

Digitization of Deep Wall Retrofits: An Integrated Insulated Panel Block (PB) System and Process

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ABSTRACT

We prototyped an integrated process using prefabricated insulated Panel Blocks (PBs) with integral vinyl siding cladding that could greatly reduce on-site labor and installed cost of high-performance exterior wall retrofits for 1- to 4-family low-rise residential buildings. Prototype testing of the lightweight (<5 pounds) polyisocyanurate foam PBs, ~1' x 4' by 4" thick, installed over the existing cladding increased the wall R-value by ~R-24 while reducing wall-based air leakage by about 80%. We also prototyped and demonstrated portions of an integrated and digitalized design, production, and delivery system on a mock-up wall. First, we developed a process that analyzes point-cloud data from laser scanning of the subject building to generate a dimensionally accurate CAD model of the exterior walls. Next, we determined the optimal PB set to panelize (clad) each wall and created CAD drawings for each PB. Subsequently, a foam manufacturer used the PB CAD files to feed a computer-aided manufacturing (CAM) process to fabricate the full PB set. Finally, we created an augmented reality (AR) experience that guides workers as they install the PBs and trim, highlighting *which* of the many PBs on a pallet to install next and projecting *where* it goes and its orientation on the wall. In sum, the AR empowers semi-skilled workers and provides quality control. Process, materials and manufacturing cost modeling completed in Q3 of 2021 indicate profitability at an installed cost of <\$8.00/ft², potentially at \$6.00/ft² in high volumes, with installation in less than a week. This capital-lean approach is compatible with existing small contractors' business models, and obviates the need for cranes or other heavy-lift equipment required for larger panelized construction techniques.

Introduction

Several states in the Northeast have established aggressive greenhouse gas (GHG) reduction goals, e.g., Massachusetts has committed to achieving net-zero GHG emissions by 2050 (Commonwealth of Massachusetts 2021). Achieving these goals will require decarbonization of building space heating, which policymakers primarily seek to achieve through widespread conversion of fossil-fired space-heating systems to heat pumps powered by renewable electric sources. Energy efficiency has a crucial role to play in this transition by: 1) reducing the electric energy required (kWh); 2) mitigating the peak demand impacts of space heating; and 3) reducing the required heat pump capacity (Btu/hour) and associated cost.

Currently, market-viable enclosure deep-energy retrofit (DER) approaches do not exist for the 1- to 4-family homes that account for a large majority of housing units and residential

HVAC energy consumption. Although viable approaches for attic and roof retrofits exist (e.g., Petit et al. 2013), cost-effective approaches for walls and windows remain elusive.

Wall DERs apply insulation on the exterior of the structural wall to mitigate thermal bridging and moisture condensation (Lstiburek 2010). Interior insulation approaches are very disruptive to inhabitants, reduce valuable floor space, and are hygrothermally inferior. The typical exterior approach to achieve R-30+ ($^{\circ}\text{F}\cdot\text{ft}^2\cdot\text{h}/\text{Btu}$) whole-wall retrofits for 3.5-4" wall cavities affixes layers of rigid-board insulation to the exterior wall along with a rainscreen and siding. This process is time-intensive due to the extensive labor required to achieve acceptable finishes at the interface of the insulation and the control layers at wall penetrations and connections (windows, doors, pipes, porches, vents, electrical boxes, etc.). Workers custom cut the insulation to fit around each penetration, build out extension boxes around windows, cut and apply air and vapor retarders and sealants, seal all insulation joints, etc. (BSC 2013). Alternate approaches that build a structure on the outside of the existing wall (e.g., Larsen truss) to carry additional insulation are similarly labor intensive and, hence, costly. Unsurprisingly, a field study of DERs for single-family homes more than a decade ago found an *incremental* cost for exterior insulation of $\sim\$10/\text{ft}^2$ of wall area, or $\sim\$25,000$ for a 2,400 ft^2 home before adding a similar cost for exterior cladding (Neuhauser 2011), while a recent study estimated costs ranging from $\$14$ to $19/\text{ft}^2$ (PNNL 2022). In short, this is truly “death by a thousand cuts.”

Emerging panelized approaches, e.g., EnergieSprong,¹ show appreciable potential for multi-family homes with very basic and regular façades. That said, this approach can be problematic for many single-family homes. Notably, they often require an on-site crane that can reach all walls. Since one home would typically be retrofitted at a time (individual homeowners making individual decisions), this could prove costly, as well as problematic at sites with larger trees, appreciable slope, and/or nearby abutters. Moreover, many U.S. homes have more complex geometries than those addressed by EnergieSprong, which increases site work and installed cost. Recent cost estimates for panelized systems range from $\$20$ to $\$45/\text{ft}^2$ (PNNL 2022).

The national energy savings potential of wall DERs is significant. PNNL (2022) modeled the energy savings from applying $\sim\text{R-24}$ insulation to the exterior walls of a DOE prototypical single-family home in different climates. For homes lacking wall insulation, this reduced whole-home space conditioning energy consumption by 34% to 38% in climates with appreciable space heating.² For a home with dense-pack cellulose already in the wall cavity, reductions ranged from 16% (mixed-humid) to 21% (cold). Wall DERs applied to pre-2000 1- to 4-family homes in mixed, cold, and very cold climates have a national site energy savings potential of 750 TBtu.³

A Novel Integrated Deep-energy Wall Retrofit Process

To address the dearth of existing market-viable wall DER solutions for smaller buildings, we developed an exterior wall-insulation retrofit system that uses an insulated panel block (PB) system to deliver superior thermal, hygrothermal, and water management performance customizable to the unique geometries of each home. The PBs are integrated into highly digitalized design and deployment processes that enable mass production of custom PB sets to

¹ See: <https://energiesprong.org/>.

² Reductions in conductive heat losses accounted for 60-65% of energy savings, with the model assuming that the wall retrofit reduced air leakage from 15 AHC₅₀ to 10. Savings were greatest in very cold climates, 38%.

³ Based on DOE-EIA RECS 2015 baseline HVAC data (EIA 2015). We assume that 1/3 of homes have no wall insulation and 2/3 have dense-pack cellulose cavity insulation.

clad each home and eliminates on-site cutting, waste, and greatly simplified installation. The basic building blocks are lightweight (<5 pounds) ~1'H×4'W×4" thick insulated panel blocks made of polyisocyanurate foam. They are prefabricated offsite with integrated vinyl siding (see Figure 1). The PB and process designs explicitly focus on creating a low-cost and quick-install wall retrofit package/system with an aesthetic already established in the market that, when manufactured and deployed at scale, could achieve:

1. R-30 to 40 total wall insulation and ≤ 0.25 cfm/ft² (@50Pa) air barrier performance;
2. Installation on a single-family home in ≤ 5 days by two semi-skilled workers, and
3. Installed cost of $\leq \$6.00/\text{ft}^2$ of wall area (at volume production).

The integrated design, manufacturing, and delivery process applies digital technologies to support these objectives, and comprises the following steps:

1. *Laser scanning* generates a digital representation (point cloud) of the building surfaces;
2. *Scan-to-BIM algorithms* analyze the point cloud data to generate a high-fidelity building-information model (BIM) of the opaque wall surfaces and their dimensions;
3. *A Panelization algorithm* determines the optimal combination of insulated PBs with standard details/features to clad a home's walls, creating a CAD file for each component (PB and trim piece);
4. *Computer-aided Manufacturing (CAM)* process uses component CAD files as inputs to fabricate the custom component set for each home, which are subsequently kitted and delivered to the retrofit site; and
5. *Augmented reality (AR)* guides semi-skilled workers in the installation of the PBs and trim, showing workers what PB or trim piece on the shipping pallet to install next and where it goes on the façade.

As currently designed, the PB system can be applied to a large portion of the existing 1- to 4-family building stock and, with relatively simple modifications, can be applied to an even larger fraction. In particular, the PB design targets buildings located in cold and very cold climates and is also applicable to mixed climates. With some design optimization, e.g., different finish materials (stucco), adding high-reflectance coatings, potentially reducing thickness, etc., the PB system could be applied to warm/hot climates. Similarly, although the attachment system was designed for wood-frame walls, it could be adapted to masonry and stucco with different anchors. Finally, the PB system could be applied to larger multi-family and commercial buildings as well. That said, we expect that systems using much larger craned-in panels (e.g., 8' high by 15' long) would start to make more economic sense once buildings reach a certain size, assuming sufficient clearance for a crane access exists.

The next subsections describe each component of the process in further detail, while subsequent sections describe a demonstration of the system.

Panel Block (PB)

A standard full-size tongue-and-groove PB (see Figure 1) is ~12 inches high by ~48 inches long and ~4-inch thick polyisocyanurate insulation with integral vinyl siding cladding⁴

⁴ The PB system can also work with factory-integrated stucco, metal, or thermally treated wood siding.

that weighs less than five pounds, making it easy for one person to handle. Analysis and testing find that the PBs achieve whole-wall R-values of 27 to 37 (without and with cavity insulation, respectively; PNNL 2022).⁵ The PBs install over the existing wall cladding using 4-inch fasteners that are screwed into the existing cladding and sheathing.⁶

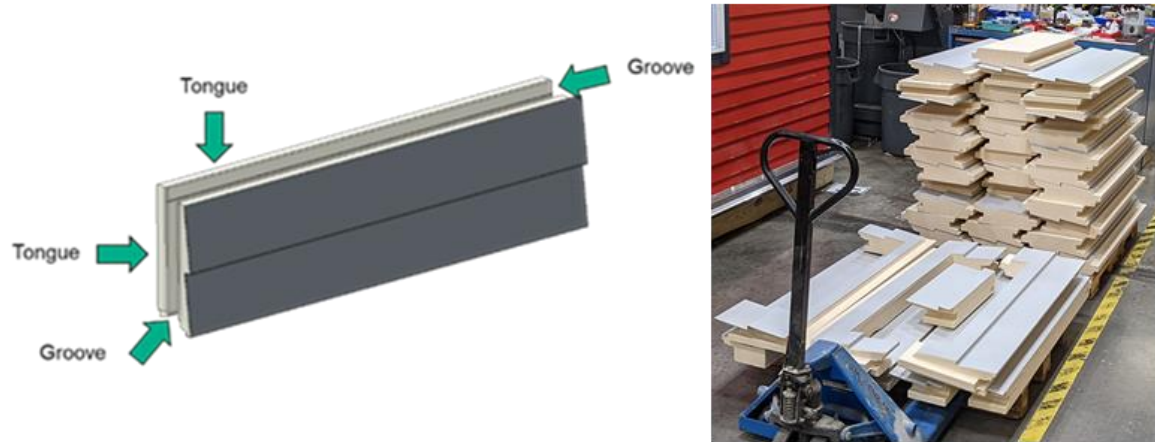


Figure 1. *Left:* Panel block (PB) design. *Right:* Pallets with panel blocks ready for installation on mockup wall.

We successfully adapted the original PB design developed by HC Fennell⁷ to the target building types. Decisions about design and design features took into account several factors, including: 1) water intrusion/performance; 2) air sealing; 3) ease of assembly; 4) aesthetic quality; 5) adaptability to mass production methods; 6) ease of installation with semi-skilled labor; and, not least, 7) material and installed cost. Key features defined include:

- A standard PB size, ~12" H x 48" W based on analysis of the number of PBs possible, number of PBs to install, length of PB joints (potential water and air leakage sites), and ease of handling (no cranes), shipping, and manufacturing.
- Tongue/groove design for all sides that interface with other PBs, creating a labyrinth-path joint to reduce air leakage and water intrusion and guide PB installation while retaining physical integrity and considering ease-of-manufacture (i.e., the processes used to create PB features). The space in the joints also allows the PBs to accommodate out-of-plane deviations in the existing façade as well as thermal expansion/contraction, enabling installation of the PBs over the existing cladding (i.e., no need to remove existing cladding unless underlying sheathing or structural issues exist).
- Quick-install starter strip for bottom edge of PBs supports PB installation; provides insect protection, terminates the air barrier, and drains water that may get behind the PBs.

⁵ U. Minnesota conducted field testing of the PB system at its Cloquet, MN test facility in both north- and south-facing test bays from December 2020 through April 2021. Based on field temperature and heat-flux measurement and THERM modeling, PNNL (2021) estimates that the PB system with *an uninsulated cavity* achieved a whole-wall R-value of R-27.6, adding ~R-24 to the wall; this translates to ~R-35 for a wall cavity filled with dense-pack cellulose. For comparison, existing insulated vinyl siding adds ~R-2 to -5 to the wall.

⁶ If the integrity of the existing siding is compromised, it needs to be replaced.

⁷ Autonomous Real-time Remote Observatory (ARRO) structures were designed and produced under contract with the Cold Regions Environmental Research Laboratories and the University of New Hampshire Aerospace Department, both funded by the National Science Foundation for deployment in Antarctica.

- Integral vinyl cladding adhered to the PB surface as the cladding material and defining a viable manufacturing process at scale.
- Water-resistant barrier (WRB) included to reduce air leakage and provide a drainage plane for any water intrusion behind the PBs.
- Trim design with features to enable quick offsite fabrication while effectively managing liquid water (builds on vinyl siding practices, particularly for windows and corners).
- PB edge taping process to prevent water intrusion at wall penetrations and terminations.

To avoid extensive on-site finish work, our design integrates COTS clapboard-style vinyl siding to minimize on-site work. The cladding of one PB overlaps that of adjacent PBs to minimize water intrusion, allow for thermal expansion and contraction, and improve aesthetics. Although we used this style due to its broad market acceptance and affordability, the PB design could readily incorporate factory-applied stucco, thermally treated wood, or metal siding.

To work around terminations and openings (doors, windows, soffits, corners, etc.), the full-size PBs are factory-cut to match existing conditions (see range of shapes shown in Figure 2). Although manually fabricated for a demonstration, ultimately these will be produced using automated CNC equipment, such as an abrasive wire cutter.

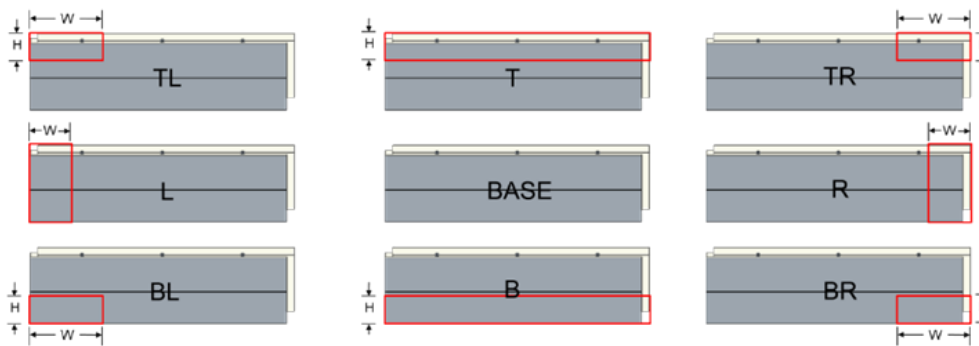


Figure 2. Different PB modifications and cuts to create custom PB shapes.

Water Resistant Barrier (WRB): We install a WRB over the existing cladding to create a drainage plane for any water that gets behind the PBs and to reduce air leakage. Workers install the WRB prior to the PBs, and seal the WRB back to the house (traditionally, it would be taped back to the framing or sheathing, but that is not possible in many DERs). The WRB is cut ~1.5" short around fenestrations and taped to the trim around the fenestration (see Figure 3).

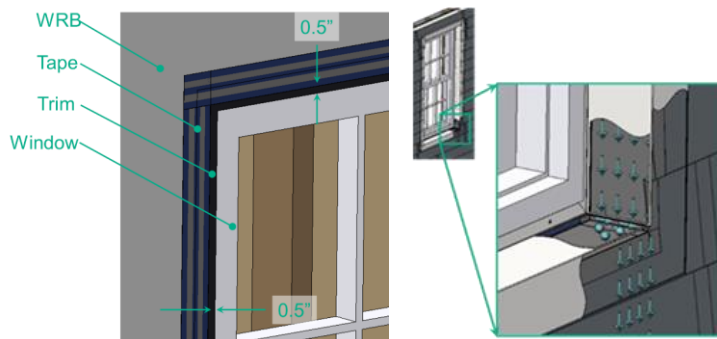


Figure 3. Taping around window trim (left) and at PB-window interface (right).

Existing Cladding: A standard PB deployment would leave the existing cladding in place, reducing the overall wall retrofit cost, unless it has damage that clearly needs to be remediated. The PBs install snug to the wall and can accommodate modest deviations in the wall surface from planar; indeed, gaps between the WRB and PBs facilitate water drainage.

Trim Design: Trim details have a major impact on the integrity and installed cost of the PB system, particularly around the often numerous and water-damage prone windows (a similar design is used around doors and other wall penetrations). We created two levels of trim, outer and inner trim. The outer trim is visible after assembly and must be: 1) visually appealing; 2) durable, weather and UV resistant; 3) hides the cut ends of the panel blocks; and 4) seals to the building to prevent water intrusion. In contrast, the inner trim fits right up against the PBs to seal the PB edges, primarily to prevent water intrusion but also to mitigate air leakage.

Inner Trim: After considering approximately a dozen different designs and ruling out most because of their complexity and cost (e.g., requiring a complex geometry cut into the PB edge), we identified straight cuts as a design requirement, but fastening to a straight cut poses a challenge. Ultimately, we chose butyl waterproofing tape as the inner trim material due to its low material cost and extensive use in construction; it also can adhere strongly to the cut edge of the foam when the cutting dust has been removed.⁸

Outer Trim: We considered about a dozen potential different designs of fenestration trim. The requirements were: 1) high aesthetic quality; 2) easy to install; 3) factory prefabricated; and 4) low cost. In particular, many designs were too complicated for semi-skilled workers to easily install in the field. We chose a Z-trim approach installed with color-matched screws.⁹ To reduce installation time, the window trim assemblies would be made in a factory and shipped to the site as a single four-sided piece.¹⁰

Starter Strip: This sheet aluminum element establishes the base level of the first PB course on each side of the home, engaging with and holding in place the bottom PB groove. It attaches and seals to the foundation at a vertical position determined by the lowest point on the first siding course.¹¹ The starter strip has integral weeps for water drainage and serves as a termite shield.

Corner Trim: The corner trim is supported by flexible clips that are installed on the building first. The corner trim has a u-shaped channel that engages with the legs of the clip. The corner trim has polyiso foam pre-installed to provide insulation at the corners. It also has flexible foam that acts as a spring to ensure the firm engagement of the trim and corner.

Façade Scanning

We use laser-scanning technology to accurately measure the dimensions of the opaque wall area that the PBs will clad. For the demonstration, an existing building scan provider scanned the mock-up wall with a Faro scanner at many locations to obtain accurate dimensions

⁸ Based on the time tape application took in the mockup wall demonstration, we will strongly consider alternate approaches that could reduce application time, such as fluid-applied sealants, as we refine the system.

⁹ The short screws simplify installation, enhancing cost effectiveness; that said, they lack aesthetic appeal, and we will likely explore a form of trim cover.

¹⁰ The Z-trim assembly is bonded in the corners, while the back surface of the trim has a compressible foam seal to keep water out of the joint between the outer trim and the old house trim.

¹¹ After marking a reference point relative to the first course of siding to locate the starter strip, the worker projects a level line on the building (laser level), transcribes the distance between the reference mark and level line to other key locations on the building, and snaps a line at the mark that guides the installation of the starter strip.

of critical features (see Figure 4). Since we did not find software to automatically convert the point cloud data directly into a BIM (Building information model), we reduced the point cloud data into groups of data we exported for spreadsheet analysis. We reduced the imported data groups to two dimensions (e.g., x-y, or y-z, depending on the feature being analyzed), and then fit the data with one (or more) linear curve fits to find “break points” defining key building features such as corner posts and edges of doors and windows (see Figure 5). The dimensions derived from the point-cloud data usually matched tape measurements to within $\pm 1/8$ ” (some cases closer to $\pm 1/16$ ”).



Figure 4. Point cloud scan of mock-up wall.

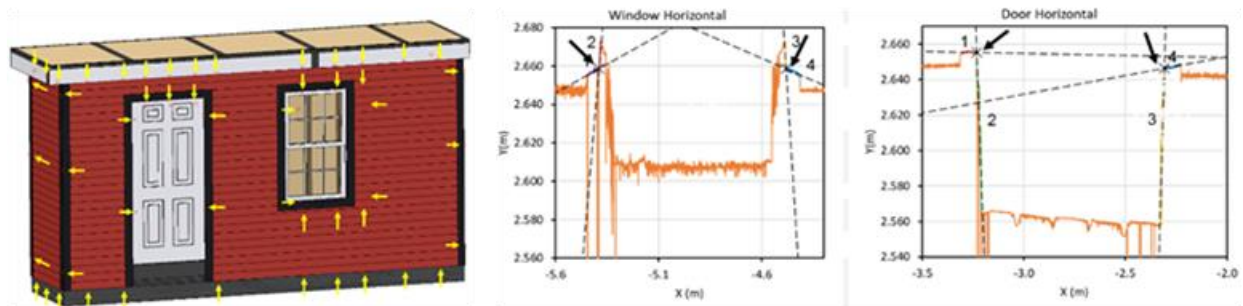


Figure 5. *Left:* Point cloud data turned into key building dimensions. Note the image is of the CAD model of the building and the points show the as-built; the window location was off by several inches.

Right: Curve fitting process to locate the corners of doors and windows.

One issue we discovered is that some fenestrations are “innies” and others are “outies.” For example, the door shown in right half of Figure 5 is an “innie” where the desired edge is a surface that slopes in toward the building. This difference reflects detail differences between the door and window and, more broadly, highlights the challenge of accurately obtaining building dimensions from scans.

With the data in hand, we determined how complex a model to create. Fortuitously, the mockup wall was out of square and level (as are many buildings) by as much as 1” and walls were moderately trapezoidal. To deal with these variances, we followed four basic principles when considering how to translate the wall CAD dimensions to block CAD dimensions: 1) the starter strip / first PB course should be level; 2) vertical edges must follow the building; 3) ignore small variations; and 4) use only PBs with square edges (no angled cuts).

Going forward, we expect this process to leverage ongoing advances in computing and data processing that will decrease cost while improving dimensional accuracy and edge feature recognition. In particular, smart phone-based processes are promising.

Façade Panelization

We created a process to determine the ideal set of PBs to clad the building. To prototype the system on the mock-up wall, we use an interactive approach for panelization. At scale, we expect this process to be largely automated, using optimization algorithms that take into account: PB size(s); number of PBs to install/installation time and cost; efficiency of foam utilization, edge length (potential leakage sites), and aesthetics (where PB transitions occur). After review and validation by a designer, it would generate CAD models for each PB and all trim pieces, as well as a bill of materials for each retrofit project and an installed cost estimate and price.

When performing this process manually, some rules became clear: 1) in locations where one PB can be used, e.g., between door and window, use one PB; 2) use full PBs above and below fenestrations; and 3) stagger PB joints so one is not directly above the other. With the basic layout created, we generated a list of cuts needed for a CAD model of each PB.

We then defined an installation order for the PB set and used that to assign each PB a unique identifier (see Figure 6). All of the lower blocks (A,B,G) that can be installed without a ladder (or other staging) were completed first before installing the higher blocks (C,D,E,F,H). Siding installers typically use “pump jack staging” that spans the complete length of a wall (or a significant portion of a wall) and can be raised and lowered with minimal effort. They will install several courses of siding across the complete wall then raise the pump jack staging up to continue. The installation scheme of the PBs follows the same workflow.

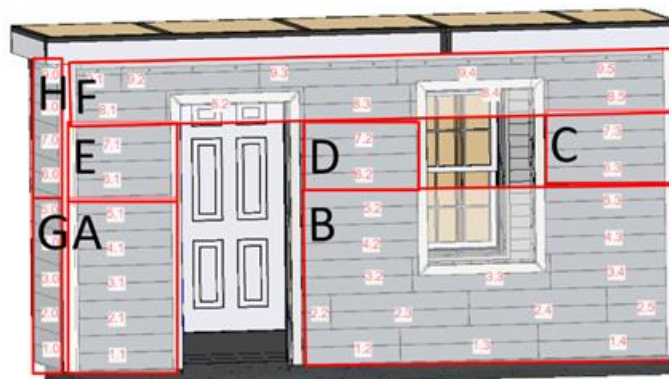


Figure 6. PB installation order for the mock-up wall demonstration.

CNC Machining

We developed a conceptual design of a process that enables affordable fabrication of standard and custom PBs at commercial scale; it is described in the Cost Modeling section. In contrast, we manually produced the full set of PBs for the mock-up wall demonstration (see Prototype Testing and Results).

Augmented-Reality (AR) assisted Installation

We developed and implemented an augmented reality (AR) experience in PTC's Vuforia Studio environment that guides workers through the PB installation process. Installers work in pairs, one who wears AR headset to retrieve and place PBs (see Figure 7), the other who then screws PBs into place using a power drill and 4-inch screws. Based on a voice request from a worker wearing a Microsoft Hololens, the AR experience projects a 3D hologram of the next PB (or trim piece) to install in the worker's field of view of the shipping pallet and, upon receiving a second voice command, projects where to install it on the façade (see Figure 8).



Figure 7. Worker using the Microsoft Hololens headset to install insulated panel blocks.

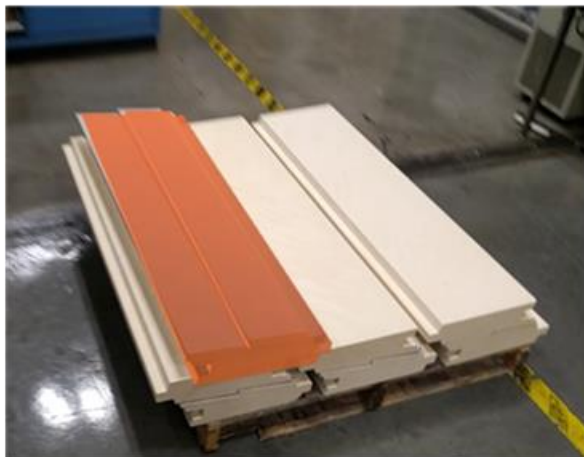


Figure 8. AR highlights for the worker the next PB to install (left) and, when prompted, shows where to install it (right; note that the PB highlighted on pallet differs from that projected on the wall).

Based on initial testing, we incorporated several features into the experience. Notably, we added “hide” and “show” voice commands to the experience to “hide” and “show” the virtual PBs. In the final experience, we may use proximity information to determine PB opaqueness, i.e., as the installer gets closer to the façade, the virtual PB should become more transparent/disappear. This is not possible with the current development environment.

We also identified future improvements. Currently, the AR is limited to coarse PB location and identification/verification (via barcode) tasks; it cannot be used to precisely align PBs (i.e., placing virtual objects within a couple mm of their true location without shifting as the

user changes perspective). We would develop a modified registration approach using multiple reference points to determine a “best fit” approach between the virtual and physical worlds. In addition, the AR experience relies on voice commands to proceed to the next step (“next”), go to the previous step (“back”), and to “hide” and “show” the PBs. We found that background noise could interfere with voice commands, requiring the operator to repeat them. For a commercial system, we would explore different input mechanisms, e.g., a physical input device the installer wears, a better microphone arrangement to better pick up installers’ commands, and/or virtual buttons visible in the operators’ field of view (these controls, as implemented in the development environment, were somewhat distracting and somewhat difficult to control during testing).

Cost Modeling

The commercial potential of the PB system is predicated on achieving high production volumes; hence, our costing analysis assumes high-volume PB fabrication, allowing us to achieve similar price efficiencies to commodity products. Prices will be higher in early product implementation before volume efficiencies and supplier competition benefits are realized.

We estimated the cost of standard materials (vinyl cladding, WRB, screws, etc.) based on prices from home centers; this likely yields higher prices than volume purchasing. To estimate the cost of non-standard materials, e.g., vinyl trim pieces, we examined similar commodity products and computed their unit price in terms of \$/weight and adjusted them to the weight or volume of the non-standard parts. Given its importance, we analyzed the foam separately.

Installation labor also accounts for a significant portion of cost. Our model assumes installation with a two-person crew at \$50/hour/person labor (fully burdened).¹² We estimated installation time based on the mockup wall installation, normalized per ft² of opaque wall area,¹³ with an adjustment factor applied on some operations to account for the 26% Window-to-Wall Ratio (WWR) of the mockup wall (versus 14% for a typical home).

The total cost for materials plus installation labor equals \$5.94/ft² (see Figure 9), with the foam (\$2.20), installation labor (\$1.50), vinyl (\$0.95), and window trim (\$0.48) accounting for ~85% of the cost. These costs reflect information available in Q3 in 2021, i.e., they do not reflect cost increases that have occurred since then.

¹² Based on discussions with a contractor and on-line sources.

¹³ We expect to achieve significant reductions in installation time from process refinements and installer experience; that said, we do not change the time to reflect additional time needed for site set-up and break-down, breaks, etc.

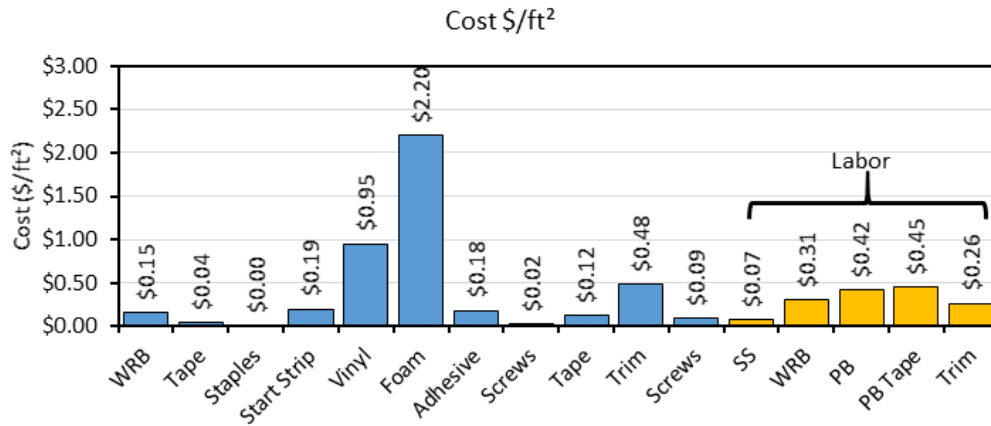


Figure 9. Component and Installation Cost

Foam procurement/manufacturing

We considered several ways to procure and/or manufacture the basic PB foam profile:

- Procure commodity sheet product. 4" polyiso is a commodity good for the commercial construction industry.
- Procure cured slabstock direct from producer. In high volume, foam is typically produced as a continuous extrusion with a profile up to 2m x 1.2m (width x height).
- Manufacture and cure slabstock in house.
- Mold and cure individual profiles in house. Mold individual near net shape profiles that are 12-24' in length possibly with the cladding on them.
- Extrude individual profiles in house. Extrude a continuous near net shape in a continuous injection molding process possibly with integral cladding on it.

Each approach has unique benefits and challenges; Table 1 highlights the differences.

Table 1: Pros and cons of potential methods for procuring foam for the insulated PBs

	Method	Pros	Cons
A	Procure sheet product	– Commercially available produced in volume – No curing warehouse – No capital expense to produce foam	– Less material efficient (cut from sheets) – Likely length limited to 8' – Intermediate shipping costs
B	Procure slabstock	– Long lengths possible – No curing warehouse – No capital expense to produce foam	– Less material efficient - Must work within manufactures profile – Intermediate shipping costs
C	Manufacture slabstock	– Long lengths possible – Can define profile for maximum raw material utilization – Once running less labor intensive	– Requires operating chemical plant – Requires a large (5+ days) climate controlled warehouse for FIFO curing

	Method	Pros	Cons
D	Mold individual profiles	– Potentially more material efficient – Likely more cost effective in very high volumes – Can mold w/ cladding in place	– Same as C – Less efficient (non-continuous process) – Relatively labor intensive
E	Extrude individual profiles	– Same as D – More efficient than D, as it is a continuous process – Once running less labor intensive	– Same as C

Buying cured foam from a commercial producer (A and B) represents a significant advantage during initial commercialization since the raw material purchased from a supplier can be used immediately. It eliminates the capital costs of building and commissioning a foam manufacturing and curing facility. After initial commercialization, the business could transition to in-house foam manufacturing and curing once the volumes warrant.

The costs of the paths range from \$1.55 (long-term contract with large producer) to \$2.95/ft² (purchasing slabstock) to procure cured foam, with an average cost of \$2.20/ft².

Panel Block Manufacturing

After the cured foam arrives at the PB manufacturing plant, it is custom-cut to produce the panel blocks required for a particular job. We envision a highly automated factory driven by a digital workflow to accomplish this. The digital workflow will determine the installation order and manufacturing order, where the manufacturing order will reflect the most material-efficient process to minimize waste. The general process flow is:

1. Receive cured foam and transport to a small first-in/first-out (FIFO) warehouse
2. Cut raw foam to required preform dimensions.
3. Finish top, bottom, and front: Mill with a multi-axis planer
4. Cut to length: Horizontal wire saw to finish the Left and Right, including any tongue and grooves
5. Clean and ID
 - a. Remove dust from the cutting process (for adhesion to the cladding substrate)
 - b. Barcodes inkjet printed on the top, bottom, and back to facilitate ID in the field
6. Cladding Assembled: Cladding is cut to length and glued to the foam panel block
7. Cut notches and cutouts: Vertical wire saw to finish any required corner notches, middle cutouts, height reduction
8. Kit panel blocks for shipping
 - a. Blocks produced out of order will be set aside and inserted when required
 - b. Finished pallets will be wrapped and stored for shipment

To estimate the fabrication cost, we conceptualized a prototypical 50,000 ft² factory that can manufacture 2,000 ft² of PBs per hour, enough to clad about 5,000 homes per year when operating three shifts per day / five days per week / 50 weeks per year (employing around 75 people full-time). The input and finished goods warehouse can house about four days of production.

Investment Analysis

We conducted an investment analysis for the prototypical factory (Figure 10) assuming:

- \$10M initial investment including \$5M in hardware and fit-out to commission the customization factory
- The factory reaches full capacity after three years
- Factory costs
 - \$4.5M Labor cost per year for the factory (fully loaded labor rate = \$30/hour)
 - \$340K Rent and utilities
 - \$200K maintenance
 - \$1M overhaul every 5 years
- \$5.94 per square foot materials plus installation labor cost
 - \$1.50 - Installation labor cost (\$3,000 for the average home)
 - \$2.20 - Foam
 - \$0.95 - Vinyl
 - \$1.28 - All other materials (WRB, trim, tape, starter strip, screws, etc.)
- Net present Value (NPV) assumes a 10% annual rate of return

Our analysis shows profitability at an installed cost (sales price) just below \$7.00/ft² and a three-year payback at <\$8.00/ft². This is similar to current costs to install *uninsulated* vinyl siding (\$7.58/ft²) and appreciably less than installing metal siding panels (PNNL 2022).

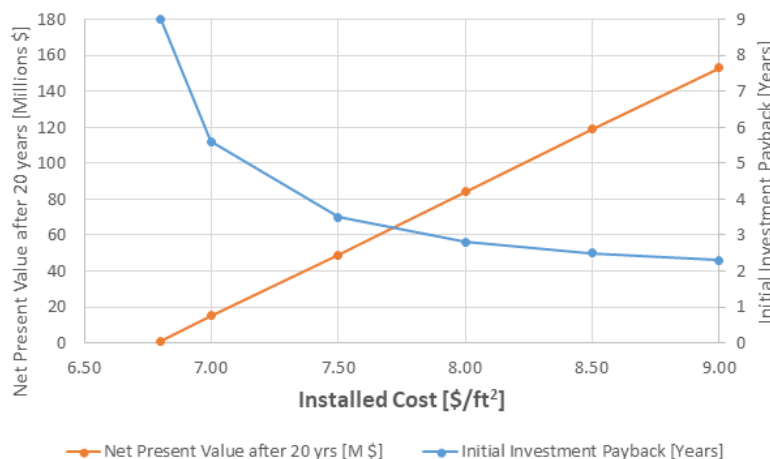


Figure 10: NPV and initial investment payback as a function of installed cost/price.

Prototype Testing and Results

To demonstrate the viability of the PB system and identify ways it could be refined, we applied the complete PB system process to a ~10-foot-high by ~20-foot-long (including a 4-foot return wall) mockup structure including several features that complicate wall retrofits, i.e., a door, window, soffit, outside corner, clapboard cladding, and foundation (see Figure 11). The walls were built 1950's style with 1"x6" sheathing boards rather than modern plywood and covered with tar paper rather than modern WRB, making the walls somewhat leaky. We

thoroughly sealed off the other two walls as well as the floor, ceiling, door and window to prevent them from having an impact on the leakage measurements.

We generated CAD models for all PBs and trim used to clad the building based on the façade scanning and panelization processes described earlier. We then used the PB CAD model designs to manually fabricate all 44 PBs as follows:

- 1) A foam manufacturer produced the foam blocks using abrasive wire 3D CNC technology, making two passes: one for the top/bottom profile and a second for the left/right profile.
- 2) Vinyl cladding came from a clapboard-profiled vinyl siding product backed with insulation, where we cut off the interlock feature on its top edge.
- 3) We removed the existing EPS insulation using a knife and an adhesive tool.
- 4) We glued the cladding to the PBs using a caulking gun and foam adhesive and compressed the blocks with 160 pounds of weight for 24 hours while the glue dried.

Two workers, one wearing the Hololens, installed the WRB, the complete set of 44 PBs fabricated, taped all PB edges, and installed all trim pieces in just under 3.5 hours on our first attempt, achieving our goal of ≤ 4 hours.



Figure 11. Sequence of steps for installing the panel-block system on the mock-up wall from left to right: 1) Pre-retrofit; 2) WRB installed and taped; 3) PBs installed and joints taped; and 4) Trim pieces installed.

The prefabricated PBs and trim pieces achieved a good fit with the wall, with no sizeable gaps observed. Based on the mock-up wall install, we estimated the installation time for a single-family home by normalizing the time per ft² of wall area,¹⁴ with an adjustment factor applied for some operations.¹⁵ This yielded a project installation time of 30 hours (almost four days) for a two-person crew. Our time-and-motion study of the installation found that the AR-assisted installation of the actual PBs took about 50 minutes, as did installing the trim pieces. The taping step took appreciably longer, about 70 minutes; we see clear opportunities to reduce this time, e.g., using liquid-applied sealants. WRB installation accounted for the rest of the time.

We also measured air leakage using a TEC duct blaster fan with either ring 3 or ring 4 installed with the fan connected to a DG1000 meter, following ASTM E779, “Standard Test Method for Determining Air Leakage Rate by Fan Pressurization,” adapted for the mock-up wall. We normalized the data in two ways. First, we had previously measured a baseline air leakage by covering the front and side walls in plastic sheeting and carefully sealing the edges. We subtracted this baseline from the CFM50 measured during the retrofit process. Secondly, we

¹⁴ We expect to achieve significant reductions in installation time from process refinements and installer experience. That said, we did not change the time to reflect additional time for site set-up and break-down, breaks, etc.

¹⁵ The mockup wall has a 26% Window-to-Wall Ratio (WWR) versus 14% for a typical home.

normalized the leakage per ft² of opaque wall surface, we found that the WRB reduced air leakage from 0.34 to 0.08 CFM50 per ft² of unsealed opaque wall area, and the addition of the PBs further reduced air leakage to 0.06 (we did not perform testing to determine how applying the PBs without the WRB reduced air leakage, because the WRB is a key element of the water management system, so that configuration is not likely to be used.).

Conclusions and Future Paths

We designed and prototyped a highly digitalized wall deep-energy retrofit system and process that adds ~R-24 of continuous exterior insulation with integral cladding. The lightweight PBs (<5 pounds) proved very easy to handle and eliminated the complexity and cost associated with craning larger panels or sophisticated staging. The PBs are integrated into highly digitalized design and deployment processes that uses emerging scan-to-BIM and wall panelization technologies to determine the ideal PB and trim set to clad each home. This enables mass production of custom PB sets (not yet demonstrated) to eliminate on-site cutting, waste, and greatly simplify installation. In short, we replaced the extensive worksite cutting that makes current weather-dependent wall DERs unaffordable with reliable and accurate CAM cutting in a factory. Finally, we prototyped and demonstrated an AR experience integrated with the panelization process that empowers semi-skilled workers by guiding them through the installation process. In a demonstration, two workers installed the WRB, 44 PBs, and the full trim set on a mock-up wall in 3.5 hours, which translates to about 31 hours for a 2,000 ft² home. Cost, manufacturing and installation models suggest profitability at <\$7.00/ft² sales price based on a single factory producing PBs for retrofitting ~5,000 homes/year, with the potential for lower costs at higher volumes.

Extensive work remains to move the system closer to commercialization. We plan to continue to refine the PB and trim designs, particularly to address a wider range of wall penetrations and features, while conducting water intrusion and wind testing to assure the system's environmental integrity. We also will pursue several key process refinements including:

- *Scan-to-BIM*: Testing and refining processes and algorithms on full-size homes under a range of outdoor conditions.
- *Panelization*: Largely automating this process, i.e., designer primarily reviews outputs.
- *CAM*: Working with manufacturers on manufacturing integration
- *AR Experience*: Extending it to work with multiple concurrent users, on all sides of homes (multiple anchors), and expanding AR QC functions to address other problematic areas (e.g., sealing around windows).

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