Fraunhofer USA Center for Manufacturing Innovation CMI

Phase I Technical Report:

Mass Customization of Prefabricated Panel Blocks for Deep Wall Insulation Retrofits

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Project Overview

Our Phase 1 Project sought to develop an exterior wall-insulation retrofit system that delivers superior thermal, hygrothermal and water management performance customized to the unique geometries of each home. To achieve that, it re-engineers and digitizes the entire façade retrofit process by applying 1) high-resolution facade imaging/scanning; 2) automated generation of retrofit façade and component design; 3) computer numerically controlled (CNC) machining of façade panels; and 4) AR-assist installation technologies to create an integrated process to generate low-cost and quick-install wall retrofit package that achieve:

1. Post-retrofit R-30 to 40 and ≤0.28 cfm/ft^2 (@75Pa) wall; [1]
2. Installation on a single-family home in ≤5 days by two semi-skilled workers, and
3. Installed Cost of <\$6.00/ft^2 of wall area (at volume production).

We conclude that we have met all three objectives, and review each separately.

Objective 1: Post-retrofit R-30 to 40 and ≤0.28 cfm/ft2 (@75Pa) wall
As shown in Figure 1, the insulated panel-block (PB) retrofit system comprises a weather-resistive barrier (WRB) and ~4-inch thick polyisocyanurate insulation installed directly over the existing cladding.[2] Thus, it nominally adds ~R-26 to the existing wall. Under contract to PNNL, the U. Minnesota conducted field testing of the PB system at its Cloquet, MN test facility in both north- and south-facing test bays (see Figure 1) from December 2020 through April 2021. Based on field temperature and heat-flux measurement and THERM modeling, a DOE analysis concluded that the PB system *with an uninsulated cavity* achieved a whole-wall R-value of R-27.6.[3] Adding dense-pack cellulose cavity insulation, a staple energy conservation measure (ECM) in utility energy efficiency (EE) programs, increases the base wall R-value from ~R-4 to R-11[4]. Thus, the PB system yields whole-wall R-values of around R-34 to 38. In addition, we performed blower-door testing of the PB system with different components on the wall (see Figure 5). We found that the combination of the WRB and the PBs reduced the wall air leakage from 0.34 to 0.06 CFM50/ft^2. *We achieved this objective.*


Figure 1: PB Field Testing at Cloquet Outdoor Test Facility

Objective 2: Installation on a single-family home in ≤5 days by two semi-skilled workers: We installed the complete PB system on a ~10’ high by ~20’ long mock-up wall; Figure 2 shows the different stages of the installation. Two staff members completed the full AR-assisted installation in just under 3.5 hours, with the taping of the PB edges taking the most time (see Figure 3). We estimated single-family home installation time from the installation of the system on the mockup wall and normalized per ft^2 of wall area,[5] with an adjustment factor applied for some operations to account for the mockup wall having a 26% Window-to-Wall Ratio (WWR)

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[1] Note that 50 Pa is typical for testing residential air leakage, and we pressurized to 50Pa during tests.

[2] If the underlying sheathing has appreciable damage or deterioration, it should be removed and remedied.

[3] PNNL. 2021. “Wall Upgrades for Energy Retrofits: A Techno-Economic Study.” Draft Final Report by Pacific Northwest National Laboratory. PNNL-28690.

[4] PNNL (2021) estimates a whole-wall R-value of R-14 for dense-pack cellulose, which is higher than values typically used in utility energy efficiency programs (e.g., ~R-11), relative to an uninsulated wall R-value of ~R-4.

[5] 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.

versus 14% for a typical home. *This yields a project installation time of 30 hours (almost four days) for a two-person crew, meeting this objective.*

Figure 2: Complete installation of the PB system on the mock-up wall.

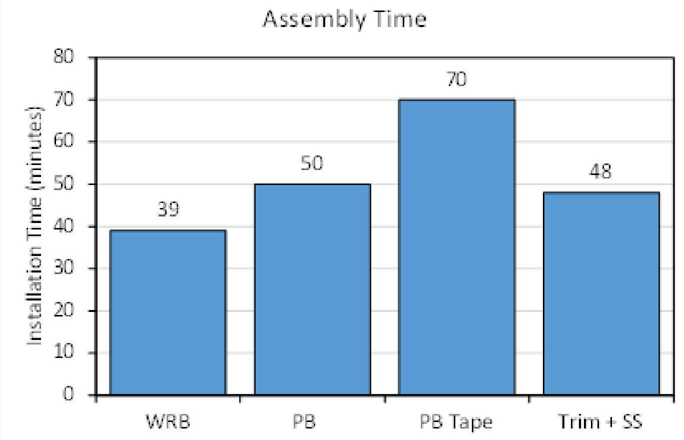

Figure 3: Assembly time breakdown by task for the installation of the PB system on the mock-up wall (total time ~3.5 hours).(SS=start strip)

Objective 3: Installed Cost of <\$6.00/ft^2 of wall area (at volume production): As described in the “Cost Modeling and Analysis” section, we developed a cost model for all material and labor components of the PB retrofit system. Our costing analysis assumes fabrication of the panel blocks in large volumes, allowing us to achieve similar price efficiencies to commodity products. At those volumes, we estimate an installed cost of \$5.94/ft^2. At more modest volumes, e.g., a dedicated factory producing PBs to clad approximately 5,000 homes/year, an investment analysis with a 10% IRR finds profitable, integrated business at ~\$7.00/ft^2 (see Figure 19). Although higher than the original \$6/ft^2 cost target, it is similar to installed costs for *uninsulated* vinyl siding and appreciably less than that for a metal siding panel.[6] *We have met this objective.*

Phase 1 progress by task and high-level Phase 1 results

Task 1 Refine Panel Block (PB) Design: In Phase 1, we successfully adapted the original PB design 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) ease of installation with semi-skilled labor; and, not least, 6) material and installed cost. Key features defined included:

- A standard PB size, approximately 12”Hx48”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, shipping, and manufacturing.
- Tongue/groove design creating a tortuous path to reduce air leakage and water intrusion and guide PB installation.
- Quick-install starter strip design for bottom edge of PBs: supports installation of PBs; insect protection, and drains water that may get behind PBs (through weeps).

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[6] PNNL (2021) reports that *uninsulated* vinyl siding has an installed cost of ~\$7.58/ft^2 of opaque wall area.

- Integral vinyl cladding glued to the PB surface as the cladding material and defining a viable manufacturing process at scale.
- 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.

Milestone: Delivered PB CAD drawings for design features and full PB set for demonstration installation on mock-up wall.

Task 2– Generate PB CAD Models: A façade-scanning contractor generated a point-cloud of our ~10'H x~20'W mockup wall. We successfully applied algorithms to convert the point cloud into key building dimensions (façade width and height, façade penetration dimensions), generating a wall CAD drawing. We then used a manual process to determine the full set of 44 PBs, including each PB's geometry and features, to clad the mockup wall.

Milestone: Delivered images of complete set of dimensioned PB CAD files to DOE.

Task 3 – Fabricate PB and Hardware for Demonstration on Mockup Wall: We used the PB CAD model designs (Task 2) to manually fabricate all 44 PBs. The production process included:

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) Removed the existing EPS insulation using a knife and an adhesive tool.
4) 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.

Milestone: We fabricated the full PB set and procured all trim and hardware required for the demonstration installation on the mock-up wall.

We also completed a conceptual design of a highly automated PB fabrication process; see the "Cost Modeling and Analysis" section for details.

Milestone: Delivered conceptual manufacturing process design for automated PB fabrication.

Figure 4: Worker using the Microsoft Hololens headset to install insulated panel blocks.

Task 4 – Develop and Implement Basic AR Installation Experience: We developed and implemented an augmented reality (AR) experience in project partner PTC's Vuforia Studio environment. Based on a voice request from a worker wearing a Microsoft Hololens 2 (see Figure 4), the AR experience projects a 3D hologram of the next PB (or trim piece) to install on the worker's field of view which appears as a highlight of the proper PB on the shipping pallet. Upon receiving a second voice command, projects a hologram where to install it on the façade. Thus, the AR experience empowers workers, reduces installation time and ensures installation accuracy. We used the AR experience to guide the installation of all 44 PBs and all trim pieces on the mock-up wall.

Milestone: AR development environment selected.

Milestone: AR experience implemented and demonstrated to DOE (on quarterly webinar).

Task 5 – Demonstrate Process on Mockup Wall: We constructed a ~10’H×20’W mockup wall comprising several real-world features that complicate deep wall retrofits, including a door, window, soffit, outside corner, clapboard cladding, and foundation. 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. Our time-and-motion study (see Figure 3) revealed several opportunities to streamline the installation process.

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 CFM_{50} measured during the retrofit process. Secondly, we normalized the leakage per ft^2 of opaque wall surface, yielding the results shown in Figure 5.

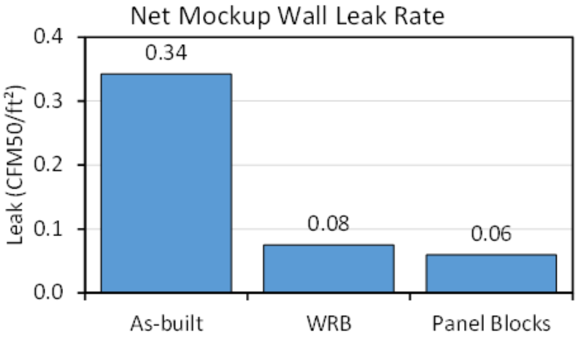

Figure 5: Blower door air leakage rates for the mock-up wall as-built, with WRB applied, and with PBs installed.

Milestone: All PBs installed on the mockup wall with a panel-to-panel gap <¼” in ≤4 hours.

Milestone: Tested air tightness ≤0.28 CFM/ft^2 of wall area @50 Pa per ASTM 779.

Task 6 - Update Cost Model: We developed an updated model for the installed cost of the PB system at volume; the “Cost Modeling and Analysis” section presents this in further detail. The model found, at larger volumes yielding commodity costs, a total cost for materials plus installation labor of \$5.94 / ft^2 of opaque wall area. The foam (\$2.20), installation labor (\$1.50), vinyl (\$0.95), and window trim (\$0.48) accounted for about 85% of the total cost. At more modest annual production volumes, e.g., enough to clad ~5,000 homes, an integrated business would be profitable at a sales price of just under \$7.00/ft^2, a cost similar to current costs to install uninsulated vinyl siding (PNNL 2021).

Milestone: Updated cost model completed, shows viable pathway to ≤\$6.00/ft^2.

Task 7 – Advanced Building Construction (ABC) Collaboration:
We participated in the ABC Consortium, fulfilling the milestones listed below.

Milestone
M7.1: Presented project overview, networked with other attendees
M7.2: Participate in BTO’s 2021 Peer Review
M7.3: Coordinated with the ABC Collaborative on identifying the elements of a whole-building solution along with demonstration sites.
M7.4: Present project progress at quarterly ABC meetings; presented “Using Augmented Reality (A/R) to Facilitate Installation of Prefabricated Panel Blocks for Deep Wall Insulation Retrofits” at DOE BTO ABC Initiative Retrofit Workshop Series: Installation, (February 2021), participated in other Workshops in the series.
M7.5: Attended the 2021 Annual ABC Collaborative Summit.
M7.6: Responded to requests from PNNL: 1) testing results; 2) ABC Technology Scaling Framework; and 3) Customer discover (i.e., identify target customers and why will they buy our innovation).

Energy Savings Potential

PNNL (2021) modeled the energy savings for our PB system applied to the walls of a DOE prototypical single-family home in different climates. For homes lacking wall insulation, the PB system reduced whole-home space conditioning energy consumption by 34% (mixed humid) to 38% (very cold) in the target climate zone.[7] For a home with dense pack cellulose already in the wall cavity, reductions ranged from 16% (mixed-humid) to 21% (cold).

We applied the RECS 2015 Pivot Table provided by DOE-BTO with the ABC FOA to estimate the national energy savings potential. Assuming that 1/3 of homes have no wall insulation and 2/3 have dense-pack cellulose cavity insulation and applying these values to 1- to 4-family homes built before 2000 in mixed, cold, and very cold climates yields a national **technical site energy savings potential of 750 TBtu** (see Table 1).[8]

Table 1: Energy savings potential of the insulation PB system.

Climate Zones	# Buildings (millions)	Floorspace (million ft^2)	Site HVAC Energy (TBtu)	Site Energy (%)	Site Energy (TBtu)
Cold, Very Cold	25.9	70,658	1,897	27%	506
Mixed	19.2	48,224	1,079	25%	245
TOTAL	45.1	118,882	2,976	28%	751

Technical/Engineering Design

Summary: We have developed and demonstrated an integrated process that reduces the installed cost and installation time for deep exterior wall retrofits. The basic building blocks are lightweight (<5 pounds) ~1'H×4'W×4" thick insulated panel blocks made of polyisocyanurate. They are prefabricated offsite with integrated vinyl siding (see Figure 6). DOE-BTO-funded field testing and analysis shows this creates a hygrothermally sound wall that adds ~R-24 to existing walls, achieving whole-wall R-values R-28 and R-38 (for walls without and with existing cavity insulation PNNL 2021).

The integrated design, manufacturing, and delivery process comprises the following steps:

1. Laser scanning to generate a 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. 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)
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.

The following subsections describe each component of the process in further detail

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[7] 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 AHC_{50} to 10. Savings were greater in very cold climates, 38%.

[8] We expect that the "Cold" climate zone results apply to most of the Cold-Very Cold stock in the Pivot Table. Although the Pivot Table did not break down energy consumption between the Mixed, Dry and Mixed, Humid climate zones, their modeled energy savings differ minimally.

Insulated Panel Blocks: Figure 6 shows an image of a PB. Each PB incorporates several design features that reflect tradeoffs among several factors: material cost and use efficiency; ease of manufacture for mass customization; ease of handling and shipping; ease of installation; cost (material efficiency); aesthetics/market appeal; and preventing water intrusion and air sealing.

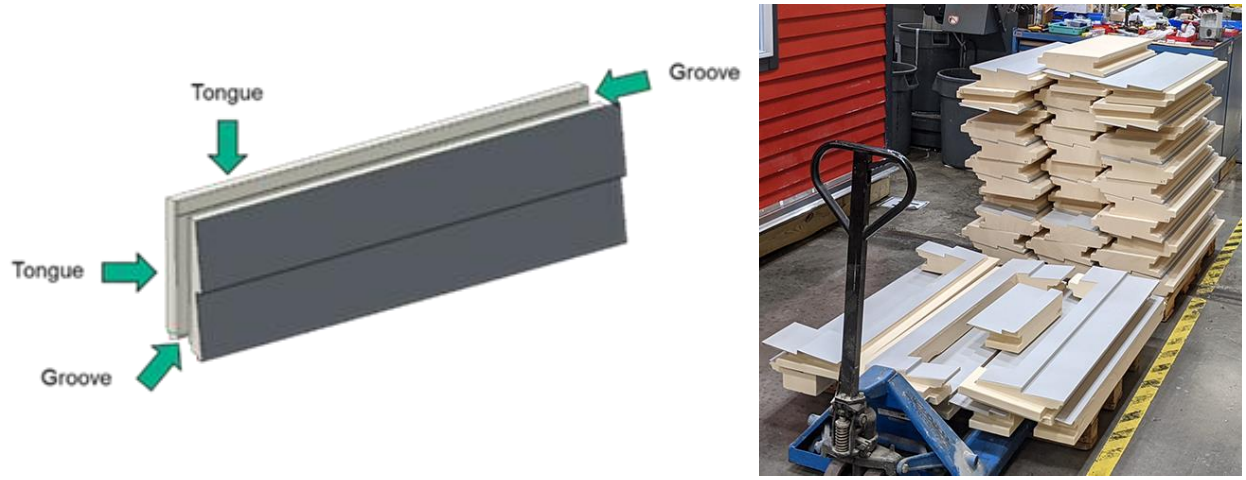

Figure 6: Left – Panel block (PB) design, Right – Pallets with panel blocks ready for installation on mockup wall.

- Seals: Labyrinth seals using a tongue and groove system on the top, bottom, right and left edges abutting another PB; we use a simple straight end cut for PB edges abutting a wall penetration or corner.[9] The tortuous path minimizes water intrusion and air leakage and guides installation of adjacent PBs.
- Fasteners: Four-inch screws with washers fasten the top PB edge to the existing façade, with the screws driven to the point where the PB is snug, but not necessarily flush, with the existing cladding (preventing over-tightening or bending in non-planar façades). The PB above hides the screws and the horizontal PB joints.

Figure 7: PB overlap.

Integral Vinyl Siding Cladding: Prior deep wall retrofits required extensive on-site finish work,[10] so our design integrates COTS clapboard-style vinyl siding offsite to minimize onsite work, in this case CertainTeed Cedarboards.[11] The cladding of one PB overlaps the cladding of adjacent PBs to minimize water intrusion and improve aesthetics (see Figure 7). 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.

- Terminations and Openings: The full PBs are approximately 4' long by 1' high, and are cut to accommodate terminations and openings, e.g., corner of a wall, window, door, etc. (see range of shapes shown in Figure 8). We used several "standard" PB modifications (Figure 8) to fabricate the PBs

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[9] We considered several potential forms for the PB end cut before deciding on a simple straight cut. Although there are benefits to having a tongue, groove, or shiplap cut to the modified block edges, we decided not to for two reasons: 1) Ease of manufacturing (much more difficult to cut a tongue or groove feature into a block, particular in corners (requires using a rotary cutter); 2) need to mate those features a matching feature on the trim piece, making the trim pieces and their installation more complicated.

[10] Building Science Corporation (BSC). 2013. "Mass Save Deep energy retrofit builder Guide."

[11] Our design uses "Double 6" or D6 which is a panel with two 6" reveals simulating clapboard.

cladding the mock-up wall; ultimately, these will be produced using automated CNC equipment, such as an abrasive wire cutter.

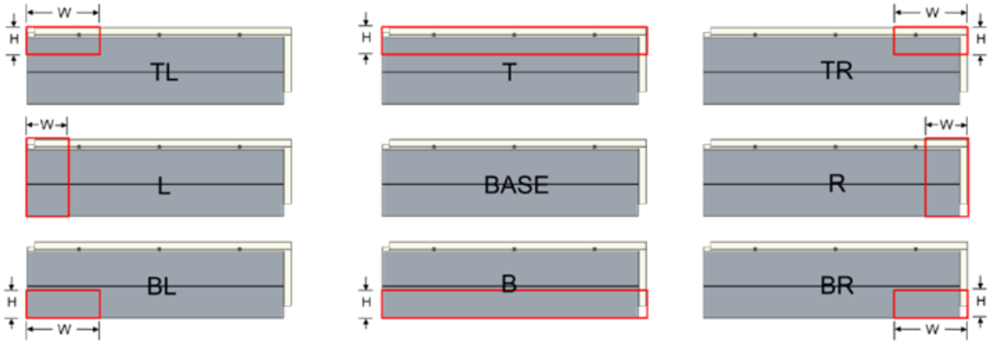

Figure 8: Different PB modifications and cuts to create custom PB shapes.

- Standard Panel-Block Dimensions: We analyzed the pros and cons of different standard PB sizes, ranging from 12"x12" to 48"x96" (see Table 2). Ultimately deciding to keep the 12"x48" size in Phase 1; in Phase 2, we may pursue multiple standard sizes.

Table 2: Pros and cons of larger and smaller PB sizes

Attribute	Larger PB	Smaller PB
Number of Custom Panel Blocks	Higher	Lower
On-site Labor Cost	Lower	Higher
Air Leakage	Lower	Higher
Aesthetics	Fewer vertical joints visible	More vertical joints visible
Shipping Cost	Higher	Lower
Ease of Installation	Lower	Higher
Weight	Higher (48"x48" still <20 pounds)	Lower

Weather Resistant Barrier (WRB): The design incorporates a WRB over the existing cladding to create a drainage plane for any water that gets behind the PBs and reduce air leakage. Workers install the WRB prior to the PBs, and seal the WRB back to the house.[12] We decided to cut the WRB 1.5" short around fenestrations and tape to the trim around the fenestration (see Figure 9).

Existing Cladding: We decided that a standard PB deployment would leave the existing cladding in place, unless it has damage that clearly needs to be remediated, reducing the wall retrofit cost. The PBs install snug but not flush to the wall to 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 (we use a similar design around doors and other wall penetrations). We created two levels of trim, 1) the outer trim, and 2) the 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 seals the PB edges to prevent water intrusion.

Inner Trim: After considering approximately a dozen different designs and ruling out most because of their complexity and cost (e.g., requiring complex geometry cut into the PB edge), we identified straight cuts as a design requirement, but fastening to a straight cut poses a challenge.

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[12] Traditionally it would be taped back to the framing or sheathing, but that is not possible with a retrofit.

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.[13]

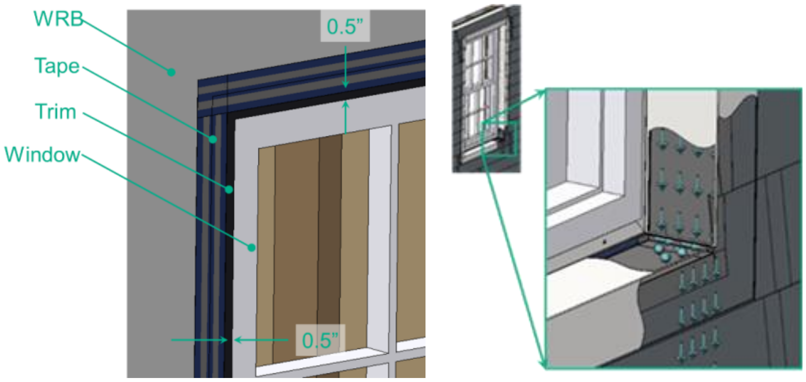

Figure 9: Taping around window trim (left) and at PB-window interface (right)

Outer Trim: We also examined about a dozen potential different designs of fenestration trim. The requirements were: 1) High aesthetic quality; 2) Easy to install; 3) Prefabricated in the factory; 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,[14] as shown in cross section in Figure 10. The window trim assemblies would be made in a factory and shipped to the site as a single piece.[15]

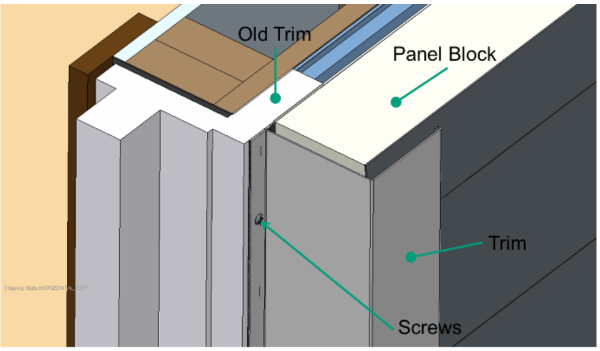

Figure 10: Cross section of Z-trim in window application.

Starter Strip: This extruded 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 to the foundation at a vertical position determined by the lowest point on the first siding course.[16] The starter strip has integral weeps for water drainage and serves as a termite shield (see Figure 11).

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

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[13] Based on the time tape application took in the mockup wall demonstration, we will strongly consider alternate approaches in Phase 2 with the potential to reduce application time, such as fluid-applied sealants.

[14] The short screws simplify installation, enhancing cost effectiveness; that said, they do not have the highest aesthetic appeal, and we will likely design some form of trim cover in Phase 2.

[15] The Z-trim assembly will be bonded in the corners with small pieces of vinyl and adhesive. 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.

[16] 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.

trim has polyiso foam installed to provide insulation. It also has flexible foam that helps ensure the firm engagement of the trim and corner (see Figure 11).

Figure 11: Left: Starter strip design. Center and Right: Corner and corner trim pieces.

Additional Wall Penetrations: Real homes have additional wall penetrations that were not considered in Phase 1 and were not in the mockup wall, including electrical outlets, water spigots, electric lights, vents, and utility meters that need attention during the DER. While we have not yet completed designs for these features, conceptually they can be split into two categories: 1) leave in place, side around, and 2) bump out and side under.

Features like electric light will likely need to be bumped out to the new finished surface. Special "work boxes" will be developed that allows for waterproof electric connections to be made inside as well as supplying a place for mechanical support of the light. The PBs will have a hole cut in them to accommodate the work boxes. Other features like spigots might be better suited to be left in place and creating an opening in the siding large enough that they are still operational. We plan to refine and finalize these approaches further in Phase 2.

Laser Scanning and Panelization

Figure 12: Point cloud of Mockup Wall

We use laser-scanning technology to accurately measure the dimensions of the opaque wall area that the PBs will clad. In Phase 1, an existing building scan provider, Deep Design Studios, scanned the mock-up wall with a Faro scanner at many locations to obtain accurate dimensions of critical features (see Figure 12). 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 dimension (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 13). The dimensions derived from the point-cloud data generally matched tape measurements to within ± 1/16" (some cases closer to ± 1/8").

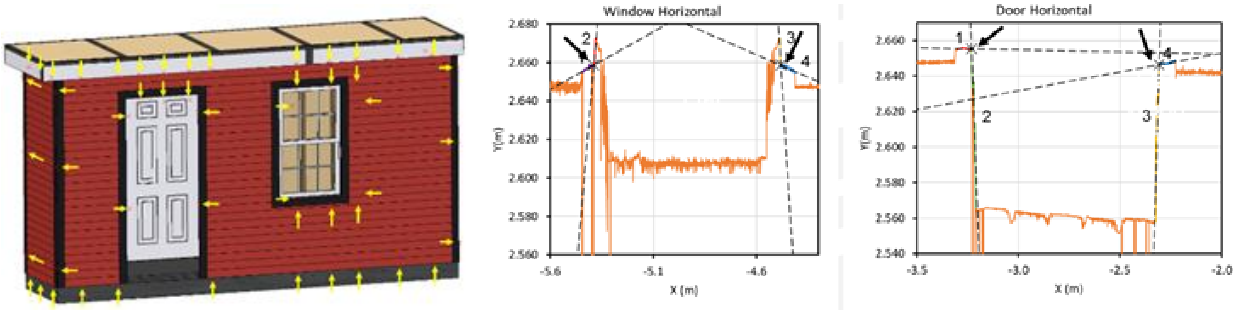

Figure 13: Left: Point cloud data turned into key building dimensions. Note the image is of the CAD model of the building and the points show the as-built; note that the window location was off by several inches. Right: Curve fitting process to locate the corners of doors and windows.

One issue we discovered is that some fenestrations are "innies" and others are "outies." For example, the door shown in right half of Figure 13 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 shows some of the challenges identifying the right surface for a BIM.

With the data in hand, we next decided 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 (see Figure 14). To deal with these variances from "perfect," we followed three 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).

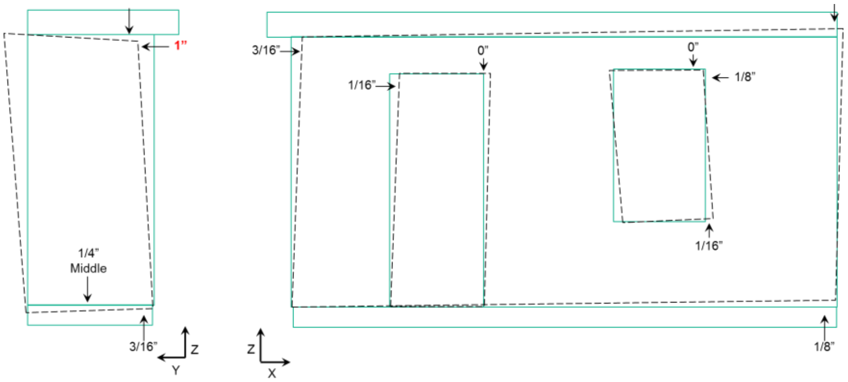

Figure 14: As built mock-up walls were not plumb or square.

In Phase 2, we would apply and refine the logic developed for the mock-up wall scan to largely automate these processes. 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.[17]

Panelization approach: In Phase 1, we use an interactive approach for panelization of the mock-up wall. The first step in the process is to add in the appropriate set-back distances from edges (door, windows, etc) to leave room for the trim. The next step was to layout the 1'×4; foot PBs to see how many needed to be modified to fit the building. After a few attempts, 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.

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[17] For example, see https://canvas.io/ . They can combine targeted field measurements to increase dimensional accuracy.

We then defined an installation order for the PB set and used that to assign each PB a unique identifier (see Figure 15). All of the lower blocks (A,B,G) that can be installed without a ladder (or other support structure) 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.

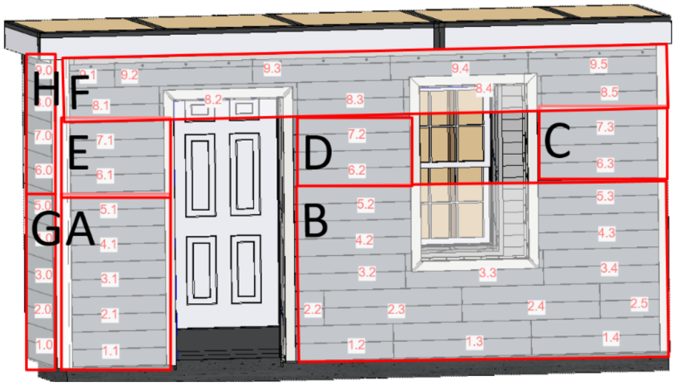

Figure 15: Diagram showing PB installation order.

We will largely automate the panelization process in Phase 2, using optimization algorithms that take into account: PB size(s); Number of PBs to install; efficiency of foam utilization, edge length (potential leakage sites), aesthetics (where PB transitions occur).

Highly automated Computer-aided Manufacturing (CAM) Process

Although we manually produced each PB installed on the mock-up wall, we developed a conceptual design of a process that enables affordable fabrication of standard and custom PBs at commercial scale. The generalized process is:

1. Prepare the finish cladding
2. Dispense liquid foam onto the finish cladding in a mold to make a preform
3. Cure in forms (several minutes)
4. Release forms
5. Cure in a temperature- and humidity-controlled environment until foam is completely stabilized (up to several days)
6. Finish the preform into a panel block(s) for a particular job
7. Kit the panel blocks on shipping pallets
8. Ship the panel blocks to the job site.

Molding Workflow: We identified two methods to manufacture the rough preform that are feasible: per-piece molding and continuous molding. A per piece molding workflow would be similar to high-end garage door manufacturing. The preform is laid up (finish cladding, end cap, release agent/film) in a mold cavity and filled with a fixed liquid foam volume to achieve the desired foam density after curing. Subsequently, the mold is held in a heated press and cures for several minutes, and then the mold is stripped and the preform fully cures.

A continuous molding workflow would be similar to the production of foam board at scale. It starts with a continuous roll of finish cladding (vinyl) that continuous roll-forming equipment forms into its final shape. Liquid foam is then dispensed onto the finish cladding. During the initial curing the foam/vinyl assembly moves down a conveyor belt, constrained by a moving extrusion form (tractor feed). After the initial cure the extrusion is cut to a common preform length with a flying cutoff saw and allowed to cure.

The per-piece workflow is relatively inexpensive to setup requiring minimal sophisticated and/or specialized equipment compared to a continuous extrusion workflow that requires several specialized pieces of equipment. Conversely, the continuous extrusion workflow will require less labor to operate as once running, it can run with minimal operator support. Therefore, the per-piece workflow is more amendable to smaller/lower volumes and the continuous extrusion is better suited for high volumes.

Panel Block Finishing and Palletizing: After a preform is manufactured, it is finished / customized for installation. First, the top and bottom tongue and groove are finished with a molder / shaper. Next, the preform is cut to its final length (and shape, if notches are required) with a CNC wire saw. Next, each PB is barcoded, indicating where it goes on each building and its installation order for the building (ultimately feeding the AR installation experience), and then proceeds to the next cell to be palletized for shipment. The PBs are finished in near-packing order (reverse installation order) to facilitate palletizing and minimize product waste

Augmented Reality (AR): We developed and implemented an augmented reality (AR) experience in project partner PTC’s Vuforia Studio environment. Workers work in pairs, one who wears AR headset to retrieve and place PBs, the other who then screws PB 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 16). Thus, the AR experience empowers workers, reducing installation time and ensuring install accuracy.

Figure 16: AR highlights for the worker the next PB to install and, when prompted, shows where to install it (note: 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 the opaqueness of the PBs, i.e., as the installer gets closer to the virtual PB, the PB should become more transparent / disappear. This is not possible to accomplish with the current development environment, however.

We also identified several future improvements:

- Currently, AR is limited to coarse block location and identification/verification (via barcode) tasks; it cannot be used for fine PB alignment (place virtual objects within a couple mm of their true location that do not shift as the user changes perspective). In

Phase 2, we would develop a modified registration approach that uses multiple reference points to determine a "best fit" approach between the virtual and physical worlds.

- 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 would cause the AR to miss voice commands, requiring the operator to repeat them. For commercialization, we would explore different input mechanisms, e.g., a physical input device worn by the installer, a better microphone arrangement to better pick up of the installers commands, and/or virtual buttons visible in the operators field of view (these controls, as implemented in the development environment, were distracting and somewhat difficult to control during testing).

Integration Requirements:

We are developing – and have prototyped several aspects of – an integrated design-production-delivery *process* to reduce the installation time and cost of deep exterior wall retrofits. To a significant extent, this process occurs independent of other comprehensive deep retrofit components, although it does have several integration aspects. We have identified these integrations points in Phase 1 and would address them in more depth in Phase 2. Succinct discussion of each one follows.

HVAC: The PB system works with a range of ducted and ductless HVAC systems. Integration occurs for HVAC components that penetrate the wall, such as integrated through-the-wall HVAC systems, e.g., PTHP, ductless minisplit heat pumps, and outdoor air (OA) mechanical ventilation systems. In those cases, the panelization algorithms, including the resulting PB and trim CAD files and features, must accommodate the wall penetration(s) associated with each and requires inputs from the HVAC design process to accommodate those penetrations. The space required is similar to other wall penetrations we need to address (e.g., utility meters, hood vents), and we expect to use similar prefabricated trim and taping designs for those as the solutions developed for windows, albeit at a smaller scale.

Roof Integration: We use a cornice receiver to mate with the top of the existing PBs. This works with roofs that have an overhang of at least 6 inches. Aesthetically, extending the roof overhang for roofs with a limited overhang may be desirable, although that would increase installation time and cost. For roofs without an overhang, we expect to install a top-sealed flashed cap to prevent water from inundating the PB system that does not trap water at the roof edge.

Windows: Our primary approach to improve window performance, while minimizing cost, will be to add high-performance interior window inserts, i.e., no modifications to the existing windows that interact with the exterior PB system. If, however, the owner wants to replace the existing windows, e.g., due to their poor condition and/or the presence of lead paint, the characteristics of the replacement window need to be integrated into the exterior interface between the PB trim and the window trim. This could be accomplished by using windows with known exterior dimensions and interfaces that can be readily integrated into the panelization algorithm, or by first installing the windows and then scanning the building to obtain final PB dimensions.[18]

Business Model: The PB system is designed to work with smaller contractors' business models, as it uses AR to empower semi-skilled works and the AR requires relatively small capital

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[18] If homeowners wanted to bring the windows flush with the PB exterior surface, that would require building out structural ~boxes for the window to mount to, a more involved approach.

investment (e.g., <$10k for headsets, likely to decrease appreciably in the future). It also does not require the lease of costly cranes.
DHW: No integration anticipated.
Basements: We do not plan to insulate the basement exterior walls, no integration anticipated.

Implementation Diversity and Ability to Operate Efficiently Across a Range of Buildings: As currently designed, the PB system can be applied directly 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. We discuss several aspects of implementation diversity below.
Applicable Colder Climates: 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-R coatings, potentially reducing thickness, etc., the PB system could be applied to warm/hot climates,
Building Construction: We designed the attachment system for wood-frame walls and it could be adapted to masonry and stucco with different anchors.
Larger and Commercial Buildings: Although we see 1- to 4-family buildings as the target market, 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 (we have not yet estimated that breakpoint), assuming sufficient clearance for crane access exists.
Roof Overhang: The PB system is designed to work with roofs having an appreciable roof overhang to accommodate the additional wall thickness. As discussed in the prior section, it can be adapted to work with buildings lacking (or without appreciable) roof overhangs by designing an integrated solution that caps and flashes the top edge of the PBs. Alternately, the overhang could be extended (as done in prior deep energy retrofits).
Insulation Materials: The integrated process currently uses polyisocyanurate insulation due to its proven high thermal performance (~R-6.5/inch) and attractive cost. As the availability of foam insulations with lower embodied GHG emissions increases, their field performance, cost-effectiveness and durability demonstrated, the manufacturing approach can work with foams made from less energy- and GHG-intensive insulation systems
Cladding Material: We chose vinyl siding due to its low cost, market acceptance, and durability. The PB fabrication process could readily be modified to incorporate factory-applied stucco, as well as metal siding or thermally treated wood (somewhat heavier). In the per-piece version of the factory, these different finishes can be bonded onto the foam in the same manner as the vinyl will be done. Challenge areas will be maintaining high aesthetic quality at PB gaps.
Adding New Architectural Details/Features/Accents: In the future, the panelization software could potentially add these details to PB trim around windows, cornices, floor transitions, doors, etc., to enable homeowners to create a specific, special look and feel for their home (e.g., Victorian, modern, etc.)
Space-constrained Environments: Because it does not require a crane for installation and is thinner than state-of-the-art exterior wall retrofit solutions, the PB system can be applied to buildings located in just about any environment. In cases where vegetation impinges on the walls, it will need to be trimmed back to accommodate the PBs (generally good practice).

Cost Modeling and Analysis

We completed an analysis of the manufacturing and installed costs of the PB system. Estimating the costs of performing a deep-wall retrofit using PB technology is challenging as the process is pre-commercial. The PB system requires no subsequent on-site building measuring and no on-site cutting of materials allowing semi-skilled labor to quickly and accurately install the panels, disrupting the standard models of installation time/labor.

Our cost analysis considers the following categories:

1. Foam procurement/manufacturing panel block manufacturing
2. Procuring other components
3. Installation labor.

Component Procurement and Installation:

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 adjusting them to the weight or volume of the non-standard parts. Given its importance, we conducted a separate analysis for foam (see below).

Installation labor also accounts for a significant portion of cost. Our model assumes installation with a two-person crew at \$50/man-hour labor (fully burdened).[19] We estimated installation time based on the mockup wall installation, normalized per ft^2 of opaque wall are,[20] 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/ft^2 (see Figure 17), with the foam (\$2.20), installation labor (\$1.50), vinyl (\$0.95), and window trim (\$0.48) accounting for ~85% of the cost.

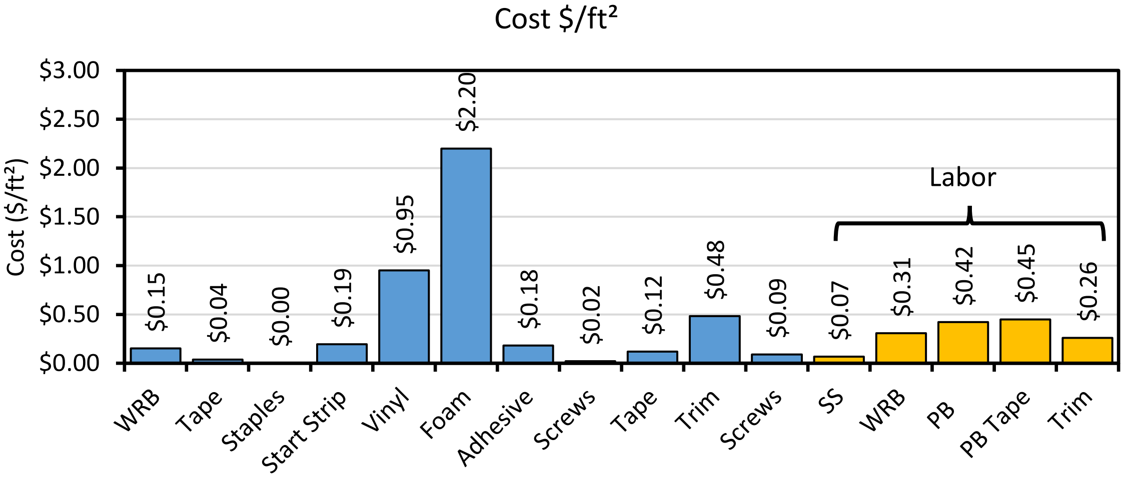

Figure 17: Component and Installation Cost

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[19] Based on discussions with a contractor and on-line sources.

[20] In practice, 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 for site set-up and break-down, breaks, etc.

Foam procurement/manufacturing

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

A. Procure commodity sheet product. 4" polyiso is a commodity good for the commercial construction industry.
B. 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).
C. Manufacture and cure slabstock in house.
D. Mold and cure individual profiles in house. Mold individual near net shape profiles that are 12-24' in length possibly with the cladding.
E. Extrude individual profiles in house. Extrude a continuous near net shape in a continuous injection molding process possibly with the cladding.

Each approach has unique benefits and challenges; Table 3 highlights the differences.

Table 3: 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 the operation a chemical plant – Requires a large (5+ days) climate controlled warehouse for FIFO curing
D	Mold individual profiles	– Has the potential to be more material efficient – Likely more cost effective in very high volumes – Can mold with 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 > 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 to build and commission a foam manufacturing and curing facility. After initial commercialization, the business can transition to in-house foam manufacturing and curing once the volumes warrant.

Table 4 summarizes the cost of three different paths to procure cured foam; the average of those costs is $2.20/ft^2.

Table 4: Cost estimates for different cured foam sources

Source	*Cost per ft^2*
Slabstock from Producer (26"x48"x16')	$2.95
4'x8'x8" sheet from Wholesale	$2.11
Estimate from Industry Insider (long-term contract with large producer)	$1.55
Average	$2.20

Panel Block Manufacturing

Once 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, while 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
   a. Mill with a multi-axis planer
   b. Continuous process
4. Cut to length: Horizontal wire saw to finish the Left and Right, including any required Tongue and Groove
5. Clean and ID
   a. Removing dust from the cutting process is critical to adhere 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 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 developed a prototypical 50,000 ft^2 factory that can manufacture 2,000 ft^2 of PBs per hour, enough to clad 5,000 homes per year when operating three shifts per day / five days per week / 50 weeks per year (employing ~75 people full-time across the three shifts). The input and finished goods warehouse has capacity for approximately four days of production

Investment Analysis

Figure 18 presents the investment analysis, based on the following assumptions:

- $10M initial investment including $5M in hardware and fit-out to commission the customization factory
- The factory will reach full capacity after 3 years
- Factory costs
  - $4.5M Labor cost per year for the factory[21]
  - $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.)

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[21] Assuming an average fully loaded rate of about $30/hour, based on prior Fraunhofer manufacturing cost analyses.

- 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/ft^2 and a three-year payback at around \$8.00/ft^2. Although higher than our original \$6.00/ft^2 cost target, it is similar to current costs to install *uninsulated* vinyl siding (\$7.58/ft^2) and appreciably less than the installed cost of a metal siding panel.[22]

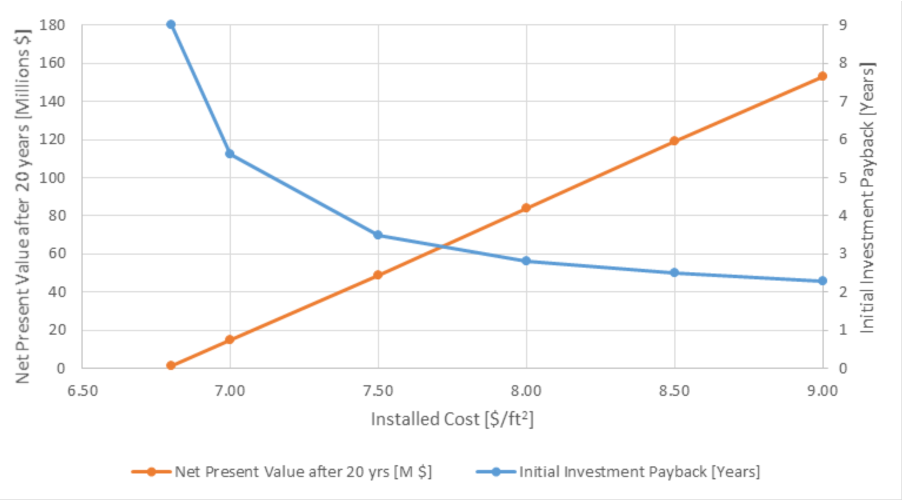

Figure 18: PB factory investment NPV and payback as a function of installed cost.

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[22] PNNL. 2021. "Wall Upgrades for Energy Retrofits: A Techno-Economic Study." Draft Final Report by Pacific Northwest National Laboratory. PNNL-28690.