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ADVANCED BUILDING CONSTRUCTION Collaborative

ABC TOPIC 1

PHASE I PROJECTS

advancedbuildingconstruction.org

Emergent Innovation in Advanced Whole-Building Retrofits

Report on Advanced Building Construction Topic 1 Phase I Projects

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Authors & Acknowledgements

Authors

Andrew Brooks, AEA
Martha Campbell, RMI
Meghan Duff, AEA
Diana Fisler, ADL Ventures
Lucas Toffoli, RMI
Alyssa Watson, ADL Ventures

Authors listed alphabetically.

Contact

advancedbuildingconstruction.org/contact-us/

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About Us

About the ABC Collaborative

The Advanced Building Construction Collaborative (ABC Collaborative) is a market facilitation hub that brings together a diverse network of incumbent and emergent buildings sector actors—across construction, manufacturing, real estate, development, and related areas. It works to accelerate the uptake, scaling, and mainstream adoption of new construction and retrofit solutions combining energy-efficient building decarbonization with streamlined, scalable industrialized construction approaches while supporting—and leveraging—modernization of the US construction industry. Its mission is to support decarbonization of the US buildings sector by 2045 while improving affordability, resilience, and equity. The ABC Collaborative is led by RMI in partnership with ADL Ventures, AEA, VEIC, and Phius.

About ADL Ventures

ADL Ventures is a venture consulting firm that focuses on developing new products and services, and launching new businesses, on behalf of corporate and government clients in critical infrastructure sectors. We are a team of experienced entrepreneurs and technologists with strong backgrounds in the building construction, power, and transportation sectors. ADL has offices in Boston, Denver, San Francisco, and Washington, DC.

About Association for Energy Affordability

The Association for Energy Affordability, Inc. is a technical assistance and training organization dedicated to achieving energy efficiency in new and existing buildings in order to foster and maintain affordable and healthy housing and communities, especially those of low-income. AEA representatives engage in a broad range of educational, technical and construction management activities and services to promote this mission and develop the industry that advances and sustains it. AEA has become a leader in the multifamily decarbonization movement, implementing greenhouse gas reduction and energy savings incentive programs, providing green building consulting for all-electric retrofits and new builds, and engaging in grant-funded research and development studying how decarbonization retrofits can be higher performing, faster and more affordably deployed, and scaled in the market. AEA is headquartered in the Bronx, NY, and has an office in the Bay Area, CA, each office having a geographically regional focus.

About RMI

RMI is an independent nonprofit founded in 1982 that transforms global energy systems through market-driven solutions to align with a 1.5°C future and secure a clean, prosperous, zero-carbon future for all. We work in the world's most critical geographies and engage businesses, policymakers, communities, and NGOs to identify and scale energy system interventions that will cut greenhouse gas emissions at least 50 percent by 2030. RMI has offices in Basalt and Boulder, Colorado; New York City; Oakland, California; Washington, D.C.; and Beijing.

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Executive Summary

The Advanced Building Construction Initiative (ABC Initiative) was created by the US Department of Energy's (DOE) Building Technologies Office (BTO) to support and leverage technology and innovation to help modernize the US construction industry and make new and existing buildings part of the solution to meet US federal climate goals. The ABC Initiative supports the development of industrialized construction technologies and processes that can improve on the construction industry's lagging productivity, achieve whole-building decarbonization for retrofit and new build applications, and scale up the deployment of these advanced building construction (ABC) solutions.

Through the ABC Initiative, BTO has funded 20 research, development, and demonstration (RD&D) projects with the purpose of developing and testing innovative, industrialized building solutions for new construction and retrofits. Additionally, BTO has funded the Advanced Building Construction (ABC) Collaborative to support the RD&D projects' technology and market scaling for industry transformation. 14 of those 20 research teams are "Topic 1" awardees, focused on building retrofit solutions (six "Topic 2" awardees under the same ABC funding opportunity are focused on new construction solutions), and are deemed the Topic 1 teams participating in Phase I of DOE BTO's ABC Initiative. This report introduces the ABC Initiative's Topic 1 awards, summarizes each of the Topic 1 Phase I research teams (including their project work products and high-level findings), reviews the ABC Collaborative's support of these teams, and provides a look-ahead to Phase II.

Introduction:

The Advanced Building Construction Initiative and Topic 1 Awards

The US Department of Energy's (DOE) Advanced Building Construction (ABC) Initiative aims to foster modernization of the US construction industry—which has seen flat or declining productivity over the last 50 years—by introducing innovative new technologies and building processes. The goal of the DOE's ABC Initiative is to integrate energy-efficiency solutions into highly productive US construction practices for new buildings and retrofits.

The US Department of Energy's (DOE) Advanced Building Construction (ABC) Initiative aims to foster modernization of the US construction industry—which has seen flat or declining productivity over the last 50 years—by introducing innovative new technologies and building processes. The goal of the DOE's ABC Initiative is to integrate energy-efficiency solutions into highly productive US construction practices for new buildings and retrofits.

The ABC Initiative targets critical challenges in the buildings sector, including productivity, housing affordability, and emissions. Advanced building construction (ABC) practices can help unlock greater construction productivity in service of decarbonization of the US building stock, while also yielding benefits to the economy and housing attainability.

Through the ABC Initiative, BTO supports several efforts, including ABC RD&D funding and the ABC Collaborative. The ABC Collaborative is a market facilitation hub and national network of diverse buildings sector stakeholders engaged or interested in ABC technologies and approaches and the market barriers that hinder them. Participants in the ABC Collaborative help inform thought leadership, understanding of pain points, and potential emergent solutions and may be involved in commercialization of emerging technologies. The core ABC Collaborative team—consisting of staff from RMI, ADL Ventures, AEA, VEIC, and Phius—supports RD&D efforts to help bridge the gap between research and the market and creates an ecosystem for ABC technology manufacturers and startups to leverage industry input and form constructive relationships. The combination of ABC innovation and relevant industry stakeholders positions the ABC Initiative and Collaborative as drivers of industry transformation.

The RD&D opportunities funded by BTO through the ABC Initiative in the Federal Fiscal Year 2019 Advanced Building Construction Funding Opportunity Announcement (FY19 ABC FOA) included two categories for whole-building solutions: Topic 1, focused on retrofit technologies and building processes, and Topic 2, focused on new construction applications. The scope of the first phase (Phase I) of Topic 1 was to develop industrialized construction technologies and approaches for building retrofits. 14 unique awardee teams were funded over an approximately 18-month period for technology research and development. Toward the conclusion of Phase I, the awardee teams reorganized into Phase II proposal teams with the intent of each presenting a whole-building solution that would achieve a 75% reduction in energy consumption from thermal loads and could be demonstrated on at least two operational buildings during Phase II. (Each Phase II proposal team consisted of at least one Phase I lead plus any combination of other Phase I leads, Phase I sub-awardees, and additional external partners.) 11 of the 14 Phase I awardees applied for Phase II with expanded, holistic retrofit scopes and, at the conclusion of a downselect process, BTO selected seven Phase II teams. The remainder of this report reviews the research and development outcomes of Phase I for the Topic 1 awardee teams, with a brief preview of Phase II.

"Our Advanced Building Construction Initiative is reinventing the ABCs of building, unlocking higher...performance levels at even lower costs while helping you build better and faster."

Jennifer M. Granholm
US SECRETARY OF ENERGY

Technology, Market, and Commercialization

Technology Categories

Topic 1 of the FY19 ABC FOA (ABC Topic 1 FOA) aims to support development of building retrofit solutions that can be deployed quickly with minimal on-site construction time, are affordable and appealing to the market, and leverage related efforts to increase the productivity of the construction industry. The categories outlined in the ABC Topic 1 FOA support this goal. The technology categories for the ABC Topic 1 FOA are synthesized into four key areas of focus, summarized below, and the 14 Topic 1 projects fall into one or more of these categories:

1. **Advanced energy-saving components and systems**, including high-performance whole-building envelope solutions; panelized envelope systems with low embodied energy that are particularly suited to retrofits; envelope-integrated heating, ventilation, and air conditioning (HVAC) components; other innovative sub-assemblies that improve performance, installation, or offer other benefits; packaged modules that provide heating and cooling, water heating, energy recovery ventilation, controls, and connections to photovoltaics, batteries, electric vehicles, and other distributed energy resources;
2. **Advanced manufacturing approaches and technologies that promote affordability and scalability**, such as rapid prototyping for customization of energy-saving retrofits or installation-ready systems created off site;
3. **Technologies and automation strategies that make on-site tasks faster, easier, or more productive**, including robotic systems to apply solutions to building areas inaccessible to humans and prefabrication of retrofit components; and,
4. **Digital tools and remote sensing that can seamlessly capture building information**, including dimensions to inform retrofit design, manufacturing, and installation, and subsequent operation, commissioning, and measurement and verification.

Categories in the Broader Context of ABC

While the goals of the Advanced Building Construction Initiative are multifold, the ABC Topic 1 FOA focus supports four key technology categories. The technologies of interest aim to accelerate the decarbonization of the US building stock and improve energy efficiency through holistic, deep energy retrofits. With the support of the DOE, the development of the ABC Topic 1 technologies can be rapidly deployed to support the goals of the broader ABC Initiative and related efforts.

Advanced energy-saving components and systems support retrofit solutions to improve building envelope efficiency and performance to reduce operational energy consumption. Technologies within this category improve performance at scale with componentized systems that target the building envelope and/or HVAC. Advanced manufacturing approaches allow for the industrialization of whole-building retrofits to promote the scalability of these retrofit technologies. Technologies and automation strategies that improve the speed, ease, and productivity of on-site tasks can reduce barriers to deep energy retrofits such as inaccessibility, occupant disruption, and labor shortages. With the strategic use of prefabrication, automation, and robotics ABC solutions can be readily deployed on-site at scale. Digital tools and remote sensing of existing buildings allow for informed retrofit design, manufacturing, and installation to reduce on-site delays and deploy solutions rapidly with lower costs. Each of these technology categories are also presented in the forthcoming ABC Innovations Roadmap (to be made available on the ABC Collaborative website), which seeks to identify and prioritize innovations that support the industrialization of whole-building retrofits and rapid growth of efficient new construction. The Roadmap focuses on the integration of technologies and the industrialization of installation processes. The Roadmap is designed to be complementary to ABC Topic 1 Phase I projects, focusing on the integration, industrialization, and scaling of processes and technologies developed in Phase I.

The four key technology categories support one another to create a multi-pronged framework that enables the deployment of deep energy retrofit technologies at scale. This allows for the broader ABC goals to decarbonize the US building stock to accelerate with actualized results.

Definition and Discussion of TRL and MRL

Technology readiness levels (TRL) are a uniform method for describing the maturity of a technology. TRL defines stages of technology development on a scale of one through nine to enable consistent comparisons of technology readiness across different technology types and is based on technology concepts, requirements, and demonstrated capabilities (DOE).

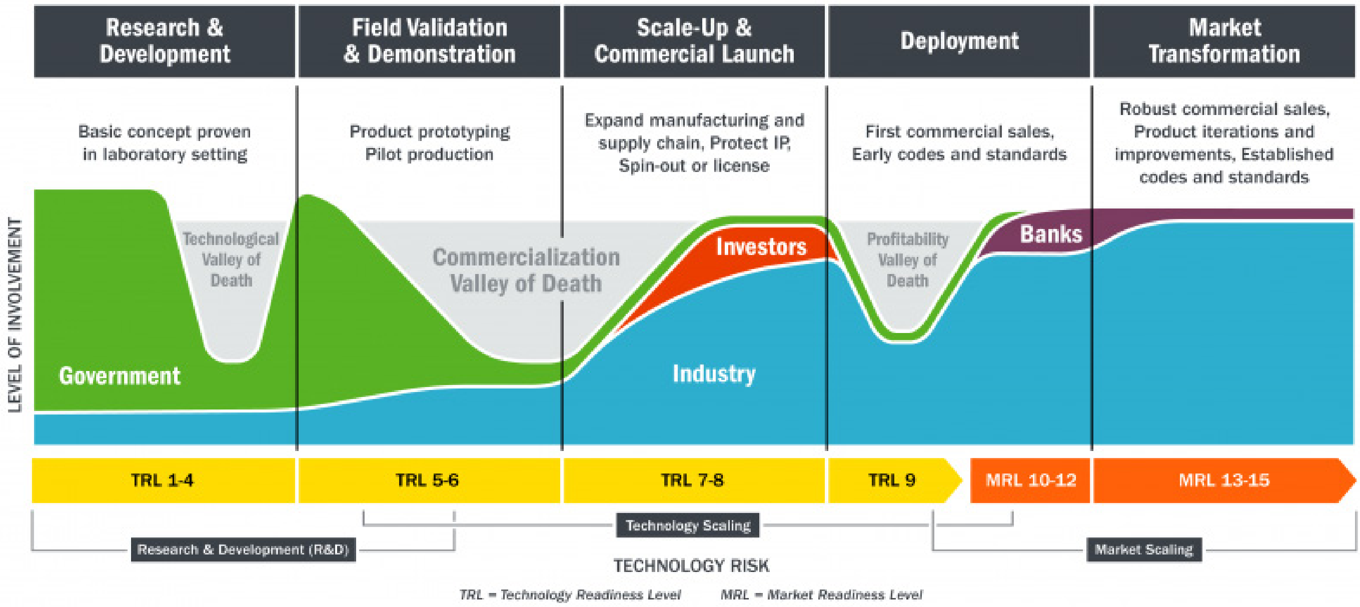
One goal of the ABC Topic 1 FOA is to advance early-stage technologies from TRL levels between one and four to levels seven through nine, while encouraging thoughtful commercialization strategy throughout technical development. TRL one through four describes the research and development phase that aims to prove technology within a lab setting. Levels five through nine describe the maturation of technology from demonstration through scaling, commercialization, and deployment. Technologies need the most assistance through stages one to nine to overcome the technological, commercialization, and profitability valleys of death. By offering targeted support and involvement in the Topic 1 teams' progression through these stages, the ABC Initiative increases the likelihood of successful deployment. Exhibit 1 summarizes the progression of TRL through its nine levels.

Market readiness level (MRL) follows the demonstration of technology capabilities, commercial launch, and robust commercial sales. MRL refers to the level of maturation where steps toward market penetration and transformation are well-developed and codes or standards are established. Exhibit 1 also summarizes the progression of MRL through its six levels.

While MRL, including commercial sales, follow TRL 9 as a linear progression, market readiness strategies should be considered and implemented throughout technical development and demonstration. Thoughtful commercialization strategies, including developing customer personas, stakeholder validation, and market entry strategy should be considered in tandem with technological development. Simultaneous commercialization and technology development are critical components of successful deployment and ABC Topic 1 teams have been encouraged to do so.

The standardized TRL and MRL classification system allows for consistent comparison of maturity across the ABC Topic 1 projects at a given time. The Topic 1 teams have varying levels of early market readiness strategy developed at any given TRL stage to prepare for success in MRL 10 through 15. TRLs and MRLs remain useful and allow for a standardized evaluation of the state of the technology and market readiness.

Exhibit 1 Technology and Market Readiness Levels correlated with technology development and market scaling phases, and relevant stakeholder groups



Source: Department of Energy, Office of Energy Efficiency & Renewable Energy, Technology-to- Market.

Summary of Topic 1 Teams' Technology and Market Readiness Levels

Technology readiness levels were determined using the definitions and descriptions in Exhibit 2 in the Appendix.

Organization	Title	TRL
Oak Ridge National Laboratory	Advanced Manufacturing for Building Envelope Retrofits	4
National Renewable Energy Laboratory	Innovative Technologies to Overcome Interface Challenges for Wall Retrofit Systems	6
Rocky Mountain Institute	Integrated Mechanical System Pods	5
Syracuse University	Integrated Whole-Building Energy-Efficiency Retrofit Solution for Residences in Cold/Very Cold Climates	5
Fraunhofer USA Center for Manufacturing Innovation	Mass Customization of Prefabricated Panel Blocks for	4
Princeton University	Deep Wall Insulation Retrofits	4
Oak Ridge National Laboratory	Membrane Dehumidification as Facade-integrated	5
Home Innovation Research Labs, Inc.	Building Screens for Latent Cooling	6
The University of Central Florida (Florida Solar Energy Center)	Modular overclad composite panels for envelope retrofits	5
Signetron Inc.	Next Generation Wall Retrofit Panels with Integrated VIPs	5
Oak Ridge National Laboratory	PV-GEMS: Photovoltaic Powered, Grid Enhanced Mechanical Solution.	2
WinnCompanies/Open Market ESCO LLC	Transforming Public Housing with Deep Energy Retrofits	6
Oak Ridge National Laboratory	Wall Embedded Multi-Functional Heat Pump with Energy	3
National Renewable Energy Laboratory	Storage Systems for Grid-Responsive and Weather-Transactive Controls	2

Summary of Topic 1 Teams and Technologies

Advanced Manufacturing for Building Envelope Retrofits (DE-NL0036649)

Summary of Technology:	An overclad panel envelope solution that utilizes building scanning, 3D printing, and a machine-learning algorithm to optimize the panel design and manufacturing processes.
Technology Category	Digitized process for panelized envelope retrofit / panelized envelope system
Team and Principal Personnel	Oak Ridge National Laboratory (PI: Diana Hun), Autodesk
Project Objective	Explore the feasibility of implementing novel advanced manufacturing techniques to mass customize energy-efficient overclad panels to retrofit building envelopes. The team aimed to establish a procedure to mass customize overclad panels for building envelope retrofits by utilizing digitized advanced manufacturing processes with the use of building scanning and 3D printing.
Technology Description and Background	Overclad retrofit panels were developed and are created through the advanced manufacturing process developed under the research award. The overclad panels are designed for thermal and moisture performance to result in an energy-efficient and moisture-durable envelope retrofit. Building scanning is used for data collection to inform component design, and 3D printing is used to create envelope system components and automated assembly of those components. The 3D printed panel consists of a structural frame, a gasket material, and foam insulation targeting a total thermal performance of R-23–42 and a maximum planar extension beyond the existing façade of 8 inches. An algorithm was developed to collect key features of the façade and translate those into panel dimensions, placement, and address of openings, which aims to reduce design time.
Value Proposition	The project's R&D initiatives strive to result in both a prefabricated envelope retrofit product and a manufacturing process that leverages automation, digitization, and industrialization. The overclad envelope retrofit product in and of itself is an ABC-relevant technology that shows promise for high performance, energy reduction, and moisture durability. The process by which it is created promotes the concept of digitizing the design and fabrication workflow to reduce design time, material use, and eventually cost.
TRL	4
Key Research Findings	The team determined that the most cost- and time-effective means of printing the structural frame was to utilize a hexagonal pattern infill. This pattern choice helped reduce printing time and material used. The algorithm developed for panel design and layout was demonstrated to determine accurate location and dimension of rough openings on an existing façade 12 times faster than traditional manual surveying, reducing data collection time from one hour to six minutes. Weight and size optimization was conducted that again resulted in hexagonal design to allow for lightest panel to satisfy the anticipated load and structural needs, and a size of 24 ft2 (6-ft by 4-ft with a 4-ft by 4-ft frame portion and a 2-ft by 4-ft semicircular frame portion). Energy modeling conducted showed a 71% mechanical systems energy savings when the overclad envelope retrofit was paired with a comprehensive mechanical retrofit.

Innovative Technologies to Overcome Interface Challenges for Wall Retrofit Systems (DE-NL0036669)

Summary of Technology	An overclad panel envelope solution that utilizes building scanning, 3D printing, and a machine-learning algorithm to optimize the panel design and manufacturing processes.
Technology Category	Digitized process for panelized envelope retrofit / panelized envelope system
Team & Principal Personnel	National Renewable Energy Laboratory (PI: Chioke Harris), Trimble, Sto Corporation, Canmet Energy
Project Objective	Develop an envelope retrofit system for residential buildings that reduces install cost, install time, and has the ability to scale for mass deployment. Five sub-goals were identified to contribute to the larger objective: 1. Demonstrate proof-of-concept mixed reality (MR) guidance/support functionality for on-site surveying. 2. Develop a preliminary model training dataset using building archetypes specific to the initial target building type and typology (e.g., facade materials, construction methods), vintage, and climate zone. 3. Demonstrate prototype conversion of site assessment data into appropriate panel specification (control layer specification and manufacturing data) for site and building. 4. Identify a method for automated production of joining parts and demonstrate installation. 5. Evaluate energy savings potential and assess product performance and total installed cost.
Technology Description and Background	There are several different product components to the overall concept developed: mixed-reality technology, overclad envelope panels, panel adjoining components, and a workflow for the entire retrofit process. The mixed-reality component can be applied to the data collection informing the design phase, to allow for visualization of the end-product upfront, to the manufacturing process for proper fabrication, and to the installation phase for install assistance. A machine learning algorithm is used to guide the design phase based on the building typology, which helps specify standardized components for typical building types.
Value Proposition	The panel design and associated workflow process aim to achieve a low-cost and rapidly deployable high-performance envelope retrofit. The workflow process utilizes technology and machine learning to simplify and speed up design, fabrication, and installation while also helping reduce errors in each of the three retrofit phases. The overclad panel is prefabricated off site using digitized manufacturing and presents a rapidly deployable high-performance retrofit product. The installation of the panels reduces labor time and therefore cost, improves site working conditions by moving much of the work into a controlled factory setting, and minimizes installation errors and tenant disruption.
TRL	6
Key Research Findings	Four workflows were evaluated to identify the appropriate hardware and software to employ the mixed-reality component and assist the overall process. Further analysis is required to determine the software-hardware combination that will be pursued, based on cost and functionality (e.g., ability to use hands-free). Modeling was conducted of 12 overclad envelope retrofit packages to evaluate energy savings potential. Of the 12 packages modeled, the retrofit packages that consist of only envelope upgrades showed a 34-50% thermal load reduction while two of the whole-building packages that include mechanical retrofit showed approximately 80% savings. The latter resulted in a modeled total upgrade cost increase of 64–80%. The current installed cost for the overclad panel system is modeled at $25.46/ft2; however, a 15–30% reduction is anticipated once production is scaled, particularly in field labor savings through increased familiarity.

Integrated Mechanical System Pods (DE-EE0009064)

Summary of Technology	All-electric packaged mechanical systems that combine all major mechanical end uses into one product to deliver high-efficiency space conditioning, ventilation, and water heating cost-effectively and with rapid deployment.
Technology Category	Packaged mechanical system
Team & Principal Personnel	RMI (PI: Brett Webster), tkFabricate, Staengl Engineering, Syracuse Center of Excellence, Lawrence Berkeley National Laboratory, Association for Energy Affordability
Project Objective	Develop, manufacture, and commercialize Integrated Mechanical System Pods (IMSPs) for small and large multifamily buildings across the US to facilitate rapid deployment of deep energy retrofits by using standardized, modular, and prefabricated components. The goal is for the packaged mechanical product to help reduce install time and cost of deep energy retrofits in multifamily buildings.
Technology Description and Background	Two prototypical packaged mechanical pod systems were designed and fabricated: IMSP-U and IMSP-C (integrated mechanical system pods -unitary and -central, respectively). The IMSP-U is designed for in-unit applications where all major mechanical systems—space conditioning, ventilation, and domestic water heating—are in each individual apartment. The IMSP-C is designed for central applications where HVAC and DHW systems are centrally located and feed the entire building. Both IMSP prototype products are all-electric, prefabricated, designed to minimize tenant disruption during installation, adaptable to a variety of existing building and system conditions, and able to achieve cost compression for retrofits at scale. Ultimately, the IMSP-C became the main focus of the project and was prioritized for comprehensive testing and validation and creation of final designs.
Value Proposition	:The IMSPs aim to deliver deep energy retrofits by providing high-efficiency, all-electric mechanical retrofits in a cost-effective and rapidly deployable way. By combining all mechanical end uses into one system, the products can achieve greater energy efficiency, leverage economies of scale in system components for cost reduction, and present the potential for reducing installation time and tenant disruption. Further, if installation time and complexity can be reduced, the installation cost can be come down, in addition to manufacturing-side cost compression.
TRL	5
Key Research Findings	:Before generating product findings, there were challenges related to intellectual property and agreeing upon the IP terms for product development. IP surfaced as a major barrier in developing and scaling emerging technology in the current product development framework. The IMSP-C surfaced as the most viable product developed under the product and was ultimately chosen for sole pursuit. The team found that, with the IMSP-C system, there was greater opportunity for cost compression, a wider compatibility for replacing existing systems, and many applicable buildings in need of this type of retrofit system. Performance energy modeling results for the IMSP-C product found 27% energy savings compared to the median EUI from the pod alone; when paired with a panelized envelope retrofit to achieve a whole-building deep energy retrofit package, this grew to 77% energy savings in cold climates, 93% savings in mixed-dry climates, and 75% savings in mixed-humid climates.

Integrated Whole-Building Energy-Efficiency Retrofit Solution for Residences in Cold and Very Cold Climates (DE-EE0009060)

Summary of Technology	A whole-building deep energy retrofit with a panelized envelope retrofit system and a packaged mechanical "pod" system.
Technology Category	Panelized Envelope System / Packaged Mechanical System / Building Components Database
Team & Principal Personnel	Syracuse University – School of Architecture, Mechanical & Aerospace Engineering (PI: Elizabeth Krietemeyer), TKFabricate, Cocoon Construct
Project Objective	Develop a "one-stop-shop" solution with potential market adoption of at least 30.5M US residential buildings in cold/very cold climates to deliver 75% thermal EUI reduction from the existing baseline condition, improve indoor air quality by maintaining less than 800 ppm of CO2, and provide competitive cost benefit targeting $15/ft2 installed cost for the panel system.
Technology Description and Background	Three key technical innovations were developed to achieve the project objective: a) a novel highly-insulated exterior building envelope system that can be modularly attached to existing building enclosures, which includes a flashing solution for windows, doors, and penetrations for mechanical services; b) an envelope-integrated HVAC solution that connects to an optimally sized modular mechanical pod; and c) a retrofit "kit-of-parts" database to assist with configuring the retrofit system for site-specific conditions. Six mid-scale integrated building retrofit envelope prototypes were designed and built to address the six key envelope details the team identified as critical: 1) opaque structural panel; 2) panel-to-panel horizontal seam and gasket detail; 3) panel-to-panel vertical seam and back gasket detail; 4) panel-to-panel vertical and horizontal seam; 5) panel-to-window with integrated flashing system; 6) panel-to-HVAC penetration and integrated flashing system.
Value Proposition	The project provides insights into the design and engineering requirements for an envelope panel product and an integrated mechanical solution product, the fabrication process, and assembly approach. This whole-building retrofit approach leverages prefabricated products that are assembled off site for rapid deployment on site. The retrofit components aim to achieve a very high performance and, when combined, drastically reduce on-site energy usage. The component database intends to provide standardized retrofit options to shift away from customization and enable scaling.
TRL	5
Key Research Findings	The modeled energy savings potential of this whole-building retrofit approach is 78% relative to the median thermal EUI for the single-family attached building type. The cost of the panel envelope system was measured to be $70/ft2 and $80/ft2 inclusive of shipping costs. The labor for installing the envelope system was quoted at $28/ft2. Lab chamber testing was conducted on the envelope panels and measured a thermal resistance of R-27, which met expectations, but a much greater air-leakage than was expected, particularly at each type of seam. The panel incorporating mechanical pod integration (including hydronic piping and ductwork penetrations) met insulation and air-tightness expectations and informed revised gasket design. After the chamber testing and revisions informed by this testing, a full-scale prototype of the integrated envelope and mechanical retrofit system, including revised panel modules and gasket strategies, and a compatible mechanical pod, was designed and fabricated for installation on Syracuse University's BEST facility.

Mass Customization of Prefabricated Panel Blocks for Deep Wall Insulation Retrofits (DE-EE0009066)

Summary of Technology	Small panelized blocks for exterior wall retrofit paired with an augmented reality–supported installation process.
Technology Category	Panelized envelope retrofit / technology-assisted planning and installation process
Team & Principal Personnel	Fraunhofer USA Center for Manufacturing Innovation (PI: Kurt Roth), HC Fennell Consulting
Project Objective	Develop an exterior wall insulation retrofit system that delivers superior thermal, hygrothermal, and water management performance customized to the unique geometries of each home. The wall retrofit product paired with the digitized process flow seek to achieve post-retrofit R-30–40, and air-tightness of <0.28CFM50/ft2, installation on a single-family home in <5 days with two semi-skilled workers, and an installed cost of <$6.00/ft2 of wall area (at volume production).
Technology Description and Background	Develop and fabricate a panelized wall insulation retrofit product that utilizes a technology-assisted design and installation process. The technology-assisted process utilized building scanning and augmented reality to deliver the retrofit. The digitized process consists of four steps: 1) high-resolution façade imaging/scanning, 2) automated generation of retrofit façade and component design, 3) computer numerical control (CNC) machining of façade panels, and 4) augmented reality–assisted installation. A standardized panel block size was determined and a tongue-and-groove design utilized to maximize air and water tightness, in addition to a weather-resistive barrier at the cladding plane.
Value Proposition	This is, in effect, an ABC panelized (or modularized) envelope technology as it leverages prefabrication and delivers a high-performance envelope with little tenant disruption and an aim for rapid deployment. The product achieves high thermal performance and very low air leakage while utilizing technology to simplify and speed up the installation, reduce installation errors and the need for rework, allow for workforce training on the job, and be delivered cost-effectively. This technology and process aim to change how building envelope retrofits are delivered and what performance and energy savings results they can achieve.
TRL	4
Key Research Findings	Through modeling, the panel blocks were shown to deliver thermal performance of R-27.6 on their own and, when paired with dense-pack wall insulation, R-34–38. Blower door testing of a mock-up prototype installation showed a wall air leakage reduction of 0.28 CFM50/ft2, going from 0.34 to 0.06 CFM50/ft2. The installation of the mock-up prototype on a 10-ft-high and 20-ft-long mock-up wall took just under 3.5 hours by two staff members (taping the panel block edges took the most time). Scaling this up to a single-family home, the estimated installation would be 30.1 hours, or about four workdays. The cost compression analysis yielded an installed cost of $5.94/ft2 at large production volumes and around $7.00/ft2 at more modest volumes of production. Ultimately, it was determined that the most effective standard panel block size was 12-in height by 48-in width. The Microsoft Hololens augmented reality product was used successfully for the digitized process component with voice commands and visual prompts during the mock-up installation. Energy modeling for the envelope intervention alone showed expected savings results of 34% reduction in space conditioning energy consumption in mixed-humid climates and 38% reduction in cold climates, both in homes that did not already have dense pack wall insulation. For homes with existing dense pack wall insulation, the respective modeled energy reductions were 16% and 21%.

Membrane Dehumidification as Façade-Integrated Building Screens for Latent Cooling (DE-EE0009061)

Summary of Technology	Two types of alternate cooling systems that provide cooling through dehumidification: a liquid desiccant–based system and a vacuum-based system integrated into an operable window opening.
Technology Category	Envelope-integrated mechanical system
Team & Principal Personnel	Princeton University (PI: Forrest Meggers), Harvard University, Massachusetts Institute of Technology, Transsolar, AIL Research, Inc, National Renewable Energy Laboratory
Project Objective	Revolutionize the concept of air conditioning by shifting from systems of forced-air air-cooling that rely on recirculating air in buildings to a technology that manipulates the humidity and velocity of air to achieve improved comfort and health conditions, focusing on passive or semi-passive dehumidification and increased fresh air introduction. The project's goals are to evaluate, optimize, and prototype a liquid desiccant–based system and a vacuum-based system, that each pull water vapor out of the air through a membrane and address the latent heat load of a building.
Technology Description and Background	A façade-integrated membrane system to remove water vapor from air as it either passively or actively moves into the building through a prefabricated façade system-section and eventually through a system easily retrofitted into a window. The team split and developed two technology prototypes: a liquid desiccant–based window system and a vacuum-based system, which underwent a planned internal down-select process. The façade-integrated systems deliver cooling through dehumidification and promote higher quality indoor air through greater introduction of fresh air. The systems can be paired with a low-capacity heat pump that provides active cooling to address small sensible heat loads, in partnership with and developed by Gradient (formerly Treau).
Value Proposition	The project rethinks the paradigm of how air conditioning is accomplished and delivered by addressing moisture removal and attenuating latent heat load. These cooling technologies utilize passive latent heat reduction and have the potential to drastically reduce cooling-related energy consumption, as well as reducing the energy consumption typically associated with improving indoor air quality by bringing in larger amounts of fresh air. Partnership with Transsolar offers a commercialization pathway to develop liquid-desiccant and vacuum systems into commercialized products that are normalized in the market.
TRL	4
Key Research Findings	The membrane prototypes with vacuum and liquid desiccant systems were installed in an office building in Miami for demonstration, which found that 1–2 m^2 of contact area per person was needed to meet the design parameters of <50% humidity for a high-humidity climate (80% humidity and >80F). By modeling and comparing standard air conditioners and natural ventilation potentials to effectively address COVID, which traditionally puts energy usage and fresh air at odds, natural ventilation can be strategically increased by developing new technology that puts energy savings and fresh air delivery in tandem by integrating system operation with natural ventilation. Performance lab and field testing were conducted to determine system COP.

Modular Overclad Composite Panels for Envelope Retrofits (DE-NL0036660)

Summary of Technology	Fiber-reinforced composite envelope retrofit panel that is created through digitized manufacturing.
Technology Category	Panelized envelope retrofit / Digitized process for panelized envelope retrofit
Team & Principal Personnel	Oak Ridge National Laboratory (PI: Diana Hun), University of Tennessee, Institute for Advanced Composites Manufacturing Innovation
Project Objective	Develop a prefabricated, modular, overclad composite panel system for envelope retrofits that is cost-effective, easy to install, and aesthetically appealing. In addition to developing the proof of concept for the materials, the design, manufacturing, and assembly process would be optimized for use of these materials. The goal is for the panels to be durable and lightweight (~4lb/ft^2), achieve cost-effective design layout, meet fire safety regulations by using low-flammability treatments, utilize air- and water-tight fastenerless connections to improve quality and speed of installation, be supported by digitized manufacturing, and be suitable for modular design. and prototype a liquid desiccant–based system and a vacuum-based system, that each pull water vapor out of the air through a membrane and address the latent heat load of a building.
Technology Description and Background	A fiber-reinforced composite panelized envelope retrofit product that is composed of composite glass fiber reinforced beams with foam cores. The beams are assembled and conjoined using vacuum-assisted resin transfer molding, the foam core of the beam provides the insulative characteristics, and the composite glass fiber becomes the structural frame. Three prototypes were constructed to demonstrate: 1) thermal performance (2-ft by 2-ft by 5.75-in prototype), 2) aesthetic finishing for the outer face based determined by assembly steps (4-ft by 4-ft by 5.75-in prototype), and 3) scalability of the manufacturing process (4-ft by 10-ft by 5.75-in prototype). Panel connections do not require fasteners and instead utilize a tongue-and-groove design for air- and water-tight connections. Additionally, Oak Ridge National Laboratory has developed a digitized panel manufacturing process to select the fewest panels based on the existing façade, and dimensions and locations of openings. Computer numerical control (CNC) cutting was used to cut the panels as part of the digitized manufacturing process, and the connector components created brought an air- and water-tight seal that resulted in eliminating the need for a traditional window flashing.
Value Proposition	A panelized envelope retrofit product that can be manufactured at scale, deliver high thermal and hygrothermal performance and durability, and optimize the design and installation process of that product for faster, easier envelope retrofits and digitize the traditionally manual design process. This product takes on the spirit of prefabricated, digitized retrofits with the potential for industrialized production and installation. There is great potential to increase envelope performance through this retrofit product and decrease design and manufacturing time.
TRL	5
Key Research Findings	The project found that including a drainage plane between the overclad panel and the existing envelope decreases concerns about moisture problems as a result of trapped water from having low-water-vapor-permeance materials used either in the panel or the existing envelope. Experimental testing found the panel's thermal resistance to be R-3.8 per inch and the finite element analysis (FEA) modeling determined R-3.95 per inch. Additional modeling found that a whole-building retrofit using the fiber composite panelized system paired with a mechanical system retrofit would save 71% mechanical systems energy usage.

Next Generation Wall Retrofit Panels with Integrated VIPs (DE-EE0009063)

Summary of Technology	Panelized wall system incorporating vacuum-insulated panels (VIPs)
Technology Category	Panelized envelope retrofit
Team & Principal Personnel	Home Innovation Research Labs, Inc (PI: John Peavey), Oak Ridge National Laboratory
Project Objective	Develop a next-generation building envelope retrofit solution that achieves deep operational and embodied energy savings, while increasing rapid deployment, affordability, and desirability, and reducing tenant disruption. achieve cost-effective design layout, meet fire safety regulations by using low-flammability treatments, utilize air- and water-tight fastenerless connections to improve
Technology Description and Background	Four wall panel configuration concepts were developed and each incorporated vacuum-insulated panels: exterior insulation finish system, retrofit insulated panels (RIP), insulated concrete panels, and insulated metal panels. Three of these four panel designs were turned into prototypes and, ultimately, the final panel design product was the retrofit insulated panel with embedded VIPs: the V-RIP. By using a VIP in a wall panel, both the thickness and weight of the product can be reduced to help meet retrofit design needs. One of the drawbacks to VIPs is their fragility and need for being handled with care, which is a benefit of embedding them in a retrofit panel.
Value Proposition	Exploring the potential for cost, installation time, and energy savings from integrating vacuum insulation technology in wall retrofit panels. VIP R&D seeks to support lower-cost retrofits that are deployed simply and quickly and result in deep energy savings. VIPs have not traditionally been used in this application, so this R&D effort could yield an emerging technology to contribute to advancing building construction.
TRL	6
Key Research Findings	All four wall panel configurations incorporating VIPs were assessed for thermal performance, moisture resistance, ease of manufacturing and incorporating VIPs, durability, ease and speed of installation, and cost. Based on cost analysis fortwo proposed demonstration buildings, the cost of the wall V-RIP is around three-to-four-times cheaper than a comprehensive energy retrofit. Findings indicate that there is great promise for the technology, but to maximize thermal performance, R-VIPs must be installed on virtually the full exterior wall surface area and coupled with air sealing.

PV GEMS Photovoltaic Powered Grid Enhanced Mechanical Solution (DE-EE0009065)

Summary of Technology	Heat pump water heating and supplemental space conditioning system powered directly by solar photovoltaic cells with “on-system” battery storage and full independence from the electric utility grid.
Technology Category	Direct solar-PV powered “packaged” mechanical system
Team & Principal Personnel	University of Central Florida Energy Research Center (PI: Eric Martin), CyboEnergy, Rheem
Project Objective	Develop and assess a photovoltaic, grid-enhanced mechanical system retrofit for existing buildings and build two prototypes with different capacities to be installed and monitored in the laboratory setting.
Technology Description and Background	A photovoltaic-powered, grid-enhanced mechanical solution (PV-GEMS) that integrates a grid-independent photovoltaic (PV) system to power a high-efficiency heat pump water heater and a high-efficiency mini-split heat pump to supplement a home’s existing space conditioning system. PV-GEMS generates solar electricity and uses it directly for the connected mechanical systems with independence from the utility grid. Any extra power generated charges a connected storage battery.
Value Proposition	The project offers a mechanical retrofit package intended to be prefabricated via off-site construction and delivered as a “pod” for simplified, rapid deployment. The product seeks to address retrofit needs in buildings where an envelope upgrade is either not cost effective or is unfeasible due to structural upgrade needs. Additionally, it promotes resilience and decreases strain on power infrastructure. PV-GEMS combines mechanical systems and powers them directly with renewable energy for rapid deployment, energy cost reduction, and building resilience.
TRL	5
Key Research Findings	The two prototype systems were operated and tested in two respective lab environments: the smaller-capacity prototype in the Manufactured Housing Laboratory (MH Lab), which is around 1,600 ft^2 to represent a single-family home; and the larger-capacity prototype in the Building Science Laboratory, which is around 2,000 ft2 to represent a small commercial or larger single-family home. Monitored lab data was collected from the smaller-capacity prototype in the MH Lab and showed an average savings of 41.7% (or 50.1% when considering all components of the system, including solar PV and battery storage), which were also paired with traditional attic air sealing and insulation, and duct sealing measures. Further simulation modeling was conducted to understand impact in other climates, which resulted in a range of energy savings of 50–90% across six cities, two building vintages/types, and three heating baselines. Estimated installed cost for the PV-GEMS is $17,215, found during the Phase I research.

Streamlining BIM-CAD-CAM Conversion for Panel Manufacturing (DE-EE009067)

Summary of Technology	3D scanning-to-shop fabrication workflow for exterior prefabricated envelope retrofits for low-rise multifamily buildings.
Technology Category	Digitized design process workflow for panelized envelope retrofits
Team & Principal Personnel	Signetron Inc. (PI: Avideh Zakhor), RMI, Kieran Timberlake, Cocoon Construct
Project Objective	Develop a digitized workflow to support the design of a prefabricated envelope retrofit to minimize tenant disruption and reduce installation time.
Technology Description and Background	A technology-assisted workflow that takes a 3D laser scan of a building, creates a 3D point cloud through a series of mathematical and computational algorithms for digital representation of the existing façade, and delivers digital information to a panel fabricator to inform shop drawings. The shop drawings are then fed to cutting machines and computer numerical control (CNC) printers, which cut sheets of insulation to create insulation panels for installation on a building's exterior. The workflow has three outputs: 1) polygonised representation of the existing, scanned facades and fenestrations; 2) deviation maps showing the deviation of a façade from planarity; and 3) panelization of the polygonal representations.
Value Proposition	The digitized workflow enables faster and easier design process for prefabricated panelized retrofits, with a secondary result of cutting design-related costs associated with rework and design complexity. The BIM-CAD-CAM workflow. The software workflow helps address typical barriers of a panelized retrofit design, which are: it is difficult to capture real-life irregularities not reflected in building plans such as foundation settlement or nonplanar warped facades; current panel configuration design process is complicated, error prone, and manual; and it is challenging to anticipate coordination needs with other retrofit components that ultimately impact the envelope. Overall, it achieves a more efficient envelope design process in time and effort.
TRL	5
Key Research Findings	The workflow was applied to a real building in Corona, California, to assess process and workflow functionality, and measure impact of the workflow on a potential installation process. The workflow demonstration measured an approximate time savings of 30% for the low-rise building, and it is expected that even more time would be saved when applied to a more complex building typology. Time reduction is yielded from removing hand measurements from the design process, supporting the designer's panel layout design process, and assisting with placement in the construction process. At the case study demonstration site, the initial building scan for two buildings cost $4,000 and took one day. The team estimates that manual collection of the same data would have required survey professionals and cost around $10,000–15,000.

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Transformative Building Envelope Retrofit Using Insulation-Inflatable Walls (DE-NL0036668)

Summary of Technology	High-performance retrofit envelope system utilizing polymer foam–filled inflatable insulation that is fabricated off site and expands when filled on site
Technology Category	Retrofit envelope system
Team & Principal Personnel	Oak Ridge National Laboratory (PI: Anthony Aldykiewicz), Lighter Than Air Projects LLC, Southern Company
Project Objective	Develop an envelope retrofit that is low cost and designed to retrofit older homes built before energy codes were implemented. The process targets cost reduction at each point of the retrofit cycle, material sourcing to installation. Part of the cost reduction is intended to come from digitized manufacturing and the simplified and rapid installation process. The goal is to deliver an envelope retrofit of R-20 to a building in three to four days with two workers that achieves an installed cost of $10/ft2 and minimal tenant disruption.
Technology Description and Background	An envelope retrofit that combines inflatable structure and spray polymer foam to achieve a high performance retrofit system that is low-cost, uses digitized manufacturing, and is rapidly deployable. The retrofit consists of four steps: 1) collect measurements via onsite manual data collection or digital imaging; 2) CAD file created from measurements is fed to a fabrication machine to cut envelope components through digitized manufacturing; 3) retrofit components are shipped to the site, installed in a similar manner as a weather-resistive barrier, and once affixed, filled with polymer foam insulation that expands inside the cavity; and 4) cladding is installed for exterior building finish.
Value Proposition	The approach studied offers a rapidly deployable envelope retrofit product that utilizes digitized manufacturing and prefabrication to deliver a high-performing, low-cost retrofit that minimizes tenant disruption during the installation process, which aligns with the tenets of ABC. Its flexibility allows it to tolerate small measurement errors or building façade irregularities, and the product's thickness can be varied to allow a wide range of thermal resistance values and accommodate specific building's needs. Additionally, due to the lightweight nature of the product, mechanized lifting equipment is not necessary for installation.
TRL	2
Key Research Findings	Four different fabric materials and four different insulation materials were evaluated for the overall product. Ultimately, the most optimal fabric was spun-bonded polyolefin and the most optimal insulation was Versi Foam Slow Rise polyurethane. Each was selected for its favorable cost-to-performance profile. In-depth modeling and measurements were conducted to find the ideal spacing of baffles and fill of the insulation: the results indicated baffle spacing should be 4 inches, and baffle width 3 inches. The insulation material is R-6.7 per inch at 3-inch baffle width thickness, resulted in a nominal thermal resistance of R-20.1. Thermal conductivity and air leakage testing were conducted on a mock-up finished sample and found to be R-14.8.

Transforming Public Housing with Deep Energy Retrofits (DE-EE0009062)

Summary of Technology	Creating a process approach to carry out a deep energy retrofit by integrating project design and construction teams, structuring financing, and engaging and training the resident community.
Technology Category	Process to successfully conduct a deep energy retrofit
Team & Principal Personnel	Open Market ESCO LLC / WinnCompanies (PI: Christina McPike)
Project Objective	The project had six objectives: 1. Fully integrate architects, engineers, and other relevant participants of record in the deep energy retrofit design process; 2. Engage general contractor and key vendors to participate throughout the design development process to streamline pricing and inform constructability; 3. Identify financing barriers, and solutions, and create a roadmap for new financing and/or grant funding applicable to RAD conversions and low-income housing tax credit (LIHTC) projects; 4. Create a replicable deep energy retrofit design solution for affordable multifamily housing projects pursuing major recapitalization events, such as Rental Assistance Demonstration (RAD); 5. Structure a resident and building staff engagement/education/training program that will ensure long-term savings and project success; 6. Drive demand in the marketplace by sharing lessons learned with stakeholders, including the US Department of Housing and Urban Development (HUD), state finance agencies, public housing authorities, and owners.
Technology Description and Background	Tools and standardized approach to implement a deep energy retrofit for all major stakeholders
Value Proposition	The project pursues a standardized approach for deep energy retrofits, aligned with the ABC Initiative's core goals of advancing the way buildings are built and retrofitted and creating ways to rapidly upgrade existing buildings to be far more energy efficient. The developed approach offers a process by which project teams can successfully implement deep energy retrofits and incorporate high-efficiency technologies emerging in the market, offering a pathway to successfully achieve a deep energy retrofit and address the common barriers to doing so. This process is a clear application of ABC as it identifies and standardizes pathways to overcoming the barriers to deep energy retrofits via optimized process development.
TRL	6
Key Research Findings	In carrying out the design process, the goal-oriented and collaborative design approach engaging all stakeholders was identified as far from business as usual. Structural analysis of the existing building is the most important factor for design in an overclad retrofit and dictates what products and materials can be used. It was critical to engage the contractors in the design and specifying processes, and this was most useful for HVAC design. Pricing a scope that includes emerging technologies is extremely difficult. This contributes to the supply side of financing being a barrier; demand-side challenges include pulling funding together for high-upfront-cost investments. It was critical to engage residents to understand building retrofit needs and also to achieve energy and cost savings since those are behaviorally dependent.

Wall Embedded Multi-Functional Heat Pump with Energy Storage Systems (DE-NL0036646)

Summary of Technology	Combining a multi-function mechanical retrofit and a wall retrofit by embedding a high-performance, variable-speed heat pump that fits between two wall studs in a phase change material (PCM)–embedded wall that is also connected to a hot water storage tank.
Technology Category	Envelope-integrated packaged mechanical system
Team & Principal Personnel	Oak Ridge National Laboratory (PI: Bo Shen), Oklahoma University, Katerra Construction Company (replaced by Emerson)
Project Objective	Develop a wall-embedded multi-function mechanical system that achieves high performance and delivers a cost-effective retrofit. The project aims to improve the existing variable-speed compressor's performance through modification, with the following targets: improve the EER from 11 to 12, improve the IPLV from 17 to 19, and improve the COP from 3.3 to 3.7.
Technology Description and Background	A wall-integrated high-performance, variable-speed heat pump that provides heating, cooling, and domestic hot water. This heat pump is connected to a hot water storage tank and a PCM system via a refrigerant-to-water heat exchanger. The heat pump component fits between two wall studs. The PCM is embedded in the wall panel in which the heat pump sits and provides thermal energy storage for the system. Additionally, the unit has an ice storage mechanism for cooling energy storage. Oak Ridge National Laboratory initially was partnered with Katerra Construction Company to modify the latter's KTAC product to achieve a higher efficiency and also be embedded in a wall panel with energy storage capabilities. Oak Ridge National Laboratory then brought Emerson on as a partner to continue its envelope-integrated mechanical system product development, targeting a system cost of $900 excluding the PCM.
Value Proposition	The wall-integrated mechanical system is prefabricated and combines multiple end uses into one piece of equipment with the potential for rapid deployment and cost-effectiveness. Combining mechanical end uses into one system could achieve cost compression of utilizing fewer mechanical components; integrating it into a wall and coupling the mechanical and envelope retrofits presents even further cost reduction opportunities. Use of PCM thermal storage in the wall promotes thermal comfort, reduction in power grid strain, and resilience. Modification of the heat pump component strives to deliver a high-performance system for deeper energy savings.
TRL	3
Key Research Findings	Results pending.

Zonal Heat Pump for Whole-Home Panelized Retrofits (DE-NL0036674)

Summary of Technology	Combining low-capacity, zonal heat pump technology for space conditioning with an airtight, insulated exterior envelope retrofit panel.
Technology Category	Envelope-integrated mechanical system
Team & Principal Personnel	National Renewable Energy Laboratory (PI: Lena Burkett), Mitsubishi Electric US, Cocoon Construct
Project Objective	Develop an integrated whole-building retrofit product that delivers a high-performance envelope retrofit with an embedded high-efficiency mechanical retrofit. This retrofit product strives to achieve cost reduction by combining the envelope and mechanical retrofit components, and a better mechanical retrofit as a result of the low-capacity HVAC for a zonal retrofit application.
Technology Description and Background	A combined envelope and mechanical retrofit that delivers a high-efficiency whole-building retrofit through one product with an HVAC product optimized for zoned mechanical design. A low-capacity HVAC heat pump is embedded in an exterior wall panel product to deliver a packaged envelope and mechanical retrofit and address the existing heating and cooling load through envelope improvement and more appropriately sized HVAC zoning to address the smaller thermal loads. The integrated product has its own technical specifications and design requirements to view the envelope-mechanical retrofits holistically and as one designed and installed system product. The main integration component is embedding the mini-split head unit in the panelized wall assembly.
Value Proposition	The prefabricated and integrated system presents the potential and opportunity for a cost-effective and rapidly deployable retrofit. The two-in-one solution enables the pursuit of a whole-building retrofit by virtue of the combined retrofit components and through the potential cost compression resulting from combination. The combined product is produced—packaged and constructed (eventually to be manufactured)—in a factory, leveraging an industrialized construction approach. Use of low-capacity heat pump equipment presents opportunity for right-sized—as opposed to oversized—zonal equipment and cost reduction associated with low-load equipment.
TRL	2
Key Research Findings	Results pending. The team intended to build a mock-up unit and conduct lab testing. The mock-up consisted of a mock-up existing wall with a mock-up wall panel with embedded HVAC heat pump.

ABC Collaborative Involvement in Phase I

In an effort to provide technology and market scaling support to Topic 1 research teams in Phase I, the ABC Collaborative facilitated several different engagement pathways. These engagement touchpoints included:

- A formal consultation meeting with each of the 14 Topic 1 Phase I teams;
- Informal, one-off consultations via phone or email as requested and on an as-needed basis;
- Informal email touch-base prior to the close of Phase I;
- Assistance in identifying potential demonstration site and ABC-relevant partnership opportunities, and facilitating introductions and connections;
- Monthly "coffee chats" for voluntary participation by all FY19 ABC FOA teams covering a wide range of topics, including an outside technology showcase to support Phase II teaming activities and a dedicated Phase I down-select information session;
- Creating and leading recurring topic-specific ABC Collaborative Working Groups composed of various ABC-relevant stakeholders, including from industry; and
- Hosting an ABC Summit and Convening with a wide range of ABC-relevant stakeholders, with an opportunity for a selection of FY19 ABC FOA teams to present on their work.

Some of the Topic 1 Phase I teams took advantage ABC Collaborative support more than others, but equal access and opportunity to resources and support were provided to all teams. At a minimum, each team engaged with the Collaborative through the first formal consultation in early 2021. The ABC Collaborative plans to continue offering similar (and, if appropriate, develop additional) support pathways during Phase II.

Look-Ahead to ABC Topic 1 Phase II

Topic 1 Phase I closed with a down-select process resulting in a condensed number of Topic 1 teams receiving funding for Phase II. BTO included this down-select process to allow for teams to reorganize after making initial strides in technology and process development during Phase I, and to encourage more innovation in the whole-building solutions proposed. 11 of the 14 Topic 1 Phase I teams joined a Phase II proposal team. In March 2022, BTO selected seven teams to advance to Phase II, with a total of $31.8 million in funding:

1. **Fraunhofer USA Center for Manufacturing Innovation** (Massachusetts) will test prefabricated, super-insulated wall retrofit panel blocks with a suite of high-performance building technologies across four locations in Massachusetts, Vermont, and Pennsylvania. (Award Amount: $4.9 million.)
2. **Home Innovation Research Labs, Inc.** (Maryland) will test an innovative wall system with vacuum insulated panels in three residential, multifamily public housing buildings in Albany, New York. (Award Amount: $4.5 million.)
3. **National Renewable Energy Laboratory** (Colorado) will use software tools to properly size and install retrofit packages in two residential low-income, multifamily buildings in Arvada, Colorado. (Award Amount: $4.4 million.)
4. **Oak Ridge National Laboratory** (Tennessee) will demonstrate 3D-printed modular overclad panels with heat pump systems in eight to 12 single-family attached public housing homes and one commercial building in Knoxville, Tennessee. (Award Amount: $5 million.)
5. **RMI** (Colorado) will demonstrate an integrated retrofit package of envelope panels, a heat pump pod, and innovative financing in a mid-rise, 120-unit low-income multifamily building in Cambridge, Massachusetts. (Award Amount: $4.4 million.)
6. **Syracuse University** (New York) will pair overclad panels with real-time performance monitoring capabilities and an HVAC pod in single-family attached dormitories in Syracuse, New York. (Award Amount: $5 million.)
7. **The University of Central Florida Board of Trustees** (Florida) will demonstrate a solar photovoltaic-integrated multi-functional heat pump system for space and water heating in four single-family homes and eight manufactured homes across numerous locations in six states. (Award Amount: $3.6 million.)

Technologies in the Broader Context

The goal of Phase II for the ABC Topic 1 teams is to expand technology capabilities to create whole-building retrofit solutions that achieve a 75% reduction in thermal load energy consumption. The above seven teams selected for Phase II represent a variety of approaches to tackling this challenge.

The collaboration of teams to create holistic retrofit package solutions results in significant benefits for building owners, tenants, workforce, and stakeholders along the construction value chain. With holistic deep energy retrofit packages, building owners can reduce operational energy costs while simultaneously improving occupant comfort with minimal disruption. Precisely modeled retrofit solutions can be pre-determined through time-efficient remote sensing allowing for effective, streamlined, and prompt fabrication and deployment. In addition, the introduction of automated technologies supplements existing workforce capabilities by reducing on-site workload, improving worker safety, and enabling new capabilities. With investment in off-site manufacturing of components and systems, on-site work can be completed swiftly to reduce occupant disruption.

Phase II will focus on further refining technologies developed and tested during Phase I, combining technologies to yield comprehensive retrofits, and demonstrating those retrofit solutions in the field. Phase II emphasizes the technology or workflow demonstration component to provide a real example of how the solution could be applied and collect field data on its effectiveness. The results of the field demonstrations will provide critical data on the efficacy and viability of the retrofit solution, including market fits and the ability to address the overarching goals of the ABC Initiative.

Beyond the ABC Initiative

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Appendix

Exhibit 2 Definitions of Technology Readiness Levels

Relative Level of Technology Development	Technology Readiness Level	TRL Definition
System Operations	**TRL 9**	Actual system operated over the full range of expected conditions.
System Commissioning	**TRL 8**	Actual system completed and qualified through test and demonstration.
	TRL 7	Full-scale, similar (prototypical) system demonstrated in relevant environment
Technology Demonstration	**TRL 6**	Engineering/pilot-scale, similar (prototypical) system validation in relevant environment
Technology Development	**TRL 5**	Laboratory scale, similar system validation in relevant environment
	TRL 4	Component and/or system validation in laboratory environment
Research to Prove Feasibility	**TRL 3**	Analytical and experimental critical function and/or characteristic proof of concept
Basic Technology Research	**TRL 2**	Technology concept and/or application formulated
	TRL 1	Basic principles observed and reported

Source: Adapted from Standard Review Plan Technology Readiness Assessment Report, Office of Environmental Management, Department of Energy, March 2010. energy.gov/sites/prod/files/em/Volume_I/O_SRP.pdf.