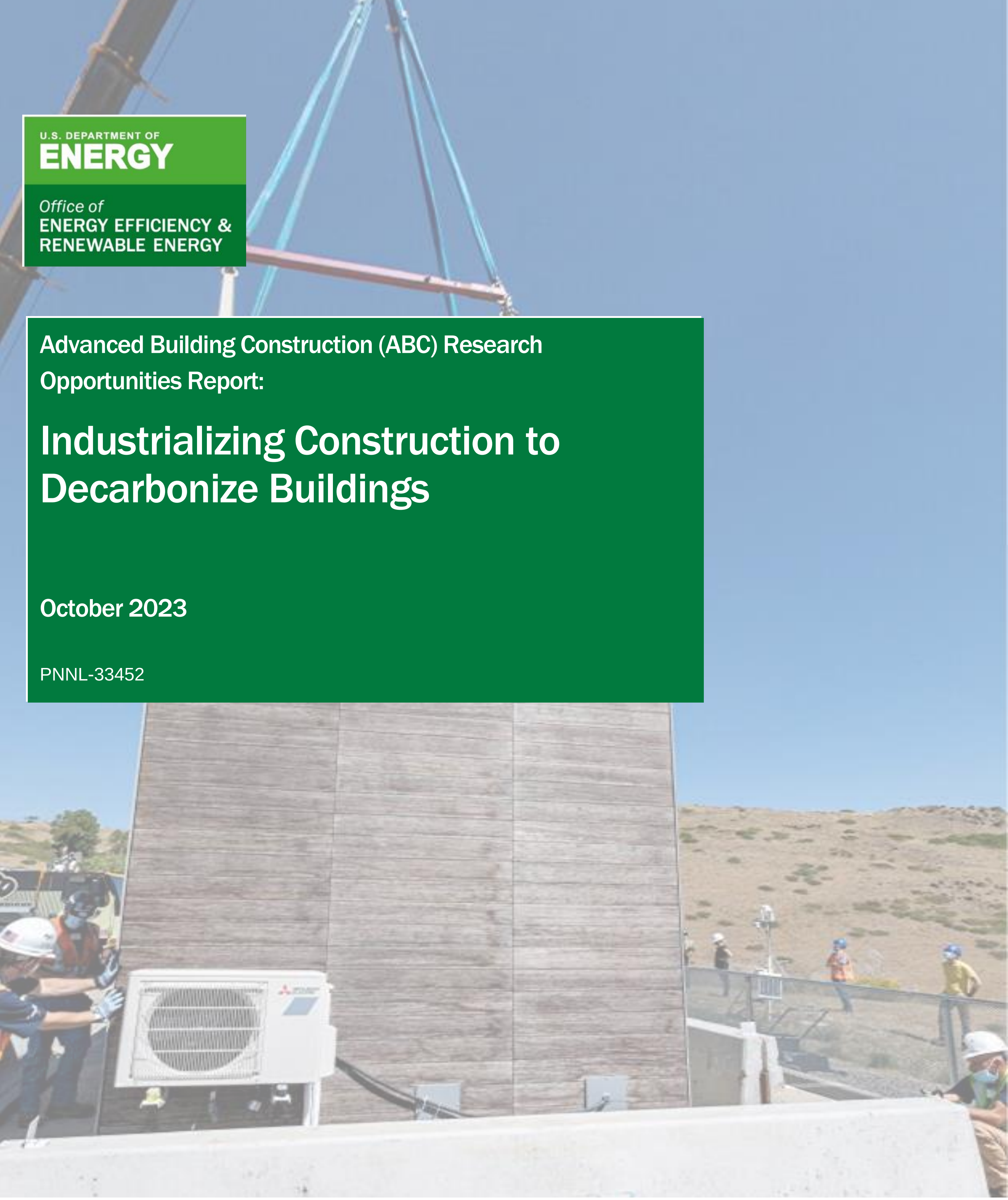

U.S. DEPARTMENT OF ENERGY

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Advanced Building Construction (ABC) Research Opportunities Report:

Industrializing Construction to Decarbonize Buildings

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Disclaimer

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List of Acronyms

A	Amps
ABC	Advanced Building Construction
ACEEE	American Council for an Energy-Efficient Economy
AEC	Architecture, engineering, and construction
AFDD	Automatic Fault Detection and Diagnostics
AM	Additive manufacturing
AR	Augmented reality
ASHRAE	American Society of Heating, Refrigeration and Air-Conditioning Engineers
AWP	Advanced Work Packaging
BIM	Building Information Modeling
BTO	Building Technologies Office
CAD	Computer-aided design
CAM	Computer-aided modeling
CNC	Computer numerical control
DfMA	Design for Manufacturing and Assembly
DOE	Department of Energy
EAF	Electric arc furnace
EERE	Energy Efficiency and Renewable Energy
ET	Emerging technologies
GEB	Grid-interactive efficient buildings
GWP	Global warming potential
HPWH	Heat pump water heater
HVAC	Heating, ventilation, and air conditioning
IAQ	Indoor air quality
ICC	International Code Council
IECC	International Energy Conservation Code
IMU	Inertial measurement units
IoT	Internet of Things
IP	Intellectual property
IPD	Integrated Project Delivery
JIT	Just in time
LBNL	Lawrence Berkeley National Laboratory
MR	Mixed reality
NREL	National Renewable Energy Laboratory
ORNL	Oak Ridge National Laboratory
PHIUS	Passive House Institute US
PNNL	Pacific Northwest National Laboratory
PPE	Personal protective equipment
PV	Photovoltaics
QA	Quality assurance
QC	Quality control
R&D	Research and development
RD&D	Research, development, and demonstration
RDO	Research and Development Opportunity
RESNET	Residential Energy Services Network
ROI	Return on investment
RVI	Remote Virtual Inspection
TLS	Terrestrial laser scanner
VOC	Volatile organic compound

Executive Summary

The U.S. building stock is responsible for 75% of total U.S. electricity use, 40% of energy use, and 35% of CO_2 emissions (EIA 2021). To meet bold national climate change goals, the U.S. must decarbonize the building stock by 2050 (Fisler et al. 2021, SDSN & FEEM 2021, Mahajan 2019, Leung, 2018). However, today's practices to build or renovate buildings to low-carbon, high-performance levels are generally labor intensive, disruptive, and too costly to quickly scale in the U.S. To retrofit 80% of the U.S. building stock in the U.S. by 2050, the retrofit rate will need to increase by about 15 times for residential buildings and two times for commercial buildings (Nadel and Hinge 2020, EIA 2019, Census 2019, EIA 2015). Additionally, there is a major housing deficit in this country where nearly 600,000 people lack adequate or stable shelter, and the pace of construction is not keeping up with the growing demand (HUD 2022).

New, more industrialized,[1] replicable, and technologically driven approaches to renovation and new building construction are imperative to help meet such significant national needs and achieve the necessary speed and scale to meet national building decarbonization goals.

Major research-related achievements to date for the ABC Initiative include:

- **Awarded $26.3M in 2020 to 40 competitively selected projects led by 29 different organizations**
- **Awarded $32M in 2022 to fund over 30 projects that demonstrate and validate processes that impact the whole building**
- **Published the *Market Opportunities and Challenges for Decarbonizing US Buildings* report to aid industry**
- **Published the *Residential U.S. National Building Characterization Study* and dashboard, a first of its kind analysis in the U.S. and in use by industry and state and federal entities**
- **Engaged 194+ industry stakeholders in a series of workshops to identify RD&D and tech scaling gaps and opportunities to inform public and private investments**
- **Collaborated with states including CA, NY, and MA, and federal agencies such as HUD to align investments and identify needs**

Advanced Building Construction Initiative

The U.S. Department of Energy's (DOE's) Building Technologies Office (BTO) seeks to develop, demonstrate, and accelerate the adoption of cost-effective technologies, techniques, and tools in support of an equitable transition to a decarbonized building stock and energy system by 2050. BTO launched the Advanced Building Construction (ABC) Initiative, including an industry-led ABC Collaborative, in 2019 to work directly with industry to address the opportunities and challenges stated earlier and encourage the integration of high-performance and low-carbon building approaches into new and ongoing industry modernization efforts.

The ABC Initiative focuses on scaling the renovation and construction of low-carbon, appealing, and affordable U.S. residential and commercial buildings through more industrialized construction innovations and solutions. This includes addressing gaps and

[1] Industrialization of an industry means to streamline it in a way that is reproducible at scale. In this case, industrialization could refer to streamlining product manufacturing, system manufacturing, business models, sales, and workforce, as well as installation.

creating handoffs from individual technology research and development to the development, demonstration, commercialization, and deployment of innovative, scalable approaches that lead to buildings with the following key attributes:

High-performance, low energy use with a low-carbon footprint (operational and embodied).

Reducing lifecycle carbon emissions can be achieved through two means: reducing operational carbon emissions (e.g., ongoing energy use reduction in general as well as electrification to reduce emissions) and reducing embodied carbon emissions (e.g., reduced use of carbon-intensive materials such as steel, concrete, and certain types of insulation as well as reduced intensity of manufacturing processes for products).

Affordable to developers, owners, and tenants

Reducing the first cost,[2] especially soft costs, of building decarbonization approaches compared with the current business as usual will be critical for innovations. In general, the costs discussed in this report should compress at each major stage of innovation development, including during research and development, technology scaling (e.g., more optimized factory layout), and market scaling (e.g., higher volume sales).

Faster construction and less invasive to occupants, easier to implement renovation for contractors with less training required

Business as usual renovation and construction costs are typically dominated by labor due to the customization required for every project. To achieve the volume required to meet national climate goals in a relatively short timeline, this process needs to be quicker and more streamlined without sacrificing the quality or safety of the installation or the needs of the workforce.

Added value

There are several non-energy-related benefits that can increase the appeal and resulting economic value of the building (for both owners and occupants) including aesthetics, comfort, health, durability, resilience (possibly providing insurance premium discounts), ease of use, convenience (e.g., occupants not displaced during remodel, so rent can continually be charged), and grid services (e.g., load shifting capabilities that enable utilities to make better use of renewable energy resources).

The ABC Initiative aims to industrialize construction and renovation process innovations across the supply and delivery chain as illustrated in Figure E.1. Because the residential and commercial building segments account for 70% of total US electricity consumed and 42% of total US energy consumed of which heating, cooling, ventilation, and water heating loads (classified in this document as thermal loads) are the largest loads (EIA 2022b), it is critical to prioritize development of more scalable, industrialized solutions for retrofit packages that *include* envelope upgrades to reduce the thermal loads in buildings. The ABC Initiative emphasizes approaches that reduce the installation time and cost and increase the value proposition of such retrofits.

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[2] In the future, incentives, financing mechanisms, maintenance costs, and the added value to the property will be part of the affordability equation. However, without those details available at this time, first cost (e.g., cost of purchase and install) will be used as a reference to affordability for this version of the document.

In addition to streamlining construction delivery and reducing costs and carbon emissions, BTO's ABC Initiative aims to provide safer, more desirable (e.g., increased wages, more consistent work, less physically demanding) jobs for our country, and prioritize environmental justice and equity and diversity to focus on historically under-resourced communities or market segments at the state and local levels. Preliminary analysis shows that the ABC Initiative can help contribute to a savings of approximately 92 million metric tons of CO_2 annually and result in approximately $17 billion in annual utility bill savings in just the U.S. residential building stock.[3]

Credits: Tocci (Design), Factory Zero (Components), Energiesprong (Installation)

Figure E.1. Innovation across the supply chain + streamlined delivery

No one entity will reach such ambitious building decarbonization savings and goals alone. For this reason, BTO is partnering with other key federal, state, and local agencies as well as private and nonprofit leaders including through the ABC Collaborative. The ABC Collaborative helps align key stakeholders and create bridges between public and private sector funding to help speed commercialization and mass market adoption of innovative processes and approaches.

ABC Research Opportunities Report

This Research Opportunities Report specifically identifies the challenges and R&D opportunities to innovations that support the industrialization of whole building retrofits and rapid growth of low carbon new construction. The content relates to the *industrialization of processes associated with new building construction and renovation and how technology innovation supports process enhancement.* Table E.1 shows the primary focus areas of this report to further industrialize related innovations – indutrialization of envelope improvements and equipment installation.

This report cross-applies innovations in both the new and existing building sectors with a focus on widescale applicability. Installation flexibility is key to commoditizing solutions that are applicable for a wide variety of buildings and to help simplify decarbonization processes for the workforce.

The innovations listed in Table E.1 were identified through primary and secondary research as well as stakeholder input through a series of public meetings (see Appendix A for more details). This table summarizes the primary innovations covered in this report and the goal areas that the innovative solution aims to help achieve.

[3] See Section 1.3 for more detail. Note, this analysis is in progress. Commercial building information will be added when it is available.

Table E.1. Summary of ABC Primary Innovations in Report

Innovation Category	Primary Innovation	Current State	Innovation Goals	Value Added
 **Industrialization of Envelope Improvements**	**Insulation and Air Sealing for Existing Building Cavities**	• Solutions are costly, disruptive, and not viable across climates, building types • Improved methods are needed to assess existing conditions and quality check installation	• Costs less than $1,000 for average single-family homes • Installs: 1-2 days for single-family homes, 8-10 apartment units per day, or ≤8 days for small-medium commercial buildings	Convenience, Comfort, and Resilience
	Wall and Window Panel Systems	• Insulating panels are only available for new construction • Panel connection points are not easy/fast to install or universal	• Cost ≤$10/sq. ft. installed • Installed on typical home in ≤7 days, small commercial building in ≤15 days	Aesthetics and Resilience
	Adding Exterior Insulation When Residing	• Insulating panels are only available for new construction • Panel connection points are not easy/fast to install or universal	• Cost ≤$1/sq. ft. installed	Convenience, Comfort, and Resilience
	Streamlining High Performance Window Installation	• Window installation is labor- and time-intensive (not automated) • Air and water sealing and retrimming is labor- and time-intensive	• Window, trim, and sealant installed in less than 10 minutes • Costs are equivalent to onsite trimming (about $1,800 for a 2,000 sq. ft. building)	Resilience
 **Industrialization of Equipment Installation**	**Improved Duct Retrofit Process**	• Insulation and air sealing is time-intensive and expensive • Aerosolized sealant is relatively fast, and relatively expensive	• Cost ≤$0.75/sq. ft. installed • Installed in less than a day for a typical home	Comfort
	Wall Panels with Mechanical System Integration	• In RD&D phases – not yet available in the U.S. • Can also include integrated PV	• Cost reduced compared to separate systems	Less Disruptive Install, Comfort, Resilience

This report also provides substantial information related to *enabling innovations*. These are innovations in design, materials, production, and installation assistance that could be used in combination with each other to support the achievement of the goals related to the primary innovations. These enabling innovations are listed in Table E.2.

Table E.2. Summary of ABC Enabling Innovations in Report

Innovation Category	Enabling Innovation	What does it enable?
 Design and Tools	**Retrofit Decision Applications**	Quick and easy determination of which retrofit measures are possible and make the most financial sense for that building
	Non-Destructive Evaluation of Existing Building Envelopes	Easy determination of potential challenges to the implementation of an envelope retrofit
	Air Leakage Testing, Equipment, and Methods for Large Buildings	Quick, easy, and inexpensive detection of air leakage locations and rates in building envelopes, especially for existing large multifamily and commercial buildings
 Materials	**Advanced Insulation**	Easily installed insulation for quick incorporation into wall panel systems, residing, and building cavities to enable more resilient buildings and reduced heating and cooling demand
	Advanced Sealants	Streamlined building envelope retrofits for reduced heating and cooling demand
 Production and Installation	**Data Collection, Modeling and Analytics**	Optimization of onsite activities and offsite factory processes to broadly support improvements to end-to-end operations for building envelope retrofits
	Subtractive Manufacturing	More controlled and less wasteful production of pre-fabricated wall panels, siding and insulation boards for building envelope retrofits
	Additive Manufacturing	Supports precise control, rapid production, and less material waste, especially useful in complex building or component geometries
	Portable Machines for Distributed Manufacturing	Industrialized construction of building components onsite to reduce transport costs and delivery time
	Advanced Scanning for Retrofit Construction	Easily designed and manufactured customized, prefabricated retrofit panels for easier and faster installation and fitting
	Retrofit Robots (Including Automated Insulation Installation and Inspections)	Fast, high-quality, and affordable installation and inspection tasks that are necessary for building envelope retrofits
	Real-Time QA/QC Using Visual Indicator or Internet Connected Sensors	Near-real-time QA/QC of building efficiency measures, including building envelopes, to improve installation and inspection quality
	Augmented/Mixed Reality	Improved building retrofit and new construction technology installation by providing training, guidance, inspections and QC of work

Public and private funders may use this document to help shape critical investments. This Research Opportunities Report helps inform the public and private sector of R&D related opportunities for process innovations. This report is complementary to and builds on other BTO technology specific Research and Development Opportunity (RDO) documents on topics such as heating, ventilation, air-conditioning (HVAC), lighting, energy storage, and windows. This document also identifies linkages to other cross-cutting BTO initiatives such as the Energy, Emissions, and Equity (E3) Initiative and the Grid-Interactive Efficient Buildings (GEB) Initiative where possible. More information on the connections to these other program activities and initiatives are provided throughout this report.

Near-Term Priorities

A rigorous stakeholder engagement process informed the *primary innovations and enabling innovations* in this report. This evolving list of innovations focuses on supporting near-term goals associated with industrializing or streamlining building envelope upgrades and industrializing processes that enable an equitable transition to beneficial building electrification for both renovations and new construction projects.

Some of the innovations in this document exist today but only partially meet the described key attributes or require further development to become commercially viable products or practices. Other enabling innovations are only ideas and do not yet exist as solutions. Industrialization and process innovation is one key tool in the “toolbox” to support decarbonization in buildings. This Research Opportunities Report illuminates the needs and opportunities for process-focused innovations that can help transform and modernize the building industry and, in concert with other public and private efforts, help reach the necessary speed and scale to decarbonize U.S. buildings by 2050.

Next Steps

As this research opportunities report will provide context for investment through 2035, it is imperative that it be regularly updated to reflect the latest innovation status and cost targets. This research opportunities report is considered a living document, which will be periodically updated and is open for stakeholder feedback by emailing industrialized.opportunities@pnnl.gov.

Stakeholders who are interested in providing feedback may also participate in stakeholder engagement opportunities that will aim to understand the progress made on specific topics any new potential gaps or challenges. Such stakeholders will ideally include a diverse group of both the public (e.g., U.S. Department of Housing and Urban Development, U.S. Department of Defense, General Services Administration, and state and local governments) and private (e.g., building portfolio owners, builders/contractors, manufacturers, researchers, architects, private investors) sectors.

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1 Introduction

1.1 Decarbonizing the Building Stock by 2050

Buildings are critical infrastructure that affect all Americans' lives, from their comfort to their mental and physical well-being. The 139 million homes and 5.9 million commercial buildings in the U.S. account for about 40% of U.S. energy demand (EIA 2020a, EIA 2022a). The construction and operation of these buildings account for the largest share of carbon emissions from energy.

It is well established that to meet climate change goals, the U.S. must decarbonize the building stock by 2050 (Fisler et al. 2021, SDSN & FEEM 2021, Mahajan 2019, Leung, 2018). Today's practices to build or renovate buildings to high-performance, low-carbon levels are generally slow, disruptive, and too costly to quickly scale in the U.S. The primary challenge addressed in this research opportunities report is the *pace* of high-performance, low-carbon building retrofits in the U.S. To decarbonize the building stock in the U.S. by 2050, the retrofit rate will need to increase by 15 times for residential buildings and two times for commercial buildings (Nadel and Hinge 2020, EIA 2019, Census 2019, EIA 2015).

The Advanced Building Construction (ABC) Initiative helps accelerate the decarbonization of U.S. buildings through new construction and renovation innovations focused on more industrialized[4] production and installation processes that can help deliver low-carbon, affordable, and appealing new buildings and retrofits at the speed and scale required to meet national goals by 2050.

Improved processes, both onsite and offsite approaches, directly or indirectly support the necessary elements to decarbonize the building stock. Aligned with the U.S. Department of Energy's (DOE's) Office of Energy Efficiency and Renewable Energy (EERE) high level building decarbonization strategy, these elements include energy efficiency, beneficial electrification, clean energy sources and flexibility, and remaining emissions. This research opportunities report primarily supports scalable energy efficiency and electrification of buildings and indirectly supports clean energy sources and load flexibility. Given the Thermal Energy Storage RDO, GEB Roadmap, and DOE's Solar Office have established clear goals and

[4] Industrialization of an industry means streamlining it in a way that is reproducible at scale. In this case, industrialization could refer to streamlining product manufacturing, system manufacturing, business models, sales, and workforce or installation of technologies.

strategies for addressing these needs, this report does not include separate recommendations. The prescribed innovation goals, challenges, and needs in this document recognize the importance and encourage the integration of innovative processes and solutions where possible to increase adoption of clean energy sources and a more dynamic and flexible building stock with the grid.

Figure 1 shows the primary focus areas of this report to further industrialize related innovations.

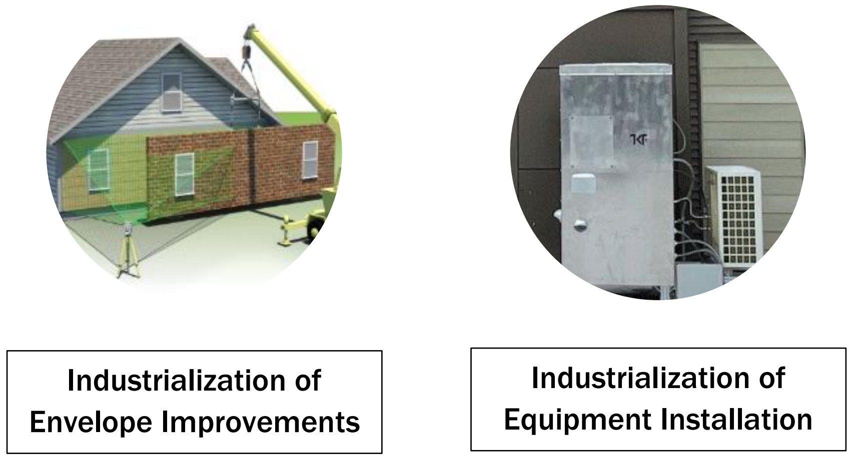


Figure 1. Primary focus areas of this report: processes and approaches to industrialize envelope improvements and equipment installation (Source: ORNL)

Policy and Program Context

National goals and DOE program efforts inform the direction of this research opportunities report. Administration priorities include proposed public investments to achieve the following high level goals toward a more sustainable and prosperous future (The White House 2021):

1. **Produce, preserve, and retrofit two million affordable, resilient, accessible, energy efficient, and electrified housing units**
2. **Build and rehabilitate more than 500,000 homes for low and middle-income homebuyers**
3. **Put union building trade workers to work upgrading homes and businesses to save families money**

The DOE's EERE is focused on creating and sustaining American leadership in the transition to a global clean energy economy. Its vision is a strong and prosperous America powered by clean, affordable, and secure energy.

Within EERE, the [Buildings Technologies Office] (BTO) focuses on reducing energy intensity and cost for technologies across the buildings sector while maintaining or enhancing occupant comfort, productivity, and product performance. BTO believes buildings must not only use less energy but also use energy more productively and efficiently, which will help reduce cost and provide benefits for U.S. families and businesses.

To do this, BTO develops, demonstrates, and accelerates the adoption of affordable technologies, techniques, tools, and services that enable high-performing, energy efficient, and demand-flexible residential and commercial buildings in both the new and existing building markets in support of an equitable transition to a decarbonized energy system by 2050, starting with a decarbonized power sector by 2035. As shown in Figure 2, the ABC Initiative is part of the BTO portfolio and cross cuts BTO programs, with a focus on process innovation that links emerging technologies with scaling and market integration efforts.

Within the BTO portfolio, the ABC Initiative cross cuts the BTO programs and primarily focuses on connecting individual emerging technologies and practices into more integrated, streamlined, and reproducible production and installation solutions that can be scaled in the market with a strong value proposition to both the building industry and consumers. This research opportunities report is part of the ABC Initiative, and along with other technology specific research and development opportunity (RDO) documents from BTO, is part of a portfolio of research into building decarbonization technologies. Appendix B provides information on how this research opportunities report fits in the BTO portfolio.

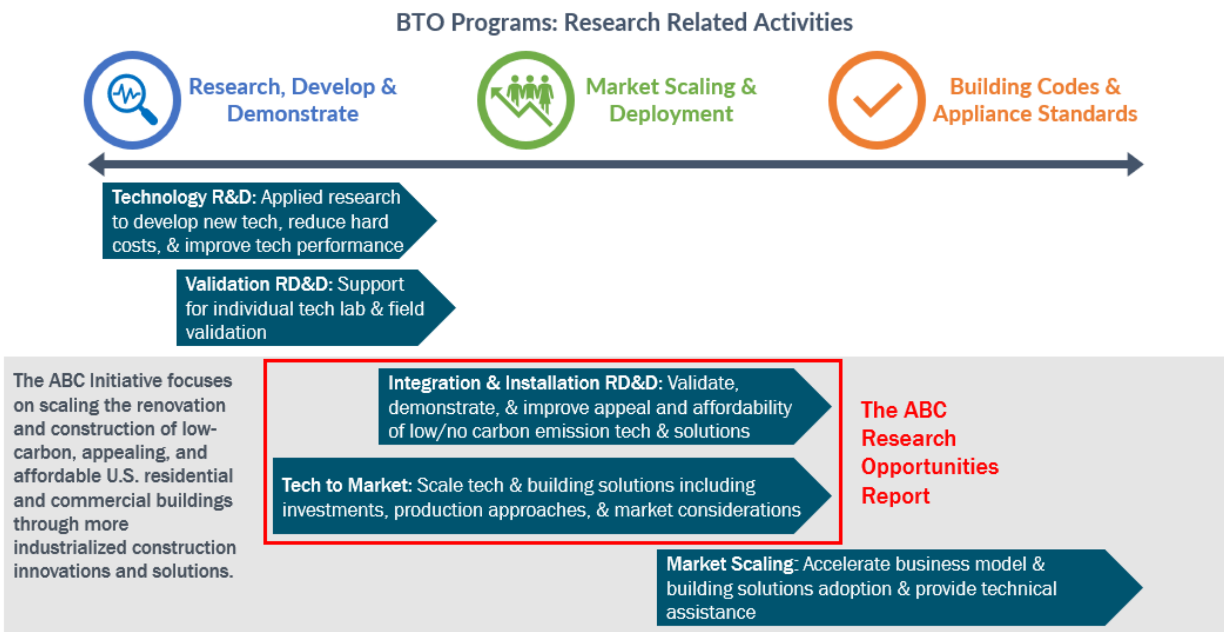


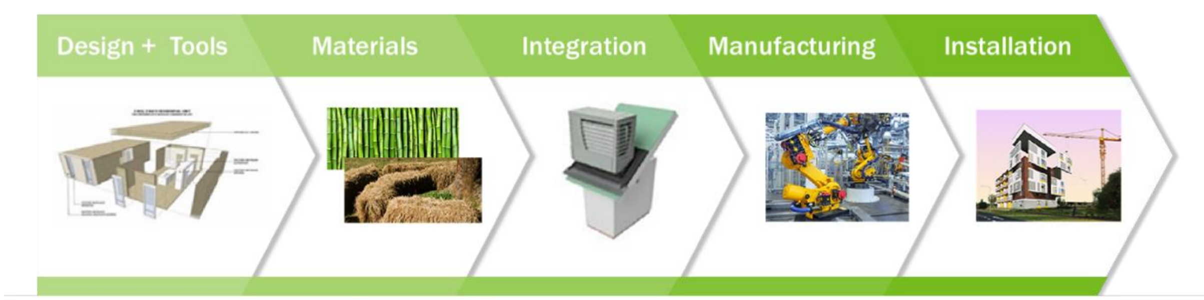
Figure 2. The ABC Initiative within BTO

1.2 The ABC Initiative

The DOE BTO launched the ABC Initiative in 2019 to address timely opportunities and challenges in the building construction industry and help meet critical national needs to decarbonize the building sector. The primary goal is to increase the speed and scale at which the residential and commercial building sectors can be decarbonized through industrialization of construction and renovation processes, which includes integration of high-performance and low-carbon solutions into ongoing building industry modernization efforts. Faster and more replicable, affordable, and appealing solutions are critical to greatly improve the dismally low uptake of high-performance, low-carbon building renovation and construction practices and solutions (Goldstein, Turnbull, and Higgins 2018). For these reasons, the ABC Initiative focuses on accelerating and scaling the decarbonization of U.S. residential and commercial buildings through development, demonstration, commercialization and scaling of process-focused innovations that can deliver low-carbon, affordable, and appealing new buildings and retrofits. Such innovations refer to streamlining production processes, systems production approaches, business delivery models, and installation practices that focus on the consumer and the workforce within building construction and retrofits in a way that is reproducible at scale.

The ABC Initiative focuses on accelerating the decarbonization of U.S. residential and commercial buildings through industrialized construction and renovation innovations that deliver low carbon, affordable, and appealing new buildings and retrofits at scale.

As Figure 3 illustrates, the ABC Initiative aims to industrialize construction and renovation process innovations across the supply and delivery chain. In addition to streamlining construction delivery and reducing costs and carbon emissions, the ABC Initiative focuses on providing safer, more desirable jobs (e.g., increased wages, more consistent work, career growth) while prioritizing environmental justice and equity including solutions for historically under-resourced communities and market segments.



Credits: Tocci (Design), Factory Zero (Components), Energiesprong (Installation)

Figure 3. Innovation across the supply chain + streamlined delivery

The road for new, industrialized processes and technology innovations that support those processes from conception and research in a lab to adoption into the market can be long, complex, nonlinear, and challenging to achieve at scale. Promising innovations can fall off during three different valley of death points in the illustrative technology-to-market continuum that Figure 4 shows. Aligning processes and innovations with market drivers, gaining insights from critical industry players and consumers, and continuing to refine and improve innovations are necessary to prepare for and bridge the multiple valleys of death.[5] More details, including frameworks for industry, related to early consideration of commercialization and market adoption in the R&D process is provided in Appendix C.

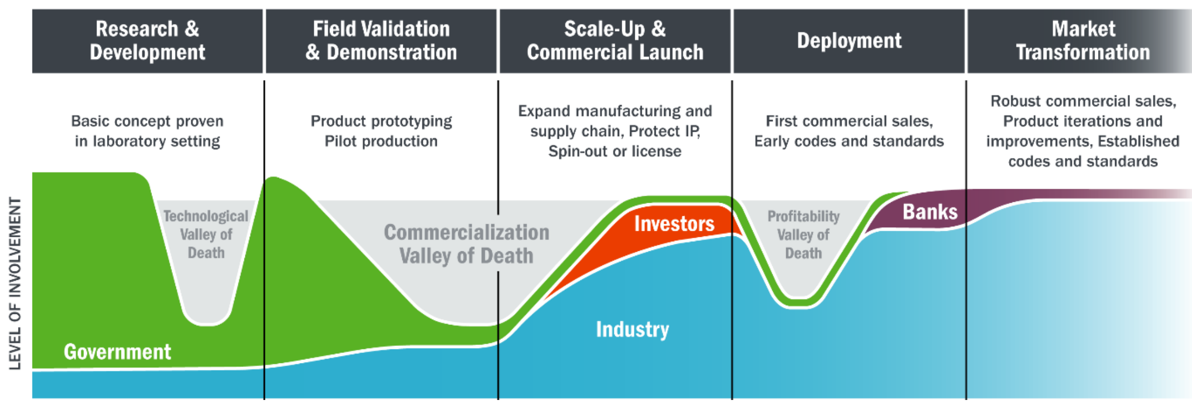


Figure 4. Illustrative technology-to-market continuum (Source: DOE)

To help build bridges across these valleys, the ABC Initiative established the industry-led ABC Collaborative,[6] which, among other things, helps align key public and private industry stakeholders to sustainably finance investments in ABC innovations. The ABC Collaborative is a first-of-its-kind effort to align key stakeholders and harness collective industry knowledge to accelerate action and demand. Key stakeholders involved in the ABC Collaborative include researchers, manufacturers, factory owners, building owners, investors, and market enablers (e.g., professional associations, nonprofits, nongovernment organizations, and other supportive organizations).

Feedback loops are critical to gain market input and tailor features within a product's innovation cycle to improve the likelihood of market success. Consideration of both the supply chain players and the end customers improve the success of promising innovations to reach their full potential and progress from proof of concept to prototype and pilot programs to full deployment. The ABC Initiative also uses the ABC Collaborative to obtain critical feedback from the industry that will continue to be incorporated into this research opportunities report.

[5] See Appendix C for more on Technology Commercialization and Market Adoption considerations for industry.
[6] The ABC Collaborative is led by RMI and other key industry stakeholders such as ADL Ventures. Visit the website or contact them through the website with any questions or with interest in joining: https://advancedbuildingconstruction.org/.

The ABC Collaborative is also leading several broadly applicable working groups that will help drive the commercialization and market adoption of ABC-related innovations and packages.

Key Attributes of ABC

In support of the overall vision to decarbonize the building stock by 2050, the ABC Initiative focuses on industrialized construction process innovation that contributes to the following key attributes:

- High-performance, low energy use with a low-carbon footprint (operational and embodied)
- Affordable to developers and consumers
- Faster construction and less invasive to occupants, easier to implement renovation for contractors with less training required
- Value added and non-energy benefits, such as better indoor air quality, improved comfort, resilience, and reduced maintenance

Although new construction and renovation industries can benefit from streamlined, modernized approaches, customer-oriented solutions are critical to result in broad market adoption. For building retrofits, owners need options that address the characteristics of their existing building but can still be manufactured at scale to ensure affordability. Novel processes that are prepackaged, easy to install, and deliver energy savings along with added value, such as attractive facades and improved resilience, are essential to driving demand.

The following list provides more detail for each key attribute, and each innovation section provides a table that indicates to which key attributes the innovation contributes:

High-performance, low energy use with a low-carbon footprint (operational and embodied)

Reducing lifecycle carbon emissions can be achieved through two means: reducing operational carbon emissions (e.g., ongoing energy use reduction in general as well as electrification[7] to reduce emissions) and reducing embodied carbon emissions (e.g., reduced use of carbon-intensive materials such as steel, concrete, and certain types of insulation as well as reduced intensity of manufacturing processes for products). Where applicable, specific carbon reduction goals for each innovation will be developed in the next version of this living document in close partnership with other DOE offices.

Affordable to developers, owners, and tenants

Affordability is critical to the success of any product or service and must be part of each innovation’s critical path toward commercialization to enable mass-scale adoption of low-carbon new buildings and retrofits. The ABC Initiative focuses on reducing the first

[7] Electrification of building loads is defined as the action of replacing gas equipment in buildings with electrically powered equipment. Electrification also allows renewable energy sources to either directly or indirectly power the equipment in a building.

cost,[8] especially soft costs, of building decarbonization approaches compared with the current business as usual. Individual installed costs related to each process innovation area will ultimately affect the cost of whole building construction or retrofit costs.

In general, the costs discussed in this research opportunities report should compress at each major stage of innovation development, including during research and development ([R&D] e.g., using less expensive materials or designing a new installation technique), technology scaling (e.g., more optimized factory layout), and market scaling (e.g., higher volume sales). Eventually, this research opportunities report aims to dive deeper into material, acquisition, labor, permit, operations, and maintenance costs for each innovation area and determine more specific paths to reduce both hard and soft costs.

Faster construction and less invasive to occupants, easier to implement renovation for contractors with less training required

Business as usual renovation and construction costs are typically dominated by labor due to the customization required for every project. To achieve the volume required to meet national climate goals in a relatively short timeline, this process needs to be quicker and more streamlined without sacrificing the quality or safety of the installation or the needs of the workforce. The innovations described in this research opportunities report should dramatically change the timescale of building construction. For retrofits, one example of a goal is completing a safe, durable, cost-effective whole building retrofit (for about a 2,000 sq. ft. home) in 7 days or less (once the construction process has started). For new construction, an example of a goal is to construct a typical 2,000 sq. ft. home in 4 days or less.

Added value

The innovations identified in this research opportunities report may add value in several ways to the entities that will be paying for the products or services. Entities may include homeowners, building owners, utilities, insurance companies, and contractors (if the product is a new tool or installation process).

There are several non-energy-related benefits that can increase the appeal and resulting economic value of the building (for both owners and occupants) including aesthetics, comfort, health, durability, resilience (possibly providing insurance premium discounts), ease of use, convenience (e.g., occupants not displaced during remodel, so rent can continually be charged), and grid services (e.g., load shifting capabilities that enable utilities to make better use of renewable energy resources).

1.3 Prioritization of Building Energy Improvements

A common question that comes up when analysts discuss building stock decarbonization is "What combination of energy efficiency measures are needed to decarbonize the building

[8] In the future, incentives, financing mechanisms, maintenance costs, and the added value to the property will be part of the affordability equation. However, without those details available at this time, first cost (e.g., cost of purchase and install) will be used as a reference to affordability for this version of the document.

stock?" To help answer this question, RMI, Lawrence Berkeley National Laboratory, Pacific Northwest National Laboratory, and National Renewable Energy Laboratory collaborated to produce an ABC Collaborative-led companion report to this document entitled, *Accelerating Building Decarbonization: Market Guidance to Scale Zero-Carbon-Aligned Residential Buildings*. The Market Guidance Report seeks to provide guidance, in the form of retrofit packages, to accelerate the transition to zero-carbon-aligned U.S. building stock. The Market Guidance Report achieves this through the following:

- Establishing a baseline for the current building stock in the *U.S. Building Stock Characterization Study* (Reyna et al. 2022) and grouping building segments by climate zone, building type and vintage, and building characteristics.
- Defining a number of possible packages with varying levels of first cost. These packages were designed to decarbonize the building stock at an aggregate level while remaining cost-effective on an individual basis. The retrofit packages are as follows:
    - All equipment upgraded with high-efficiency electric-powered equipment, including space conditioning systems and EnergyStar appliances
    - Conventional envelope + equipment upgrade
    - Approximately 2021 International Energy Conservation Code (IECC)-level envelope + equipment upgrade
    - Approximately Passive House Institute US (PHIUS)-level envelope + equipment upgrade
- Identifying where each of these packages made the most sense for the existing building stock based on the following criteria:
    - Determining which building segments should not be prioritized for any of these upgrades because they are already well on their way to zero energy ready (which can be defined by DOE Zero Energy Ready Home specifications)[9]
    - Determining which buildings can cost-effectively achieve zero energy ready while only replacing equipment and electrifying
    - Determining which buildings require exterior envelope retrofits, and their level of envelope retrofit required, in addition to equipment replacement/electrification to achieve zero energy ready performance levels

The Market Guidance Report serves as a companion document to this report, as it provides deployment guidance for many of the innovations described within this opportunities report. Conversely, the ABC Research Opportunities Report highlights research gaps, cost compression opportunities, and discrepancies in the scale required to deploy many of the packages described in the Market Guidance Report.

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[9]A DOE Zero Energy Ready Home is a high-performance home that is so energy efficient that a renewable energy system could offset most or all the home's annual energy use. (Source: DOE Zero Energy Ready Home Program)

The results of the Market Guidance Report analyses are summarized in Table 1.[10]

Table 1. Percentage of Residential Building Stock Most Applicable to Each Type of Retrofit Package

Note: Each retrofit package represents a level of energy efficiency upgrade from no upgrade needed to complete electrification of equipment and PHIUS-level envelope. For some building stock typologies, achieving decarbonization will require fewer upgrades (e.g., electrifying all building end uses but without comprehensive envelope insulation upgrades), whereas in other segments, especially those in climates with greater thermal demands, decarbonization will require higher-performance whole-building upgrades.

Building Type	Package	Count of Units (M)	Percentage of Residential Building Type
SF/Mobile/Low-rise Multifamily	Not prioritized for upgrade	16	13%
	Equipment Only	19	15%
	Market-ready Envelope + Equip	44	35%
	2021 IECC Envelope + Equip	15	12%
	PHIUS Envelope + Equip	33	25%
High-rise Multifamily	Not prioritized for upgrade	0.6	10%
	Equipment Only	1.4	23%
	Market-ready Envelope + Equip	2.4	38%
	2021 IECC Envelope + Equip	0.7	11%
	PHIUS Envelope + Equip	1.1	17%

[10] Note, more detail about these analyses and the methodology can be found in the ABC Collaborative-led *Accelerating Building Decarbonization: Market Guidance to Scale Zero-Carbon-Aligned Residential Buildings*.

These Market Guidance Report packages correspond to the following research opportunities report innovations:

Table 2. Mapping Market Guidance Report Packages to Research Opportunity Report Innovations

Package	Relevant Research Opportunity Report Innovations
1. Equipment Only	2.3 Adding Exterior Insulation When Residing
	3.1 Improved Duct Retrofit Process
2. Conventional Envelope + Equipment Upgrade	2.1 Insulation and Air Sealing Solutions for Existing Building Cavities
	2.3 Adding Exterior Insulation When Residing
	3.1 Improved Duct Retrofit Process
3. 2021 IECC Envelope + Equipment Upgrade	2.1 Insulation and Air Sealing Solutions for Existing Building Cavities
	2.2 Wall and Window Panel Systems
	2.3 Adding Exterior Insulation When Residing
	2.4 Streamlining High Performance Window Installation
	3.1 Improved Duct Retrofit Process
	3.2 Wall Panels with Mechanical System Integration
4. PHIUS Envelope + Equipment Upgrade	2.2 Wall and Window Panel Systems
	2.4 Streamlining High Performance Window Installation
	3.1 Improved Duct Retrofit Process
	3.2 Wall Panels with Mechanical System Integration

1.4 ABC Research Opportunities Report

The ABC Research Opportunities Report identifies RD&D innovations that support the industrialization of whole building retrofits and rapid growth of efficient new construction. The ABC Research Opportunities Report focuses on the *industrialization of processes associated with building construction and renovation and how technology innovation supports process enhancement.*

This research opportunities report informs RD&D and innovation scaling aspects of the ABC Initiative, and along with other technology specific research and development opportunity (RDO) documents from BTO, is part of BTO's portfolio of research focused on building decarbonization technologies. This includes other initiatives such as the Energy, Emissions and Equity (E3) Initiative the Grid-Interactive Efficient Buildings (GEB) Initiative, and other technology specific roadmaps on topics such as heating, ventilation, air-conditioning (HVAC), lighting, energy storage, opaque envelopes, and windows detailed in (RDO) documents. More information on the connections to these other programs and initiatives are provided throughout this research opportunities report.

The innovations listed in Table 3 were identified through primary and secondary research as well as stakeholder input through a series of public meetings (see Appendix A for more details). Table 3 summarizes the primary innovations covered in this research opportunities report and the goal areas that the innovative solution aims to help achieve.

Table 3. Summary of ABC Primary Innovations in Report

Innovation Category	Primary Innovation	Current State	Innovation Goals	Value Added
 **Industrialization of Envelope Improvements**	**Insulation and Air Sealing for Existing Building Cavities**	• Solutions are costly, disruptive, and not viable across climates and building types • Improved methods are needed to assess existing conditions and quality check installation	• Costs less than $1,000 for average single-family homes • Installs: 1-2 days for single-family homes, 8-10 apartment units per day, or ≤8 days for small-medium commercial buildings	Convenience, Comfort, and Resilience
	Wall and Window Panel Systems	• Insulating panels are only available for new construction • Panel connection points are not easy/fast to install or universal	• Cost ≤$10/sq. ft. installed • Installed on typical home in ≤7 days, small commercial building in ≤15 days	Aesthetics and Resilience
	Adding Exterior Insulation When Residing	• Insulating panels are only available for new construction • Panel connection points are not easy/fast to install or universal	• Cost ≤$1/sq. ft. installed	Convenience, Comfort, and Resilience
	Streamlining High Performance Window Installation	• Window installation is labor- and time-intensive (not automated) • Air and water sealing and retrimming is labor- and time-intensive	• Window, trim, and sealant installed in less than 10 minutes • Costs are equivalent to onsite trimming (about $1,800 for a 2,000 sq. ft. building)	Resilience
 **Industrialization of Equipment Installation**	**Improved Duct Retrofit Process**	• Insulation and air sealing is time-intensive and expensive • Aerosolized sealant is relatively fast, and relatively expensive	• Cost ≤$0.75/sq. ft. installed • Installed in less than a day for a typical home	Comfort
	Wall Panels with Mechanical System Integration	• In RD&D phases – not yet available in the U.S. • Can also include integrated PV	• Cost reduced compared to separate systems	Less Disruptive Install, Comfort, Resilience

The ABC Research Opportunities Report also provides a substantial amount of information related to *enabling innovations*. These are innovations in design, materials, production, and installation assistance that could be used in combination with each other to support the achievement of the goals related to the primary innovations. These enabling innovations are summarized in Table 4.

Table 4. Summary of ABC Enabling Innovations in Report

Innovation Category	Enabling Innovation	What does it enable?
 Design and Tools	**Retrofit Decision Applications**	Quick and easy determination of which retrofit measures are possible and make the most financial sense for that building
	Non-Destructive Evaluation of Existing Building Envelopes	Easy determination of potential challenges to the implementation of an envelope retrofit
	Air Leakage Testing, Equipment, and Methods for Large Buildings	Quick, easy, and inexpensive detection of air leakage locations and rates in building envelopes, especially for existing large multifamily and commercial buildings
 Materials	**Advanced Insulation**	Easily installed insulation for quick incorporation into wall panel systems, residing, and building cavities to enable more resilient buildings and reduced heating and cooling demand
	Advanced Sealants	Streamlined building envelope retrofits for reduced heating and cooling demand
 Production and Installation	**Data Collection, Modeling and Analytics**	Optimization of onsite activities and offsite factory processes to broadly support improvements to end-to-end operations for building envelope retrofits
	Subtractive Manufacturing	More controlled and less wasteful production of pre-fabricated wall panels, siding and insulation boards for building envelope retrofits
	Additive Manufacturing	Supports precise control, rapid production, and less material waste, especially useful in complex building or component geometries
	Portable Machines for Distributed Manufacturing	Industrialized construction of building components onsite to reduce transport costs and delivery time
	Advanced Scanning for Retrofit Construction	Easily designed and manufactured customized, prefabricated retrofit panels for easier and faster installation and fitting
	Retrofit Robots (Including Automated Insulation Installation and Inspections)	Fast, high-quality, and affordable installation and inspection tasks that are necessary for building envelope retrofits
	Real-Time QA/QC Using Visual Indicator or Internet Connected Sensors	Near-real-time QA/QC of building efficiency measures, including building envelopes, to improve installation and inspection quality
	Augmented/Mixed Reality	Improved building retrofit and new construction technology installation by providing training, guidance, inspections, and QC of work

2 Industrialization of Envelope Improvements

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, 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 2016). 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.

2.1 Insulation and Air Sealing Solutions for Existing Building Cavities

Introduction

Well-insulated and sealed external cavities prevent air leakage and can drastically increase the performance of a building's envelope. To insulate enclosed cavities, the most common approach is for a professional to blow or inject insulation material into the cavity. Insulation material options can include blown-in cellulose, low density foam, mineral wool, or expanded polystyrene beads to fill empty wall cavities. For this installation solution, this section is specially focused on solutions for insulating and air sealing enclosed cavities for retrofitting existing buildings.

Minimally invasive "drill and fill" solutions using very small openings in a building's facade is one approach to streamline the installation process and make it more appealing to building owners and tenants. In this solution, small holes are drilled through the interior wall or exterior façade of the building or roof to access the cavity. Metering and thermal imaging tools are often used to assess the amount of insulation material to be injected. The hole is then repaired, sealed, and any exterior paneling, brick, stucco, or other façade type is replaced or installed.

Insulating and air sealing enclosed cavity approaches can apply to single-family and multifamily homes and commercial buildings primarily with wood or light gauage steel frame walls and is a promising solution for affordable housing upgrades. This type of energy efficiency upgrade is generally more difficult to sell to individual homeowners than multifamily or commercial building owners because of the cost and potential disruption. More case studies on proven results and verified savings for different building types would be beneficial.

Minimally invasive and less disruptive approaches to insulate enclosed cavaties are especially needed in the residential sector. About 80% of homes today have enclosed cavaties, and homes built more than 20 years ago have uninsulated empty cavities. Approximately one-third of the heat loss from most homes is through the walls, so insulating wall cavities can save about 7–27% of annual energy depending on the climate zone (Zheng et al. 2020).

Key stakeholders include insulation material suppliers and manufacturers, air barrier manufacturers, insulation energy performance trade contractors, potentially siding contractors, building owners, and homeowners.

Where Are We Now?

Minimally invasive and streamlined installation methods, equipment, and assessment tools provide an opportunity to increase market adoption, quality, and performance and decrease installed cost. For single-family and multifamily buildings, there are active R&D projects in this area related to easier and less disruptive installation methods, improved foam products to fill cavities, and low global warming potential (GWP) blowing agents. One DOE-funded project is focused on minimally invasive drill-and-fill and requires a hole only 1/4-inch in diameter. New methods have also drastically reduced the potential for interior or exterior sheathing blowouts due to overfilled cavities.

The installed cost largely depends on the geographic location, the size of the building, the exterior façade, and the amount of insulation already installed. Today, enclosed cavity insulation approaches like “drill and fill” can take 1-2 days for most homes but can take upward of 9 days to address old and historic single-family homes and can be weather dependent. For multifamily units, it generally takes a small crew about one day to insulate 6-10 apartment units. Despite a lack of case studies performed specifically on commercial buildings, test wall configurations in residential applications can be extrapolated to demonstrate potential in commercial buildings, especially in small businesses and converted residential buildings.

Today, there are only a few tools that assist installers to inspect inside the cavity for structural integrity, damage, or other issues before and after the installation. Opaque building envelopes can also be unique from one building to another and are made up of several layers and configurations that can ultimately impact the performance of the inserted insulation. Low cost, quick, and innovative installation solutions are also needed to assess the cavity or in some cases reach very difficult to access areas, which might incorporate robotics or advanced camera or scanning technologies. Many of these scanning and remote insulation technologies were demonstrated among the American-Made E-Robot Prize winners

(Source: DOE Building America Solution Center)

(American Made Challenges 2022). Further discussion about retrofit robots can be found in Section 4.3.6.

Innovation Outlook

Table 5 provides a summary of the current state of the technology, goals, and challenges.

Table 5. Innovation Outlook for Insulation and Air Sealing Solutions for Existing Building Cavities

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 (e.g., it is necessary to store blown-in foam insulation in high pressure containers or pressure vessels, which is costly and labor intensive for contractors) • 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 • Need for standardized testing protocols to ensure proper fire and water testing of materials • Not every façade type can be accessed or drilled from the outside • Plumbing and electrical wiring 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 perform in all temperatures) • Few low-cost, easy to use tools exist to quality control installation of fill-and-fill processes

Innovation Needs

Table 6 provides a summary of identified innovation needs and key potential solution areas.

Table 6. Innovation Needs for Insulation and Air Sealing Solutions for Existing Building Cavities

Technical Needs

Category	Activities Needed
Technical Performance	• Identify and validate minimally invasive installation methods, equipment, and materials that can perform in all climates and temperatures • Develop installation methods and assessment or scanning tools that work across building types, facades, and configurations and can easily direct remediation to necessary areas • Improve standardization of testing protocols related to fire and moisture testing for innovative installation methods • Improve the throughput rate for foam insulation through the dispenser guns to decrease installation time
Cost Reduction	• Decrease the cost of equipment and materials directly related to ease of installation for workers and minimal occupant disruption • Field-validate residential and commercial replicable and minimally invasive installation approaches in several building configurations and across climate zones

Market Needs

Category	Activities Needed
Customer Use Case	• Pilot new innovative installation approaches and products with insulation and siding contractors • Conduct case studies specific to commercial building types where test wall configurations cannot be extrapolated from residential to commercial building applications
Ease of Use/Install	• Identify guidance on how to address different façade types and building configurations with validated installation approaches and tools and include best practices
Awareness	• Document proven non-energy benefits and potential savings data as well as how approaches work within a whole building envelope solution • Document benefits and impacts of low GWP materials/blowing agents over conventional materials • Increase incentives in utility, state, and local incentive programs

Workforce Needs

Category	Activities Needed
Career Development	• Improve working conditions and opportunities for year-round work through process and equipment innovation • Help identify career pathways for building envelope/insulation workforce

2.2 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, Emrath 2018). 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. Technologies and automation strategies for pre-fabricated wall and window panel systems can make envelope retrofits faster, easier, and more productive 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 is applicable to many types of existing buildings. Unlike the insulation and air sealing solutions discussed in Section 2.1, these solutions would primarily apply to envelope retrofits of the entire exterior windows and walls as well as insulation, providing structure, insulation, and air and water barriers.

Key stakeholders include new construction and retrofit panel manufacturers and installers, chemical bonding companies, siding contractors, researchers, siding installers, building scientists, historical societies, building owners, and architects. This technology is applicable to approximately 70% of existing residential buildings and approximately 50% of commercial buildings that require an exterior wall retrofit according to the analysis provided in Section 1.3 and the Market Guidance Report.

Where Are We Now?

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 new construction wall panels are purely structural (BMC 2021), while others also add insulation and cladding (Dryvit 2021). These panels all have proprietary connection points, which are meant to be quick, but do require some training/onboarding for contractors to know how to install the products. Existing panels typically focus on providing structure, insulation, and rainwater management in the form of cladding. These panels sometimes provide air barriers and vapor barriers and sometimes rely on those tasks to be completed onsite in separate steps. To ensure these insulation, rainwater management, and air and vapor barrier functions perform reliably, wall and window panels need to be well sealed to each other and the existing structure (if applicable). Advanced sealants are further discussed in Section 4.2.2.

The prefabricated panels that exist today require 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 still 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 onsite; however, the materials in most structural panels are rigid and require some amount of cutting, trimming, and re-sizing while onsite. Multiple retrofit wall panel technologies are under development through existing research projects funded by BTO under the 2019 ABC FOA awards (EERE 2020) and 2022-2023 BENEFIT FOA awards (EERE 2023). These projects include mechanisms to connect panels to each other; however, they do not focus on developing universal quick connections for retrofit panels. More work is needed to make high-quality, robust connections easier to apply with limited training; universal connections is a reasonable goal although may be modified for different applications. The California Energy Commission and New York State Energy Research & Development Authority also have exterior retrofit projects underway and panel manufacturers are part of the research teams.

Another challenge to panelized systems 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 development and evaluation of quick connect innovations. Automatic detection systems do not currently exist for building envelope installations. One technology discussed during stakeholder workshops is the need for certain building products to include color changing technology so installers and inspectors can visibly see that a product was installed correctly. There are many products on the market with color changing indicators that either represent a proper installation or can notify if something has been tampered with; however, most of these products exist within other industries. Processing industries requiring a sterilized environment, such as pharmaceutical and medical manufacturing, utilize packaging tape with sterilization indicators. Another common use of indicator tape is in the electronics industry to demonstrate whether a product has been exposed to water. Water indicator tape will change color if water has been detected.

Pressure indicating films and pressure-sensitive adhesives are other market available products, which have been used in the automotive, electronics, aerospace, and packaging industries and are now being researched for application in buildings (DOE 2020a). This material is used in testing processes to determine the distribution and magnitude of pressure being applied to a surface. (See the Real-Time QA/QC Using Visual Indicator or Internet Connected Sensors section for more information on the technical challenges associated with inspectable verification of completed connection).

(Source: Dryvit)

Innovation Outlook

Table 7 provides a summary of the current state of the innovation, goals, and challenges.

Table 7. Innovation Outlook for Wall and Window Panel Systems

Current State	• Insulating wall panels are only available to purchase for new construction, and all feature proprietary connection points that require some 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 (i.e., there may be different product lines for different climate conditions, but there should be solutions for all extremely hot and cold temperatures in the U.S.) • Universal quick-connect mechanisms to preserve compatible 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.
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 manufactured, workers will need training in panel installation procedures and QA/QC

Innovation Needs

Table 8 provides a summary of identified innovation needs and key potential solution areas.

Table 8. Innovation Needs for Wall and Window Panel Systems

Technical Needs

Category	Activities Needed
Durability	• Develop durable systems and have 30+ year life expectancy in each climate zone (including all extremely hot and cold temperatures in the U.S.)
Technical Performance	• Develop a thin wall panel system that exceeds current IECC (or American Society of Heating, Refrigeration and Air-Conditioning Engineers [ASHRAE]) energy code standards, is easy to install, and offers comparable aesthetic value • Develop systems with adhesives that are cost-effective and work between various insulation and moisture barrier layers in the panel wall systems • Develop easy to install connection mechanisms for retrofit panels that maintain the critical control layers • Validate panel system performance in various architectural configurations and different climate zones • Increase compatibility and interoperability with advanced 3D scanning tools and software systems to streamline panel design and manufacturing
System Integration & Flexibility	• Develop panel systems that are flexible enough or can be adjusted to fit most building oddities, including out-of-square windows, doors, corners • Utilize Building Information Modeling (BIM) and other measurement tools to ensure panel compatibility with existing structures • Develop universal panel connection systems
Cost Reduction	• Maximize installation productivity benefits and minimize overall system manufacturing costs • Develop open source panel system designs for use across panel manufacturers to reduce cost and production time and provide starting options for building owners, designers, architects, and contractors
Environmental	• Develop reusable and recyclable material systems • Use low or no VOC adhesives and other materials • Create connectors out of recycled materials like steel or aluminum or ensure connectors could be recycled when the building is eventually decommissioned

Market Needs

Category	Activities Needed
Production & Supply Chain	• Determine manufacturers and suppliers in the new construction panel industry or new entities to produce panel systems for existing building applications and understand their needs • Implement manufacturer and supplier matchmaking activities • Develop methods to streamline manufacturing processes • Understand the needs of contractors onsite, including connectors that are easy to hold with working gloves, etc.
Ease of Use/Install	• Streamline installation methods to reduce installed cost and increase efficiency to prove value to contractors with tight margins • Develop guidance or training on panel installation (especially related to connections between panels) that are available to national installer outfits and regional installers
Customer Use Case	• Build a consistent pipeline of demand for existing building panel systems via aggregated demand or bulk purchasing programs • Identify successful business models for existing homes and how contractors sell the systems • Identify builders/developers willing to utilize all-in-one panel solutions to demonstrate benefits at scale
Building Energy Codes & Industry Standards	• Educate industry standards bodies like the International Code Council (ICC) and ASHRAE through increased showcasing at conferences and other industry events, also with code officials • Support the development and adoption of standardized procedures and provide resources to expand state-level approvals for prefabricated systems

Workforce Needs

Category	Activities Needed
Training & Capability Development	• Improve working conditions and opportunities for year-round work through innovation • Help identify career pathways for building envelope/insulation workforce • Workers will need training in panel installation procedures and how to perform QA/QC on panel installation

2.3 Adding Exterior Insulation When Residing

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 residing and 20% for additions (Friegea 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 that they called "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 residing 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 skillset 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 residing, using only residing crews. Primary adoption drivers for this process improvement include financial savings associated with an already-scheduled residing project, improved comfort, and the opportunity to decarbonize a building relatively easily (e.g., less interface details), if R-5 to R-10 can be added to the building and still be cost-effective.

Where Are We Now?

Less than 10% of residential residing projects add 1 inch or more of insulation during residing projects (Friegea et al. 2016, Home Innovation Lab Survey and interviews). This is likely because adding insulation to the residing process requires training the siding installation crew to add insulation; tape the seams to create a weather-resistant barrier; and install siding on top of the insulation. To address this issue, PNNL is leading a project to scale training of siding installers, until a more novel approach is developed. This project found that prices for adding insulation when residing 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 residing (Friegea 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 ostenisbly 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 suplimental water management layer associated with a combined siding-plus-insulation product. Thus, a proper weather-resistive barrier needs to be applied to the existing sheating prior to adding the siding. Another drawback is that the insulated siding is usually installed in a lap-fashion, which assists with shedding bulk water but mean that lapped layers have inconsistent R-value 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 adhesive by certified contractors. One drawback of these systems is that they require a "like new" substrate to attach to, which can be cost prohibitive.

Many energy efficiency incentives and financing options in the U.S. are available for wall insulation retrofits. Awareness of these incentives is very low and marketing is generally done through contractors. States and utility regions with higher incentives have had a substantial impact on adoption. However, many programs tend to promote or focus on attic insulation and air sealing over wall insulation. In addition, the requirements to qualify for rebates may be stringent, and it can take a long time to receive the rebate.

Innovation Outlook

Table 9 provides a summary of the current state of the innovation, goals, and challenges.

Table 9. Innovation Outlook for Adding Exterior Insulation When Residing

Current State	• Insulating wall panels are mostly available for new construction, and all feature proprietary connection points that require some training to install • Panels that are currently under development have connection mechanisms but do not focus on fast and universal connections
Innovation Goals	• Reduce the steps associated with adding insulation when residing • Cost no more than $1/sq. ft. installed • No thicker than 1" • Have built in-moisture management • Installable over existing cladding and allows for cladding on top • Products that last 30+ years in each climate zone (i.e., there may be different product lines for different climate conditions, but there should be solutions for all extremely hot and cold temperatures in the U.S.)
Technical Challenges	• Creating a reliable water-resistive barrier • Details associated with wall penetrations such as pipes, vents, etc. • Relatively high cost of materials that can create a weather resistive barrier
Market Challenges	• Homeowner education about the opportunity • Utility and contractor education about the opportunity • Integrated insulation and cladding products are prohibited in some jurisdictions.
Workforce Challenges	• Simple installer training that can be learned on-site

Innovation Needs

Table 10 provides a summary of identified innovation needs and key potential solution areas.

Table 10. Innovation Needs for Adding Exterior Insulation When Residing

Technical Needs

Category	Activities Needed
Durability	• Develop durable systems and have 30+ year life expectancy in each climate zone (including all extremely hot and cold temperatures in the U.S.)
Technical Performance	• Additional R-value of at least R-5, ideally R-10 • Validate panel system performance in various architectural configurations and different climate zones and is flexible enough to effectively address various wall penetrations • Ensure solutions include a water resistive barrier
System Integration & Flexibility	• For insulation-only products, must be able to work with any cladding or siding product • For insulation-plus-cladding products, must be able to be applied directly to any structural sheathing product
Cost Reduction	• Cost no more than $1/sq. ft. installed
Environmental	• Develop reusable and recyclable material systems • Use low or no VOC adhesives and other materials

Market Needs

Category	Activities Needed
Production & Supply Chain	• Manufacturers of rigid insulation to collaborate with manufacturers of weather resistive barrier products
Ease of Use/Install	• Reduce number of steps to install R-5 to R-10 insulation when residing
Customer Use Case	• Identify contractors who are willing to demonstrate insulation installation when residing with their crews • Work with siding installers to help educate consumers about the opportunity • Work with EPA to help educate consumers about the opportunity
Building Energy Codes & Industry Standards	• Support the development of codes that allow cladding products with integrated insulation

Workforce Needs

Category	Activities Needed
Training & Capability Development	• Develop insulation installation training techniques for siding companies and organizations as applicable for existing and new solutions • Develop benefits information for contractors to provide to consumers

2.4 Streamlining High Performance Window Installation

Introduction

Windows provide views, daylighting, and aesthetics to building occupants and are a major component of building envleope systems. While windows provide many benefits, it is estimated that approximately 25-30% of energy losses in buildings occur via windows (DOEa n.d.). Windows are a pentration in a building's opaque envelope, which allow 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 are 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.

Where Are We Now?

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 spaced for onsite workers to drive nails or screws for window installation to boost productivity. Despite their benefits, flanged windows do 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 stopblocks for install, mechanical attachment of flangless 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 for 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 a 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 trimwork 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 building's structural sheathing.

(Source: Building Science Corperation)

Innovation Outlook

Table 11 provides a summary of the current state of the innovation, goals, and challenges.

Table 11. Innovation Outlook for Streamlining High Performance Window Installation

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 labeled parts; or automated onsite fabrication • Includes pre-installed sealant where applicable so that caulk does not need to be applied onsite • Includes a sloped bottom sill and sloped top plate with a drip edge • Window, trim, and sealants is installed in less than 10 minutes • Costs the same (including installation labor costs) as onsite window trim (about $1,800 for a 2,000 sq. ft. building and increasing from there, relative to building size) • Made from recycled materials or is recyclable
Technical Challenges	• No quick way to remove old caulk or foam that was previously air sealing the window • Shipping of window trim would potentially be costly and difficult due to size and shape unless solutions are created for the window trim boxes to fold flat and pop up onsite • Need for recyclable or biodegradable fire-retardant materials
Market Challenges	• There are many products and steps which must be followed to maintain air- and water-tightness in window installation. Each manufacturers 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 for exterior insulation projects

Innovation Needs

Table 12 provides a summary of identified innovation needs and key potential solution areas.

Table 12. Innovation Needs for Streamlining High Performance Window Installation

Technical Needs

Category	Activities Needed
Durability	• Ensure water management capability of the system in different architectural environments and climate zones • Ensure window does not impede the moisture management of the installed or existing envelope • Develop methods and practices to quickly assess soundness and compatibility of existing structure for window installations
Technical Performance	• Develop systems that are cost-effective and quick to install • Lab- and field-validate prefab window trim in multiple building configurations • Understand standard window sizes and minimize variability of product offering • Ensure water management capability of the system in different architectural environments and climate zones • Ensure compatibility of system materials with existing materials
System Integration & Flexibility	• Develop extended window trim that quickly connects to any building undergoing an exterior rigid foam retrofit • Develop system approach to maximize ease and productivity of installation and simplify QA • Encourage window and panel manufacturers to work on solutions together
Cost Reduction	• Determine cost reductions related to manufacturing and installation • Minimize costs through increased productivity of a systems approach and material specifications
Environmental	• Ensure trim materials are recyclable • Use low or no VOC adhesives and other materials

Market Needs

Category	Activities Needed
Production & Supply Chain	• Determine whether wall panel manufacturers or separate manufacturers would develop these products • Determine what material will be used for the window trim • Implement manufacturer and supplier matchmaking activities, including potential window manufacturers and installers to develop integrated solutions or integration kits • Explore relationships with existing retrofit cladding providers or a new generation of panel solution providers • Develop methods to streamline manufacturing processes
Ease of Use/Install	• Streamline installation methods to help reduce installed cost • Develop identification system for each window in the building to be matched with the correct window trim box
Customer Use Case	• Ensure system provides comparable aesthetic and maintenance values when compared with current practices • Build consistent pipeline of demand via beneficial value proposition to consumers or aggregated demand through use on multifamily buildings • Pilot extended window trim • Identify successful business models for existing buildings (likely in conjunction with panel retrofits)

Workforce Needs

Category	Activities Needed
Training & Capability Development	• Develop guidance or training on how to install the extended window trim

2.5 On the Horizon for Envelope Improvements

The envelope is a major building component and a unique opportunity to reduce a substantial amount of energy load. To capitalize on the impact that changes to the envelope can have on a building retrofit, there are a number of opportunities on the horizon that would integrate an envelope with other building components and features. For example, one exciting project funded by DOE's BTO aims to commercialize building envelopes with a thermal anisotropic system that redirects heat or coolness where and when needed. The system consists of one or more layers of thin conductive materials sandwiched between insulation layers and connected to thermal loops. The thermal loops are in turn connected to heat sinks or sources such as thermal energy storage systems. The package uses advanced controls to regulate heating, ventilation, and air conditioning (HVAC) loads in order to shift or shape loads, reduce peak demand, and/or lower utility bills.. These thermally anisotropic building envelope systems can be prefabricated and integrated into panelized, volumetric, or onsite construction.

Other possible integration opportunities include building-integrated photovoltaics (PV) and HVAC-integrated building envelopes (likely providing distributed HVAC on a room-by-room basis, see Section 3.2 for more information). This type of system would likely include a small heat pump unit that is integrated into the wall panel to provide the envelope and HVAC retrofit at the same time.

(Source: National Renewable Energy Laboratory)

3 Industrialization of Equipment Installation

Another key element to decarbonize the building stock is the industrialization of equipment installation. Building on RDOs related to building equipment and building controls as well as the BTO Building Electric Appliances, Devices, and Systems (BEADS) subprogram, the following innovations aim to *industrialize the installation of* and *integrate the technologies* that are necessary for beneficial electrification of approximately 90% of the existing residential building stock and applicable in some cases to new construction (e.g., wall panels with mechanical system integration) (See Table 1). While there is not as much data on the applicable existing commercial building stock for these innovations, especially because the opportunities are more scenario specific (e.g., space constraint challenges or large scale renovations), these innovations are expected to benefit the commercial building retrofit market. Further, it is important to consider the technical requirements for electrifying buildings with a sufficient level of electric service. This may require electric service (i.e., panel) upgrades or new 220-V circuit wiring for electrifying building equipment in coordination with the innovations outlined in this section. Such panel and wiring upgrades would also benefit from cost reductions and addressing common logistical challenges.

3.1 Improved Duct Retrofit Process

Introduction

Ducts are a common distribution system in new and exisitng homes. According to EIA, about 60% of homes in the U.S. have ducts (EIA 2017). In typical homes, about 20-30% of the air that moves through the duct system is lost due to leaks, holes, and poorly installed ducts. The result is higher utility bills and difficulty keeping the house comfortable, no matter how the thermostat is set (ENERGY STAR 2021). Additionally, duct leakage in large commercial buildings can be significant, often ranging from 9-26% as indicated by one case study (Wray et al. 2005). One survey confirmed that nearly two-thirds of building professionals believe that ducts in buildings have significant leakage, with 68% of respondents reporting that leaks of 15% or more are "common" (Dixon 2018).

As the country moves to more heat pumps used for space conditioning, it becomes even more important that air distribution systems are well sealed and insulated. Air from heat pumps is typically delivered at a more steady rate, but at a slightly cooler temperature than gas or electric furnaces distribute. Duct losses associated with air leakage and/or lack of insulation can become a major issue if occuring outside the conditioned building area.

Where Are We Now?

Retrofitting ducts usually involves sealing them with mastic duct sealing tape and insulating them. The cost of air sealing can vary from a few hundred dollars to more than $2,500 (for a home that is approximately 1600 sq. ft.) depending on the duct's start and end percentage leakage. Costs for insulation can vary from a few hundred dollars to more than $800 (for a home that is approximately 1600 sq. ft.) depending on the amount of insulation (up to R-8) (DOE 2011).

One novel technology being used in everything from small residential buildings to larger commercial buildings involves injecting a fog of aerosolized sealant particles into the pressurized duct system. Field studies have demonstrated in two large commercial buildings that 66% of the leakage area can be sealed in 2.5 hours, or 86% of the area within 5 hours, respectively (Modera et al. n.d.). Results from similar studies of the same technology yielded an average of 64% energy savings from heating (natural gas), 29% from fan energy (electrical), and 6% from cooling (electrical) (Quinnell et al. 2016).

In addition to air sealing and insulating ducts, there are other ways that air distribution systems can be improved in order to minimize duct losses. Some examples include: zoning the distribution system so air is only delivered to occupied spaces, running smaller (or inflatable) ducts through the exisitng ducts, running refrigerant lines through the exisitng ducts, and abandoning the distribution system altogether for packaged heat pumps.

Although residential and small commercial HVAC zoning solutions are available in the market, presently, costs and the lack of interoperability with certain systems appear to be a significant barrier. Some of the technologies that are on the market include the use of manual or automatic dampers in the duct work or manual or automatic dampers at supply registers such as Keen Home. Other solutions are hardwired into the HVAC control system increasing the complexity and cost of the installation (Supplyhouse 2021).

Small diameter (high velocity) ducts have been tested through the DOE Building America Program by IBACOS (DOE 2017). Initial tests showed that material and installation costs of small-diameter ductwork were lower in new construction. They were not tested in existing homes, but in theory they could be installed inside existing ducts (especially if those ducts are already inside conditioned space). Initial results also showed that register placement was important due to draft concerns, and that the small duct (high velocity) system made it harder for room-to-room temperature uniformity.

Low-load or single-room heat pumps do exist as well, however, there are a relatively low number of options, especially for cold climates (Ephoca 2022, Mitsubishicomfort.com). These options also tend to cost thousands of dollars per unit, which is cost prohibitive for a whole house.

Innovation Outlook

Table 13 provides a summary of the current state of the innovation, goals, and challenges.

Table 13. Innovation Outlook for Improved Duct Retrofit Process

Current State	• Duct insulation and air sealing can take a full day for a typical 2,000 sq.ft. house and cost more than $3,000 • Aerosolized sealant is relatively fast, and relatively expensive compared to business as usual
Innovation Goals	• Total installed cost of the system should be no more than $0.75 per square foot (~$1,500 for a 2,000 sq. ft. home) • Install in no more than a day (4 hrs.) for a typical house • Can integrate with HVAC equipment that is up to 8 years old and manage short cycling and equipment degradation concerns
Technical Challenges	• It is difficult to work inside the small space that exists in residential distribution systems • Reducing airflow to too many ducts or closing off the wrong configuration of ducts can cause back-pressure and result in wasted energy through high static pressure on the air handler, high duct leakage, or damaged HVAC equipment • Homes with a leaky, uninsulated building envelope, old, inefficient equipment may not benefit from an improved distribution system, important to triage the right opportunities • Massive variability of duct system designs and installation environments
Market Challenges	• Value proposition must be uniquely crafted for HVAC contractors and homeowners, with an emphasis on comfort and energy savings • Upgrade needs to be cost effective
Workforce Challenges	• Solutions will likely require workforce training

Innovation Needs

Table 14 provides a summary of identified innovation needs and key potential solution areas.

Table 14. Innovation Needs for Improved Duct Retrofit Process

Technical Needs

Category	Activities Needed
System Integration & Flexibility	• Systems designed to be installed and operated wirelessly over common platforms using onboard batteries if necessary • Installation solutions that can be used with existing ducts and systems where applicable • Evaluate the use and integration of Wi-Fi / IOT related technology
Technical Performance	• Define which installation solutions are most applicable to which building types and existing duct and HVAC systems • Lab- and field-validate solutions and processes to retrofit or adapt ducts multiple residential buildings and HVAC system types • Develop solutions that make it easier to work within the space constraints of residential ducting systems
Durability	• Develop systems that do not cause equipment degradation through short cycling and inadequate airflow • Develop solutions that can be easily tested for performance and any air leakage identified
Cost Reduction	• Focus on solutions that are flexible in many installation scenarios so that costs can be compressed.

Market Needs

Category	Activities Needed
Production & Supply Chain	• Support any new production or supply chains needed
Ease of Use/Install	• Ensure distribution system can be installed in less than 2 hours for a house around 2,000 sq.ft. • Develop guidance and training programs for installers, conduct trial installs with contractors
Customer Use Case	• Highlight product value with research on the economic, environmental, and comfort benefits associated with the product • Gather feedback from contractors installing current market products • Determine successful pilot markets based on a building stock assessment • Demonstrate energy savings with zoning technology case studies • Create demonstrations of comfort uniformity across zoned areas
Building Energy Codes & Industry Standards	• Ensure solutions and installation processes are compliant with all ICC (International Residential Code), mechanical and plumbing codes.
Cost Reduction	• Use technical scaling analysis and manufacture review to determine possible cost compression strategies • Validate energy savings and recommend technology be included in utility retrofit programs

Workforce Needs

Category	Activities Needed
Training & Capability Development	• Develop or support workforce training and education on new processes or products

3.2 Wall Panels with Mechanical System Integration

Introduction

Improving the process to renovate walls and heating, ventilation, cooling, and water heating mechanical systems at the same time is key to accelerate building retrofit rates, in specific scenarios such as retrofits of old buildings or in major renovation opportunities. 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 mechnical 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, and the existing mechanical systems can be replaced with integrated high efficiency, electric, HVAC, and water heating heat pump equipment directly in the wall panel. Integrating mechanical systems into wall panels also removes the need for HVAC equipment to consume square footage within living spaces and streamline 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 rennovation 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. Key stakeholders include new construction builders, retrofit panel manufacturers, HVAC or integrated heat pump systems manufacturers, siding contractors and installers, researchers and building scientists, building owners, and architects.

Where Are We Now?

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.

There are panels with mechanical system integration currently in development in the U.S. and Europe, but no products that 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[11] is a high-performance heat pump integrated into an enevelope upgrade panel, while the ORNL project[12] also includes water heating, ventilation, and grid response capabilities. Fraunhofer-Gesellschaf based in Germany is developing a modular façade panel with integrated heating, cooling, and ventilation, with a PV system to power the heat pump and ventilation systems. This innovation requires more RD&D to optimize operation.

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[11] https://www.energy.gov/eere/buildings/downloads/zonal-heat-pump-whole-home-panelized-retrofits
[12] https://www.energy.gov/eere/buildings/articles/wall-embedded-multifunctional-heat-pump-energy-storage-systems-grid

Innovation Outlook

Table 15 provides a summary of the current state of the innovation, goals, and challenges.

Table 15. Innovation Outlook for Wall Panels with Mechanical System Integration

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

Innovation Needs

Table 16 provides a summary of identified innovation needs and key potential solution areas.

Table 16. Innovation Needs for Wall Panels with Mechanical System Integration

Technical Needs

Category	Activities Needed
Durability	• Develop durable systems and have 10–15+ year life expectancy in each climate zone • Systems shall be designed with repairability and access in mind
Technical Performance	• Develop systems that are cost-effective and do not compromise the various insulation and moisture barrier layers in the panel wall systems • Validate the wall panel and mechanical system performance in various architectural configurations and different climate zones • Develop compatibility and interoperability with advanced 3D scanning tools and software systems to streamline panel design, manufacturing, and configuration of embedded mechanical systems • Maintain technical performance while meeting consumer preferences on system location • Adjust existing mechanical system designs to integrate within panelized envelope retrofits as opposed to separate indoor or outdoor installation
System Integration & Flexibility	• Develop integrated mechanical systems to fit into the panel that are flexible enough or can be easily designed for different configurations • Utilize Building Information Modeling (BIM) and other measurement tools to ensure panel compatibility with existing structures • Develop universal connections for integration with other panels
Cost Reduction	• Maximize installation productivity benefits and minimize labor and re-work costs associated with sizing of HVAC units • Develop open-source panel system designs for use across panel and HVAC manufacturers to reduce cost and production time and provide starting options for building owners, designers, architects, and contractors
Environmental	• Develop reusable and recyclable material systems as part of the panel system where possible • Use low or no VOC adhesives and other materials

Market Needs

Category	Activities Needed
Production & Supply Chain	• Determine manufacturers (HVAC and panels) and suppliers in the new construction industry or new entities to explore integrated panel systems for specific existing building applications and understand their needs • Implement manufacturer (HVAC and panels) and supplier matchmaking activities • Develop methods to streamline manufacturing processes
Ease of Use/Install	• Streamline installation methods to reduce installed cost and increase efficiency to prove value to contractors with tight margins • Develop guidance or training on panel installation (especially related to connections between panels and any existing systems) and benefits information that are available to national installer outfits and regional installers
Customer Use Case	• Build a consistent pipeline of demand via aggregated demand or bulk purchasing programs • Identify successful business models for existing home use cases and how contractors sell the systems • Identify energy and non-energy benefits for consumers • Identify builders, developers, and firms willing to adopt these integrated panel solutions to demonstrate benefits at scale
Building Energy Codes & Industry Standards	• Educate industry standards bodies like the International Code Council (ICC) and ASHRAE through increased showcasing at conferences and other industry events, also with code officials • Support the development and adoption of standardized and streamlined procedures and provide resources to expand state-level approvals for prefabricated systems

Workforce Needs

Category	Activities Needed
Training & Capability Development	• Develop training programs that educate workforce on panels/envelope along with HVAC/mechanical systems so that contractors are knowledgeable about installing and maintaining integrated panels

4 Enabling Innovations

4.1 Design and Tools

These enabling innovations focus on design and tools that primarily support the key elements of the industrialization of envelope upgrades.

4.1.1 Retrofit Decision Application

In the future, when widescale retrofits become more commonplace, there will be a need for contractors arriving onsite (who may or may not have 15 years of experience with building retrofits) to quickly determine what retrofits are possible and what retrofits make the most financial sense for that building. Ideally, during the 1 hour that is usually part of the job bid process, the contractor could use a decision-making app, along with a kit of tools, to identify the details (e.g., material choice, installation approach, sizing, etc.) needed to decarbonize the building, at the lowest cost possible. Having as much information as possible to make a project plan early in the process (with minimal surprises) will allow contractors to make more accurate quotes, purchase the most relevant materials in advance, and prepare the crew for any specifics of the job.

The hardware tools that would help answer some of the questions of the app more accurately are located in other sections of this research opportunities report, and in some cases, are already commercialized. For example, the *Non-Destructive Evaluation of Existing Building Envelopes* hardware topic is covered in the next section. A thermal imaging camera that is added to a phone or tablet is an example of a hardware tool that is already commercialized that would be available to assist contractors and app developers in finding out critical information quickly for the purposes of retrofit decision-making.

The primary stakeholders include software companies, contractors, and remodelers to test the app, building scientists to ensure the app is doing no harm, and building owners to understand how the application could also be used as a sales tool if possible. This solution is applicable to all existing residential and commercial buildings.

Where Are We Now?

There are some free or commercially available tools that can be used to make retrofit decisions that exist today. However, none of these decision tools are made for contractors that are on a job site, and some are not quick to use or easy to learn.

- BETTER
- Building America Building Science Advisor
- Asset Score
- ResStock Analysis Tool
- ComStock Analysis Tool
- Scout
- Xerohome
- Synapsys
- Multi-Criteria Retrofitting Building Energy Efficient Building
- Decision-Making Framework for the Selection of Sustainable Alternatives for Energy-Retrofits
- Deep Energy Retrofit—A Guide for Decision Makers
- Energy Savings and Moisture Transport Calculator
- Building America Retrofit Decision Tool

In an attempt to simplify existing knowledge for the contractor audience, a combination of national labs and forensic specialists have started to develop decision trees that help determine when and if a building envelope should be retrofitted. The inputs to the decision tree include climate zone, building vintage, health of a building (including mold status, etc.), and other wants from the building owner (e.g., improved comfort or better aesthetics). These decision trees have been field tested in a few instances; however, they need to be tested in dozens before they are finalized.

Additionally, some hardware tools exist today that can help provide more accurate inputs into a retrofit decision app. For example, the FLIR ONE (Flir 2021) can turn any phone or tablet into an infrared camera, which could help quickly determine the performance of the envelope in a building (e.g., delta of surface temperature and outdoor temperature).

Innovation Outlook

Table 17 provides a summary of the current state of the innovation, goals, and challenges.

Table 17. Innovation Outlook for Retrofit Decision Application

Current State	• Some free or commercially available tools exist today, but they are not made for quick and easy onsite use by contractors
Innovation Goals	• Uses limited data inputs to find cost-effective envelope and equipment retrofit opportunities for buildings • Utilizes decision tree for equipment, opaque envelope, windows, window attachments etc. • Focuses on decarbonization guidance (including equipment, envelope, and solar measures) • Is free to contractors and consumers • Sends building data to a cloud ideally maintained by DOE (no information about the homeowner collected or stored) • Takes less than an hour to complete an assessment • Completes a Home Energy Score at the same time as the decision assessment • Can develop a quote that can be emailed to the homeowner (for contractors that input their rates and typical material costs) • Materials list from quote potentially connects to a local big box store where the items can be ordered and delivered onsite, further streamlining the retrofit process • Connects costs to local, state, and federal incentives • Applies to at least 80% of the building stock (where the other 20% might require a more senior contractor to provide a specialty quote) • Calculations can be done in the cloud or offline with a cloud upload later, allowing for flexibility with urban and rural users
Technical Challenges	• Because existing buildings are diverse, it will take time to develop decision trees that make 80% of building stock accessible • Connectivity to external sources like hardware (assessment tools) and software (quote, DOE database, Home Energy Score) will need to be established
Market Challenges	• The app must be user friendly, which will require extensive testing with contractors
Workforce Challenges	• Contractors will need practice and experience using the app for a streamlined retrofit experience

Innovation Needs

Table 18 provides a summary of identified innovation needs and key potential solution areas.

Table 18. Innovation Needs for Retrofit Decision Application

Technical Needs

Category	Activities Needed
Data & Accuracy	• Develop APIs that connect to existing and yet to be developed hardware tools that can improve the accuracy of the inputs into the decision tool, and therefore, improve the accuracy of the suggested retrofits • Develop a national database where all data received from this app can be stored
Technical Performance	• Field-validate residential and commercial prototypes in several building configurations and across climate zones

Market Needs

Category	Activities Needed
Customer Use Case	• Obtain contractor input, pain points, and feedback to inform product design and features • Demonstrate with workforce early in product design
Ease of Use/Install	• Make app easy to use with no significant training required
Awareness	• Develop marketing strategy to increase awareness of the app
Production & Supply Chain	• Identify software vendor to develop products • Consider intellectual property (IP) implications

Workforce Needs

Category	Activities Needed
Training & Capability Development	• Create training material in collaboration with app developers and contractors to make app usage widespread and easy

4.1.2 Non-Destructive Evaluation of Existing Building Envelopes

Introduction

To enable widespread market transformation of durable building retrofits that do no harm to a building, a time-efficient assessment tool is necessary to determine if any part of a building envelope may cause challenges to the implementation of a retrofit due to the presence of structural degradation, asbestos or lead paint contamination, or substantial moisture, mold, or mildew. Critically, the assessment solution should be minimally invasive with the ability to measure moisture content or detect material degradation in walls, roofs, underlying structure, and foundations, without full removal of surface material (e.g., cladding).

Key stakeholders include manufacturers of scoping cameras and probes, infrared cameras, contractors, building diagnostic consultants, building developers and owners, and software companies. This solution is applicable to all existing buildings made with wood components.

Where Are We Now?

Some products on the market today meet some of the goals identified for this innovation; however, none are currently used for the purpose of identifying hidden issues and helping to determine a path forward for envelope retrofits. Some examples of products that could be altered slightly for this purpose include:

- A scanning device or camera (e.g., infrared, microwave, etc.) that detects thermal resistance and the minute temperature differences/temperature patterns associated with wet or dry materials.
- Lead paint and asbestos testing.

Innovation Outlook

Table 19 provides a summary of the current state of the innovation, goals, and challenges.

Table 19. Innovation Outlook for Non-Destructive Evaluation of Existing Building Envelopes

Current State	• The technologies available have some of the capabilities needed and the potential to be altered to meet all innovation goals; however, none are currently used for the purpose of identifying hidden issues and helping to determine a path forward for envelope retrofits
Innovation Goals	• Detects moisture or structural issues inside the wall even if the wall is dry and sound at the time of inspection (but may still have active mold growth) • Locates and predicts the condition of the existing structure, which is used to assess if the existing structure can hold the loads of retrofit measures • Inspection process for subsurface issues takes less than an hour for an average sized home (~2000 sq. ft.) • Cost for an average sized home is less than $100, including labor and any device rental costs • Includes clear guidance on how to inspect, mitigate, and safely proceed with exterior retrofits • Is applicable in climates with extremely high or low temperatures
Technical Challenges	• Innovation must be field validated to ensure all issues that exist can be found with the tools and methods developed • A consistent process must be conducted non-invasively and then invasively to make sure the non-invasive approach consistently catches all critical issues
Market Challenges	• Contractors must see the value of this tool and trust that the results are reliable • Clear guidance on usage must be provided • Output must be easily understandable so that contractors can demonstrate hidden issues to building owners
Workforce Challenges	• Contractors need to be trained on the technology and methods developed and how to explain issues to business owners

Innovation Needs

Table 20 provides a summary of identified innovation needs and key potential solution areas.

Table 20. Innovation Needs for Non-Destructive Evaluation of Existing Building Envelopes

Technical Needs

Category	Activities Needed
Data & Accuracy	• Develop testing methods, protocols, or ways to check the tools in real time to ensure accuracy of the tools
Technical Performance	• Develop a hardware tool that combines the abilities of several existing diagnostic tools (some of which exist in other industries) that are not disruptive to building occupants • Develop a software application that is user friendly for contractors/consultants and provides easy to understand outputs/reports for customers • Lab- and field-validate residential and commercial prototypes in several building segments and configurations

Market Needs

Category	Activities Needed
Customer Use Case	• Obtain contractor input, pain points, and feedback to inform product design and features • Demonstrate the tool's inputs and outputs with workforce and customers early in product design • Engage insurance and home financing institutions to identify ways innovations like this one can demonstrate mitigated risk and energy improvement needs.
Ease of Use/Install	• Make hardware easy to use with no significant training required
Awareness	• Develop a marketing strategy to increase awareness and understanding of the novel product and its uses
Production & Supply Chain	• Identify both manufacturer for hardware and software vendor to develop application • Consider IP implications
Building Energy Codes & Industry Standards	• Ensure that the tool's outputs use the same unit of measurement as existing code, so the user can easily determine if codes (or industry standards) are met

Workforce Needs

Category	Activities Needed
Training & Capability Development	• Create or support training material in collaboration with technology developers and contractors to make innovation usage widespread and easy

4.1.3 Air Leakage Testing, Equipment, and Methods for Large Buildings

Introduction

Air leakage is a primary driver of energy use in buildings, accounting for 30-50% of heating and cooling energy use in a home (Chan et al. 2012). Identifying and sealing leaks has consistently been demonstrated as a cost-effective retrofit approach with the potential to yield 9 TWh/yr in electricity savings across the entire U.S. single-family housing stock, assuming a 25% reduction in air leakage (Wilson et al. 2017). Air sealing also presents tremendous opportunity within commercial buildings where it accounts for approximately one quad of energy annually. According to a recent simulation-based analysis, "decreasing the air leakage rate of just standalone retail buildings throughout the country from 1.07 to 0.4 cfm/sq. ft. at 0.3 in. of water could lead to potential source energy savings of 19 TBtu and financial savings of $145M per year" (Hun et al. 2018).

The market for residential air leakage testing has been well established and successful, in part thanks to advancements in building energy codes and home certification programs. However, testing in commercial buildings, especially existing buildings, have been slow to develop due to a variety of market, policy, and technical challenges. To increase the realization rate of savings in existing commercial and multifamily buildings, several of these challenges can be addressed through advancements in testing equipment and practices.

The stakeholders necessary for the development of this technology include manufacturers, air sealing consultants, designers, engineers, and builders and developers. This solution is applicable to all existing multifamily residential buildings and commercial buildings.

Where Are We Now?

Air leakage testing was initially incorporated into the 2009 IECC residential provisions as an optional method to ensure a building does not exceed a maximum leakage rate. Testing has been a residential requirement in subsequent IECC versions and is now an optional testing method in ASHRAE Standard 90.1 and the commercial provisions of the IECC. Code requirements have advanced the testing market using blower door technology in new construction, but there is no such requirement for existing buildings that have not undergone a significant retrofit.

During residential energy code compliance or an energy audit, a blower door test is typically conducted to understand the baseline leakage rate of a building to assess code compliance or understand energy savings potential and opportunities. This process works well in low-rise residential buildings, but in large multifamily or commercial buildings, the complexity, cost, and time to conduct these tests can be significant. In particular, cost and the potential for a site to be shut down in order for the test to be conducted were identified as primary reasons industry is reluctant to adopt the practice of air leakage testing (Hun et al. 2018). Presently, air leakage is detected through building pressurization or depressurization tests with the use of one or multiple blower doors. This method offers an intuitive and robust approach to measuring building air tightness; however, it has its own set of unique challenges. The time it takes to set up and execute a blower door test varies by building type and increases for larger, more complex buildings. A single-family home may only take a few hours between prep, obtaining the results, and cleanup, but a large multifamily or commercial building could require a half to full day, depending on the number of blower doors required and interruptions from occupants or contractors onsite. Conducting a blower door test requires a skilled professional to perform the work, and, in some cases, not enough professionals exist in an area – this is particularly true when testing larger and more complex buildings.

Although cost data is limited, based on a survey of commercial air barrier testing companies, the cost of air leakage testing ranged from $0.15 to $0.50/sq. ft. for buildings between 5,000 to 50,000 sq. ft. and $0.09 to $0.15 for buildings between 50,000 to 100,000 sq. ft. It's important to note that these testing costs are limited and based on testing a newly constructed building (Hart et al. 2018). Lastly, to identify leaks, a smoke stick, or thermography is used, which is time-intensive. Current challenges with the business as usual approach have led researchers to explore non-invasive, less complicated, and less costly options to conduct air leakage testing in large multifamily and commercial building types.

Alternative Methods

Some alternative less invasive methods to estimate a building leakage rate or identify specific leakage areas have demonstrated promise, including micro-electromechanical systems (MEMS)-based sensors, acoustic-based leak detection, and refractive imaging to identify leaks and calculate the leakage rate.

Acoustic-based testing is designed to specifically locate and size leaks in building envelopes from outside the building. Put simply, this approach is conducted by producing a low frequency sound inside the building and then picking up the sound with a microphone on the outside of the building and analyzing that sound with a computer to determine the size and location of leakage areas (Zheng et al. 2020). Argonne National Laboratory patented the Acoustic Building Infiltration Measurement System, and the system is being commercialized by a company called Sonic LQ (ANL).

The MEMS-based sensor is a novel approach that uses wireless pressure sensors to assess the pressure differential in a building. This technology is particularly useful in commercial building applications because it is non-invasive and can be conducted over a period of days without interrupting occupants. However, this approach has only been tested in a limited number of building types, requires a Wi-Fi thermostat, and has accuracy concerns (Casillas et al. 2021). Additionally, this approach cannot identify specific leakage points.

Oak Ridge National Laboratory has conducted research on a promising new technology to detect and measure air leakage in a less disruptive manner. This method is conducted from the exterior of the building "using an imaging technique to visualize the flow of air leaks and calculate the volumetric flow of air based on the refraction effects imaged by cameras" (Boudreaux et al.).

Innovation Outlook

Table 21 provides a summary of the current state of the innovation, goals, and challenges.

Table 21. Innovation Outlook for Air Leakage Testing, Equipment, and Methods for Large Buildings

Current State	• Current air leakage testing is time consuming, expensive, and disruptive, especially for large multifamily and commercial buildings
Innovation Goals	• Reduces the costs to run air leakage testing in large multifamily and commercial buildings by 25% • Performs testing with less impact to onsite occupants • Testing and leakage detection methods apply to a range of building types, with specific focus on large multifamily and commercial buildings • Reduces the number of professionals needed to perform testing compared to current practices • Provides leakage rate of entire building in addition to identifying specific leakage areas for improvement
Technical Challenges	• New method of leakage testing must yield the same accuracy of results as a blower door test in a less invasive way • Leakage rates in large, leaky buildings must be quickly detectable; with current technologies, leakier buildings require additional costs and more equipment for testing
Market Challenges	• Test standard needs to be developed for approval in building codes and certification programs • Testing requires high costs, time-delays, and complexities to implement blower door tests, especially in large buildings
Workforce Challenges	• The buildings workforce is siloed and addressing air leakage is not often a high priority in any one trade • A new approach to testing would require retraining and growing an entire workforce

Innovation Needs

Table 22 provides a summary of identified innovation needs and key potential solution areas.

Table 22. Innovation Needs for Air Leakage Testing, Equipment, and Methods for Large Buildings

Technical Needs

Category	Activities Needed
Data & Accuracy	• Provide an indicator for errors or inaccurate readings • Incorporate into technologies the ability to test and seal areas of air leakage at the same time
Technical Performance	• Develop non-invasive air leakage testing methods that work across building types • Develop ability to identify leakage areas in addition to measuring total envelope tightness • Develop automated or robotic portions of the tool to improve speed and effectiveness • Lab- and field-validate novel approaches that are alternatives to testing and identify leakage areas, especially in large commercial and multifamily buildings (i.e., using sensors) and ensure results are consistent with approved testing methods

Market Needs

Category	Activities Needed
Cost Reduction	• Reduce the cost to implement airflow testing and the cost of the equipment
Ease of Use/Install	• Develop airflow testing equipment and methods that minimize time onsite, are easy to set up, and are simpler to implement
Awareness	• Develop white papers or demonstration showcases to educate the market on key benefits of understanding air leakage like lifecycle energy and cost savings • Develop air sealing campaigns to encourage uptake across building portfolios rather than one building at a time
Building Energy Codes & Industry Standards	• Encourage state and localities to adopt stretch building energy codes with testing requirements for large commercial and multifamily buildings • Conduct cost-effectiveness analyses demonstrating the ROI on envelope testing and sealing • Propose new evaluation and testing methods to standards bodies

Workforce Needs

Category	Activities Needed
Training & Capability Development	• Create training material in collaboration with contractor businesses to make new methodology widespread and easy to follow

4.2 Materials

Materials used in construction and renovations today are typically those that meet the building code (or project goals) at the lowest cost. Cost reduction through technical R&D and cost compression is critical for new and emerging materials to be widely adopted. Innovations in low-embodied carbon in common construction materials are most applicable to new construction today and the primary focus areas are described in this section.

4.2.1 Advanced Insulation

Almost all houses in the U.S. building stock would benefit from an insulation upgrade. 50-70% of energy usage in an average American home is associated with heating and cooling. Inadequate insulation and envelope leaks are the leading causes for wasted energy (DOER 2021). Older houses and commercial buildings can pay off the cost of an insulation upgrade within a few years through reduced utility bills. Insulation upgrades can also increase occupant comfort and provide a sound barrier.

Advanced insulation technologies can further improve the efficiency of the building envelope and increase the building's temperature uniformity (reducing hot/cold spots). To decrease energy used in buildings associated with heating and cooling costs, an advanced insulation solution would have a high R-value to improve thermal performance and be durable, lightweight, and easy to install in any building retrofit or new construction project. It may also be recyclable and have a low-embodied carbon lifecycle. Since almost all buildings can benefit from an insulation upgrade, advanced insulation solutions should be widespread and accessible to all homeowners and building owners (Energy Saver n.d.).

Key stakeholders include insulation manufacturers, contractors, building developers and owners. This solution is applicable to all new and existing residential and commercial buildings.

Where Are We Now?

Today there are many insulation products on the market. There are three main installation methods: blankets or insulation blatts that can roll for transport and be cut to install, blown or sprayed in insulation, and rigid boards or panels that come in large (sometimes precut) pieces.

Blankets or batts are usually made of fiberglass, mineral wools, or other fibers, have an R-value between 2.9 and 4.3 per inch of thickness, and cost under a $1.00 per square foot for 3.5 inch commercially- available batt products (DOER 2021). This form is the most widely available insulation and typically requires the least amount of prior training to install; however, these materials are more challenging for installers to handle, including requiring personal protective equipment (PPE).

Blown-in insulation is usually made of fiberglass, rock mineral wool, or cellulose, and spray foams are typically made of polyurethane. Typical R values range from 2.3 to 6.3 per inch of thickness (DOER 2021). This type of installation can be difficult to install as it can require a licensed professional with specialized training and PPE to safely install it. Costs are usually $1.50 per square foot for a 3.5 inch cavity but can be more expensive depending on if it is sprayed or blown-in and how much training and PPE is required. Blown or sprayed insulation is often utilized in retrofits as it can conform to any space shape and can be installed in hard to access spaces without temporarily altering structural elements of the building.

Foam or rigid boards are made of polystyrene, polyurethane, phenolic, or polyisocyanurate foams. These types have the highest R-value from 3.6 to 7.5 per inch of thickness (DOER 2021), and costs typically range from $0.65 to $1.50 per square foot per inch of thickness, based upon commercially available rigid insulation products. Panels are typically used in new construction but can be used in modular or prefabricated retrofits as they can be precut and assembled onsite quickly. Board-based insulation is the easiest to handle and install; however, petroleum-based plastics are highly flammable (except phenolic foam, which is fire resistant) and have high embodied carbon.

The embodied carbon and recyclability of insulation materials varies substantially. Blown-in cellulose insulation is often made of recycled newsprint, which reduces its embodied carbon. Unfortunately, due to required fire retardants in the mixture, it cannot be further recycled at the end of its lifecycle (REenergizeCO 2019). Fiberglass insulation is made of 40-60% recycled glass, and since glass is a natural fire retardant, fiberglass insulation has a larger potential for recycling after use. Currently, very few recycling centers are able to take and recycle fiberglass and the technology to do so is largely unavailable (REenergizeCO 2019). Mineral wool is currently made up of 75% post-industrial recycled content and also is naturally fire retardant (Energy Saver n.d.).

Mineral wool and other fibrous materials have the potential of being recycled and compacted into other construction items like ceiling tiles or bricks (Knauf Insulation n.d.). In 2017, a developer ground up existing insulation batts and blankets and reinstalled them as a blown insulation. This service is not commercially available and hasn’t been developed further (Harvey 2017). Lastly, cotton batts made of recycled clothing are available for purchase through Habitat for Humanity and other nonprofits. Its R-value is as high as typical insulation batts and does not have the potential to irritate skin as fiberglass does (ReStore 2020).

Innovation Outlook

Table 23 provides a summary of the current state of the innovation, goals, and challenges.

Table 23. Innovation Outlook for Advanced Insulation

Current State	• Blankets and insulation batts are R-2.9 to R-4.3 per inch of thickness, and typically cost under $1.00/sq. ft. per 3.5 inch of insulation (DOER 2021) Blown-in and spray insulation is R-2.3 to R-6.3 per inch of thickness, and typically costs from $0.65 to $1.50 per inch of thickness (DOER 2021) • Embodied carbon, recyclability, and fire resistance of each type varies substantially
Innovation Goals	• Installs easily in retrofitted spaces in less than one day per room • Has an R-value of at least 5-7, ideally over 8 per inch of thickness • Costs $1.00 or less per square foot at wholesale material cost • Is durable and lasts at least 30 years in all climate zones • Is recyclable and requires limited use of virgin materials • Meets other key resilience criteria, such as fire, mechanical strength, and moisture, without the need for toxic additives
Technical Challenges	• Rigid boards and panel insulation are most ideal for new construction and modular retrofits and have a higher thermal efficiency than sprayed foam insulation, but are difficult to install in a non-invasive manner for retrofits • Blown-in is the most flexible for installation especially in retrofits, but it has a lower thermal efficiency than rigid boards • New panel innovations need to be more flexible, pliable, and easily installed in tight spaces, or new blown-in innovations should have higher thermal efficiency • Current flexible insulation products like those used for industrial pipes are cost prohibitive for building applications on a cost vs. R-value basis • Some insulation materials are highly flammable, requiring the addition of non-recyclable fire retardants • Inflammable, biodegradable, sugar-based materials are available and cost-effective but can present installation and maintenance challenges (Lu et al. 2018, USI 2018)

Market Challenges	• Lack of understanding of the potential benefits and little willingness to pay the associated premium • Few case studies and other information on proven benefits exist • Contractors must be able to easily procure products from suppliers and install them in hard to access areas across different building types • Streamlined installation methods or equipment across buildings will be needed to reduce costs Methods must be safe and comfortable for the workforce to help reduce turnover rates
Workforce Challenges	• Technical guidance and documents are needed to educate businesses and workers on new materials and associated installation methods and equipment

Innovation Needs

Table 24 provides a summary of identified innovation needs and key potential solution areas.

Table 24. Innovation Needs for Advanced Insulation

Technical Needs

Category	Activities Needed
Technical Performance	• Increase the thermal efficiency of insulation • Develop insulation inherently less susceptible to moisture accumulation without the need of a vapor retardant • Lab- and field-test higher thermal efficiency for blown-in insulation • Lab- and field-test insulation that is moisture resistant without vapor retardant • Field-test panel insulation in a hard to access area
System Integration & Flexibility	• Develop panel insulation that is more flexible, pliable, and suitable for hard to access spaces
Durability	• Develop insulation technologies that are durable and have a 30+ year life expectancy in each climate zone
Cost Reduction	• Determine cost reduction by streamlined insulation installation methods
Environmental	• Develop non-flammable, non-toxic insulation materials

Market Needs

Category	Activities Needed
Customer Use Case	• Demonstrate advanced insulation products with contractors and understand how they use the products • Document energy and non-energy benefits for consumers using real-world data including performance of different insulation materials for different uses
Ease of Use/Install	• Streamline installation methods to help reduce installation cost • Develop guidance or training or best practices on new materials and installation methods for contractors • Develop corresponding inspection methods or tools to ensure installation quality and expected R-value performance of the installed insulation
Awareness	• Produce marketing campaigns focused on weatherization to inform homeowners, realtors and other industry professionals of different advanced insulation options and benefits • Develop high visibility case studies, pilots, and other documents to identify and demonstrate advanced insulation benefits to a wide audience including well positioned company partners
Production & Supply Chain	• Determine manufacturer and suppliers for advanced insulation products • Determine sales channels
Building Energy Codes & Industry Standards	• Participate in the national energy code development process and advocate for higher levels of insulation, particularly with respect to existing buildings • Encourage state and jurisdictions to adopt existing Building Performance Standards and higher efficiency codes addressing existing buildings • Provide technical assistance and training to increase the enforcement and implementation of energy codes in building retrofits

Workforce Needs

Category	Activities Needed
Training & Capability Development	• Guidance on new materials, installation methods, and equipment are needed for streamlined and high-quality installations

4.2.2 Advanced Sealants

Introduction

Sealants close joints between components of the air and water barriers in building envelopes. The continuous air barrier system lowers energy use by reducing the amount of unwanted infiltration and exfiltration through building envelopes. Sealing air leaks significantly reduce heating and cooling losses, making it one of the most cost-effective ways to decrease energy use in buildings and their respective CO_2 emissions. Furthermore, sealants prevent moisture flow and their potential accumulation in the envelope that can cause structural and health issues associated with rotting and mold growth, respectively (Energy Saver 2021, Baechler 2010).

Common sealing techniques include caulking, gasketing, weatherstripping, and using foam and polyolefin plastic (Energy Saver 2021, Baechler 2010). The type of sealant used (e.g., silicone, acyrlic, water-based, etc.) depends on the substrates on which they will be applied, the environmental conditions during application, exposure to detrimental conditions (e.g., UV light, joint movement), and expected longevity among others. Sealants are cost effective in new construction and retrofits, although it may be easier to install properly in new construction.

Key stakeholders include feedstock suppliers, sealant manufacturers, air and water barrier installers, subs that specialize on improving the energy performance of building envelopes, and building owners. This innovation is applicable to new and existing residential and commercial buildings.

Where Are We Now?

In the U.S., buildings lose significant amounts of energy via air leakage. Sealing buildings is considered one of the most cost-effective ways to reduce energy usage (ENERGY STAR 2021). For example, one DOE report estimates that homeowners can save ~10-20% on home energy costs by sealing their homes (Energy Saver 2017). Presently, air sealing can have better returns than standard investments such as stocks and bonds (Baechler 2010). Due to its cost efficiency, air sealing is a significant feature of building codes. Air sealing an existing 2,500 sq. ft. building costs ~$2,000[13] (How Much n.d.). It's also a commonly performed procedure in retrofits. Typical sealants that are used to reduce air leakage last 5–20 years (Dow Chemical 2017).

Some sealants have no curing times because they are made from tape, such as butyl gasket sealing tape. However, butyl gasket sealing tape has other trade-offs, such as fewer use cases. They also cannot be applied at low temperatures because they do not stick to surfaces. Standard sealants typically take 24 hours and longer to fully cure (though some can be much faster). Table 25 shows the life expectancy and curing times of various, common sealant types (Dow Chemical 2017; 3M 2017; BASF 2007; General Electric n.d.).

[13] Another LBNL study (that is currently unpublished) showed that the median cost of air sealing was $730 for a 1900 sq.ft. residential building

Table 25. Contemporary Sealants Characteristics

Sealant	Life Expectancy	Typical Curing Time
Acrylic sealants	5–20 years	24–72 hours
Butyl gasket sealing tape	5–20 years	N/A
Polyurethane sealants	5–20 years	24–40 hours
Polysulfide sealants	15–20 years	24–48 hours
Silicone sealants	10–20+ years	24–48 hours

Most sealants are installed by hand at the jobsite, inch by inch to seal each crack, which means that the task is time consuming and performance is highly dependant on the installer. One product that is being used today to increase the speed of installation of sealants is the AeroBarrier product (AeroBarrier 2021). This product is applied with an aerosol machine and a blower door fan that pressurizes buildings so that the aerosolized sealant flows toward the leaks, and accumulates and seals the leaks. While this works well for new construction, it is disruptive in retrofits of occupied buildings.

BTO is currently sponsoring the development of a new method to seal joints at the jobsite that is faster and has better performance than traditional approaches. The method involves a sealant that can be exposed to ambient conditions for a year and will not start curing until after it is triggered with pressure (Hun et al. 2020). This enables the sealant to be properly installed on prefab parts at a plant, and its curing initiates on demand when the prefab parts apply preassure on the sealant as they are assembled at the jobsite. Ongoing improvements to the sealant include decreasing its embodied carbon by at least 50% by replacing petroleum-based polymers with biobased polymers.

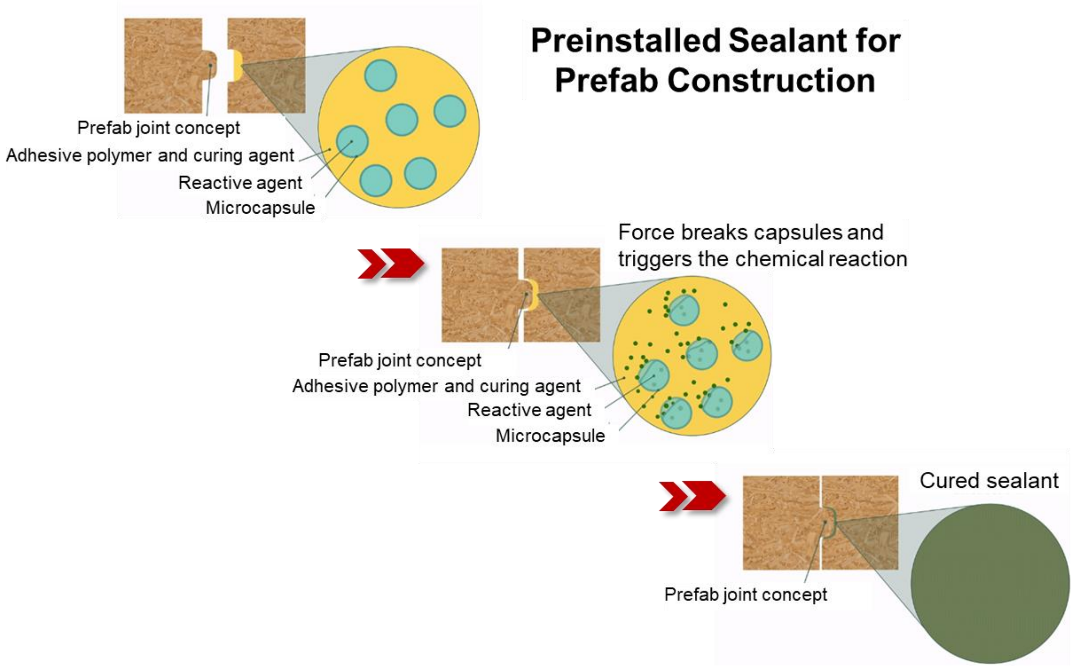

Figure 5. Preinstalled sealant that is composed of an encapsulated reactive agent that is embedded in a curing agent. (Source: ORNL)

When pressure is applied to the sealant, the microcapsules break, the reactive and curing agents mix, and the curing reaction begins.

Advanced sealants improve upon the quality of sealants available today; they can be foams, caulks, and/or tapes that are highly durable (long lifetimes), cure quickly to avoid tenant disruption, have zero to low VOCs and toxic compounds, and lower embodied carbon.

Innovation Outlook

Table 26 provides a summary of the current state of the innovation, goals, and challenges.

Table 26. Innovation Outlook for Advanced Sealants

Current State	• Many sealants are available on the market, but they have long curing times (most take 24 hours and longer to fully cure), short lifetimes (most only last up to 20 years) and can be disruptive to tenants during retrofits
Innovation Goals	• Foams and caulks fully cure within 24 hours • Foams, caulks, and tapes last at least 30 years • Can be installed without tenant disruption • Costs do not exceed current sealant prices
Technical Challenges	• Most sealants have long curing times, which can slow down the installation process • Butyl gasket sealing tape cannot be applied in low temperatures (though pre-compressed foam tapes and non-cured glazing types may reduce these issues) • Life expectancies are up to 20 years, but 50% of sealants fail by 10 years and 95% fail by 20 years (White et al. 2012) • Sealants have trouble bridging large gaps; there are some expanding sealants, but it is important to ensure they do not impact the surrounding materials • Many sealants are petroleum based and have significant embodied carbon (potential recyclable/low-carbon materials are in early development stages) • Leakage points are difficult to locate in existing buildings
Market Challenges	• Typical homeowners do not understand the value from energy cost savings of sealants • Most contractors do not offer air sealing as an independent service for existing buildings • Commercial buildings are large and take a long time to seal
Workforce Challenges	• Technical guidance and documents will be needed to educate businesses and workers on new materials, sealing methods, and equipment

Innovation Needs

Table 27 provides a summary of identified innovation needs and key potential solution areas.

Table 27. Innovation Needs for Advanced Sealants

Technical Needs

Category	Activities Needed
Technical Performance	• Improve materials to reduce curing time of sealants and ensure installation ability and performance at low and high temperatures • Improve capabilities in filling large gaps and expanding sealants; ensure the pressure does not impact the adjacent materials • Lab- and field-validate sealants across building types • Find or develop a tool that can detect air/fluid leakage for retrofits
Durability	• Increase life expectancy and durability of sealants
Environmental	• Ensure sealants have low or no VOC content • Develop low-carbon material alternatives to today's petroleum products, improve recyclability, and introduce recycled content

Market Needs

Category	Activities Needed
Customer Use Case	• Document the value proposition, including energy and cost savings and non-energy benefits • Document the business case for contractor businesses to use advanced sealants over conventional products
Ease of Use/Install	• Develop easy to understand user guidance and methods of sealant application for optimal performance, including clear and easy installation instructions for DIY use
Cost Reduction	• Reduce installed cost of existing and new advanced sealants
Production & Supply Chain	• Identify manufacturer for advanced sealants and identify suppliers • Determine sales channels—both for professionals and DIY
Building Energy Codes & Industry Standards	• Work with building performance standards bodies and regulators to increase consistency and stringency of VOC standards and codes for existing buildings • Develop standards for maximum air leakage rates in new construction and retrofits to be adopted in building codes

Workforce Needs

Category	Activities Needed
Training & Capability Development	• Guidance on new materials, sealing methods, and equipment must be developed for contractor businesses for streamlined and high-quality installations as well as information on the value proposition for building renovations

4.3 Production and Installation

The enabling innovations in this section are suitable for both new construction and production of retrofit solutions during both offsite and onsite activities. Introduction and wider adoption of these innovations to drive more industrialized construction and renovation processes will greatly increase the speed of production, reduce the cost, cut carbon emissions, and provide appeal for low-carbon building construction.

Although the discussion below highlights specific technologies and approaches that are promising for achieving ABC-related goals, implementation must consider the complex and interconnected networks of unique firms that include the design and construction industry. Modeling and study of project supply chains has demonstrated the complexity and multi-stage aspects of production, with the consequent need to take a systems perspective to understanding problems and recommending improvements. Improvements in one stage may lead to deleterious effects in other stages. Similarly, scaling production at a regional or national scale requires coordination across multiple stages of production to ensure timely delivery of finished projects at requisite quality. In all cases, analysis and recommendations need to be made from a systems perspective.

There are several relevant bodies of knowledge and concepts related to production processes in general that can also aid in the industrialization of construction processes and approaches. Ideally, these areas should be considered and or included as part of the research opportunities laid out in this report for production and installation as applicable. Such areas include:

- Constructability / Buildability (mostly for onsite work processes to consider production needs early in the design process)
- Design for Manfacturing, Assembly, and Installation (mostly for offsite factory processes to streamline production and assembly operations in a manufacturing environment)
- Lean Manufacturing or systematic approaches to improving assembly lines
- Integrated Project Delivery and Lean Construction and Advanced Work Packaging to create more coordinated design and production activities

More information describing these applicable perspectives and concepts beyond what is in this section are presented in Appendix D.

4.3.1 Data Collection, Modeling and Analytics

There are several emerging approaches in the construction industry for data collection, modeling and analytics for both onsite activities and offsite factory performance. Many of the data collection, modeling and analytics approaches described in this subsection complement each other and can be integrated to optimize onsite activities and offsite factory processes to broadly support improvements to end-to-end operations. In many cases for multimodal data collection, they are necessary elements of broader implementation of digitalization and widely used construction technologies such as inertial measurement units (IMUs), rigid-body sensors, ground-mounted, scanning drones, point cloud scanning devices, and cameras with computer vision modules. Modeling with multiple levels of detail and fidelities can be challenging with featureless data and without any semantic scene information.

To address this, a myriad of commercially available software options exist today that supports the creations of BIM, construction schedules, site information models, and factory information models. Together, they help create high-fidelity simulation models of the entire construction process. Though BIM models consolidate all necessary design-build information within its geometries, they inherently lack process information to enable optimization of the activities onsite and the production system in the offsite factories. Due to the higher degree of complexity with site activities, specifically the required resources as well as tools and techniques, modeling and analytics have proven to be more impactful for onsite work as compared to relatively predicable production flows and constraints in offsite factories. Furthermore, data collection from sensor packages provides the dimensional accuracy that is necessary for complex onsite activities that include multiple trades and hidden bottlenecks. Computer-aided environments provide construction managers, site supervisors, and factory managers with a low-risk, high-impact opportunity to optimize both the built product and the end-to-end construction process at an early development stage.

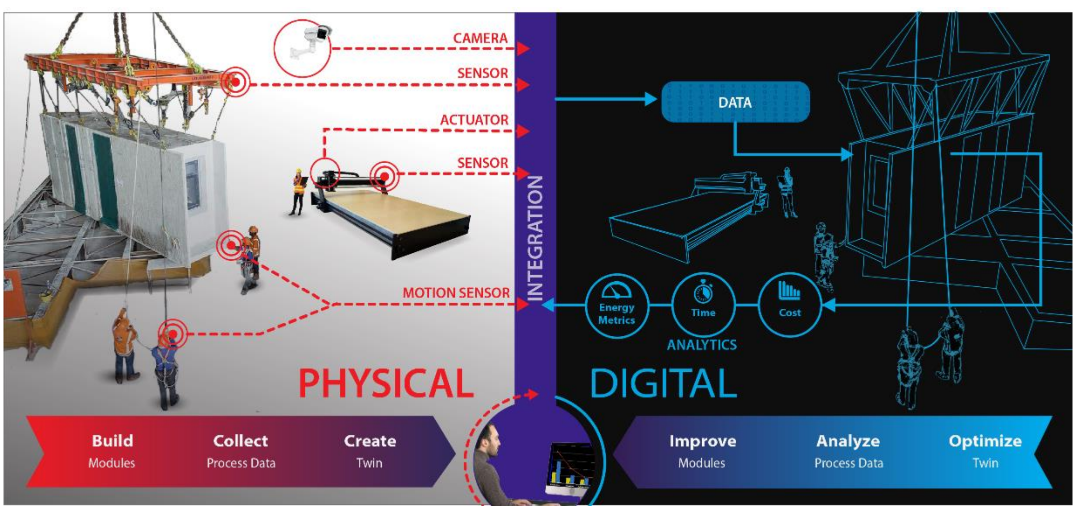

Figure 6. An integrated bidirectional information flow between the real-world offsite factory and its digital twin, enabled by deploying data collection package in the offsite factory. (Source: NREL)

A digital twin is the virtual representation of the entire construction process in the simulation model of the offsite factory. A process-based digital twin is different from dynamic digital twins of buildings for operation and maintenance. To modernize construction, it is envisioned that site construction managers and offsite manufacturers would explore opportunities to collect relevant data on the activities, improve productivity first in simulation through modeling, then implement those improvements in the real-world informed by the analytics. Today, process-based digital twins of onsite construction improve the understanding, prediction, and optimization of scheduling and help construction companies mitigate risk and deliver more with fewer resources. One of the key stages of onsite construction where digital twins have proven to be most valuable is in automating progress monitoring, which involves verification that the completed work is consistent with plans and specifications.

Data from cameras and sensor packages can be used to create digital twins of the entire construction process, leading to a paperless workflow for the construction managers which does not rely on legacy systems and fragmented Enterprise Resource Planning tools. Construction managers, site supervisors, and offsite factory managers can readily inspect the performance of both onsite activities and offsite production system in tandem under a set of hypothetical what-if scenarios by modifying the construction process in the virtual environment. While digital twins can help with planning, they can also provide significant insights into operations to ensure workforce productivity and overall efficiencies related to project delivery (particularly with real-time monitoring).

Multiple modeling approaches can be used to track labor productivity for both manual methods and various production machineries. Traditionally, methods are chosen depending on the frequency of productivity evaluations, time designated for such evaluations, and number of workers used for those evaluations. The five-minute rating is a common method used by manufacturers to measure labor productivity. This method relies on short time observations (5-minute intervals), provides insight on the effectiveness of workers, and can identify the areas where more observations are needed. The results of such analyses could be used to determine the productivity rate of different tasks as well as what should be done to improve the productivity. These metrics can be used for assessment of the extra tasks related to manual installation of the energy efficiency packages (e.g., sprayed insulation) and for activities involving subtractive and additive manufacturing (AM) technologies. Such assessment can be done periodically as a part of continuous improvement of the production line. Furthermore, at each workstation related to the component installations, manhours per installation and the efficiencies gained due to use of other enabling technologies for long production runs can be accurately recorded. With such an approach, direct labor cost and machinery operational cost related to various build and assembly activities onsite and in offsite factory could be calculated based on hourly rate of workers, the installation time, and functionalities of various machineries. This solution is applicable to all new residential and commercial buildings.

(Source: Adobe Stock Images)

Innovation Outlook

Table 28 provides a summary of the current state of the innovation, goals, and challenges.

Table 28. Innovation Outlook for Data Collection, Modeling, and Analytics

Current State	• A myriad of commercially available software options exist today that supports the creations of BIM, construction schedules, site information models, and factory information models; however, available tools and techniques, modeling and analytics have proven to be more impactful for onsite work as compared to offsite factories
Innovation Goals	• Uses data from real-world onsite activities and in-factory processes sourced from cameras and sensors to continuously update the BIM models • Integrates different data types into one high-fidelity simulation model of the entire construction process • Computer vision modules can facilitate creation of 3D construction sites and offsite factory models
Technical Challenges	• Difficulty effectively integrating different data types from various sources into one high-fidelity model of the entire construction process • Time-consuming process to create 3D models of existing and predictive conditions through the construction value chain
Market Challenges	• Lack of low-cost and easy-to-deploy data collection packages including cameras and sensors that can used by the stakeholders • Lack of awareness of benefits of data collection and advanced analytics • Data privacy concerns associated with data collection through cameras and sensors
Workforce Challenges	• Lack of broad scale adoption of emerging software tools and digital workflows

Innovation Needs

Table 29 provides a summary of identified innovation needs and key potential solution areas.

Table 29. Innovation Needs for Data collection, Modeling, and Analytics

Technical Needs

Category	Activities Needed
Technical Performance	• Develop and publish technical support documents and guides explaining the integrated workflow of data collection, simulation modeling and performing advanced analytics • Develop easy-to-learn user interfaces that supports simple interaction and working with advanced computer-aided environments to avoid need for steep learning curve while training teams with various levels of experience/skills • Develop data and modeling integration to effectively analyze multiple data types and computer vision modules from real-world onsite activities and in-factory processes
Data & Accuracy	• Implementation of high-accuracy data collection instrumentation package including IMUs, rigid-body sensors, ground-mounted, scanning drones, point cloud scanning devices, and cameras with computer vision module

Market Needs

Category	Activities Needed
Ease of Use/Install	• Develop low-cost and easy-to-deploy data collection instrumentation package with cameras and sensors • Oversight and continuous improvement to manage the functionality of data collection instrumentation package along with simple data warehousing options
Awareness	• Promote benefits of data collection and advanced analytics to construction managers, site supervisors, factory owners and general contractors • Disseminate about the need for data-driven digitalization and computer-aided environments with advanced analytics in other industries as well such as advanced manufacturing industry • Maintain strong communication with site workers and factory workers to maintain credibility and ensure the workers' privacy while they are aware of the presence of data collecting hardware such as cameras and sensors.

Workforce Needs

Category	Activities Needed
Training & Capability Development	• Incentivize, train, and support workforce to adopt emerging software tools and digital workflows • Support cross-sector knowledge sharing by encouraging data scientists, machine learning experts, simulation modelers, and advanced analytics and simulation experts to actively contribute solutions to applications of industrialized construction • Upskill building industry professionals such as construction schedulers and BIM modelers to familiarize them with data science, simulation modeling and advanced analytics

4.3.2 Subtractive Manufacturing

Subtractive processes are widely used in manufacturing in which material is removed from a crudely-shaped initial material feedstock part to achieve the final shape and dimensions (Hutchings and Shipway 2017). Subtractive manufacturing tools include computer numerical control (CNC) machining tools, laser cutting machines, and waterjets. CNC machining tools are being used to create entire buildings, but they are also being widely utilized to panelize exterior siding, cut insulation boards for building envelopes, and create interior elements. A typical subtractive manufacturing process is usually used to manufacture components with high levels of surface finish and dimensional accuracy. Today, computer aided manufacturing (CAM) tools provide improved control on minimizing waste created by the material removal process in environments that can support the capital intensity for such setups. A key innovation needed here is to make such capabilities cheaper and easily accessible for the construction industry. Subtractive processes lend themselves well to prefabrication and have seen relatively higher penetration in offsite factories compared to other types of advanced manufacturing methods, such as 3D printing. However, RD&D is needed to integrate design workflows so that building design professionals can design for subtractive manufacturing using both traditional materials (wood products) and emerging materials (composites); train workers in offsite factories to operate, troubleshoot, and maintain subtractive manufacturing tools; showcase the high extent of human supervision and collaboration still needed with subtractive manufacturing; and develop automated material handling and assembly systems to support manual installation of precision-cut finished parts or components. This solution is applicable to all new residential and commercial buildings.

Subtractive manufacturing tools are being widely used by tiny home manufacturers and do-it-yourself builders. Popular crowdfunded open source building system platforms such as WikiHouse have promoted small-size CNC machining tools as an affordable technology that can be leveraged to cut-and-build wooden houses at scale. Because these high-precision tools are being used to cut material feedstock, it is vital to complement downstream processes of assembly and installation with precision systems as well. A high extent of human supervision and collaboration is still needed to successfully manufacture material feedstock into finished products or components. It is often seen that manual assembly and installation of precision-cut products or components lead to misalignment and tolerance errors. This is regarded throughout literature as the tolerance propagation problem. The tolerance propagation problem continues to persist in the construction industry, which limits the ability for more automated approaches and inhibits quality.

Innovation Outlook

Table 30 provides a summary of the current state of the innovation, goals, and challenges.

Table 30. Innovation Outlook for Subtractive Manufacturing

Current State	• Subtractive processes and tools are used today to manufacture components with high levels of surface finish and dimensional accuracy, but they are expensive and not widely accessible; they are being widely used by tiny home manufacturers and do-it-yourself builders
Innovation Goals	• Integrates with familiar design workflows • Is affordable and easy to operate, troubleshoot, and maintain • Provides a safer and more productive method for workforce to adopt the tools as opposed to using hand tools for both traditional materials (wood products) and emerging materials (composites) • Requires little training to become an expert in operating them with a wide variety of existing and new materials • Has complementary downstream processes of assembly and installation with laser guidance systems and human-robotic collaboration to mitigate tolerance errors
Technical Challenges	• Lack of automated material handling and assembly systems; manual assembly and installation of precision-cut products or components lead to misalignment and tolerance errors • Lack of capabilities for emerging materials (composites)
Market Challenges	• Expensive and not widely accessible in the construction industry • Lack of awareness of subtractive manufacturing tools and benefits to workers and manufacturers
Workforce Challenges	• A high extent of human supervision and collaboration is needed to successfully manufacture material feedstock into finished products or components • Need for training for offsite factories to operate, troubleshoot, and maintain subtractive manufacturing tools

Innovation Needs

Table 31 provides a summary of identified innovation needs and key potential solution areas.

Table 31. Innovation Needs for Subtractive Manufacturing

Technical Needs

Category	Activities Needed
Cost Reduction	• Develop low-cost CNC machining tools for low-carbon materials and advanced materials such as composites
Data & Accuracy	• Assess and document complementary downstream processes of assembly and installation with precision systems for finished products or components that have been created from high-precision subtractive tools by incorporating machine-induced tolerances for a particular material in CAD drawings and CAM processes

Market Needs

Category	Activities Needed
Awareness	• Hold demonstrations to onsite and offsite factory workers to illustrate the high extent of human supervision and collaboration needed to successfully manufacture finished products or components • Identify and promote the benefits of subtractive manufacturing tools to offsite factory workers and manufacturers and identify clear ROI models

Workforce Needs

Category	Activities Needed
Training & Capability Development	• Make training available to offsite factory workers and manufacturers to learn how to operate, troubleshoot, and maintain subtractive manufacturing tools

4.3.3 Additive Manufacturing

Additive manufacturing (AM) involves manufacturing a part by depositing material layer-by-layer. This differs from conventional processes such as subtractive processes, formative processes such as casting or forging, and joining processes such as welding or fastening. Today, there is a wide range of AM technologies applied in a variety of industries, including the aerospace, automotive, and medical industries, as well as in the building construction industry. Complex geometries created through AM are also a benefit to supporting rapid installation, quality, potential reuse, or disassembly. There is still a high first cost of 3D printers that are purpose-built for construction. Extrusion processes in 3D printers are based on print-heads (nozzles) mounted on frames, robots, or cranes that deposit successive layers of building material, frequently concrete, from the base to the top of the structure. Today, large structures are already being manufactured using concrete extrusion technologies and functionally graded materials (Craveiro 2020). Functionally graded materials are a special kind of composite in which the material properties vary smoothly and continuously from one surface to the other (Reddy 2007). Functionally graded materials have been discussed in more detail under the Advanced Materials subsection of this section.

Today, CAM tools that help operate the 3D printers provide improved control on minimizing material waste created by the extrusion process. While AM methods such as fused deposition modeling and selective laser sintering lend themselves to prefabrication of 3D components, they have not been mass-produced by original equipment manufacturers for offsite factories and have not been adopted at scale by offsite factories compared to subtractive manufacturing tools. RD&D is needed to:

- Integrate design workflows so that building design professionals can design for AM
- Take advantage of the opportunities presented by AM with complex geometries. New shapes and 3D morphologies are possible than with traditional methods
- Train workers onsite to learn how to operate, troubleshoot, and maintain AM tools such as large-scale gantry-based 3D printers
- Evaluate and reduce the human supervision and collaboration needed with AM tools
- Develop 3D printer parts that work with alternative low-carbon materials
- Develop material handling and assembly systems to integrate 3D printed prefabricated components into whole building systems.
- Test and demonstrate the durability of 3D printed components in comparison to standard built components.

This solution is applicable to all new residential and commercial buildings.

Contour Crafting is a mega scale fabrication technology based on layered manufacturing process and extends its fabrication capabilities to new construction of houses (Khoshnevis and Hwang 2006). This fabrication technique can utilize various types of materials to produce parts with high surface quality at high fabrication speed. Today, most materials used for development of AM in the construction industry are cementitious materials because they lend themselves to the extrusion and layered deposition processes. Other methods are also being actively developed such as Big Area Additive Manufacturing and SkyBAAM by Oak Ridge National Laboratory.

Despite the clear benefits, the application of 3D printing in construction, and particularly concrete, has been relatively slow. Many emerging 3D printing construction technology companies that use the technology to create in-situ or prefabricated walls either have narrow scope for 3D printing (combined with traditional stick-built methods) or are restricted to creating low-rise, single story detached homes if creating the whole wall with 3D printing.

Innovation Outlook

Table 32 provides a summary of the current state of the innovation, goals, and challenges.

Table 32. Innovation Outlook for AM

Current State	• Extrusion processes and 3D printed buildings and components are used today, but costs are high and adoption has been slow • Methods including fused deposition modeling and selective laser sintering lend themselves to prefabrication of 3D components, but they have not been mass-produced
Innovation Goals	• Integrates with familiar design workflows so that building design professionals can design for AM • Made affordable and easy to operate, troubleshoot, and maintain • Identifies and addresses opportunities for AM to be used in conjunction with other methods • Provides a safer and more productive method for workforce to adopt the tools as opposed to using hand tools • Is flexible to be re-programmed and re-tooled with alternative low-carbon materials and functionally graded materials • Has complementary downstream processes with laser guidance systems and human-robotic collaboration to mitigate tolerance errors
Technical Challenges	• Lack of 3D printing hardware that allows the use of alternative low-carbon materials and functionally graded materials • Lack of hybrid AM systems to build medium to high-rise buildings at scale • Difficulty developing 3D printed structures with no thermal bridging while allowing the efficient installation of insulation and mechanical systems • Limited 3D printing tolerances; manual assembly and installation of 3D printed products or components to whole building systems lead to misalignment and tolerance errors
Market Challenges	• Lack of awareness of applicability of AM tools and high extent of human supervision and collaboration needed • Lack of awareness of the benefits of AM tools to workers and manufacturers • High upfront investment cost for 3D printers • Worker concerns over potential job loss from increased automation
Workforce Challenges	• Need for training workers on how to operate, troubleshoot, and maintain AM tools such as large-scale gantry-based 3D printers • A high extent of human supervision and collaboration is needed for AM tools

Innovation Needs

Table 33 provides a summary of identified innovation needs and key potential solution areas.

Table 33. Innovation Needs for AM

Technical Needs

Category	Activities Needed
Technical Performance	• Develop flexible 3D printer hardware parts, including feeders and nozzles, that allow the use of alternative low-carbon materials and functionally graded materials using the same 3D printer • Develop material handling and assembly systems to integrate 3D printed prefabricated components into whole building systems.
Data & Accuracy	• To address misalignment and tolerance errors in 3D printed parts of components, assess the complementary downstream processes of scanning, assembly, and installation with error mitigation systems for 3D printed products or components, by accounting for printing-induced tolerances for a particular material
System Integration & Flexibility	• Develop hybrid manufacturing systems that include AM to create or address medium to high-rise multistory buildings as well as systems that can create 3D printed structures with no thermal bridging
Cost Reduction	• Develop low-cost 3D printers that can be part of future offsite factories without the need for a large upfront investment

Market Needs

Category	Activities Needed
Awareness	• Hold demonstrations for onsite and offsite factory workers to illustrate the application of AM tools and the high extent of human supervision and collaboration needed. • Promote benefits of AM tools to offsite factory workers and manufacturers by creating clear, practical real-life documentation of benefits and ROI models.
Customer Use Case	• Hold demonstrations for consumers to help overcome consumers current perspectives of printed houses.

Workforce Needs

Category	Activities Needed
Training & Capability Development	• Support training for onsite and offsite factory workers and manufacturers to learn how to operate, troubleshoot, and maintain AM tools

4.3.4 Portable Machines for Distributed Manufacturing

Several studies recommend onsite pop-up factories which combine advanced manufacturing in micro-factories and using portable machines with industrialized construction onsite. The principal reason for pop-up factories is reducing transport costs as noted by Rauch et al. (2015). Onsite pop-up factories allow temporary use of fully functioning mobile mini-factories or mobile production cells at a site when they are needed, as shown in Figure 7. Through a highly flexible as well as scalable design, they can be suitable for different temporary manufacturing requirements, reducing transport costs and delivery time. Particularly, this concept of a mobile factory is well suitable for situations with long distances and therefore high logistics costs like fabrication of components on the construction site.

Figure 7. Facit's CNC machine, transported to home sites in a shipping container, cuts customized pieces for homes. (**Source: Facit**)

RD&D is needed on portable machines as a distributed manufacturing pathway to evolve and expand the influence of offsite factories by moving toward decentralized near end user-driven activities. These could take the form of packaging a set of technologies, equipment, and data collection hardware in a custom mobile shipping container to be shipped to a new construction or retrofit site. This solution is applicable to all new and existing residential and commercial buildings.

Several prototypes and demonstrations of mobile pop-up factories inside shipping containers exist today (Sondergaard et al. 2020, Aouf 2018, Facit 2021). The advantage of this concept is not only the proximity to customers, but also the economic efficiency combined with a high level of flexibility. Both subtractive and AM tools can be integrated and packaged into a distributed manufacturing system.

Innovation Outlook

Table 34 provides a summary of the current state of the innovation, goals, and challenges.

Table 34. Innovation Outlook for Portable Machines for Distributed Manufacturing

Current State	• Prototypes and demonstrations of mobile pop-up factories inside shipping containers exist today, but they are still emerging and not widely adopted
Innovation Goals	• Is easy to deploy on or near sites following safety protocols • Serves as a mitigation strategy to high uncertainties in material and component deliveries in cases where raw materials are available • Provides flexible production that can adapted to site needs by proximity • Provides a physical and digital extension of offsite factories with flexible stations or bays • Is resilient and can be operated with battery backup in case of power loss • Is validated for its value and ROI in each unique building environment in which it's being asked to operate.
Technical Challenges	• High logistics costs and difficulty with transportation management over long distances due to inefficient demand-supply management
Market Challenges	• Uncertain and unproven value and ROI of a distributed manufacturing system for standard scenarios of operating conditions • Lack of awareness of applications of a distributed manufacturing system
Workforce Challenges	• Need to train workers to efficiently operate, troubleshoot, and maintain pop-up mobile factories • Need to train manufacturers and offsite factory workers in efficient coordination with transportation, logistics, and onsite manufacturing stakeholders

Innovation Needs

Table 35 provides a summary of identified innovation needs and key potential solution areas.

Table 35. Innovation Needs for Portable Machines for Distributed Manufacturing

Technical Needs

Category	Activities Needed
Data & Accuracy	• Develop a user-friendly GIS-integrated tool for efficient demand-supply management over long distances to visualize, manage, and operate the hub-and-spoke distributed manufacturing system
System Integration & Flexibility	• Conduct physical prototyping and deployment studies in a controlled environment prior to shipping pop-up factories to sites to develop fully fitted custom shipping containers with advanced manufacturing tools

Market Needs

Category	Activities Needed
Awareness	• Promote efficiency and just in time (JIT) benefits to manufacturers through case studies and other materials
Customer Use Case	• Value a distributed manufacturing system in each unique building environment to create clear ROI models

Workforce Needs

Category	Activities Needed
Training & Capability Development	• Support or develop training to effectively operate, troubleshoot, and maintain pop-up mobile factories

4.3.5 Advanced Scanning for Retrofit Construction

A highly impactful solution is the ability to scan and model a building and then design and manufacture customized, prefabricated retrofit panels to completely wrap its exterior seamlessly and automatically. The technical potential to reduce energy use in existing buildings through this solution is significant given the long-term benefits and limited disruption to a building owner. However, to date, the process of converting a 3D scan to a BIM model and then into a useable format for manufacturing purposes of a retrofit panel is complex, time consuming, and costly.

The development of an automated process to go from 3D scan to BIM to CAM is critical to unleashing the retrofit market potential and scaling deep energy retrofits. This innovation has the potential to substantially make installation easier by reducing the time of fitting panels to a building envelope for buildings with protrusions, and thus, reduce overall labor costs for the project. It also has the potential to reduce waste and avoid costs of manufacturing additional paneling.

Necessary stakeholders to engage in the development of this technology include manufacturers of 3D scanners, scanning consultants, software developers, architects, BIM designers, contractors, and panel and cladding manufacturers. This solution is applicable to all existing residential and commercial buildings.

According to a recent survey, nearly half of stakeholders involved with prefab or modular construction projects use BIM on 50% or more of their projects (Dodge 2020), but this likely only pertains to new construction as the use of BIM is limited in panelized deep energy retrofit projects. Presently, an automated process that goes from scan to customized prefab retrofit panels only exists in R&D demonstration projects. DOE funded a project in July 2020 with a specific focus on streamlining the scan to BIM to CAM process for retrofit panels. The project involves developing project workflows and an algorithm that supports all phases from scanning and design to manufacturing (Zakhor 2020). Separately, similar research was funded through a European Union grant related to building energy renovation using timber prefabricated modules. Through this work, a software solution was developed to serve as both a client and manufacturer tool to establish technical feasibility, potential energy savings, and ROI and provide a direct output to CAM and CNC machines (Lasarte et al. 2017).

This process can be thought of in two parts, scan to BIM and BIM to computer-aided design and manufacturing (CAD/CAM). Currently, the scan to BIM process is not automated and requires significant manual input during the process to translate data from a 3D scan to a BIM. This process of interpreting 3D point cloud data and translating it into a complete as-built model can span weeks or even months, given the BIM developer needs to classify objects and establish interrelations with aspects of the building (Perez 2020). Software does exist to automate some of the modeling processes through the use of spatial correlation, object recognition, or object classification, but these techniques still rely on manual inputs, so this approach is described as semi-automated (Esfahani 2021). The second part of the process takes the BIM and translates that data into a CAM or CNC machine to write plans to produce customized retrofit panels. This process to go from BIM to CAM does exist for the new construction market. For example, plugins are available for Autodesk Revit to outline framed wall patterns and move directly into CAM and then to production lines. Conceivably, this same technology could be applied in a retrofit scenario, but an automated market-ready technology does not exist.

Innovation Outlook

Table 36 provides a summary of the current state of the innovation, goals, and challenges.

Table 36. Innovation Outlook for Advanced Scanning for Retrofit Construction

Current State	• There is a lack of automated processes to go from a 3D scan to BIM to CAM for retrofit construction projects and processes are complex, time consuming, and costly; automated processes only exist in RD&D projects
Innovation Goals	• Process that can go from 3D scan to BIM to CAM software and is automatic with limited manual data cleanup and can be completed with a typical desktop processor • Software can automatically create a customized set of retrofit panels that will completely cover the exterior of a building, creating a thermal break • Retrofit panel plans are interoperable with any manufacturing plant and can be designed to include various elements (i.e., windows, doors) • Integrated software that an AEC team member can use without additional training

Technical Challenges	• Hardware (such as 3D scanner):
	    • Incompleteness and accuracy of data collection during the scanning process (Esfahani 2021)
	    • An overwhelming amount of data is created during the scanning process, which requires high computing power and sophisticated software to process, clean, and manage it (Esfahani 2021)
	    • A scan will not provide information on a building's structural components, such as support columns, beam, joist, etc.
	• Software (such as Point Cloud to BIM): difficult to develop comprehensive algorithms or object typologies to accurately and automatically identify all building elements (Esfahani 2021)
	• Retrofit Panel Production (such as BIM to CAM to Retrofit Panel)
	    • Lack of precision in software conversion tools from point cloud to BIM which is needed for models for prefabrication (Peraudeau 2019)
	    • Paneling for building retrofits is often inflexible and difficult to adapt or adjust in the field if it does not fit as expected with the façade
	• Lack of software interoperability due in part to the lack of approved open source software standard (i.e., IFC format in Europe) in the U.S. market
	• Lack of standard interfaces and specifications for panel manufacturers to integrate to CAD/CAM software

Market Challenges	• High device cost for 3D scanners and difficulty selecting the 3D scanner due to complexities/variation in precision and accuracy needs (Pica and Abanda 2019) • Need for new relationships and business models to be developed to support this potentially growing industry (Peraudeau 2019)
Workforce Challenges	• Need for new skills and workforce to adapt to the changing digital construction landscape

Innovation Needs

Table 37 provides a summary of identified innovation needs and key potential solution areas.

Table 37. Innovation Needs for Advanced Scanning for Retrofit Construction

Technical Needs

Category	Activities Needed
Data & Accuracy	• Create data algorithms to transform complex point clouds into 3D models with high degree of accuracy in terms of penetration locations, deviations, and overall dimensions • Increase precision in automated modeling so data is useful for manufacturing and for all different building types and configurations
Technical Performance	• Develop or improve software to consolidate/cache detail data when not needed, and have error/tolerance-checking capabilities when handing off data between scanning, modeling, design, and manufacturing • Develop specific manufacturing software or plugins applicable to retrofits • Develop standard interfaces and specifications for panel manufacturers to integrate to CAD/CAM software • Lab- and field-validate automated workflow from BIM to CAM to manufacturer and for different manufacturing processes
System Integration & Flexibility	• Improve panelized cladding designs and automate manufacturing for building protrusions • Develop advanced flexible and adaptable paneling solutions that can be used to add paneling/cladding on and around protrusion areas in buildings

Market Needs

Category	Activities Needed
Customer Use Case	• Obtain manufacturer input and feedback on specific needs and understand current pain points, especially for prefabrication • Demonstrate or pilot with contractors and manufacturers
Ease of Use/Install	• Develop easy to understand user guidance and training on software and scanning applications • Make tools easy to operate and interoperable
Production & Supply Chain	• Identify software vendor to develop application • Consider IP implications • Consider any data privacy issues and any cybersecurity needs
Building Energy Codes & Industry Standards	• Support development of industry standards and guidelines for scan to BIM to CAM innovations and processes and approved open source software standard

Workforce Needs

Category	Activities Needed
Training & Capability Development	• Support worker training on 3D scanners and BIM and CAM software to help the workforce to adapt to the changing digital construction landscape

4.3.6 Retrofit Robots (Including Automated Insulation Installation and Inspections)

There are some tasks that are dangerous, uncomfortable, or impossible for a human to complete, especially when retrofitting buildings. Some examples of this include the inspection and insulation of crawlspaces, inside ducts, attics, and floor cavities. Robots can complement and support the existing workforce by increasing worker safety and well-being, while also creating new employment and business opportunities. Usage of robotics in confined spaces can also ensure quality and consistency when installing energy efficiency measures.

New advancements in robotics may include actions like spraying foam, welding, or vacuuming up loose or old insulation or other materials.

Key stakeholders include manufacturers of scoping robots, manufacturers of cameras or other tools, contractors, building owners, and software companies. This solution is applicable to all existing residential and commercial buildings with crawlspaces and or ducts.

Many construction robots that exist in the marketplace perform tasks such as bricklaying, lift assistance, rebar tying, excavation, data collection, and inspections (DBR Innovation 2019). The industry is changing rapidly, however, and tasks that are dangerous, remote, difficult to access, heavy, awkward, or repetitive are ideal for robot assistance. Robots assisting with building retrofit solutions are just beginning to emerge. A UK company has developed a robot that can access an uninsulated crawlspace and apply spray foam insulation to the underside of the floor decking and joists. Although a considerable breakthrough in retrofit technology, this robot was developed for UK housing stock which has similar crawlspace foundations. As the U.S. building stock is more diverse, a broadening or new complementary technologies are needed to achieve similar capabilities for national retrofits.

The challenge around using cutting edge technologies is that they still need a lot of development and business cases are not fully understood. Who will own them? Maintain them? Program them? What is the business case for a large fleet of capitally expensive equipment?

With the potential to improve construction retrofit productivity, DOE initiated the E-Robot prize with the intent to grant several companies seed money for innovations that are holistic, low-cost, minimally invasive, and time-efficient; use long-lasting materials; and provide opportunities to workers (DOEb n.d.). Selected projects will likely develop robots to travel through one type of small space and perform at least one function. The E-Robot prize is implemented in two phases, with the first phase focusing on technologies that address individual retrofit solutions, and the second phase addressing retrofits more holistically.

(Source: DOE American Made E-ROBOT Prize Winners: RoboAttic)

Innovation Outlook

Table 38 provides a summary of the current state of the innovation, goals, and challenges.

Table 38. Innovation Outlook for Retrofit Robots

Current State	• Construction robots perform various construction tasks that are dangerous, uncomfortable, or impossible for a human to complete • Robots assisting with retrofit tasks are just emerging and the DOE recently launched the E-Robot prize to incentivize retrofit robot innovation
Innovation Goals	• Maintains a relatively small profile and weight compared with a human • Has camera capabilities • Performs at least one retrofit action • Workers can easily learn to operate and maintain the robot • Helps reduce the cost of confined work significantly compared to current best practices • Tethered robots can clear the space necessary to access difficult to reach cavities and locations • Completes time-efficient, high-quality installations in a wide variety of situations that might exist in the U.S. building stock
Technical Challenges	• Robots will need to be flexible enough to perform a variety of retrofit tasks in distinct building types • No two buildings are the same, and a combination of autonomous and operator-controlled actions is envisioned to meet the complex needs of retrofit activities • Construction tasks are complex and current technology to complete those tasks is immature (i.e., ineffective algorithms, robot intelligence, limited functional integration) • Need targeted investment to create more capable retrofit robots, even though R&D investment in the construction industry is generally low
Market Challenges	• Lack of insight into the business case of how retrofit robots can successfully make contractors' jobs easier, safer, and more productive • Lack of demand for robot innovations is compounded by low R&D budgets in the construction industry or low awareness of the market potential in the robotics industry • Initial capital investment costs required for new and immature technologies is high and appears risky to contractors and construction firms, especially small firms (Delgado et al 2019) • Limited incentives to improve retrofit labor productivity, so robots should aim to provide many benefits to workers such as reaching cavities that are hot and uncomfortable
Workforce Challenges	• The workforce will need training in operating and repairing the robots, as well as any associated software to ensure that the new processes fit into their typical workflow • In some cases, it might make sense to have highly skilled operators for the robots, and in other cases it may be more effective to deploy robots that require less training to utilize

Innovation Needs

Table 39 provides a summary of identified innovation needs and key potential solution areas.

Table 39. Innovation Needs for Retrofit Robots

Technical Needs

Category	Activities Needed
Data & Accuracy	• Develop any software IP needed for robot and testing methods or protocols to ensure accuracy of tools across different building types • Incorporate camera into hardware that can accurately identify existing building conditions • Develop a product that performs to a high level of accuracy to maneuver around electrical and HVAC materials
Technical Performance	• Innovate robots with small profile and weight that are very nimble and mobile to reach building cavities • Develop robot hardware prototypes and partner with manufacturers and researchers to develop solutions, especially existing robotics manufacturers • Develop technology to administer insulation or sealant without a hose tether • Develop a software application that is user friendly for contractors to operate and understand • Lab- and field-validate residential and commercial prototypes in several building segments and configurations • Develop robot innovations with recycled materials as much as possible
Durability	• Able to withstand high moisture areas and to travel in 1-in. of water • Able to travel over concrete, sand, fiber insulation, or gravel surfaces
Cost Reduction	• Investigate the primary cost drivers and areas of inefficiency for manufacturing robots and mobilizing them in existing homes
Environmental	• Develop recycling solutions for materials and battery specifications

Market Needs

Category	Activities Needed
Customer Use Case	• Establish the energy reduction value proposition to the homeowner with the utilization of the robot technology • Determine clear use cases for contractors and how the robot aids the workforce • Obtain contractor input, pain points and feedback to inform product design and features • Demonstrate with workforce and customers early in product design • Develop contractor information on the benefits of these systems on how it makes work easier and safer
Ease of Use/Install	• Make hardware and software applications easy to use with no significant training required • Develop applications that are easy to trouble shoot • Identify methods or tactics to address cybersecurity and potential privacy issues
Awareness	• Develop a marketing strategy to increase awareness and understanding of the novel product and its uses
Production & Supply Chain	• Utilize robotics companies and retrofit installation trades on product performance and installation advantages • Identify both manufacturer for hardware and software vendor to develop application • Consider IP implications
Cost Reduction	• Identify eventual cost reduction opportunities or how to gain economies of scale

Workforce Needs

Category	Activities Needed
Training & Capability Development	• Training is required for businesses and workers to be able to operate, maintain, and repair the robots they are utilizing, as well as use any applicable software

4.3.7 Real-Time QA/QC Using Visual Indicator or Internet Connected Sensors

Introduction

Contractors, supervisors, and building officials all perform a certain level of QA/QC of installed building measures to ensure a proper installation and guarantee the health, safety, welfare, and economic and environmental benefits to the eventual occupants. Despite these verification measures, it's often impossible to QA/QC all building connection points, insulation, or mechanical equipment installations due to a building's size or because components are covered up prior to inspection. Although current inspection processes exist for each building component, performing a thorough and accurate inspection takes time for both the contractor and building inspector. Developing new technologies and processes that enable near-real-time QA/QC of building efficiency measures would help prevent (or detect quickly) costly mistakes in the field and alleviate some of the pressure on municipal building department resources.

Key stakeholders to help develop these new technologies and processes include material and equipment manufacturers, researchers, insurance agencies, contractors, building officials, architects, and software developers. This solution is applicable to all new and existing residential and commercial buildings.

Where Are We Now?

There has been a trend to increase remote inspection which the COVID-19 pandemic has accelerated. Building departments have developed guidance around Remote Virtual Inspection (RVI) processes so worker safety was not comprised when inspecting and approving new construction and retrofits. The ICC has since developed Recommended Practices for RVI, and building departments across the country now allow RVI for certain inspections (ICC 2020). Conducting an inspection via a cellphone or similar device is not a significant technological leap, but it does demonstrate the ability for industry to move quickly and adapt. RVI can solve a lot of building department challenges by increasing inspection bandwidth, reducing costs, and improving worker safety with the elimination of travel and onsite time, but continued technological and process advancements are needed to truly harness the potential benefits of RVI. There are limits to visual inspection with cameras at fixed points in time. Technical enhancements to RVI could be enable building departments the flexibility and time to inspect building retrofits, something that is not always performed given time and resource constraints. Similarly, technical enhancements could support QA processes during installation, decreasing rework and enhancing operational performance.

Another QA/QC technology and process that is now becoming standard on certain HVAC equipment is Automatic Fault Detection and Diagnostics (AFDD). This technology can automatically identify when an HVAC system was either not installed correctly or needs maintenance due to poor performance.

A similar automatic detection system does not currently exist for the building envelope. However, ORNL is currently developing the Real-time Evaluator tool (shown in Figure 8) which provides instantaneous feedback to the installation crew on how to place prefab components so that they meet the required tolerances of the building. The goals of the tool is to provide QA/QC feedback in real-time.

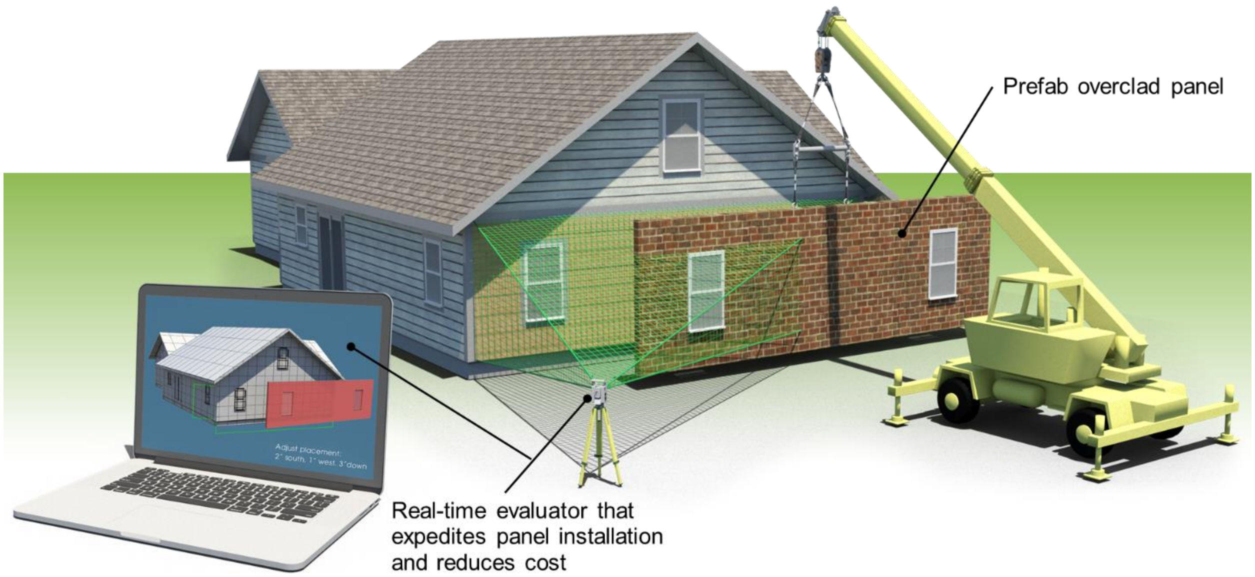

Figure 8. The Real-time Evaluator is currently being developed by ORNL. (Source: ORNL)

One technology discussed during stakeholder workshops is the need for certain building products to include color changing technology so installers and inspectors can visibly see that a product was installed correctly. There are many products on the market with color changing indicators that either represent a proper installation or can notify if something has been tampered with; however, most of these products exist within other industries. Processing industries requiring a sterilized environment, such as pharmaceutical and medical manufacturing, utilize packaging tape with sterilization indicators. Another common use of indicator tape is in the electronics industry to demonstrate whether a product has been exposed to water. Water indicator tape will change color if water has been detected.

Pressure indicating film is another market available product, which has been used in the automotive, electronics, aerospace, and packaging industries. This material is used in testing processes to determine the distribution and magnitude of pressure being applied to a surface.

The use of an indicator on bolts is another current application in the marketplace. Currently, companies are producing metal bolts with a dot on the top of the bolt that changes color as the bolt is tightened. In one example, the bolt has a spectrum of five colors to indicate various tightness levels of the bolt, with red being loose and black being tight.

The underlying technologies for color changing could be incorporated into more construction applications both to support inspection and to ensure quality during installation.

An ongoing BTO funded project expedites prefab construction by following the position of prefab components using a robotic tracker, comparing it to their as-designed location in a digital twin, and providing real-time feedback to the installation crew on how place the panels so that they meet the required tolerances. When installation of the component has been completed, its as-build location is recorded and used to update the digital twin. The real-time feedback will enhance the installation quality and reduce the installation time and cost of prefab components by at least 25% (ORNL 2022).

Innovation Outlook

Table 40 provides a summary of the current state of the innovation, goals, and challenges.

Table 40. Innovation Outlook for Real-Time QA/QC Using Visual Indicator or Internet Connected Sensors

Current State	• RVI exists but not at its fullest potential; improvements will allow for more retrofit inspections and will ensure quality installations for peak performance • AFDD is becoming standard on HVAC equipment to identify performance issues • No similar QA/QC system exists for building envelopes, although many visual indicators exist in the market in other industries
Innovation Goals	• Indicator demonstrates whether a product or installation meets desired quality to installer in real time • False positives are minimized • QA/QC process or technology is automatic or drastically reduces the amount of time taken in the current inspection and rework processes • Installation processes of products is not more costly
Technical Challenges	• RVI –Lack of inspection accuracy, measurement verification, performance testing, storing associated data, and ease of technology access among building departments • AFDD – Possible to get false positives after installation, indication of whether an alarm requires a technician or if it's a minor blip, and the time taken to properly install the system • Visual Indicators – Research has not been done on visual indicators in the construction materials industry, so challenges aren't yet identified; R&D is needed to applications and challenges
Market Challenges	• Need industry support, especially with RVI as building officials need to make sure they do not miss something critical during a remote inspection • Little understanding of use cases or potential solution areas; Need compelling value propositions for each technology and market actor
Workforce Challenges	• The workforce will need to be trained in how to use each QA/QC technology, and understand next steps if the quality standard is not met

Innovation Needs

Table 41 provides a summary of identified innovation needs and key potential solution areas.

Table 41. Innovation Needs for Real-Time QA/QC Using Visual Indicator or Internet Connected Sensors

Technical Needs

Category	Activities Needed
Technical Performance	• Technologies that provide accurate readings that are easy to interpret
System Integration & Flexibility	• Technologies and processes that can be easily integrated into existing construction materials without compromising performance

Market Needs

Category	Activities Needed
Customer Use Case	• Obtain contractor, building official, and manufacturer input to identify key solution area
Ease of Use/Install	• Installation of products should be similar to the current business as usual approach
Awareness	• Conduct research to identify the benefits of real-time QA/QC
Building Energy Codes & Industry Standards	• Work to incorporate real-time QA/QC technologies and processes in building codes and standards
Production & Supply Chain	• Obtain contractor, building official, and manufacturer input to identify key solution area

Workforce Needs

Category	Activities Needed
Training & Capability Development	• Training is required for the workforce to be able to understand how to use each QA/QC technology, and understand next steps if the quality standard is not met

4.3.8 Augmented/Mixed Reality

Introduction

Virtual reality transports users into a digital world that is experienced in a fully immersed way through sensor devices. Augmented reality (AR) is the process of integrating digital visual images into the real-world environment using head-mounted devices (HMDs) (i.e., lenses) or tablets. AR is a mixture of the real-world and the virtual world of digitized renderings, allowing users to interact with both. Mixed reality (MR) blends digital content with real-world objects, interactively and in real time. MR helps users interpret both physical and digital information, including the spatial relations between them; it can include AR and other mixed configurations.

For both retrofits and new construction, AR is used to help train workers, speed up construction, and help reduce mistakes made by workers and designers:

- AR is used for on-the-job construction support, including to help guide workers performing new tasks and help workers QC their work and stay on schedule. It is also helpful when working with other trades to understand material and equipment layouts. AR is particularly useful for retrofits because it can provide information about unique, existing structures from scanning tools.
- Training programs have utilized AR to help workers gain active, first-hand experience without the cost and risk associated with using real materials. Additionally, training programs use AR to help provide visual and audio instructions for trainees, allowing senior staff to focus less time on instructing.
- AR enables individuals to interact with building design visualizations. AR is used by architects and engineers to review 2D and 3D models of their structures, something blueprints cannot offer. Building developers also showcase building designs to clients using AR. These tools can also serve as powerful marketing tools in building retrofits as well, including allowing clients to clearly visualize and step through the plans and models of the upgrades.
- MR can connect with smart technologies and Internet of Things (IoT) devices to understand how connected equipment is operating and their current state.

These uses have the potential to increase worker productivity and reduce project costs (Ahmed 2019; Delgado et al. 2020).

The key stakeholders include VR, AR, and MR hardware manufacturers and software companies; remodeler companies; construction firms; suppliers; and building owners. Owners may benefit from the use of VR/AR/MR models developed for construction to support operations, increasing the value proposition of these technologies. These technologies could also support inspections (RVI) and increase communication of design intent from architects and engineers. This solution is applicable to new and existing residential and commercial buildings.

Where Are We Now?

AR is used by a minority of construction firms but has the potential to scale quickly. Surveys have shown that large construction firms are much more likely to use AR than small and medium sized firms due to greater ability to purchase equipment, develop content, and partner with academic institutions. Most of these companies only use AR for offsite design visualizations. However, some firms have used AR for training and onsite construction support. Basic components of the software and hardware must improve to increase the usage by construction firms. However, due to their potential, most construction firms anticipate investing in AR technology by 2023 (Delgado et al. 2020).

Innovation Outlook

Table 42 provides a summary of the current state of the innovation, goals, and challenges.

Table 42. Innovation Outlook for AR/MR

Current State	• AR is used by a minority of construction firms but has the potential to scale quickly • AR is more likely to be used by larger firms with greater ability to purchase equipment, develop content, and partner with institutions • Most firms only use AR for offsite design visualizations, but some use it for training and onsite construction support • Most construction firms anticipate investing in AR technology by 2023 Delgado et al. 2020
Innovation Goals	• Software can communicate degree of accuracy (using a percentage, colors, etc.) • AR can reliably recognize marker-less, smooth objects • Mobile technology can be used with either tablets or phones • It is interoperable with scanning tools and with BIM software and facility management or controls software • Hardware/software can be easily used in the field
Technical Challenges	• AR systems are not accurate enough for widespread, onsite usage; especially for marker-less, smooth objects with few distinguishing features, AR has difficulty offering precise details (Delgado et al. 2020) • AR and MR systems have difficulties updating in real time and there's limited real-time integration with IoT technologies; AR visualizations cannot be easily viewed simultaneously • Construction firms would like to record AR experiences to use in training and demonstration videos, but AR systems currently don't allow users to save recordings of experiences • AR headsets are heavy and obscure portions of workers' vision, limiting their use cases • AR head-mounted devices have batteries that only last around 30 minutes, which is insufficient for onsite, construction support work. (Delgado et al. 2020)
Market Challenges	• More content and applications are needed to accompany hardware that are easy to use • Users also don't always understand accuracy of AR technologies and displaying percent certainty or using colors to communicate accuracy could help (Green 2016) • Cybersecurity and data privacy issues can inhibit investment and adoption • High upfront cost of hardware and software are a challenge, especially for smaller contracting or construction firms with capital restraints
Workforce Challenges	• Operation requires some training and level of comfort for workers related to the specific hardware and software (Delgado et al. 2020)

Innovation Needs

Table 43 provides a summary of identified innovation needs and key potential solution areas.

Table 43. Innovation Needs for AR/MR

Technical Needs

Category	Activities Needed
Data & Accuracy	• Develop software applications that can identify accuracy levels of AR/MR technologies • Develop AR technologies and tools that can better identify marker-less, smooth objects and with more precision • Innovate technologies that can more quickly and seamlessly update in real time and can access multiple visualizations at a time • Develop AR/MR technologies that can archive content and be used for training purposes
Technical Performance	• Improve IoT/smart technologies' interoperability and real-time update abilities • Develop more nimble and lightweight headsets and glasses that do not obscure any vision area • Create easy to use applications and hardware with phones, tablets, or other devices • Extend the battery life or make battery switching easy to do in the field
Cost Reduction	• Develop lower cost hardware and software for specific applications that even smaller firms can afford

Market Needs

Category	Activities Needed
Ease of Use/Install	• Include AR/MR in educational curricula to get future workforce comfortable with hardware and software • Demonstrate new features or software with workforce to understand how they learn to use AR/MR and any difficulties • Identify methods or tactics to address cybersecurity
Awareness	• Develop information on the benefits and uses for AR/MR in building retrofit/renovation projects • Demonstrate AR/MR technologies with building owners and developers for marketing purposes

Workforce Needs

Category	Activities Needed
Training & Capability Development	• Create training material in collaboration with developers for how to best use software and hardware

(Source: Fraunhofer)

5 Next Steps

As this research opportunities report will provide context for investment through 2035, it is imperative that it is periodically updated to reflect lessons learned, expert and stakeholder input and technological and market changes that impact the innovation status and cost targets. It is considered a living document and open for feedback by emailing industrialized.opportunities@pnnl.gov.

Stakeholders who are interested in providing feedback may also participate in annual stakeholder engagement opportunities that will aim to understand the progress made on specific topics since the previous year and any new potential gaps or challenges. Such stakeholders will ideally include a diverse group of both the public (e.g., U.S. Department of Housing and Urban Development, U.S. Department of Defense, General Services Administration, and state and local governments) and private (e.g., building portfolio owners, builders / contractors, manufacturers, researchers, architects, private investors) sectors.

One key near-term activity for updating this research opportunities report includes identifying specific cost compression opportunities. More detailed timelines of activities that will help accomplish the identified goals will also be added to each of the primary innovations.

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Appendix A: Industry Stakeholder Input

To help identify challenges and opportunities related to decarbonizing the U.S. building stock by 2050, an initial set of four virtual workshops involving hundreds of industry stakeholders were held between December 2020 and February 2021. Stakeholder participation included a diverse set of building industry and construction actors as highlighted in Figure A-1. This first set of stakeholder workshops focused on input related to:

- Stakeholders' needs and wish list innovations to facilitate low-carbon, affordable building retrofits and zero carbon new construction[14]
- The greatest technical challenges and gaps to achieve those objectives
- Potential high-impact R&D solution areas to overcome challenges and gaps
- The first workshop focused on new construction and primarily offsite and panelized construction topics. Each subsequent workshop focused on a different step in the process of facilitating a low-carbon building retrofits. The first retrofit workshop on data collection, focused on streamlining the process to collect, analyze, and manipulate data collected onsite to identify and manufacture a solution. The second retrofit workshop on system design and manufacturing, gathered feedback on key challenges and solutions related to processing data to develop a market-ready solution. The final retrofit workshop on installation discussed the applicability and challenges related to installing and providing QA/QC on new technologies and ABC-focused solutions. The results from these workshops provided a substantial amount of input into this research opportunities report.

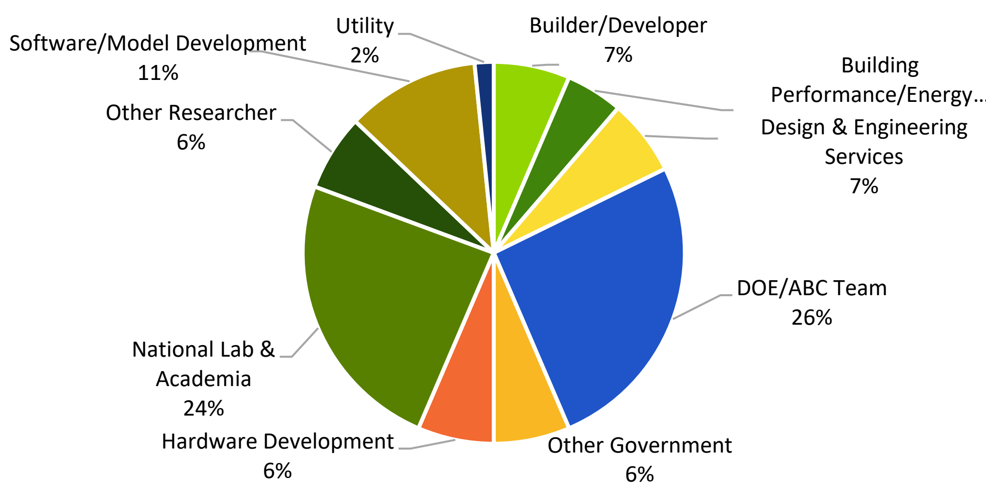

Figure A-1. ABC 2020–2021 workshop series stakeholder participation

[14] All of the high priority wish list items are in this research opportunities report. Additional items based on other inputs are also included.

After the workshops, the ABC innovations list was further refined. This set of workshops helped to define the initial list of ABC innovations, which will continually be refined with more stakeholder engagement and information.

Appendix B: BTO RD&D Portfolio and the ABC Initiative Research Opportunities Report

The innovations in this research opportunities report and related efforts complement and support the BTO ET RD&D portfolio by accelerating the scaling of individual technologies into more integrated, standardized solutions that are available to the market. This research opportunities report primarily focuses on the integration, installation and technology-to-market aspects of any technologies coming out of the ET porfolio that can specicially help increase the speed and scale of building decarbonization through industrialized construction approaches. Figure B-1 provides more information on how this research opportunities report fits in the BTO RD&D portfolio. This illustrative figure is currently a work in progress and is intended to reflect the ongoing coordination across BTO.

Figure B-2. The ABC Initiative within BTO

Appendix C: Technology Commercialization and Market Adoption Considerations

The road for new innovations can be long and complex, nonlinear, and challenging to achieve scale. Because the technology-to-market commercialization to scalable growth process is so inter-linked, this research opportunities report covers RD&D technical and market needs, and potential solution areas from technology commercialization and market growth perspectives. The ABC Initaitive also includes technology-to-market plans as an early requirement in RD&D proposals and project documents to ensure consideration of both the supply chain players and the end customers to improve the success of promising technologies to reach their full potential as innovations progress from proof of concept, to prototype and pilot programs, to full deployment. To accelerate scalable growth and readily available ABC-related innovations in the market, it is critical that market players across the continuum understand *all* needs and challenges.

These needs will evolve over time and require private and public sector support. Some of the innovations in this research opportunities report that exist today may only partially meet the described key attributes and thus require further development to become truly commercially attractive products. Other innovations are only at the concept stage and do not yet exist. The goal is to drive new innovations and industrialized approaches in the market with the aim that these solutions become widely commercialized and used regularly in buildings.

Promising technologies can fall off during three different valley of death points in the technology-to-market continuum, as Figure C-1 shows. Aligning an innovation with market drivers, gaining insights from critical industry players, and continuing to refine and improve the innovation is necessary to prepare for and bridge the multiple valleys of death. These valleys or bridges along the technology-to-market journey represent pivotal points, such as sustainably financing the investment, as the technology continues to progress and as it potentially moves from public to private funding.

The public sector often plays a heavy role in funding initial R&D with the greatest societal impact and that is not otherwise funded in the private sector. Once the technical and commercialization risk is reduced, public government funding eventually trails off. At that point, private investors increase financial contributions as demand for the innovation becomes more evident and profitability projections become more concrete. The final valley of death focuses on the ability to move the innovation to a profitable business that can adequately scale.

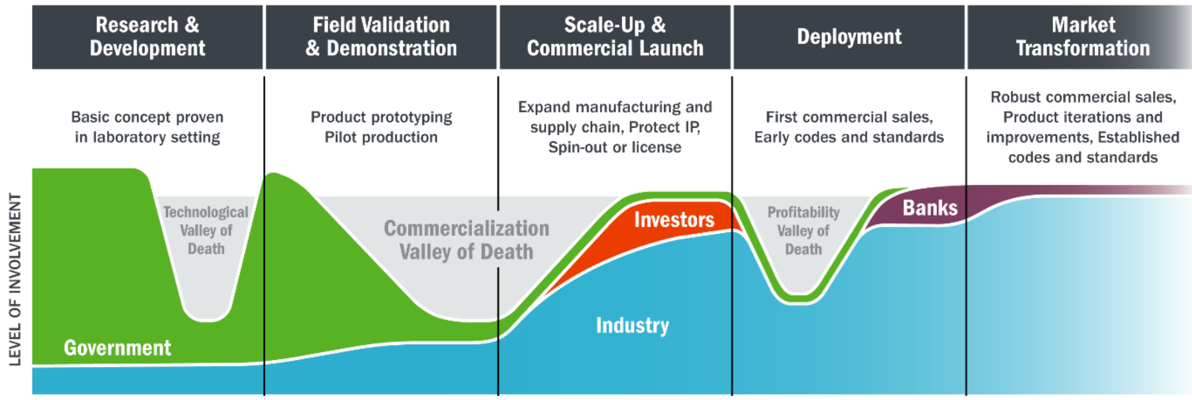

Figure C-1. Technology-to-market continuum. (Source: DOE)

The technology-to-market framework outlined in Figure C-2 provides a summary of how those individuals or companies that are developing innovations and products might consider the technology-to-market continuum from R&D to full commercialization and market adoption. The ABC Initiative uses this framework to generally help the public and private sectors understand the critical elements that must happen across the scale-up process and highlight where they can assist as well as to help track innovation progress along the scaling spectrum.

The rows of the framework outline the strategic paths of a product or technology from ideation to commercialization and ultimately to successful business growth. The three strategic paths of technology/R&D, commercialization, and scalable business growth provide the essential components in each of the vertical column phases. Each path also shows a breakdown of activities to consider that propel the innovation through continuous product development to a mature business model.

The technology-to-market phases identified in the vertical column break down the activities to consider throughout the technology-to-market continuum. These represent the unique considerations, with distinct activities and goals, for a business to transition from incubation to maturity.

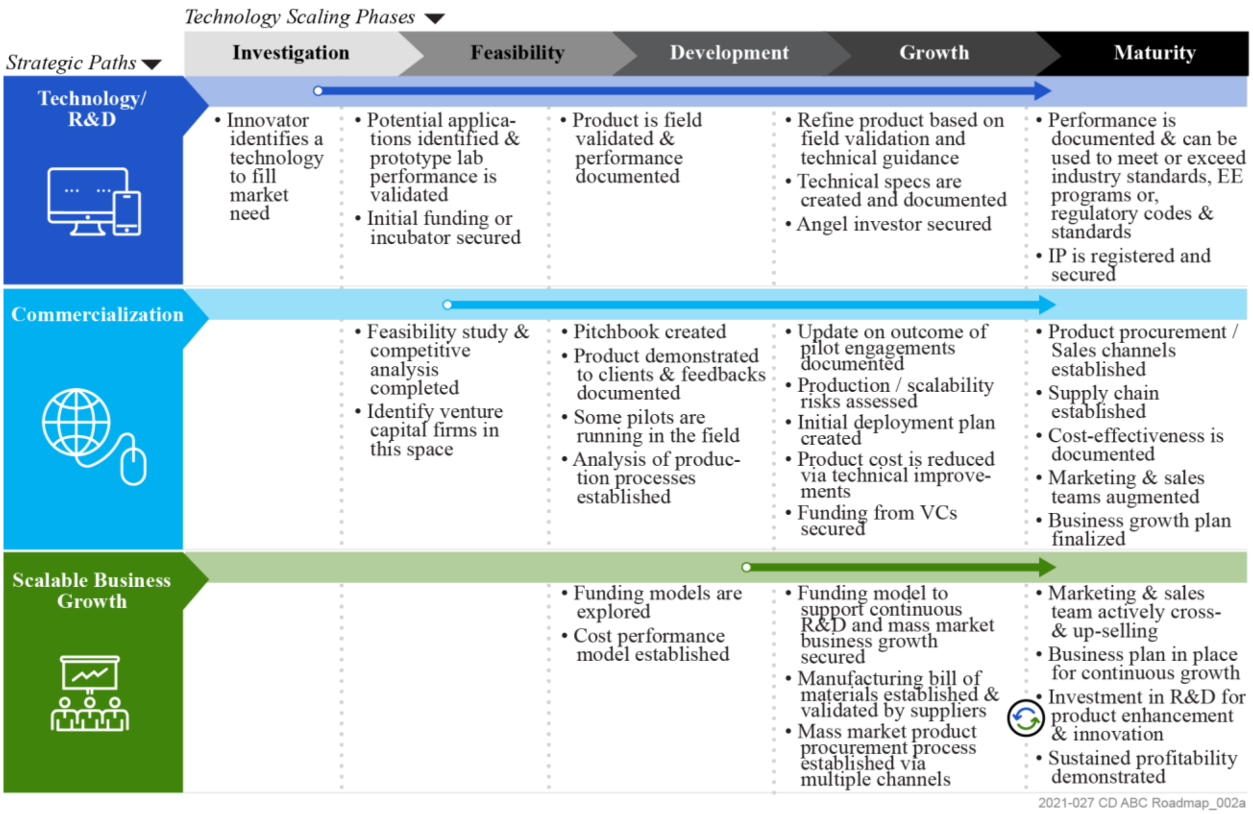

Figure C-2. Technology-to-market framework: R&D to successful business growth. (Source: Guidehouse 2021)

The framework in Figure C-2 also has dependencies between the paths and phases and should be customized depending on the strategic path or phase where an individual technology or product resides and the type of product. For example, while launching a competitive product in the market, or making an incremental update to a product, it might not be necessary to re-prove the market viability of the product, but it will be necessary to focus on the technical feasibility and business value of the competitive feature and the incremental cost of production of the new feature/function.

Strategic Paths

- **Technology/R&D** – The first step in the technology scaling process is to build a product prototype and validate it in the laboratory and in the field with a goal to make it ready for commercialization. The role of the R&D team extends even further than making a product market ready. The team uses the technology/R&D process to continuously refine the product to meet performance targets as well as add new features and functions to stay ahead of the market trend and continuously meet evolving needs in the field and customer demand. Preliminary customer interviews should occur at this stage, as well as engagement with larger investors and strategic partners who can support future scaling, given the complexity and lead time often associated with those interactions. Continuous customer engagement helps generate valuable feedback on the product's usability. This helps in continually tweaking product features and helps course correct based on customer feedback.

- **Commercialization** – The activities outlined in this path detail the commercial viability and product readiness for commercial launch followed by mass market commercialization. This path typically begins following completion of a technology feasibility assessment. This can include a market study, competitive analysis, launch of a commercially viable product, and identification of market outlets, manufacturing options, hiring and management of labor, and supply chain logistics (suppliers, manufacturers, and distributors). Sales and revenue can grow, input funding may shift from early incubators toward private investment, and these investors often have an appetite for higher-risk, higher-reward investment opportunities. Focus groups and customer feedback should be incorporated in this stage.
- **Scalable Business Growth** –Innovators typically begin this path after a few pilots have been successfully accepted in the market and good feedback is provided from customers. The goal of this path is to fully deploy the product at scale, moving to a profit-funding model for the business. Product features and functions are well defined, a process for continued refinement is in place, the business plan is functioning, and marketing and sales channels are active for broader customer outreach and scaled **deployment**. This path drives toward a sustainable business where the innovation is continually refined based on customer feedback as part of ongoing business concern. Technology production processes are continually enhanced to continue to drive revenues and profitability while growing broader market opportunities. Funding moves to financial institutions that sustain the de-risked investment.

Technology Scaling Phases

The phases represent unique steps, with distinct activities and goals, for a business to follow from incubation to maturity. The activities help guide innovators and the product owners through each phase, which are:

- **Investigation –** This phase is for identifying and validating the product or the innovation first in the laboratory. It also analyzes the business drivers and builds a proof of concept that is aligned with a perceived market need. Product requirements are outlined.
- **Feasibility** – Product applications are identified and the prototype is laboratory or test facility validated to attract funding from early incubators. Market scope, size, growth opportunities, and competitive landscape are analyzed. Early incubators are signed up and potential venture capital firms are identified to look for potential future funding needs.
- **Development –** The goal of this phase is to get the product field validated and ready, with all the supporting documentation including the user manual and certification. The product should be demonstrated to target customers and a few clients/pilots must be secured. The product manufacturing process should be outlined. Suppliers/manufacturers/distributors are identified, and the supply chain is established. Feedback from customers/pilot runs should be requested and documented.

- **Growth –** The product is refined, and technical specifications are clarified and documented based on supplier, workforce, and user feedback. Suppliers and manufactures are engaged and contracted for large scaled-up production. Marketing and sales channels are established. Modifications to suppliers of material or equipment specifications are identified. Costs and benefits are analyzed for cost optimization. The sales channel is expanded and engaged, and funding from venture capitalist firms are secured for further business growth. Alternate funding models are analyzed for continuous R&D and business growth. Mass market product procurement and deployment process is established.
- **Maturity –** At this phase, the product performance is documented and can be used to meet or exceed industry standards, energy efficiency programs, or regulatory codes and standards. Sales, marketing, and business development teams are continuously engaged to implement scalable business growth. Sustained sales, revenue, and profitability growth is demonstrated at this phase.

Customization

The framework also has dependencies between the paths and phases and should be customized. Considerations for further customization are included as follows:

- **Dependencies within paths and phases.** The market research activities within the commercialization strategic path typically start once the product has passed through the feasibility study and laboratory test portion of the technology and R&D path. The main activities within the scalable business growth path typically start after the product has gone through the development and initial deployment phases within the commercialization phase. This process ensures that there is viability for scalable business growth for the product.
- **Software vs. hardware product**: An end-to-end supply chain must be established to develop a hardware product, and there will be dependencies on external manufacturers and suppliers. This process can be eliminated in the case of a software product where the various phases of the product development (ideation, requirements development, product development, and quality control) is managed and controlled in-house.
- **Incremental update to an existing competitive product:** While launching a competitive product in the market, or making an incremental update to a product, it might not be necessary to re-prove the market viability of the product, but it will be necessary to focus on the technical feasibility and business value of the competitive feature and the incremental cost of production of the new feature or function.

A much more detailed framework is available which can be provided to private and public sector partners or funding awardees to help them understand important technology-to-market considerations at various points of the commercialization process.

Appendix D: Production Concepts to Enable Industrialized Construction Solutions

We have identified the following components of enabling knowledge that provide important analytics as well as context that supports the implementation and production of industrialized construction technologies and solutions. Additional research using the concepts below can also provide additional support for ABC by, for example, providing a basis for predicting productivity improvements and modeling skills for projected workforce needs for scalable implementation of ABC technologies. More stakeholder input is needed to understand what specific RD&D investments are needed to better enable adoption of these methods in the context of ABC-related solutions.

Constructability/Buildability (mostly for Onsite Work processes) and Design for Manufacturing, Assembly, and Installation (mostly for Offsite Factory processes)

To modernize construction, it is envisioned that building design professionals and manufacturers will make early design decisions in upstream stages of the project (conceptual design, design development, schematics design, and prototyping) that will enable efficiencies and benefits in cost and productivity in downstream stages. Constructability and Buildability are understood as bodies of knowledge and approaches to early consideration of site production needs in design. Design for Manufacturing and Assembly (DfMA) represents a similar body of knowledge around production in manufacturing environments, with well-established concepts for streamlining assembly operations. DfMA is important to production of offsite new construction and production of retrofit components, but it is yet to be widely adopted by the AEC sector. Onsite, Constructability/Buildability, and in-factory, DfMA support building components and building systems to be standardized and productized into prefabricated panels, integrated mechanical systems, and volumetric modules. (For bespoke designs, these concepts also provide useful concepts to translate design concepts into manageable production.) Practicing Constructability and DfMA can significantly reduce the incidence of rework and redesign, thereby encouraging replicability of same products across different projects.

It is important to effectively utilize existing computer-aided tools such as CAD and BIM to be able to perform Constructability and DfMA and optimize a product catalog. However, there is a lack of know-how about DfMA principles in the AEC sector, while constructability/buildability is unevenly applied. This calls for the need to retrain and retool design professionals and the need to hire and attract significant talent to this area of work. Since DfMA principles such as chunking and fusing originated in manufacturing and industrial engineering, it does not necessarily consider the unique systems and processes involved in design buildings, modules, panels, and integrated mecahnical systems for offsite new construction and production of retrofit components. For example, unlike automotive and aircraft factories, today's offsite factories do not necessarily operate as fully automated facilities with conveyor belts and assembly lines. There is still a significant amount of manual installation of components and equipment that happens in offsite factories. Therefore, any early undertaking of DfMA to productize a set of building components and systems should also consider design for installation.

Lean Manufacturing

Significant interest in improving manufacturing processes followed the significant gains in cost, quality, and productivity made by Japanese automakers compared to their competitors. Lean manufacturing, also known as the Toyota Production System, is seen as a systemic approach to improving assembly lines. Principal tenets of Lean manufacturing include high levels of quality and reliability and low levels of inventory or buffers. Variability is removed and production is tightly coupled across workstations with simple control of flows between stations. Lean manufacturing was proven to be a highly successful method of improving quality and productivity and has been widely adopted by industry with high volume or line flow production such as automotive assembly lines.

There are limitations to direct application of Lean manufacturing principles to lower volume production (typically batch or job shops) where balancing production on a line across several workstations is not possible or practical. Indeed, Lean manufacturing has been shown to be an incorrect approach when there is high inherent variability in demand and a need for buffers of some kind. Quick Response Manufacturing is a systemic approach to accommodating such environments and makes an interesting contrast to Lean precepts. Nonetheless, the systemic view of improvement taken by Lean approaches has been useful and has driven much of the manufacturing sector to closely examine its practices and reduce variability and buffers (with consequent improvements to cycle time and productivity) where possible. Contemporary approaches to modeling production activities have incorporated Lean concepts with more traditional understandings from inventory and queuing theory (also known as production and operations analysis). This has led to an effective body of knowledge that can support a broad range of production settings and volumes. The text *Factory Physics* is perhaps the leading tome of such knowledge.

Lean manufacturing principles have been applied to construction where possible, although the inherent variability and limited repeatability of construction has made direct application difficult. Lean construction has had successes with a broader view of production, with recent understandings translated from current production and operations analysis theory. Particularly useful to construction has been the view of systems production with an emphasis on flows instead of single activity analysis. Production shielding and management of constraints (aka the Last Planner system) has also been widely deployed as a method of assuring that work released to the field has no holds or constraints. This ensures a smooth flow of production in at the work front.

Integrated Project Delivery + Lean Construction and Advanced Work Packaging

Implementation of productivity enhancing techniques such as production shielding have shown significant successes but have also reinforced the need for systemic improvements. It is difficult for field installation to occur in a timely manner if design and procurement is late. Focused efforts on productivity improvement have quickly run into limitations and there has been a need for broader coordination of design and production activities.

Projects are typically a one-off design with a unique agglomeration of firms to produce the design. Even when there is repletion across projects, every project is unique in some way such as location, team composition, etc. This has made structural improvements similar to those in manufacturing difficult to organize and implement. As there is a long-standing need for improved coordination and alignment of the firms participating on a project (basic pre-requisites to successful production interventions), there has been broad exploration of improvements to project delivery systems. These have principally been contractual in nature; the prototypical example of delivery system being design-bid-build where design is complete before construction is bid. Design-build is a contrasting delivery system where the design and construction team are contracted at the start of the project to increase coordination and alignment from the start.

With increasing pressure to achieve faster and more predictable project completion, there has been significant interest in combing productivity improvements with project delivery systems. Integrated Project Delivery (IPD) + Lean Construction in the commercial sector and Advanced Work Packaging (AWP) in the industrial sector as leading examples of a systemic approach to improvement. IPD is a contractual mechanism to bring multiple stakeholders together with a joint risk/reward scheme during preliminary design of the project. When combined with Lean approaches and tools, it has been shown to be an effective mechanism for achieving ambitious project targets. AWP is similar to IPD + Lean, although it has more emphasis on enhancing work processes to ensure coordination during early design and continuing that alignment through field execution. Both IPD + Lean and AWP place a strong emphasis on the identification and management of constraints to ensure effective and productive work; both are effective examples of the capability and mechanisms to deploy systemic improvement to project activities.

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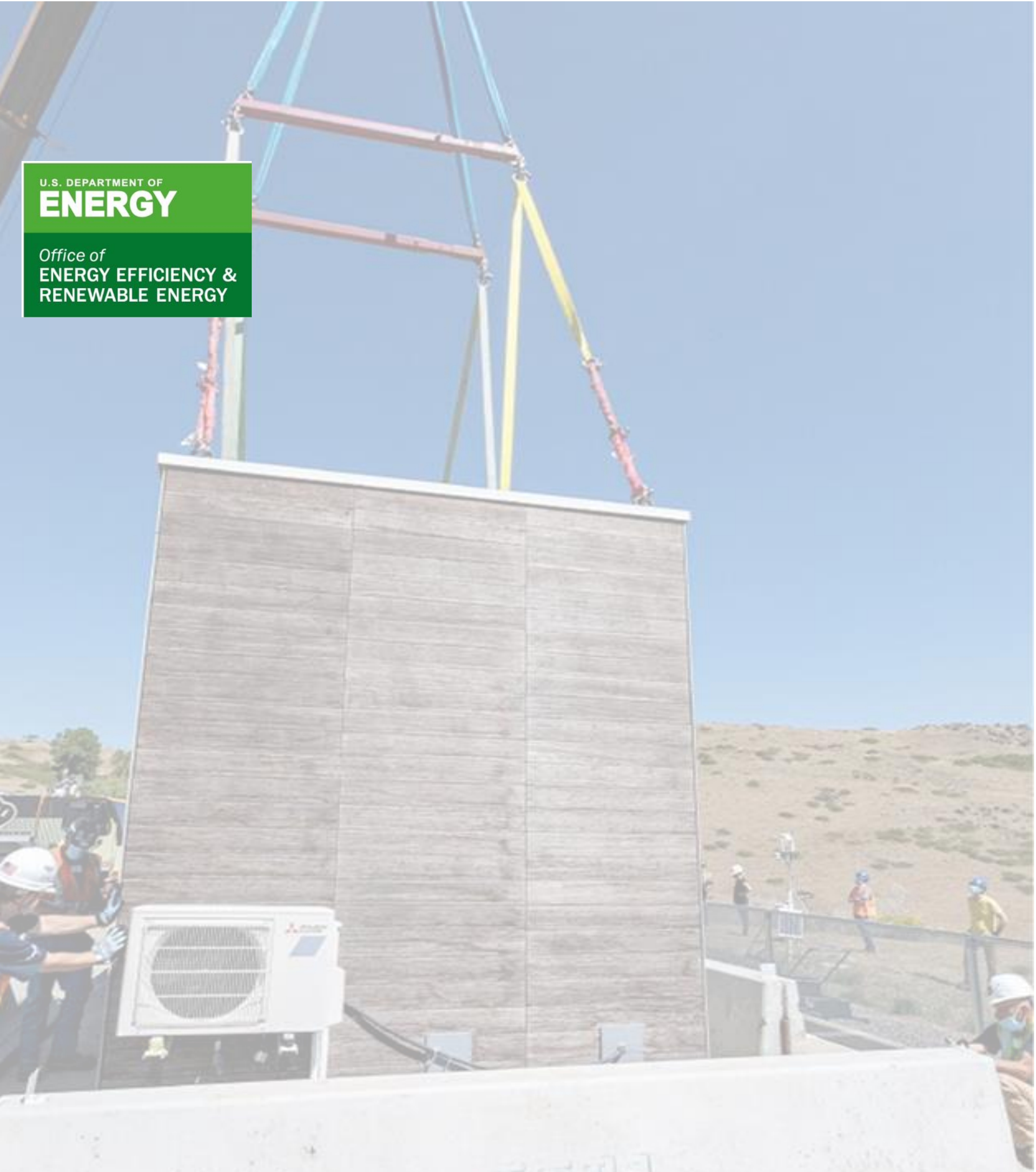

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