research for smart windows. With this technology, smart windows can modulate infrared radiation, reducing visible light. Another form of smart glass is solar energy storage glass, which can convert solar energy to electricity, as well as store excess energy (Wang, G. et al. 2024; Narbut and Vanaga 2023). The primary drawback with this technology is the high upfront cost

This report is available at no cost from the National Laboratory of the Rockies (NLR) at www.nlr.gov/publications.

compared to traditional glass. Smart windows may also require installation techniques involving specialized workers or training, and a learning curve exists for end users.

Advanced Insulation Materials

Insulation is a necessary component of the building envelope that prevents temperature transfer from within and outside of the building. Traditional insulation methods include using materials such as fiberglass, spray foam, rigid foam, mineral wool and cellulose. Fiberglass comprises tiny glass fibers that are woven together and formed into rolls. This material is one of the most widely used insulation materials and is highly effective at increasing energy efficiency. For this reason and because of its fire-resistant and acoustic insulation properties, fiberglass is an attractive option. However, because of its composition, fiberglass can release tiny particles into the air if disturbed, irritating the respiratory system (Allen et al. 2023). If skin comes into contact with fiberglass, these tiny glass particles can irritate the skin, posing further safety concerns (Agency for Toxic Substances and Disease Registry 2014). Fiberglass can also be susceptible to moisture damage if there are any water leaks, decreasing its efficiency (Duong Hung Anh and Pásztory 2021)

Spray foam is another common method of building insulation. Spray foam is composed of polyol resin and isocyanate and is sprayed onto the surface with a spray gun. The foam expands to fill gaps, requiring about one day to fully cure and harden—tenants should be outside of the building to avoid exposure. Although effective as an insulator, spray foam can be difficult to remove, cost more than other insulation, damage electrical wiring, and contract over time (Snugg 2024).

Cellulose insulation is a slightly less used insulation option that can be spray-applied. Cellulose insulation can also be blown into wall cavities and comprises at least 85% recycled paper that has fire-retardant properties. However, it can also absorb more water than other insulation options, leading to an increased risk of mold or mildew. Cellulose insulation can produce more dust than some options, have a higher initial cost, and settle over time, forming pockets of weaker areas (Hurtado et al. 2016; Bird 2021).

Although these more traditional methods have proven effective, there are noticeable drawbacks—some of which could be addressed with new technologies. Advanced insulation materials such as silica aerogels were originally used in the aerospace industry and have become more popular as a building insulation option. Aerogels comprise 95% air, contributing to their light weight and strong insulation properties. Silica aerogel can surpass the thermal performance of traditional insulation by two to four times and have been shown to result in 39.1% less energy lost through windows in simulated testing (Thie et al. 2023).

However, aerogels have a higher production cost—in one case, a calculated 45% higher cost than traditional insulation materials (Orsini et al. 2020). Newer materials generally take longer to become common because of the large number of regulations, codes, and standards required by the building industry. These factors can make aerogels a less attractive option and therefore less competitive on the market. Research on aerogels and advanced insulation materials in use for more than 15 years is lacking, which means the long-term performance of this technology cannot be determined. However, within this the past 15 year time frame, there have been few cases of malfunction or failure, which suggests a promising outlook (Johansson and Adl-Zarrabi 2018).

This report is available at no cost from the National Laboratory of the Rockies (NLR) at www.nlr.gov/publications.

Prefabricated Building Envelope

Traditional building envelopes can be time-consuming to construct, often taking months to complete a project. Prefabricated building envelopes can help speed the construction process and improve energy efficiency. These building envelopes are by no means a new technology—it dates to the 1600s (Blasco and Cabrera 2024). Prefabrication can be an extremely efficient approach for building envelope retrofits, leading to lower costs, reductions of material waste, and faster installation times (Boafo, Kim, and Kim 2016; Sah et al. 2024).

Traditionally, the key component for prefabricated building envelope retrofits has been prefabricated wall panels comprising wood, concrete, or steel (Wells Concrete 2023). Architectural panels, precast concrete panels, and structural insulated panels are some of the most common forms of prefabricated building envelope currently used (Biro 2024). Architectural panels have continuous insulation, moisture and air barriers, and exterior cladding. These panels are especially useful for deep energy retrofits because they can be designed so building occupants can remain inside the building while the retrofit is underway (Biro 2024). Precast concrete panels are created off-site, which can help reduce material waste and environmental impacts that may result from mixing concrete on-site (Biro 2024). Where architectural panels are not feasible, structural insulated panels such as retrofit insulated panels or nail base panels are an option for prefabricated building envelope retrofits. This option can improve energy efficiency while reducing the number of layers required for installation (Building America 2025). Overall resilience can be improved when structural insulated panels are installed on roofs—it is less likely for the sheeting to be ripped off during weather events because the panels are composed of one solid sheet rather than multiple layers (Biro 2024).

However, despite the benefits of prefabricated building envelopes, some drawbacks remain. Prefabricated components limit design flexibility, which may deter some buyers and restrict customization. Although prefabricated building envelopes can generally be faster to construct, this depends on the type. For example, one case examined fully prefabricated light wood frame walls and found the assembly for one story was almost four times slower than conventional (Julien, Blanchet, and Gosselin 2022). The transportation restrictions that arise because of the module's large size and weight can pose another challenge, along with the need for a higher level of project coordination and a negative market perception (Boafo, Kim, and Kim 2016). Transportation can also pose risks because mishandling can lead to damage, increasing the project timeline. Mistakes when adjusting or handling the panels can be costly because one small error can ruin an entire panel.

Of the newer, promising prefabricated panel systems, most are best suited for new construction; however, some options may also be applicable for retrofits. Metal structural insulated panels, which comprise a full prefabricated wall including windows and cladding, show potential for retrofits. These panels can be installed easily on the building's exterior wall and are well suited to commercial buildings (Egerter and Campbell 2020). Because of the custom design of these panels, implementing this design can have a long lead time, and damage to panels can be more costly (Trout 2005).

Other emerging technologies, such as incorporating smart materials and 3D printing in prefabrication, also show promise. Materials such as self-healing concrete and adaptive insulation could be used to make prefabricated panels stronger and enhance the life span of the

This report is available at no cost from the National Laboratory of the Rockies (NLR) at www.nlr.gov/publications.

product. Using 3D printing as a method of prefabrication for panels can speed the process and allow adjustments to be more exact, reducing human error (Volpe et al. 2021). These technologies are not yet common in today's market but may become so with further research.

2.4 Assessment of Current Status of Key Long-Term Outcome Metrics

This analysis captures only a small portion of the recently commercialized technologies being developed to improve the efficiency and efficacy of building envelope retrofits, but significant technological R&D is underway to continue to improve building envelope retrofit technologies. In partnership with ETCB staff and contractors, the National Laboratory of the Rockies has identified six long-term outcome metrics that quantify the impact of ETCB on the state of technology research, development, and demonstration. Following are several examples for each metric.

Time Technologies Spend at Different Technology Readiness Levels

Technology readiness level (TRL) can vary extensively between technologies, influenced by factors such as regulations, market demand, and even accidental scientific findings. Although it is impossible to paint a full picture of the building envelope retrofit market, we can examine how various technologies have become commercialized over time to broadly estimate the current state of the market.

> "Technology Readiness Levels (TRL) are a type of measurement system used to assess the maturity level of a particular technology. Each technology project is evaluated against the parameters for each technology level and is then assigned a TRL rating based on the projects progress. There are nine technology readiness levels. TRL 1 is the lowest and TRL 9 is the highest." (Manning 2023).

The first recorded use of prefabricated panels was recorded in 1624 to build a house for a fishing fleet in Cape Ann, Massachusetts. In the early 20th century, Sears Roebuck & Co. Houses by Mail program sold 100,000 units, demonstrating that prefabricated panels are a mature technology area and that the business case has been proven out in modern situations. Improvements to prefabricated panels, such as PCMs, encompass a much briefer history. The first documented demonstration of PCM use in building applications occurred in 1948, in which an American scientist used PCMs as a form of passive heating for a home in Dover, Massachusetts. The technology was successful for two winters and kept the home heated for up to 11 sunless days (Lam 2009; Piqueras Blasco and Cabrera i Fausto 2024; Prefab Museum, n.d.).

Research on PCM began in earnest in 1962, and PCM's primary use was in computers. PCMs were finally commercialized for the buildings market in 1975 (Lam 2009; Kuznik and David 2015; Frigione et al. 2019; Wilson 2009). However, none of the available products stayed on the market for an extended period because of the sharp decrease in efficiency after a few hundred cycles of use. As of 2009, PCMs on the market can last up to 10,000 phase change cycles with no reduction in performance (Wilson 2009). PCMs vary widely in use as well as TRL, ranging from TRL 4 to 9 depending on the type of PCM (Anderson et al. 2016). It is estimated that a total of five PCM products are market-ready, suggesting a TRL of 8 or 9. If the case from 1948 were

This report is available at no cost from the National Laboratory of the Rockies (NLR) at www.nlr.gov/publications.

treated as a prototype or test of this technology, this would place the 1948 version of PCM technology at TRL 4—meaning PCM took 61 years to evolve from TRL 4 to TRL 9. According to this timeline, the average time at each TRL can be estimated to be 12.2 years.

Smart window technology was first proposed in the late 1970s, with R&D emerging in the 1980s. In 1999, the first electrochromic façade was installed commercially, in a bank. However, this installation had to be replaced after 2 years because of degradation. Numerous cases of similar degradations and research and market hurdles have arisen, demonstrating the need for further R&D for smart window technology (Kraft 2025). The proposal of the technology in the late 1970s indicates a TRL of 1 by 1979, and the short-lived commercial installation in 1999 suggests a TRL of 7. We estimate this technology took 20 years to advance six TRLs, staying at each TRL for an average of 3.3 years. It is worth noting that technological growth is not always linear—especially in the case of smart windows. Although more common during the early R&D stages, performance and research setbacks may arise at any point of the TRL process. Automized envelope sealant is an even newer technology, invented as recently as 1993. As of 2017, it was at a TRL of 7–8 (Goetzler et al. 2017). This technology arrived on the market in 1997, suggesting fast evolution through the TRLs—taking only 20 years to move 7–8 TRLs and spending an estimated average of around 6 months at each TRL (Aeroseal History 2025).

Research on polyurethane foam began in the 1930s. The technology was developed with intentions for home insulation applications in 1953 and 1963, gained popularity in the 1980s, and is now one of the more popular forms of insulation (Paragon Protection n.d.). With this timeline, it can be estimated that spray foam technology spent an average of 5.5 years at each TRL.

Fiberglass was also created in the 1930s. It emerged on the market in the 1940s and became especially popular during the energy crisis of the 1970s (Boyd 2014). Because fiberglass held a shorter development time frame and hit the market quickly, it can be estimated that fiberglass spent an average of 1.1 years at each TRL.

Modern cellulose—treated with fire retardant—began use in the 1950s, became commercialized in the 1970s, and peaked in 1978 because of the energy crisis. It faltered soon after because of stricter regulations, diminishing cellulose production in the United States, but is now beginning to grow again as a result of new research (Chemeurope.com n.d.). According to this timeline, modern cellulose can be estimated to have spent an average of 2.2 years at each TRL.

Aerogel insulation was invented in 1931 and commercialized as early as the 1940s—only to be abandoned by the 1970s. Aerogel insulation underwent drastic improvements in safety in the 1980s. It was popularized by National Aeronautics and Space Administration (NASA) in the 1990s, commercialized again in the 2000s, and is currently at a TRL of 7–9 (Thermablok n.d.; Aerogel.org n.d.). According to this time frame, it can be estimated that aerogel insulation has taken approximately 70 years to advance through seven to nine TRLs, spending an average of 8.75 years at each one.

New research and improvements for each of these technologies have continued to push market readiness and increase TRLs. As research capabilities and technological discoveries advance, so does the potential capacity for new technologies to enter the market. Some technologies, such as automized envelope sealant, have become “market ready” in three decades or less; other

This report is available at no cost from the National Laboratory of the Rockies (NLR) at www.nlr.gov/publications.

traditional technologies such as cellulose insulation have longer time frames—even centuries. Not every technology maintains a steady, linear growth pattern. In some cases, a technology may advance multiple TRLs and be pushed to the market quickly, only to regress after doing so.

Time It Takes To Educate Downstream Technology Vendors Decreases

It is worth considering that even if a technology is commercially available, the total timeline for adoption can be influenced by factors such as how long it takes to educate downstream technology vendors.

Many insulation installers undergo on-the-job training because no training is mandated, and no certification is required. Recommended training and certifications vary. For spray foam insulation, it can be recommended that installers undergo a written exam that can take 2–8 hours, supplemented by optional courses that can take another 8 hours as well as a 4-hour field examination. Training and certifications for working with traditional insulation, such as fiberglass, can be as brief as a 20-minute online training and certification for a Grade 1 installer (NAIMA 2020). In some cases, training and courses for working with various insulation combine insulation types so the installer can learn about multiple types of installation at once (IDI Insulation 2025).

Smart window film could be installed as a do-it-yourself, but a certified electrician is recommended for the installation of most smart window technologies. Manufacturers may have training available for their specific product, including in-person training and online presentations that describe the correct methods, techniques, and safety procedures for installation. There may be opportunities to earn credits or certifications, and training may take less than an hour in some cases (Gauzy 2023).

Some certifications for installing air barrier technologies such as automized envelope sealant can require a 2- to 3-day in-person or online course ranging from around $600 to $1,800. An examination is required to achieve the certification, with a passing grade of 80%, along with 3,000 hours of experience in barrier applications or similar fields (Air Barrier Association of America 2017).

Aerogel insulation may also require training, in which a professional trainer may travel for in-person on-the-job trainings. These training sessions generally last about 2 hours and cover best practices and questions and answers; virtual training is also available in some cases (Aspen Aerogels 2021).

Newer technologies typically require learning new ways of working by tradespeople and building professionals. This learning process is often longer than learning how to work with long-used technologies.

Performance Dimension Improvement

Loose-fill and blown-in insulation are currently popular for insulation retrofits; this insulation comprises fiberglass, cellulose, and mineral wool (U.S. Department of Energy 2025). The R-value of loose-fill cellulose ranges from 3.1 to 3.8, fiberglass 2.2 to 2.9, and mineral wool 2.5 to 3.3 (Beauchamp 2024). High-density fiberglass insulation is an example of an improvement in fiberglass insulation—this version has a denser structure, resulting in a higher R-value at R-4.3

This report is available at no cost from the National Laboratory of the Rockies (NLR) at www.nlr.gov/publications.

per inch (The Home Depot 2023). In general, R-value is more easily improved by adapting the density and application strategy rather than the physical insulation product. Therefore, the R-value of fiberglass and cellulose insulation itself has not changed much over the decades; rather, the strategy and methods with which each insulation is applied have improved to result in a stronger R-value (U.S. Department of Energy 2025).

Window performance can be measured by the U-value, or thermal transmittance, as well as the solar heat gain coefficient. The U-value of single-glazed windows is 5.2 watts per square meter Kelvin (W/[m^2·K]), double-glazed 1.6 W/(m^2·K), and triple-glazed 0.8 W/(m^2·K), with lower values highlighting stronger thermal insulation efficiency. Triple-glazed windows therefore provide the highest level of thermal and acoustic insulation. Double-glazed windows entered the market in 1935 but required improvements, which led to this technology finally being commercialized in 1952 (Gorsia 2024; McGawn Designs 2023). Triple-glazed windows entered the market in the 1980s and are still in the process of becoming widely used (Julin 2021; Gorsia 2024). Solar heat gain coefficients also follow this pattern, in which single-glazed windows have a higher value on average, and triple-glazed windows have the lowest (Overbey 2015).

The ACH-50, or air changes per hour at 50 pascals, can also be used to measure the performance of an envelope retrofit product or measure. For example, one study examined 116 homes that had undergone a deep energy retrofit and found the average post-retrofit airtightness was approximately 4.7 ACH-50 (Less and Walker 2025). A minimum leakage rate of 5 ACH-50 is set by the 2015 and 2021 versions of the International Energy Conservation Code (IECC) (International Code Council 2016). The 2021 version also notes an option for improved air sealing and ventilation for residential buildings, in which the requirements are more stringent at ≤3 ACH-50 (International Code Council 2021). This option is even more stringent in the 2024 version for residential buildings, in which the improved air sealing and ventilation option ranges from 1 to 2 ACH-50 depending on the ventilation options installed (International Code Council 2024). Within the 2024 code, a crediting system allocates a specific number of credits that depends on climate zone and the energy efficiency measure. Note that for a building to comply with the IECC additional energy efficiency requirements, a minimum of 10 "credits" is necessary. This system allows a mixture of energy efficiency technologies to meet the requirements. For example, having an ACH-50 of ≤2.0, with a balanced ventilation system, contributes to 4 credits in Climate Zone 6 but 0 credits in Climate Zone 3, whereas heat pumps contribute to 12 credits in Climate Zone 3 but are not applicable for Climate Zone 6.

Advances to the performance frontier often come from technological improvements. However, these improvements sometimes come from how a technology is used or can be easily quantified only through regulatory requirements such as building codes. Within a given technology space, advancements may be large or small.

Change in Energy Use by Relevant End Uses

Building envelopes traditionally do not consume energy; however, the building envelope is a key driver of how much energy is used in the HVAC of a building. Between 2012 and 2018, energy use intensity (per square foot and/or per capita) for heating and cooling in commercial buildings decreased by 14% despite an increase in total floorspace. The energy intensity of all major fuels for commercial buildings has decreased by nearly 40% since 1979 and by 15% since 2003-2018 (U.S. Energy Information Administration 2023).

This report is available at no cost from the National Laboratory of the Rockies (NLR) at www.nlr.gov/publications.

However, assessing the change in energy use attributable to building shell improvements is complex and beyond the scope of this overview. A significant portion of these improvements can reasonably be credited to improvements in the efficiency of the existing building stock; this progress must be shared with the improvements in HVAC efficiency.

Time Technology Spends at Different TRLs May Decrease for a Given Improvement in Commercial Version of Technology, per Performance Improvement

Technologies are moving into the market quickly. It took more than 40 years from first conceptualization to commercialized technology for double-pane windows but less than 30 years for triple-pane windows (History of Double Glazing 2018). The performance improvement from a single-pane to double-pane window can result in 60% less heat transfer, and switching from a 1980's double-pane window to a 2020's double-pane window can result in more than 40% improvement (Isaacs 2023). Analyzing the compound rates of improvement for window technologies results in a 1% annual rate of performance improvement with respect to heat transfer from moving from single-pane to double-pane windows and a nearly 2% annual rate of performance improvement from double-pane to triple-pane windows.

Time Technology Spends at Different TRLs May Decrease for a Given Improvement in Commercial Version of Technology, per Cost Reduction

Improvements in performance do not necessarily come with increasing costs. As manufacturers improve their manufacturing processes through learning by doing and increase their economies of scale, and as installers improve their fluency with a technology, prices may decrease. Smart glass technology has been available since the 1980s but is still becoming fully mainstream. The current U-value of smart windows is 1.1 $W/(m^2 \cdot K)$ (Kim, Hong, and Han 2021). In 2010, smart windows cost approximately $\$100/ft^2$, or approximately \$146.33 when adjusted for inflation (Wang 2010). Today, smart windows can cost anywhere from \$85 to $\$130/ft^2$, with lower rates for larger quantities (SGC n.d.).

Since its creation in 1931, aerogel has undergone improvements that led to its commercialization in the 2000s. Aerogels generally have an R-value of 10 or higher, meaning aerogel is four times more efficient than fiberglass (U.S. Department of Energy 2021; PACOR Inc. n.d.). Aerogel prices range from \$15 to more than $\$50/ft^2$—much higher than most insulation methods but lower than its previous cost. For example, in 2008, opaque aerogel insulation blankets at 10-mm thickness cost approximately $\$4{,}000/m^3$, or approximately $\$371.75/ft^2$ (Baetens et al. 2011). In 2011, analysis indicated that new manufacturing methods of mass production would lower the cost of aerogels for insulation by up to 90%, overcoming the traditional "batch" manufacturing mode that limited their production and contributed to the higher costs (Kanellos 2011). The cost of opaque aerogel insulation blankets at 10-mm thickness has declined nearly 95%; it currently sells for $\$24.22/ft^2$ (BuyAerogel n.d.).

2.5 Future Outlook

2.5.1 Market Outlook

Most sources agree that the building envelope market is expected to grow within the next 10 years. One estimation for the U.S. calculated a compound annual growth rate of 5.6% from 2025 to 2033. This would mean an increase from \$32.6 billion (2024) to \$53.3 billion by 2033 (Grand

This report is available at no cost from the National Laboratory of the Rockies (NLR) at www.nlr.gov/publications.

View Research, n.d.). Another source valued the building envelope market at $135 billion in 2024 and calculated a compound annual growth rate of 5.5%, which would lead to a value of $210 billion by 2033. (Verified Market Reports 2025) The overall market for revenues from building envelope retrofits is expected to grow at a compound annual growth rate of 5.7% from 2023 to 2032, which is greater than the rate of 1.5% expected for new construction (Davis and Bastian 2023).

However, inflation and supply chain concerns are likely to be some of the main barriers to this growth; regulations and building codes are estimated to be some of the largest driving factors of building envelope technology market growth (Davis and Bastian 2023).

2.5.2 Technology

R&D for building envelope technologies is predicted to grow. Building envelope products and technologies that improve resiliency are also expected to become more common (Davis and Bastian 2023).

Many research gaps need to be addressed, and underdeveloped areas that show potential should be prioritized. New technologies may show promise but lack the cost-effectiveness needed to make them competitive in the market (Wang, G. et al. 2024). Another challenge facing nearly every aspect of any new building envelope technology is the lack of research over time (Thie et al. 2023). Building envelope upgrades often require occupants to vacate the work area, and in some cases, the entire building; unfortunately, there is a dearth of technical solutions that address this issue. Other technologies, such as prefabricated architecture, may be effective but less popular because of a negative market perception or a lack of knowledge and awareness of the technology (Boafo, Kim, and Kim 2016).

For new and lesser-known technologies to become commonplace in the market, these gaps must be addressed. Research data demonstrating the real-world performance of these technologies is a critical next step for these under-researched areas. Along with research, strategies to lower costs include mass customization, promotions, and policies (Boafo, Kim, and Kim 2016).

2.5.3 Workforce

Although the building envelope technology workforce faces many challenges, the consensus is that efficiency employment is likely to go up (Coykendall et al. 2024). Educational trends can also help indicate what the future may hold for careers related to building envelopes. Research shows that manufacturing training methods may fall behind as this sector grows. Associate degrees are commonly received in preparation for high-skill trade training but have recently remained stagnant. Certificates have grown moderately over the same time frame and are another potential educational indicator because they can provide a basis for training (Coykendall et al. 2024). The number of candidates working to obtain architectural licenses has risen by 7% and has returned near levels prior to the COVID-19 pandemic (NCARB 2022). Active apprenticeships have increased by 114% from 2014 to 2024, with the number of graduates from apprenticeships rising by 143% over the same time frame. Manufacturing and construction both rank in the top five fields for apprenticeships (Bruno and Manzo 2025).

Employment opportunities in traditional construction, architecture, and manufacturing fields are predicted to grow faster than employment opportunities in other sectors of the economy (Bureau

This report is available at no cost from the National Laboratory of the Rockies (NLR) at www.nlr.gov/publications.

of Labor Statistics 2024). As demand for emerging technologies continues to grow in these sectors, so does the need for workers capable of optimizing these technologies. The demand for soft skills, digital skills, and leadership skills will be prioritized by manufacturing, as advancements in artificial intelligence, 3D printing, sensors, robotics, computer numerical control, and similar technologies will likely become more common (Coykendall et al. 2024). These and other digital tools such as building information modeling, digital twin technologies, augmented reality, and virtual reality can increase productivity and safety but require a set of specialized digital skills (Meisels et al. 2024). These skilled roles are likely to grow the most quickly in the next decade (Coykendall et al. 2024). Industrial machinery maintenance technician roles could grow by as much as 16%—and mechanical and industrial engineer roles by nearly 11%—by 2032. Professions such as computer and information systems managers and analysts, software developers, and web developers could grow by 13%, and statistician and scientist roles could grow by almost 30% (Coykendall et al. 2024).

The importance of traditional roles will remain just as vital—if not more so—through 2032. Production roles—especially those requiring a high-level skill set such as machinists, welders, first-line supervisors, electronics assemblers, and material transport positions such as material movers, laborers, and industrial truck operators—will also grow quickly (Coykendall et al. 2024).

High-tech manufacturing environments are shown to be more appealing to the workforce and are also better at retaining workers. Although a gap remains because of the workforce shortage, the future of the building envelope workforce is likely to include new niches for digitally skilled roles, creating new opportunities and increasing demand (Coykendall et al. 2024).

This report is available at no cost from the National Laboratory of the Rockies (NLR) at www.nlr.gov/publications.

References

Aerogel.org. n.d. “The modern history of aerogel.” www.aerogel.org/?cat=46.

Allen LH, Suder Egnot N, Allen H, Chan K, Marsh G. Exposure to MMVF in residential and commercial buildings: A literature review and quantitative synthesis. Toxicol Ind Health. 2023 Sep;39(9):528-536. doi: 10.1177/07482337231187092. PMID: 37528749; PMCID: PMC10616987.

Alumtech. n.d. “Home siding vs. cladding - main differences.” alumtech.ca/home-siding-vs-cladding-main-differences/.

Anderson, W., P. Ritt, C. Tarau, and J. Weyant. 2016. “Applications for Phase Change Material (PCM) Heat Sinks.” *Thermal & Fluids Analysis Workshop*, 1–5 Aug. 2016, Mountain View, CA. tfaws.nasa.gov/wp-content/uploads/TFAWS-2016-PT-02.pdf.

Benjamin Obdyke. n.d. “Building envelope trends for 2022.” benjaminobdyke.com/insights/building-envelope-trends-for-2022/.

Bird, B. 2021. “Top 5 Problems With Cellulose Attic Insulation And Solutions.” Bird Family Insulation, March 15, 2021. birdinsulation.com/top-5-problems-with-cellulose-attic-insulation-and-solutions/.

Boafo, F. E., J.-H. Kim, and J.-T. Kim. 2016. “Performance of modular prefabricated architecture: Case study-based review and future pathways.” *Sustainability* 8 (6): 558. doi.org/10.3390/su8060558.

Bohac, D. 2024. *Aerosol envelope sealing of existing residences*. U.S. Department of Energy. DOE/GO-102024-6121. www.nrel.gov/docs/fy24osti/85625.pdf.

Boyd, J. E. 2014. “In the pink.” *Distillations Magazine*, Dec. 23, 2014. www.sciencehistory.org/stories/magazine/in-the-pink/.

Brown, M., A. Lazelle, B. Prindle, E. Johnston, and R. Sabouni. 2023. *Clean energy employment impacts and occupational analyses: Building envelope & electrification upgrades*. Golden, CO: National Renewable Energy Laboratory. DOE/GO-102023-5940. www.nrel.gov/docs/fy23osti/86711.pdf.

Chemeurope.com. n.d. “Cellulose insulation.” www.chemeurope.com/en/encyclopedia/Cellulose_insulation.html.

Dadzie, J., G. Runeson, G. Ding, and F. Bondinuba. 2018. “Barriers to adoption of sustainable technologies for energy-efficient building upgrade—Semi-structured interviews.” *Buildings* 8 (4): 57. doi.org/10.3390/buildings8040057.

Davis, W., and H. Bastian. 2023. *Forecasts on commercial building energy efficient envelopes in new construction and retrofits: 2023-2032*. Guidehouse Insights.

This report is available at no cost from the National Laboratory of the Rockies (NLR) at www.nlr.gov/publications.

D'Oca, S., A. Ferrante, C. Ferrer, R. Pernetti, A. Gralka, R. Sebastian, and P. Op 't Veld. 2018. "Technical, financial, and social barriers and challenges in deep building renovation: Integration of lessons learned from the H2020 cluster projects." *Buildings* 8 (12): 174. doi.org/10.3390/buildings8120174

Frazier, A. 2023. "Labor in commercial real estate: 5 trends the data shows." *Building Engines*, Feb. 21, 2023. www.buildingengines.com/blog/labor-in-commercial-real-estate-5-trends-the-data-shows/.

General Services Administration Public Buildings Service. 2023. *Automated building envelope sealing*. GPG-053. www.gsa.gov/system/files/53-Findings-Automated%20Air%20Sealing-12-05-23_0.pdf.

Goetzler, W., R. Shandross, J. Young, O. Petritchenko, D. Ringo, and S. McClive. 2017. *Energy savings potential and RD&D opportunities for commercial building HVAC systems*. U.S. Department of Energy. DOE/EE-1703. www.energy.gov/sites/prod/files/2017/12/f46/bto-DOE-Comm-HVAC-Report-12-21-17.pdf.

González-Torres, M., L. Pérez-Lombard, J. F. Coronel, I. R. Maestre, and D. Yan. 2022. "A review on buildings energy information: Trends, end-uses, fuels and drivers." *Energy Reports* 8: 626–637. doi.org/10.1016/j.egyr.2021.11.280.

Green ID. n.d. "Energy Audits, A/C Service, and More." www.greenintegrateddesign.com/.

Harris, C. 2021. *Opaque envelopes: Pathway to building energy efficiency and demand flexibility*. U.S. Department of Energy. www1.eere.energy.gov/buildings/pdfs/80170.pdf.

Hayes, G., C. Hoyes, and D. Tao. 2023. "Trends in the building envelope industry." Roland Berger, Dec. 7, 2023. www.rolandberger.com/en/Insights/Publications/Trends-in-the-building-envelope-industry.html.

Hurtado, P. L., A. Rouilly, V. Vandenbossche, and C. Raynaud. 2016. "A review on the properties of cellulose fibre insulation." *Building and Environment* 96: 170–177. doi.org/10.1016/j.buildenv.2015.09.031.

Imafidon, O. J., and D. S-K Ting. 2023. "Retrofitting buildings with phase change materials (PCM) – The effects of PCM location and climatic condition." *Building and Environment* 236: 110224. doi.org/10.1016/j.buildenv.2023.110224.

Janda, K. B. 2014. "Building communities and social potential: Between and beyond organizations and individuals in commercial properties." *Energy Policy* 67: 48–55. doi.org/10.1016/j.enpol.2013.08.058.

Johansson, P., and B. Adl-Zarrabi. 2018. "Super insulation materials in the building sector: Field studies and future challenges." *7th International Building Physics Conference*.

This report is available at no cost from the National Laboratory of the Rockies (NLR) at www.nlr.gov/publications.

Jones, B., A. Zamora-Duran, and Z. Lipman. 2024. *United States energy & employment report 2024*. U.S. Department of Energy. www.energy.gov/sites/default/files/2024-08/2024%20USEER%20FINAL.pdf.

Julien, E., P. Blanchet, and L. Gosselin. 2022. "Case-study: Fully prefabricated wood wall connection to improve building envelope and on-site efficiency." *Buildings* 12 (12): 2185. doi.org/10.3390/buildings12122185.

Keyser, D., M. Fiori, B. Jones, H. Ho, S. Jatkar, K. Gordon, G. Copland-Newfield, C. Frisch, and C. Veeder. 2023. *2023 U.S. Energy and employment report: executive summary*. U.S. Department of Energy. https://www.eesi.org/files/DOE-2023-USEER-FULL-REPORT.pdf.

Klöckner, C. A., and A. Nayum. 2017. "Psychological and structural facilitators and barriers to energy upgrades of the privately owned building stock." *Energy* 140 (1): 1005–1017. doi.org/10.1016/j.energy.2017.09.016.

Lam, C. H. 2009. "History of Phase Change Memories." *Phase Change Materials*, 1–14. doi.org/10.1007/978-0-387-84874-7_1.

Le Duong Hung Anh, and Zoltán Pásztory. 2021. "An Overview of Factors Influencing Thermal Conductivity of Building Insulation Materials." *Journal of Building Engineering* 44: 102604. https://doi.org/10.1016/j.jobe.2021.102604.

Lim, X. 2020. "The supercool materials that send heat to space." *Scientific American*, Feb. 17, 2020. www.scientificamerican.com/article/the-supercool-materials-that-send-heat-to-space1/.

MacPherson, M., and C. Kadoch. n.d. "Workforce Development to Enable Building Modernization." Regulatory Assistance Project. toolkits.raponline.org/building-modernization/workforce-development/.

Martinez, S. 2023. "New survey reveals biggest barriers to employment in the region." *The Lakeshore*, Oct. 31, 2023. www.secondwavemedia.com/lakeshore/features/New_WMW_survey_reveals_barriers_to_employment.aspx.

McDonald, J. 2023. "Everything you need to know about roofing, part 1: Roofing 101." Dumpsters.com, June 9, 2023. www.dumpsters.com/blog/basics-of-roofing.

Miniard, D., W. White, N. Nave, S. Means, D. Meeking, and J. Clark. n.d. "Integrating diversity, equity, and inclusion into workforce development in energy efficiency: A case study in building analyst training." American Council for an Energy-Efficient Economy. www.aceee.org/sites/default/files/pdfs/ssi23/4-96%20Miniard.pdf.

Mooney, P. 2023. "What's the biggest barrier to retrofitting commercial buildings?" *Facility Executive*, Dec. 4, 2023. facilityexecutive.com/whats-the-biggest-barrier-to-retrofitting-commercial-buildings/.

This report is available at no cost from the National Laboratory of the Rockies (NLR) at www.nlr.gov/publications.

Narbut, J., and R. Vanaga. 2023. "Revolutionizing the building envelope: A comprehensive scientific review of innovative technologies for reduced emissions." *Environmental and Climate Technologies* 27 (1): 724–737. doi.org/10.2478/rtuect-2023-0053.

Orsini, F., P. Marrone, F. Asdrubali, M. Roncone, and G. Grazieschi. 2020. "Aerogel insulation in building energy retrofit: Performance testing and cost analysis on a case study in Rome." *Energy Reports* 6: 56–61. doi.org/10.1016/j.egyr.2020.10.045.

Paragon Protection. n.d. "The history of spray foam insulation." www.paragon-protection.com/the-history-of-spray-foam-insulation/.

Pistochini, T., J. D. Feng, A. Aboud, D. Mitra, and S. Outcault. 2024. *Phase change material-enhanced insulation for residential exterior wall retrofits*. California Energy Commission. CEC-500-2024-086. www.energy.ca.gov/publications/2024/phase-change-material-enhanced-insulation-residential-exterior-wall-retrofits.

Rafter, D. 2024. "A shortage of skilled labor? It's still a challenge for the commercial construction industry." *REJournals*, March 14, 2024. rejournals.com/a-shortage-of-skilled-labor-its-still-a-challenge-for-the-commercial-construction-industry/.

Ricci, A., C. Ponzio, J. Gaspari, and E. Naboni. 2019. "A study on the impact of climate adaptive building shells on indoor comfort." *Journal of Facade Design and Engineering* 7 (1): 27–40. doi.org/10.7480/jfde.2019.1.2778.

Roberts, L. M. 2019. "How to specify building wrap." *Architect Magazine*, July 29, 2019. www.architectmagazine.com/technology/products/how-to-specify-building-wrap_o.

Rocky Mountain Institute. n.d. "Tenant protections." rmi.org/multifamily-affordable-housing-decarbonization-toolkit/tenant-protections/.

Scott, M. M., J. Axelrod, and H. D'Elia. 2024. "Who has access to good clean-energy jobs?" Urban Institute, May 1, 2024. www.urban.org/projects/clean-energy-job-access-race-gender.

Smalley, M. 2022. "Finding new links for the supply chain." *Building Enclosure*, Dec. 2, 2022. www.buildingenclosureonline.com/blogs/14-the-be-blog/post/91210-finding-new-links-for-the-supply-chain.

Snugg. 2024. "Common spray foam insulation problems (and what to do about it)." July 2, 2024. www.snugg.com/blog/common-spray-foam-insulation-problems-and-what-to-do-about-it.

Tao, Yao, Feng Wang, Tengfei Zhang, and Zhiqiang Zhai (Eds.). 2024. "Innovative materials and technologies for building envelopes." *Energy and Buildings* special issue. www.sciencedirect.com/special-issue/102D8Q3MBP2.

TechGolly. 2025. "Exploring the advancements in building envelope technology: Unveiling innovation." June 26, 2025. techgolly.com/exploring-the-advancements-in-building-envelope-technology-unveiling-innovation.

This report is available at no cost from the National Laboratory of the Rockies (NLR) at www.nlr.gov/publications.

Thermablok. n.d. “What is aerogel?” www.thermablok.co.uk/site/wp-content/uploads/2018/03/What-is-Aerogel.pdf.

Thie, C., S. Quallen, A. Ibrahim, T. Xing, and B. Johnson. 2023. “Study of energy saving using silica aerogel insulation in a residential building.” *Gels* 9 (2): 86. doi.org/10.3390/gels9020086.

Truitt, S., J. Bean, J. Sullivan, G. Paranjothi, and A. Moe. 2022. *Completing the circuit: Workforce development for advanced building construction and grid-interactive efficient buildings*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5500-80480. www.nrel.gov/docs/fy22osti/80480.pdf.

Truitt, S., J. Williams, and M. Salzman. 2020. *Building the efficiency workforce: preprint*. Golden, CO: National Renewable Energy Laboratory. NREL/CP-5500-75497. www.nrel.gov/docs/fy20osti/75497.pdf.

———. 2010. *Summary of gaps and barriers for implementing residential building energy efficiency strategies: 2010 residential buildings energy efficiency meeting*. DOE/GO-102010-3136. www.energy.gov/eere/buildings/articles/summary-gaps-and-barriers-implementing-residential-building-energy.

U.S. Department of Energy. 2016. “Building Envelope.” Aug. 30, 2016. betterbuildingssolutioncenter.energy.gov/building-envelope.

———. 2020. “ABC blog series: New technology to retrofit America.” Jan. 28, 2020. www.energy.gov/eere/buildings/articles/abc-blog-series-new-technology-retrofit-america.

———. n.d.-b. “Air Sealing for New Home Construction.” www.energy.gov/energysaver/air-sealing-new-home-construction.

———. n.d.-c. “Air Sealing Your Home.” www.energy.gov/energysaver/air-sealing-your-home.

———. n.d.-d. “Caulking.” www.energy.gov/energysaver/caulking.

———. n.d.-e. “Insulation.” www.energy.gov/energysaver/insulation.

———. n.d.-f. “National emerging technologies collaborative strategy.” www.energy.gov/eere/buildings/national-emerging-technologies-collaborative-strategy.

———. n.d.-g. “Weatherstripping.” www.energy.gov/energysaver/weatherstripping.

U.S. Energy Information Administration. 2023. “Use of energy explained: Energy use in commercial buildings.” Last updated June 29, 2023. www.eia.gov/energyexplained/use-of-energy/commercial-buildings.php

Walker, I., B. Less, N. Casquero-Modrego, and L. Rainer. 2021. *The cost of decarbonization and energy upgrade retrofits for US homes*. Berkeley, CA: Lawrence Berkeley National Laboratory. dx.doi.org/10.20357/B7FP4D.

This report is available at no cost from the National Laboratory of the Rockies (NLR) at www.nlr.gov/publications.

Wallin, E. 2023. “Air sealing: The key to improving energy efficiency in buildings.” ProptechOS, June 30, 2023. proptechos.com/air-sealing/.

Wang, G., J. Fang, C. Yan, D. Huang, K. Hu, and K. Zhou. 2024. “Advancements in smart building envelopes: A comprehensive review.” *Energy and Buildings* 312: 114190. doi.org/10.1016/j.enbuild.2024.114190.

Wang, J., Z. Li, T. Zhou, W. Deng, R. Liang, I. Y.-F. Lun, Y. Li, and R. Bao. 2024. “Global assessment of radiative cooling and low-emissivity coatings for energy efficiency in buildings across all climate zones.” *Energy and Buildings* 317: 114402. doi.org/10.1016/j.enbuild.2024.114402.

Window World. 2023. “Comparing window materials: The best options for homeowners.” Nov. 30, 2023. www.windowworld.com/blog/window-materials.

Aldykiewicz Jr, A. J., A. O. Desjarlais, D. Antunes da Silva, and S. B. Pallin. *The Environmental Impact of Deep Energy Retrofits in Residential Construction.* Oak Ridge National Laboratory, November 30, 2022. https://www.osti.gov/servlets/purl/1999091.

Harris, Chioke. *Pathway to Zero Energy Windows: Advancing Technologies and Market Adoption.* Golden, CO: National Renewable Energy Laboratory, April 2022. https://docs.nrel.gov/docs/fy22osti/80171.pdf.

Harris, Chioke. *Draft Research and Development Opportunities: Building Envelope.* Washington, DC: U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, May 5, 2020. https://www.energy.gov/sites/prod/files/2020/05/f74/bto-20200505_Draft_Envelope_RDO_0.pdf.

World Green Building Council. *World Green Building Trends 2018: SmartMarket Report.* Dodge Data & Analytics, 2018. https://worldgbc.org/wp-content/uploads/2022/03/World-Green-Building-Trends-2018-SMR-FINAL-10-11.pdf.

Narbuts, Jānis, and Ruta Vanaga. “Revolutionizing the Building Envelope: A Comprehensive Scientific Review of Innovative Technologies for Reduced Emissions.” *Environmental and Climate Technologies* 27, no. 1 (2023): 724–737. https://doi.org/10.2478/rtuect-2023-0053.

Sah, Tilak Prasad, Andrew William Lacey, Hong Hao, and Wensu Chen. “Prefabricated Concrete Sandwich and Other Lightweight Wall Panels for Sustainable Building Construction: State-of-the-Art Review.” *Journal of Building Engineering* 89 (2024): 109391. https://doi.org/10.1016/j.jobe.2024.109391.

Becqué, R., R. F. Allard, and C. Frischmann. “Building Retrofitting.” Project Drawdown, March 2, 2024. https://drawdown.org/solutions/building-retrofitting#:~:text=Most%20building%20retrofitting%20focuses%20on,)%3B%20water%20heating%3B%20and%20plug.

This report is available at no cost from the National Laboratory of the Rockies (NLR) at www.nlr.gov/publications.

Ashton, D. “A Guide to Retrofitting (and How It Could Help Us Reach Net Zero).” University College of Estate Management, May 22, 2024. https://www.ucem.ac.uk/whats-happening/articles/what-is-retrofitting/.

El-Darwish, Ingy, and M. Gomaa. “Retrofitting Strategy for Building Envelopes to Achieve Energy Efficiency.” *Alexandria Engineering Journal* 56, no. 4 (2017): 579–589. https://doi.org/10.1016/j.aej.2017.05.011.

Tsoy, N. “What Is a Double Glazed Window?” Apex Window Werks, March 21, 2023. https://apexwindowwerks.com/blog/what-are-the-benefits-of-double-glazed-windows/#How_Double_Glazed_Glass_Windows_Work.

True Blue Glass. “Advantages and Disadvantages of Double Glazing.” True Blue Glass, April 22, 2020. https://www.trueblueglass.com.au/advantages-and-disadvantages-of-double-glazing/.

U.S. Department of Energy. “Types of Insulation.” Energy.gov, 2025. https://www.energy.gov/energysaver/types-insulation#:~:text=Loose-Fill%20and%20Blown-In%20Insulation,and%20perlite%20are%20typically%20poured.

Studios, C. “The Benefits of Facades.” Lynco Facades Ltd, January 5, 2021. https://lyncoltd.com/news/the-benefits-of-facades/.

Chen, L., K. Zhang, G. Song, and F. Li. “Study on the Cooling Performance of a Radiative Cooling-Based Ventilated Roof for Its Application in Buildings.” *Building Services Engineering Research and Technology* 43, no. 6 (2022): 685–702. https://doi.org/10.1177/01436244221106342.

Wijesuriya, S., R. A. Kishore, M. V. A. Bianchi, and C. Booten. “Potential Energy Savings Benefits and Limitations of Radiative Cooling Coatings for U.S. Residential Buildings.” *Journal of Cleaner Production* 379 (2022): 134763. https://doi.org/10.1016/j.jclepro.2022.134763.

Blasco, M. P., and I. Cabrera. “Prefabricated Housing Construction Throughout History.” *ArchiDOCT* 12, no. 2 (2024): 33–41. https://doi.org/10.4995/anuari.2021.16108.

Wells Concrete. “The Complete Guide to Designing for Prefabricated Construction.” Wells Concrete, August 7, 2023. https://www.wellsconcrete.com/about/news-insights/what-is-prefabrication/.

Biro, A. “An Expert’s Guide to Prefabricated Building Materials.” *Gb&D Magazine*, 2024. https://doi.org/10.43311.43312.

PCI. “The Building Envelope.” PCI.org, 2025. https://www.pci.org/PCI/PCI/Design_Resources/Sustainability_Resources/The_Building_Envelope.aspx#:~:text=Color%20(albedo)%20of%20precast%20concrete,cooling%20dominates%20the%20energy%20requirements.

Building America. “Trade-Friendly Retrofit Insulated Panels for Existing Buildings.” NREL.gov, 2025. https://www.nrel.gov/docs/fy16osti/65184.pdf.

This report is available at no cost from the National Laboratory of the Rockies (NLR) at www.nlr.gov/publications.

Egerter, A., and M. Campbell. “Prefabricated Zero Energy Retrofit Technologies: A Market Assessment.” Rocky Mountain Institute, April 2020. https://rmi.org/wp-content/uploads/2020/04/prefabricated-zero-energy-retrofit-technologies.pdf.

Trout, A. “Analysis 2 - Exterior Wall System Background.” Pennsylvania State University, 2005. https://www.engr.psu.edu/ae/thesis/portfolios/2005/amt903/amt903Analysis2.pdf.

Volpe, S., V. Sangiorgio, A. Petrella, M. Coppola, M. Notarnicola, and F. Fiorito. “Building Envelope Prefabricated with 3D Printing Technology.” *Sustainability* 13, no. 16 (2021): 8923. https://doi.org/10.3390/su13168923.

Manning, Catherine G**.** “Technology Readiness Levels.” *Space Communications and Navigation Program*. NASA, 2023. Accessed February 12, 2026. https://www.nasa.gov/directorates/somd/space-communications-navigation-program/technology-readiness-levels/.

Less, B., and I. S. Walker. “A Meta-Analysis of Single-Family Deep Energy Retrofit Performance in the U.S.” Lawrence Berkeley National Laboratory, 2025. https://eta.lbl.gov/publications/meta-analysis-single-family-deep#:~:text=Substantial%20airtightness%20reductions%20averaging%2063%25%20(n=48)%20were,Yet%2C%20mechanical%20ventilation%20was%20not%20installed%20consistently.

Overbey, D. “Comparing Solar Heat Gain Coefficients (SHGC) and Shading Coefficients (SC).” *Building Enclosure*, May 18, 2015. https://www.buildingenclosureonline.com/blogs/14-the-be-blog/post/85233-comparing-solar-heat-gain-coefficients-shgc-and-shading-coefficients-sc.

Gorsia, P. “U-Values - Single vs. Double vs. Triple Glazing vs. C.U.in.” C.U.in, January 24, 2024. https://www.cuin.glass/blog/u-value-single-vs-double-vs-triple-glazing-vs-c-u-in/#:~:text=Triple%20Glazing%20U%20Value,0.8%20W/m2K.

Beauchamp, E. “Understanding Insulation R-Value - What Is R-Value?” *Today’s Homeowner*, November 21, 2024. https://todayshomeowner.com/insulation/guides/insulation-r-value/.

Air Barrier Association of America. “Air Barrier Installer Courses & Professional Training.” ABAA, April 6, 2017. https://www.airbarrier.org/education/installer-courses/#:~:text=Minimum%20of%203%2C000%20Hours%20of,constitute%20certification%20has%20been%20completed.

Gauzy. “AIA Smart Glass Course.” Gauzy, March 13, 2023. https://www.gauzy.com/aia-smart-glass-course/#:~:text=Gauzy%20is%20a%20Certified%20AIA,on-1%20or%20group%20presentations.

Isaacs, P. “U-Factor Differences Between Single Pane Windows, 1980s Double Pane Windows, and Double Pane Windows Today.” California Energy Consultant Service, June 2, 2023. https://www.calenergyexteriors.com/u-factor-differences-between-single-pane-windows-1980s-double-pane-windows-and-double-pane-windows-today/.

This report is available at no cost from the National Laboratory of the Rockies (NLR) at www.nlr.gov/publications.

Kim, J.-H., J. Hong, and S.-H. Han. "Optimized Physical Properties of Electrochromic Smart Windows to Reduce Cooling and Heating Loads of Office Buildings." *Sustainability* 13, no. 4 (2021): 1815. https://doi.org/10.3390/su13041815.

Wang, U. "Making Smart Windows That Are Also Cheap." *MIT Technology Review*, August 13, 2010. https://www.technologyreview.com/2010/08/13/201564/making-smart-windows-that-are-also-cheap/.

SGC. "Smart Glass Cost and Smart Film Price." Smart Glass Country. Accessed 2025. https://www.smartglasscountry.com/news/smart-glass-cost-and-smart-film-price.

PACOR.inc. "The Advantages of Aerogel Insulation Compared to Other Types of Insulation." Pacor Inc. Accessed 2025. https://www.pacorinc.com/the-advantages-of-aerogel-insulation-compared-to-other-types-of-insulation/.

U.S. Department of Energy. "Innovative Aerogel Production for Low-Cost and High-R Insulation." U.S. Department of Energy, 2021. https://www.energy.gov/eere/buildings/articles/innovative-aerogel-production-low-cost-and-high-r-insulation.

Baetens, R., B. P. Jelle, and A. Gustavsen. "Aerogel Insulation for Building Applications: A State-of-the-Art Review." *Energy and Buildings* 43, no. 4 (2011): 761–769. https://doi.org/10.1016/j.enbuild.2010.12.012.

Kanellos, M. "Aerogel Prices to Drop by 90 Percent?" *Greentech Media*, June 17, 2011. https://www.greentechmedia.com/articles/read/aerogels-to-drop-by-90-percent-in-price.

Agency for Toxic Substances and Disease Registry (ATSDR). Synthetic Vitreous Fibers. ToxFAQs. Centers for Disease Control and Prevention. Last reviewed March 26, 2014. Accessed June 2, 2026. https://wwwn.cdc.gov/TSP/ToxFAQs/ToxFAQsDetails.aspx?faqid=907&toxid=185.

BuyAerogel. "SpaceLoft®." Accessed March 21, 2025. https://www.buyaerogel.com/?s=spaceloft&post_type=product.

Coykendall, J., K. Hardin, J. Morehouse, V. Reyes, and G. Carrick. "Taking Charge: Manufacturers Support Growth with Active Workforce Strategies." *Deloitte Insights*, April 3, 2024. https://www2.deloitte.com/us/en/insights/industry/manufacturing/supporting-us-manufacturing-growth-amid-workforce-challenges.html.

NCARB. *NCARB by the Numbers 2022 Edition.* National Council of Architectural Registration Boards, 2022. https://www.ncarb.org/sites/default/files/NBTN2022.pdf.

Bruno, Robert, and Frank Manzo IV. *Living Wages in Registered Apprenticeship Programs: An Assessment by Industry, Demographics, State, and Labor Policy.* White paper, Illinois Economic Policy Institute and Project for Middle Class Renewal, January 20, 2025. https://illinoisepi.wordpress.com/wp-content/uploads/2024/12/pmcr-ilepi-living-wages-in-registered-apprenticeship-programs-final.pdf.

This report is available at no cost from the National Laboratory of the Rockies (NLR) at www.nlr.gov/publications.

Bureau of Labor Statistics. “Construction Laborers and Helpers.” U.S. Bureau of Labor Statistics, August 29, 2024. https://www.bls.gov/ooh/construction-and-extraction/construction-laborers-and-helpers.htm.

Meisels, M., M. Nikulin, K. Hardin, M. Sloane, and K. Dwivedi. “2025 Engineering and Construction Industry Outlook.” *Deloitte Insights*, November 3, 2024. https://www2.deloitte.com/us/en/insights/industry/engineering-and-construction/engineering-and-construction-industry-outlook.html.

Fisler, Diana, Roberto Interiano, Liam Keyek, Conor Larkin, Maura Mooney, Aven Satre-Meloy, and Lucas Toffoli. Market Opportunities and Challenges for Decarbonizing US Buildings: An Assessment of Possibilities and Barriers for Transforming the National Buildings Sector with Advanced Building Construction. Advanced Building Construction Collaborative, 2021. https://advancedbuildingconstruction.org.

Fiscal, Paulina Rodriguez, Han Vandevyvere (VITO/EnergyVille), and Leen Peeters (Th!nk E), with Smart Cities Marketplace managed by the European Commission Directorate-General for Energy. Solution Booklet: Building Envelope Retrofit. Smart Cities Marketplace © European Union, January 2023. https://build-up.ec.europa.eu/sites/default/files/content/230113-solution_booklet-building_envelope_retrofit.pdf.

Frigione, Maria, Michele Lettieri, and Antonio Sarcinella. “Phase Change Materials for Energy Efficiency in Buildings and Their Use in Mortars.” *Materials* 12, no. 8 (April 17, 2019): 1260. https://doi.org/10.3390/ma12081260.

International Code Council. *2015 International Energy Conservation Code (IECC)*. January 2016. https://codes.iccsafe.org/content/IECC2015.

International Code Council. *2021 International Energy Conservation Code (IECC)*. September 2021. https://codes.iccsafe.org/content/IECC2021P2.

International Code Council. *2024 International Energy Conservation Code (IECC)*. May 2024. https://codes.iccsafe.org/content/IECC2024P1.

Julin, Kiran. “High-Performance Window Demonstrates.” *Windows and Daylighting*, Lawrence Berkeley National Laboratory, March 12, 2021. https://windows.lbl.gov/news/high-performance-window-demonstrates.

Kuznik, Frédéric, and Dominique David. “Integration of Phase Change Materials into Building Materials for Thermal Storage.” In *Smart Materials for Energy, Communications and Bio-Technology*, edited by Mel Schwartz, 37–56. Cham: Springer, 2015. https://doi.org/10.1007/978-3-319-14286-9_2.

Lam, Chung H. “History of Phase Change Memories.” In *Phase Change Materials: Science and Applications*, edited by Simone Raoux and Matthias Wuttig, 1–14. Boston, MA: Springer, 2009. https://doi.org/10.1007/978-0-387-84874-7_1.

This report is available at no cost from the National Laboratory of the Rockies (NLR) at www.nlr.gov/publications.

Manning, Catherine G. “Technology Readiness Levels.” *Space Communications and Navigation Program*. NASA, 2023. Accessed February 12, 2026. https://www.nasa.gov/directorates/somd/space-communications-navigation-program/technology-readiness-levels/.

McGawn Designs. “Discover the History of Double Glazing and Its Impact on Modern Homes.” *Scotia Windows and Doors*, March 15, 2023. https://www.scotiawindowsanddoors.co.uk/the-evolution-of-double-glazing-a-comprehensive-look-at-its-history-and-development/#:~:text=The%201950s%20and%201960s%20witnessed,United%20States%20by%20Andersen%20Corporation.

Mullins, C. D., J. J. Wingate, and C. R. Edwards. “Transitioning from Learning Health Systems to Learning Health Care Communities.” *Learning Health Systems* 3, no. 2 (April 2019): e10189. https://pmc.ncbi.nlm.nih.gov/articles/PMC6515401/.

Piqueras Blasco, Maria, and Ivan Cabrera i Fausto. “Prefabricated Housing Construction Throughout History.” *archiDOCT* 12, no. 2 (October 15, 2024): 33–41. https://archidoct.scholasticahq.com/article/123914-prefabricated-housing-construction-throughout-history.

Prefab Museum. “A Short History of Prefabrication.” *Prefab Museum*, accessed February 12, 2026. https://www.prefabmuseum.uk/content/history/short-history-prefabrication.

Srivastava, Rohini, Roxana Ayalam, and Alex Aquino. Building a Workforce for Energy-Efficient Homes. Washington, DC: ACEEE, 2025. https://www.aceee.org/research-report/b2501.

Vigna, Ilaria, Lorenza Bianco, Francesco Goia, and Valentina Serra. “Phase Change Materials in Transparent Building Envelopes: A Strengths, Weakness, Opportunities and Threats (SWOT) Analysis.” *Energies* 11, no. 1 (2018): 111. https://doi.org/10.3390/en11010111.

Wilson, Alex. “Storing Heat in Walls with Phase Change Materials.” *Green Building Advisor*, November 24, 2009. https://www.greenbuildingadvisor.com/article/storing-heat-in-walls-with-phase-change-materials#:~:text=Phase%2Dchange%20materials%20(PCMs),them%20effective%20for%20heat%20storage.

Grand View Research. *The United States Building Envelope Market Size & Outlook, 2033*. https://www.grandviewresearch.com/horizon/outlook/building-envelope-market/united-states.

Kishore, Ravi Anant, Chuck Booten, Marcus V. A. Bianchi, Judith Vidal, and Roderick Jackson. 2022. “Evaluating Cascaded and Tunable Phase Change Materials for Enhanced Thermal Energy Storage Utilization and Effectiveness in Building Envelopes.” *Energy and Buildings* 260 (April): Article 111937. https://doi.org/10.1016/j.enbuild.2022.111937.

This report is available at no cost from the National Laboratory of the Rockies (NLR) at www.nlr.gov/publications.

Verified Market Reports. *Building Envelope Market Size, Industry Trends, Growth & Forecast 2033*. February 2025. https://www.verifiedmarketreports.com/product/building-envelope-market/.

Truitt, S., Williams, J., & Salzman, M. (2020, August 17-21). Building the efficiency workforce preprint. National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy20osti/75497.pdf

Truitt, S., Bean, J., Sullivan, J., Paranjothi, G., & Moe, A. (2022, March). Completing the circuit: Workforce development for advanced building construction and grid-interactive efficient buildings. National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy22osti/80480.pdf

This report is available at no cost from the National Laboratory of the Rockies (NLR) at www.nlr.gov/publications.