Research Opportunities for Building Decarbonization Through Industrialized Construction

Tyler J. Pilet and Cheryn E. Metzger, Pacific Northwest National Laboratory (PNNL)
Rachel Lebedinsky and Rebecca Ciraulo, Guidehouse, Inc.

ABSTRACT

With the U.S. building stock responsible for nearly three-quarters of U.S. electrical use and over one-third of U.S. carbon emissions, substantial work is needed to decarbonize the U.S. building stock and meet 2050 climate goals. To reach these ambitious goals, the rate of building retrofits will need to increase drastically, and practices to renovate and construct energy-efficient, low-carbon buildings are generally too labor-intensive, costly, and disruptive to scale at the required pace. To address these problems, the U.S. Department of Energy's Advanced Building Construction Initiative was developed to accelerate the speed and scale of U.S. building decarbonization through the adoption of industrialized construction techniques. These techniques include improved processes, on- and off-site fabrication, and techniques specifically engineered to streamline installation, therefore mitigating the augmented cost, labor, and time associated with high-performance retrofit and new construction technologies. This paper seeks to highlight the current state and opportunities for research, development, and demonstration within the industrialized construction market through a cohort of industrialized construction innovations. These innovations, informed by rigorous stakeholder engagement, span envelope and whole-building retrofit topic areas and are a collection of processes, technologies, and challenges that each serve a role in the decarbonization of various building typologies, vintages, and climates. For each of the industrialized construction innovations, current states, goals, and research opportunities are highlighted with an eye to near-term development and prioritization of research needed to appreciably increase the speed, scale, and reach of decarbonization within the U.S. building stock.

Introduction

The building sector in the United States currently accounts for 75% of total electricity consumption, 40% of energy usage, and 35% of CO_2 emissions (EIA 2023). To meet ambitious national climate targets the U.S. building stock must be decarbonized by 2050 (Fisler et al. 2021, SDSN & FEEM 2021, Mahajan 2019, Leung 2018). However, the current rate of building retrofits of only 0.5–1% of buildings annually falls significantly short (Langevin and Wilson. 2024), and conventional approaches to constructing or renovating buildings to achieve low-carbon, high-performance standards are typically labor-intensive, disruptive, and prohibitively expensive for widespread adoption in the U.S. (Architecture 2030 2018). To retrofit 80% of the nation's building stock by 2050, the rate of retrofitting will need to increase substantially, by approximately 15 times for residential buildings and twice for commercial structures (Nadel and Hinge 2020, EIA 2019, Census Bureau 2019, EIA 2015). Additionally, there exists a significant housing shortage in the country, with nearly 600,000 individuals lacking adequate or stable housing, and construction rates failing to meet the current need.

This paper provides support for the broad implementation of whole building energy retrofits and rapid growth of efficient new construction by highlighting key opportunity areas for research and development and pilot demonstration within the industrialized construction space. These opportunity areas address two major areas of need for building energy improvements—building envelope improvements and building mechanical system improvement—and were selected through a series of online and in-person public meetings with a group of nearly 200 stakeholders. These opportunity areas were also carefully selected to not overlap with topics currently published and addressed in U.S. Department of Energy (DOE) roadmaps and research and development opportunity reports (Harris 2021, Harris 2022, Satchwell 2021). The research opportunity areas covered within this paper are as follows:

- Insulation and Air Sealing for Existing Building Cavities
- Wall and Window Panel Systems
- Adding Exterior Insulation When Re-siding
- Streamlining High-Performance Window Installation
- Wall Panels with Mechanical System Integration

One key element of decarbonizing the building stock is retrofitting the building envelope to an appropriate level. Building on the Research and Development Opportunity (RDO) documents related to Opaque Envelope and Windows (Harris 2021, 2022), the following innovations aim to industrialize the installation of those technologies in the envelope upgrade process that is necessary for approximately 75% of the residential building stock (see Table 1). At least 50% of commercial buildings have underperforming envelopes that would benefit from these upgrade installation developments as well (Hun et al. 2018). Streamlining the installation processes and making the processes more replicable, either onsite or offsite, will potentially make them faster, applicable to more buildings, and ultimately lower cost than the business as usual today.

With the passage of the Bipartisan Infrastructure Law and the Inflation Reduction Act, there are many new energy efficiency incentives and financing options that incentivize building energy retrofits. These incentives are anticipated to spur interest and build consumer demand for affordable and effective energy retrofit technologies. In this supportive environment, there is more of a need than ever to bring new retrofit technologies to market to satisfy near-term market demand and achieve building decarbonization goals.

Insulation and Air Sealing for Existing Building Cavities

Introduction

Effectively insulating and air-sealing exterior wall cavities is crucial for preventing air leakage and significantly enhancing a building envelope's thermal performance. The most common method for insulating enclosed cavities in existing buildings is called "Drill-and-Fill", which involves professionals blowing or injecting insulation material into empty cavity spaces. Options for drill-and-fill insulation range from blown-in cellulose, low-density foams, and mineral wools, to expanded polystyrene beads, all aimed at filling empty wall cavities to impede heat and air transport through the assembly. It should also be noted that this section is specially focused on solutions for insulating and air-sealing enclosed cavities in existing buildings, as new construction buildings are either insulated with continuous insulation, cavity insulation, or a combination of both during the building's construction.

Outside of situations where envelope assemblies are taken apart and reconstructed (often only occurring during major renovation or rehab), Drill-and-fill is the prevalent technique for insulating existing wall cavities. This technique involves drilling 1- to 2-inch diameter openings in the building envelope to access the cavity, either through interior walls or exterior facades. Insulation is then inserted into the empty wall cavity often utilizing a blower or sprayer. Metering and thermal imaging tools are often utilized to determine the appropriate amount of insulation material to inject. Once the injection is complete, the hole is sealed and patched to minimize its appearance. A photo displaying an example drill-and-fill retrofit is displayed in Figure 1.

Figure 1. An insulation contractor inspecting a drill-and-fill insulation retrofit installed in an experimental facility. *Source:* Patrick Huelman, University of Minnesota

Minimally invasive and less disruptive approaches to insulating enclosed cavities are particularly crucial in the residential sector. Approximately 80% of homes currently have enclosed cavities, and those built over two decades ago may have uninsulated empty cavities. Insulating these wall cavities can reduce heat loss by 7–27% annually, depending on the climate zone (Zheng et al. 2020). Drill-and-fill methods are also applicable to both single-family and multifamily homes, as well as commercial buildings, primarily those with wood or light gauge steel frame walls. This approach shows promise for application in both subsidized and naturally-occurring affordable housing; however, drill-and-fill retrofits can be challenging to market to individual homeowners and affordable housing owners due to cost and potential disruption.

Opportunity Area Summary Table

Current State	• Some minimally invasive and streamlined installation processes exist today to insulate and seal enclosed building cavities but require advancements to lessen occupant disruption, increase viability of solutions across climates, building types, configurations, and structural conditions via innovation, improve methods to assess the condition of the walls, air leakage, and any existing insulation, improve methods to quality check, decrease the overall installed cost, and increase awareness and access to savings information, and environmental impacts
Innovation Goals	• Possible to install in all building and façade types from the outside and year-round • Any drilled holes are 3/8-inch or smaller in diameter • All cavities including around window frames and other seams or joints in the facade can be filled and sealed, and indoor air quality is considered • Foam insulations containing low GWP materials and no/low volatile organic compound (VOC) emissions • Low-embodied carbon materials which can be injected in building cavities • Costs less than $1,000 for average single-family homes • Installed in 1-2 days for all single-family homes; 8-10 apartment units per day or less than 8 days for small-medium commercial buildings • Occupant disruption limited to a half day for homes and commercial buildings with daily occupancy • Low-cost tools to assess the building cavity and check performance post-installation with minimal manual intervention
Technical Challenges	• High cost of installation process, equipment, and low GWP materials • The many layers, components, and configurations within the building envelope are often difficult to access or assess • Need for installation methods that include materials and equipment that can perform in all climates including cold temperature conditions • Not every façade type can be accessed or drilled from the outside • Plumbing and electrical wiring may become difficult to service and must be up to code before installation • Lack of equipment mobility and low throughput rate of foam insulation approaches make installation challenging and time-intensive
Market Challenges	• Lack of information and awareness on proven benefits especially in single family homes and potential savings data • Little adoption in energy efficiency programs as an approved measure for financial incentives
Workforce Challenges	• High turnover due to a largely seasonal or temporary workforce (due to lack of equipment and material options that can adequately performed in all temperatures) • Few low-cost, easy to use tools exist to quality control installation of fill-and-fill processes

Wall and Window Panel Systems

Introduction

To achieve carbon goals and meet housing demands, the U.S. will need to execute energy retrofits for about 11,000 homes per day (about 30 times our current production) and build about 6,000 homes per day (about double our current production) (Hasz et al. 2020). Building envelope retrofits can significantly improve thermal and moisture performance by integrating heat, air, and moisture barriers. However, retrofit approaches today are largely not scalable because they are labor intensive, costly, and disturb occupants or neighborhoods for long periods.

Today, there are panel manufacturers who originally made prefabricated panels for new construction that are attempting to add products that would be available for retrofits. Some panels currently on the market provide only structural support (BMC 2021), while others also add insulation and air and vapor barriers (Dryvit 2021). For these panels to perform their functions reliably, they need to be well-sealed to each other and the existing structure (if applicable). This requires a range of onsite work to customize the panels for the building on which they are being installed. Although some panels may be developed based on building scans and with specific instructions for certain parts of the building, many challenges remain onsite, such as buildings that are out-of-square, penetrations, window and door interfaces, and footing and wall-roof interfaces which may cause problems with panel fit and connection points. Most of these challenges can be assessed before the materials arrive on site; however, the materials in most structural panels are rigid and require some amount of cutting, trimming, and re-sizing while onsite. Another challenge is the lack of QA/QC cues to the installing and inspecting parties. Assuring quality during installation and to satisfy inspections are important aspects to consider during the development and evaluation of quick connect innovations. Automatic detection systems do not currently exist for building envelope installations.

Technologies and automation strategies for prefabricated wall and window panel systems can make envelope retrofits faster, easier, and more scalable by applying multifunctional solutions (e.g., air, water, and thermal protection) without requiring hundreds of cuts at every layer of the new wall, removal of existing claddings, or significant reconstruction. These new technologies and approaches should reduce labor, cost, and time while providing a robust envelope retrofit solution that applies to many types of existing buildings. Unlike the insulation and air sealing solutions discussed in the previous section, these solutions would primarily apply to envelope retrofits of the entire exterior, including windows, walls, structure, insulation, and air and water barriers. This technology applies to approximately 70% of existing residential buildings and approximately 50% of commercial buildings that require an exterior wall retrofit. A photo of a wall and window retrofit panel can be seen in Figure *2*. (Webster et al. 2024).

Figure 2. A wall and window retrofit panel being lifted from a truck bed by a crane. *Source:* RMI 2022.

To date, multiple retrofit wall panel technologies are under development through existing research projects funded by DOE under the 2019 Advanced Building Construction Funding Opportunity Announcement (FOA) awards (EERE 2020) and 2022–2023 BENEFIT FOA awards (EERE 2023). These projects include mechanisms to connect panels; however, they do not focus on developing universal quick connections for retrofit panels. Additional funding support for development of wall and window retrofit panels is also anticipated to come available via the upcoming Residential Envelope Technology Retrofit Opportunity for Value Improvement Propositions (RETRO-VIP) solicitation from the California Energy Commission (CEC), which has a specific track to increase technology readiness levels for panelized retrofit systems Along with solicitations like CEC's RETRO-VIP, additional work is needed to make high-quality, robust connections easier to apply with limited training.

Opportunity Area Summary Table

Current State	• Insulating wall panels are only available to purchase for new construction, and all feature proprietary connection points that require brand-specific training to install • Panels that are currently under development have connection mechanisms but do not focus on fast and universal connections

Innovation Goals	• Flexible enough to fit most building oddities, including out-of-square windows, doors, corners, etc. • Cost no more than $10/sq. ft. installed • Installed on a typical 2,000 sq. ft. house in 7 days or less and installed in a small (less than 5,000 sq. ft.) commercial building in 15 days or less, with installation times increasing as the square footage goes up • Products that last 30+ years in each climate zone • Product lines for varying climatic conditions and/or insulation levels • Universal quick-connect mechanisms to preserve compatibility across product lines or manufacturers.
Technical Challenges	• Panel integration with existing roof, foundation, windows, and other penetrations that is water-tight and air-tight, while addressing thermal bridges is technically complex. • High cost of materials. • Critical control layers (vapor, bulk moisture) must be kept intact, and might require multiple snapping or sealing components and currently may have a lifespan which is less than an average loan period. • Panels should be designed for net-zero carbon emissions when comparing embodied carbon to operational carbon savings over the lifetime of the product.
Market Challenges	• High installed cost due to the unique configurations of buildings across the U.S. • Need for accurate building data that can be collected in a quick and streamlined fashion so that multiple product manufacturers or suppliers can create systems that work for a variety of existing buildings • Difficulty convincing multiple manufacturers to work together to create compatible products, but if they succeed, economies of scale are possible
Workforce Challenges	• Workforce training is not widely available and is necessary to scale this innovation • Once products are market available, workers will need training in panel installation procedures and QA/QC.

Adding Exterior Insulation When Re-siding

Introduction

Siding is typically replaced because of damage, normal wear over time, or to improve the look of the home. In 2020, around 5 billion sq. ft. of siding was added to homes, about 80% for re-siding and 20% for additions (Friege et al. 2016, Home Innovation Lab Survey, and stakeholder interviews). In 2020, 3.5 million homes spent money on siding projects (replacement, repairs, and additions).

The New Jersey Institute of Technology (NJIT) conducted a field validation project from 2018–2021 entitled "Re-Side Right." They worked on 10 field projects with siding contractors to try to understand the market opportunity to add insulation at the time of re-siding and specifics about how insulation could be added to the installation process. One of the first realizations was that siding contractors working on the walls of a home are not interested in blowing insulation into the walls. Doing so requires a machine and skill set that is too different from their original scope to be realistic for them to incorporate. Therefore, the NJIT project focused on exterior insulation that can be installed with the same tools and skills that a crew would already have for installing siding alone.

This section focuses on the opportunity to add exterior insulation when re-siding, using the workforce on site during a re-siding project. Primary adoption drivers for this process improvement include financial savings associated with an already-scheduled re-siding project, improved comfort, and the opportunity to take a major step towards a heat-pump-ready building, for those homeowners and building-owners who are motivated by decarbonization. Less than 10% of residential re-siding projects add 1 inch or more of insulation during re-siding projects (Friege et al. 2016). This is likely because adding insulation to the re-siding process requires training the crew that is onsite during a re-siding project to 1) add insulation; 2) tape the seams to create a weather-resistant barrier; and 3) install siding on top of the insulation. To address this issue, PNNL is leading a project to scale the training of crews who are onsite during re-siding projects, until a more comprehensive product or novel approach is developed. So far, PNNL has completed almost 50 projects to add insulation when re-siding on single-family and multifamily buildings. This project, along with others that led up to it has found that prices for adding insulation when re-siding can range from about $1-$2 per square foot for 1 inch or R-5 of added insulation.

Insulated vinyl siding, which represents about 3-5% of the residential market, offers a potential solution to the need for multiple steps and skillsets to install insulation while re-siding (Friege et al. 2016, Home Innovation Lab Survey, and stakeholder interviews). Insulated vinyl siding offers additional R-2 or R-3 insulation integrated into the siding product so that ostensibly only one installation step is needed. BTO has also funded bio-based R-5+ insulated siding projects within the 2022-2023 BENEFIT FOA awards (EERE 2023). Regardless of insulating value, one downside of insulated siding is the lack of a supplemental water management layer associated with a combined siding-plus-insulation product. Thus, a proper weather-resistive barrier needs to be applied to the existing sheathing prior to adding the siding. Another drawback is that the insulated siding is usually installed in a lapped-fashion, which assists with shedding bulk water but means that lapped layers have inconsistent R-values and include air cavities between siding layers.

An insulation product that either snaps together or has an overlap feature that removes the moisture management step is a potential solution. It would likely save time and money and improve installation quality and reliability to further remove the possibility of human error.

Exterior Insulation and Finish System (EIFS), an exterior wall cladding that utilizes insulation boards on the exterior of the wall sheathing integrated with a textured protective finished coat, are available for residential and commercial buildings. Some systems include drainage to address water management, and are the primary system type currently installed (EIMA n.d.). EIFS are installed using mechanical fasteners or adhesives by certified contractors. One drawback of these systems is that they require a "like new" substrate to attach to, which can be cost-prohibitive (Antonopoulos et al. 2022).

Opportunity Area Summary Table

Current State	• Continuous insulation is installed in many new construction scenarios and is required in many climates to meet 2021 IECC requirements. • Siding contractors often only replace siding when re-siding buildings, and do not add insulation before replacing siding.
Innovation Goals	• Reduce the steps associated with adding insulation when re-siding • Cost no more than $1/sq. ft. installed • Have built in-moisture management • Installable over existing cladding and allows for cladding on top • Products that last 30+ years in each climate zone.
Technical Challenges	• Details associated with wall penetrations such as pipes, vents, windows, corners, etc. • The relatively high cost of materials that can create a weather resistive barrier with continuous insulation.
Market Challenges	• Homeowner education about the opportunity of adding insulation during re-siding. • Utility and contractor education about the opportunity to bundle additional services into re-siding jobs. • Integrated insulation and cladding products are prohibited in some jurisdictions.
Workforce Challenges	• Simple installer training and guidance that can be learned and utilized on-site. • Re-siding contractors typically do not insulate, and insulation contractors often do not reside buildings.

Streamlining High-Performance Window Installation

Introduction

Windows provide views, daylighting, and aesthetics to building occupants and are a major component of building envelope systems. While windows provide many benefits, it is estimated that approximately 25-30% of energy losses in buildings occur via windows (DOE n.d.). Windows are a penetration in a building's opaque envelope, which allows for heat to shortcut insulated portions of a building's envelope. Because of this, there is a significant need for high-performance, insulating windows to be installed in new construction and retrofit buildings.

In both retrofit and new construction scenarios, windows typically require the time-consuming installation of tapes, gaskets, and sealants to affix the window and maintain an air- and water-tight installation. Window installation can also be complex since drainage and flashing details must be fully integrated before the window, otherwise, water will intrude into the assembly and often appear behind the window, even if the window's flashing or installation is not the cause.

Another major challenge for windows is installation challenges associated with exterior insulation, both in retrofit and new construction scenarios. When adding more than 1 inch of exterior insulation past the wall's sheathing, window installations require several additional steps, including one very time-consuming activity of re-trimming windows to account for thicker walls and air and water sealing around window penetrations in the opaque envelope. In a factory setting, many of these issues can be addressed by the development of prefabricated trim and pre-installed control layers (both for panelized walls and for bespoke exterior insulation assemblies), which can be integrated as a whole-window panel or as a standalone solution.

Key stakeholders include contractors, researchers, manufacturers, historical societies, and architects. This innovation applies to all existing residential and commercial buildings.

At this point, window installations are costly and time-consuming, requiring significant onsite labor for each project. Conventional windows are currently sold in two major styles—flanged and flangeless. Flanged windows are shipped (mostly to new construction residential building sites) with an integral nailing flange, which speeds up installation by providing pre-marked spaces for onsite workers to drive nails or screws for window installation to boost productivity. Despite their benefits, flanged windows still require taping, sealing, and trimming to maintain the continuity of an envelope's water and air control layers. It should also be noted that flanged windows must be installed flush with the building's structural sheathing layer. (Windows in commercial buildings are often installed into steel or block openings, making flanged windows impractical in many commercial applications).

Flangeless windows are sold in both residential and commercial building markets, with flangeless windows often being a characteristic of European window products. Flangeless windows can be installed anywhere within a window's rough opening—flush with the building's exterior, flush with the interior, or anywhere in between. As compared to flanged windows, flangeless windows require significantly more effort, requiring stop blocks for installation, mechanical attachment of flangeless window "clips" (less of a clip in the conventional sense and more of a strap affixed to the building with screws), and sealing of the window via tapes, gaskets, and sealants.

Currently, window installations are a point of difficulty for buildings with exterior insulation. Exterior insulation can come in many forms, both structural and non-structural. In non-structural cases, windows must be affixed to the building's structural cladding, requiring windows to be installed inset of the envelope's exterior plane. In these cases, the space between the assembly's cladding and the window's surface must be trimmed and flashed properly to avoid water intrusion into the wall assembly. In the case of structural panels, windows can be installed at the cladding's face or inset, depending on preference. In the cases where a window is installed at the cladding's face, significant onsite effort must be employed to maintain drainage paths and to avoid water intrusion behind the installed window. In both of these cases, onsite trim work is required to install windows in walls with exterior insulation either as an interior jamb extension or as a structural window box installed outboard of the building's structural sheathing.

Opportunity Area Summary Table

Current State	• Flanged windows provide an integral flange to speed up window installation in new construction residential, but still require manual application of tapes, gaskets, and sealants • Flangeless windows provide flexibility in the installation location of windows in both residential and commercial buildings, which is especially important on buildings with exterior insulation or thick walls, but require significant effort to air and water seal • The re-trimming of windows is especially labor- and time-intensive and is currently done manually and onsite
Innovation Goals	• Process and technology innovations such as prefabricated window and trim that is shipped to the site; snap-together parts; or automated onsite fabrication • Includes pre-installed sealant where applicable so that caulk and tapes do not need to be applied onsite • Includes a sloped bottom sill and sloped top plate with a drip edge • Window, trim, and sealants are installed in less than 10 minutes • Costs the same (including installation labor costs) as onsite window and trim (about $1,800 for a 2,000 sq. ft. building and increasing from there, relative to building size)
Technical Challenges	• No quick way to remove old caulk or foam that was previously air sealing the window • Window removal and replacement can be very disruptive for occupied buildings.
Market Challenges	• There are many products and steps which must be followed to maintain air- and water-tightness in window installation. Each manufacturer has specific guidelines and requirements which must be followed, increasing onsite difficulty.
Workforce Challenges	• Many onsite workers are trained to install manufacturer's product line and require retraining due to lack of product consistency • Lack of guidance or training on how to install extended window trim or window bucks for exterior insulation projects

Wall Panels with Mechanical System Integration

Introduction

Improving the process of renovating walls and heating, ventilation, cooling, and water-heating mechanical systems at the same time is key to accelerating building retrofit rates, in specific scenarios such as retrofits of old buildings or major renovation opportunities.

As described in the wall and window panel systems section earlier, current wall panel installation techniques are labor intensive, costly, difficult to customize, and disruptive to residents and neighbors. There are also no universal or easy-to-use connection points to other panels or QA/QC indicators to tell installers and inspectors the panels have been correctly installed. Installing separate mechanical systems leads to more heat loss and less efficient systems, complex and difficult installation and maintenance procedures, and more costly, time-consuming, and disruptive experiences for residents.

In scenarios where both the envelope and mechanical systems in a building need to be upgraded, integrating wall panels with high-performance insulation and high-efficiency integrated mechanical systems is a potential solution to make the process easier, faster, and more streamlined. New panelized retrofits can provide structural support, more efficient insulation, and improved water and air distribution with ductwork, refrigerant lines, plumbing, and equipment directly within the wall panel. Integrating mechanical systems into wall panels also removes the need for HVAC equipment to consume square footage within living spaces and streamlines the delivery process by having one contractor. Finally, because the mechanical system unit is assembled in a factory setting, installation quality is improved, installation costs are reduced, and the renovation process is faster and easier, making it less disruptive to occupants.

This innovation applies to multifamily and single-family buildings, especially for new construction, and also including major renovations and additions, and for cases where both the building envelope and mechanical system upgrades are needed or where space constraints are an important factor.

There are panels with mechanical system integration currently in development in the U.S. and Europe, but no products are commercially available. The U.S. DOE is funding two RD&D projects by NREL and ORNL that are related to mechanically integrated wall panel solutions, which will be demonstrated in real buildings as part of the current project. The NREL project is a high-performance heat pump integrated into an envelope upgrade panel, while the ORNL project also includes water heating, ventilation, and grid response capabilities.

Opportunity Area Summary Table

Current State	• Prefabricated wall panels with integrated mechanical systems in different forms are currently being explored by researchers and require further RD&D and validation. These systems can also include integrated PV systems and dynamic controls.
Innovation Goals	• High-performing heat pumps and heat pump water heaters integrated into high-efficiency insulated wall or wall and window panel • Flexible enough to fit most building configurations • Easily connect to other panels and includes visual or auditory QA/QC feedback indicators • Panel and mechanical system combinations that meet the needs for every U.S. climate zone • Mechanical system integration is easily accessible for maintenance • Reduced costs as compared to separate envelope and mechanical system retrofits
Technical Challenges	• Water-tight and air-tight panel integration with existing components, HVAC penetrations, and plumbing penetrations can be technically complex and time consuming • All mechanical systems must be condensed into a narrow area to maintain desirable panel profile • Water, air, and vapor control layers must be maintained around integrated mechanical systems; some designs may require a thin high-R layer to account for recess in panel
Market Challenges	• Zoning and installing HVAC systems can bear a high installed cost due to unique configurations of existing buildings • Need for HVAC and panel manufacturers to easily share building designs and data in a quick and streamlined manner or create new designs to meet existing building needs; will likely require the manufacturers to partner or work closely together on the solution • Consumers must want both an envelope upgrade and mechanical systems upgrade at the same time and in the same specific location within the building
Workforce Challenges	• Most installations will likely require collaboration and shared knowledge between HVAC and siding or panel installers and general contractors

Conclusion

As articulated in the recent Buildings Decarbonization Blueprint (Langevin and Wilson. 2024), there is a significant need to increase the speed and scale of building energy retrofits, and industrialized construction technologies provide a unique opportunity to improve energy performance, minimize total cost, and reduce occupant disruption. Through research and development in the areas articulated in this paper, there is a significant opportunity to improve upon existing technologies and address the technical, market, and workforce research gaps and challenges for each area. These gaps are opportunities that allow for various market actors to pave the way for these retrofit technologies. For example, technical gaps create conditions for research entities and private industry to develop, pilot, and bring new technologies to market; market conditions provide the opportunity for government and trade organizations to build demand for these technologies; and workforce gaps provide conditions for trade schools, training centers, and national labs to build awareness for individual technologies.

With current social, technological, and market conditions, now is the time to capitalize upon market demand generated by current climate goals, funding mechanisms, and energy efficiency incentives to develop and leverage industrialized construction technologies to retrofit buildings. This paper illuminates the needs and opportunities for these process-focused innovations that can help transform and modernize the building industry to help reach the necessary speed and scale to decarbonize U.S. buildings by 2050.

References

Architecture 2030. n.d. "Existing Buildings: Operational Emissions." Accessed July 23, 2021. architecture2030.org/existing-buildings-operation/.

BMC. 2021. "Build With BMC." BMC Stock Holdings, Inc. Accessed June 25, 2021. www.buildwithbmc.com/bmc.

Census Bureau. 2019 "American Housing Survey (AHS) Table Creator: 2019 National – Housing Unit Characteristics – All Housing Units." Accessed June 25, 2021. www.census.gov/programs-surveys/ahs/data/interactive/ahstablecreator.html?s_areas=00000&s_year=2019&s_tablename=TABLE0&s_bygroup1=4&s_bygroup2=1&s_filtergroup1=1&s_filtergroup2=1.

DOE (Department of Energy). n.d. *Update or Replace Windows.* www.energy.gov/energysaver/update-or-replace-windows.

Dryvit. 2021. "Modulite Prefabricated Solutions." www.dryvit.com/panelization-modulite/.

EERE (Office of Energy Efficiency and Renewable Energy). 2020. "Advanced Building Construction Projects." U.S. Department of Energy. Accessed February 29, 2024. www.energy.gov/eere/buildings/listings/advanced-building-construction-projects.

EERE (Office of Energy Efficiency and Renewable Energy). 2023. "Meet DOE's Newest Research Projects from BENEFIT 22-23." U.S. Department of Energy. Accessed February 29, 2024. www.energy.gov/eere/buildings/articles/meet-does-newest-research-projects-benefit-22-23#:~:text=On%20August%207%2C%202023%2C%20DOE,sustainable%2C%20and%20resilient%20building%20operation.

EIA (Energy Information Administration). 2015. "A Look at the U.S. Commercial Building Stock: Results from EIA's 2012 Commercial Buildings Energy Consumption Survey (CBECS)." Commercial Buildings Energy Consumption Survey (CBECS). Accessed June 25, 2021. www.eia.gov/consumption/commercial/reports/2012/buildstock/.

EIA (Energy Information Administration). 2019. "Table: Residential Sector Key Indicators and Consumption." *Annual Energy Outlook 2019*. Accessed June 25, 2021. www.eia.gov/outlooks/aeo/data/browser/#/?id=4-AEO2019&region=0-0&cases=ref2019&start=2017&end=2050&f=A&linechart=ref2019-d111618a.4-4-AEO2019~ref2019-d111618a.5-4-AEO2019~ref2019-d111618a.6-4-AEO2019~ref2019-d111618a.7-4-AEO2019&map=&sourcekey=0.

EIA (Energy Information Administration). 2023. "Reference Case Projections Tables." Tables 5, 6, and 18. *Annual Energy Outlook 2023*. www.eia.gov/outlooks/aeo/tables_ref.php

EIMA (EIFS Industry Members Association). n.d. "What Are EIFS?" Accessed March 1, 2024. www.eima.com/abouteifs.html.

Fisler, D., R. Interiano, L. Keyek, C. Larkin, M. Mooney, A. Satre-Meloy, and L. Toffoli. 2021. "Market Opportunities and Challenges for Decarbonizing US Buildings." RMI. advancedbuildingconstruction.org/decarbonizing-us-buildings/.

Friege, J., G. Holtz, and É. J. L. Chappin. 2016. "Exploring Homeowners' Insulation Activity." *Journal of Artificial Societies and Social Simulation* 19 (1): 4. https://jasss.soc.surrey.ac.uk/19/1/4.html.

Harris, C. 2021. "Opaque Envelopes: Pathway to Building Energy Efficiency and Demand Flexibility: Key to a Low-Carbon, Sustainable Future." *U.S. Department of Energy*. https://www1.eere.energy.gov/buildings/pdfs/80170.pdf.

Harris, C. 2022. "Pathway to Zero Energy Windows: Advancing Technologies and Market Adoption." *U.S. Department of Energy*. https://www.nrel.gov/docs/fy22osti/80171.pdf.

Hasz, A., R. Nicholas, and J. Glickman. 2020. *Advanced Building Construction (ABC) – A Not Quite "Easy as 1-2-3" Initiative to Scale Deep Energy Retrofits and Transform U.S. Buildings*. U.S. Department of Energy Building Technologies Office. studylib.net/doc/25495873/advanced-building-construction--abc-–—a-not-quite-"easy-...

Hun, D. E., M. Bhandari, M. V. Lapsa, S. Shrestha, S. B. Pallin, and C. Hazard. 2018. "Airtightness of Commercial Building Envelopes: Where are we and where could we go?" 2018 ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, August 12-17, 2018. www.osti.gov/biblio/1559734.

Langevin, J., and E. Wilson. 2024. "Decarbonizing the U.S. Economy by 2050: A National Blueprint for the Buildings Sector." *U.S. Department of Energy*. https://www.energy.gov/eere/articles/decarbonizing-us-economy-2050.

Leung, J. 2018. "Decarbonizing U.S. Buildings." *Climate Innovation 2050*. Center for Climate and Energy Solutions. www.c2es.org/wp-content/uploads/2018/06/innovation-buildings-background-brief-07-18.pdf.

Mahajan, M. 2019. "How to Reach U.S. Net Zero Emissions by 2050: Decarbonizing Buildings." *Forbes.* www.forbes.com/sites/energyinnovation/2019/11/05/reaching-us-net-zero-emissions-by-2050-decarbonizing-buildings/?sh=3b8c4f5a569d.

Nadel, S. and A. Hinge. 2020. "Mandatory Building Performance Standards: A Key Policy for Achieving Climate Goals." An ACEEE White Paper. Washington, D.C.: American Council for an Energy-Efficient Economy. www.aceee.org/sites/default/files/pdfs/buildings_standards_6.22.2020_0.pdf

Satchwell, A., M.A. Piette, A. Khandekar, J. Granderson, and N.M. Frick. 2021. "A National Roadmap for Grid-Interactive Efficient Buildings." *U.S. Department of Energy*. https://gebroadmap.lbl.gov/A%20National%20Roadmap%20for%20GEBs%20-%20Final.pdf.

SDSN & FEEM. 2021. *Roadmap to 2050: A Manual for Nations to Decarbonize by Mid-Century; Buildings*. Sustainable Development Solutions Network & Fondazione Eni Enrico Mattei, New York. https://roadmap2050.report/buildings/.

Webster, B., L. Toffoli, M. Campbell, L. Badger, A. Donovan, D. Lane, K. McGrath, A. Satre-Meloy, E. Wilson, J. Reyna, C. E. Metzger, and T. J. Pilet. 2024. "Accelerating Residential Building Decarbonization: Market Guidance to Scale Zero-Carbon-Aligned Buildings." www.advancedbuildingconstruction.org/market-guidance-report.

Zheng, X., E. Cooper, M. Gillott, and C. Wood. 2020. "A Practical Review of Alternatives to the Steady Pressurization Method for Determining Building Airtightness." *Renewable and Sustainable Energy Reviews* 132 (October): 110049. doi.org/10.1016/j.rser.2020.110049.