Panels, Perfect Walls, and Prefabrication: High Performance Enclosure Retrofits

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ABSTRACT

65% of buildings that will exist in 2040 are already standing. Of these, a substantial number were built before the advent of modern energy codes. These are likely to have enclosure designs that are not capable of high energy performance due to inadequate insulation and excessive air leakage. Many of these buildings also suffer from durability issues, either to exterior finishes or the structural components of the wall. These issues can be remedied through the application of a carefully considered exterior insulation retrofit. Historically, these retrofits are carried out using highly customized processes that are slow and prohibitively expensive.

Fourteen wall insulation upgrade techniques were studied at a cold climate research facility in ASHRAE Climate Zone 7 for two years. Comprehensive experimental data, taken using over 700 sensors, were used to calibrate energy and hygrothermal models for extrapolation to other climates. Preliminary cost data were also gathered. One of these techniques, known as the Overcoat Panel System (OPS), has been further developed. The panel is intended to be prefabricated in a factory, and simply hung on candidate buildings. The panel design observes "Perfect Wall" principles of control layer sequencing. Another method in the original study, using proprietary EPS foam panels with an integrated cladding attachment component, is now being deployed in a field study in Minnesota. This paper will summarize the findings of the original study and present the OPS and EPS systems and preliminary findings from its application in Minnesota.

Background

The U.S. Department of Energy (DOE) established the Building Energy Codes Program in 1992 (Livingston et al. 2014). However nearly 70% of existing residential buildings were built before then, and nearly half of those have little to no insulation in the walls (NREL 2019). In addition, most of these have high air leakage rates of ten or more air changes per hour at 50 pascals pressure difference. These factors cause homes to use far more energy than houses built to modern energy codes, or to even higher levels of performance like PassiveHouse. These deficiencies have larger impacts on energy use in colder climates.

There is a need in the marketplace for cost-effective, scalable retrofit technologies that significantly reduce heat flow and air leakage, while not causing moisture-related problems due to improper system design or implementation.

PNNL / ORNL / UMN Wall Upgrade Study

In 2018, the DOE Building Technologies Office funded Pacific Northwest National Laboratory (PNNL) to complete a three-year project to compare wall upgrade technologies across the domains of energy savings, cost, moisture performance, constructability, and scalability. Oak Ridge National Laboratory (ORNL) and the University of Minnesota (UMN) were recruited as partners. The project ultimately compared 14 wall upgrade systems using these metrics.

Performance criteria were established based on extensive expert input and a literature review. We determined that we would pursue a range of thermal performance and would explore options related to retaining existing cladding in an effort to reduce demolition cost in some cases.

UMN conducted *in situ* testing for the first phase of the project. This was accomplished at the Cloquet Residential Research Facility (CRRF), located on the campus of the UMN Cloquet Forestry Center in Climate Zone 7a (Figure 1 and Figure 2). Each wall assembly was tested in a north-facing and south-facing orientation to capture extremes of solar exposure. This testing enabled several key goals of the project:

- Local purchasing provided information on real-world product availability and cost.
- Physically installing the products gave the team insight into constructability and opportunities for streamlining of installation processes.
- Collecting extensive data on wall performance provided inputs for energy and hygrothermal models for long-term and whole-building performance, and extrapolation to other climates.

Two systems studied in this project are the subject of this paper. One, the Overcoat Panel System (OPS) is a spinoff technology deriving from previous UMN / DOE work on a technology for new construction. It is intended for highly-mechanized prefabrication. The other is a product currently available in the marketplace. It consists of proprietary EPS foam blocks with an integrated fastening system and is assembled exclusively on the jobsite.

Figure 1. Cloquet Residential Research Facility Building Exterior

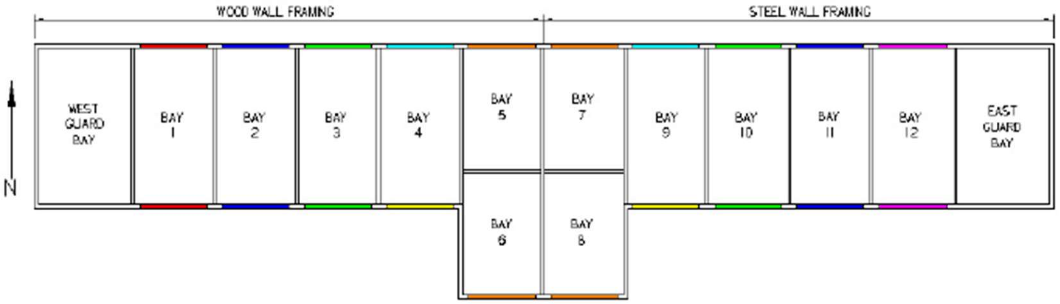


Figure 1. Cloquet Residential Research Facility Building Floor Plan

Walls were extensively instrumented to record temperature, relative humidity, and wood moisture content at each layer interface. One heat flux sensor measured heat movement through each assembly. In addition, indoor and outdoor temperature and relative humidity were measured. Figure 3 shows the location and type of these sensors in an example assembly. In total, approximately 700 individual channels of data were recorded.

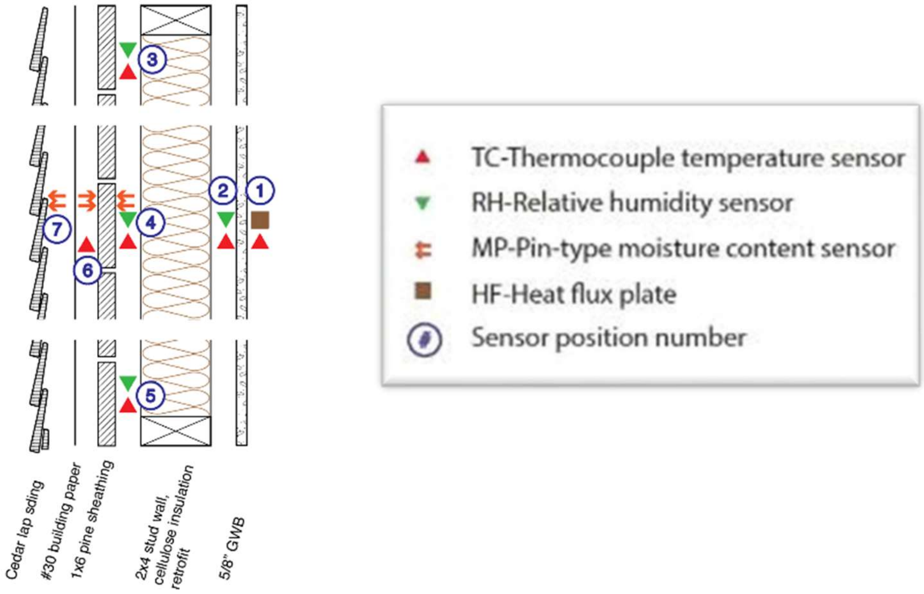


Figure 2. Sensor Type and Location in Wall Section Diagram

This paper focuses on two assemblies tested for the study, but it will be helpful to examine a few other examples to illustrate the benefits of a retrofit approach focused on continuous exterior insulation, specifically in terms of moisture performance. Figure 4 shows the assemblies that are examined here. Wall A shows the base case, a 2x4 framed wall with 1x6 board sheathing, asphalt paper water control layer, and cedar lap siding. 5/8” gypsum board is used on the interior. The interior and exterior finishes include a vapor retarder primer to simulate the low vapor permeability of multiple layers of oil-based paint found in older homes. Wall B shows a conventional “drill and fill” cellulose retrofit. Wall E is a hybrid approach, with drill and fill cavity insulation plus a layer of continuous insulation (2” XPS). Wall H is the Overcoat Panel System with 4 inches of graphite-enhanced EPS foam in two layers, and will be further described in subsequent sections of this paper. Wall D uses 4-1/2" of EPS foam. This is a commercially available product with key features including grooved faces to facilitate draining, tongue-and-groove connections between panels, and plastic "ladders" embedded in the foam on sixteen-inch centers for attachment to the structure and cladding.

In general, adding R-value will decrease heat transfer and therefore reduce heating and cooling energy use. However, the location of this insulation is critical for moisture performance. This is especially true in more extreme climates like the location of this experiment in Climate Zone 7. Figure 5 and Figure 6 describe the conditions inside these example walls at Sensor Position 4, shown in Figure 3. These are the conditions on the interior face of the sheathing. This location is critical because it is a common layer for moisture to accumulate in insulated assemblies, and the sheathing is moisture-sensitive and subject to damage from moisture accumulation. For reference, both graphs also show indoor and outdoor air temperature. Indoor temperature was maintained at approximately 70°F, and humidity was maintained at 40% RH for these experiments. The graphs show the coldest portion of the study year, from late January through the end of March.

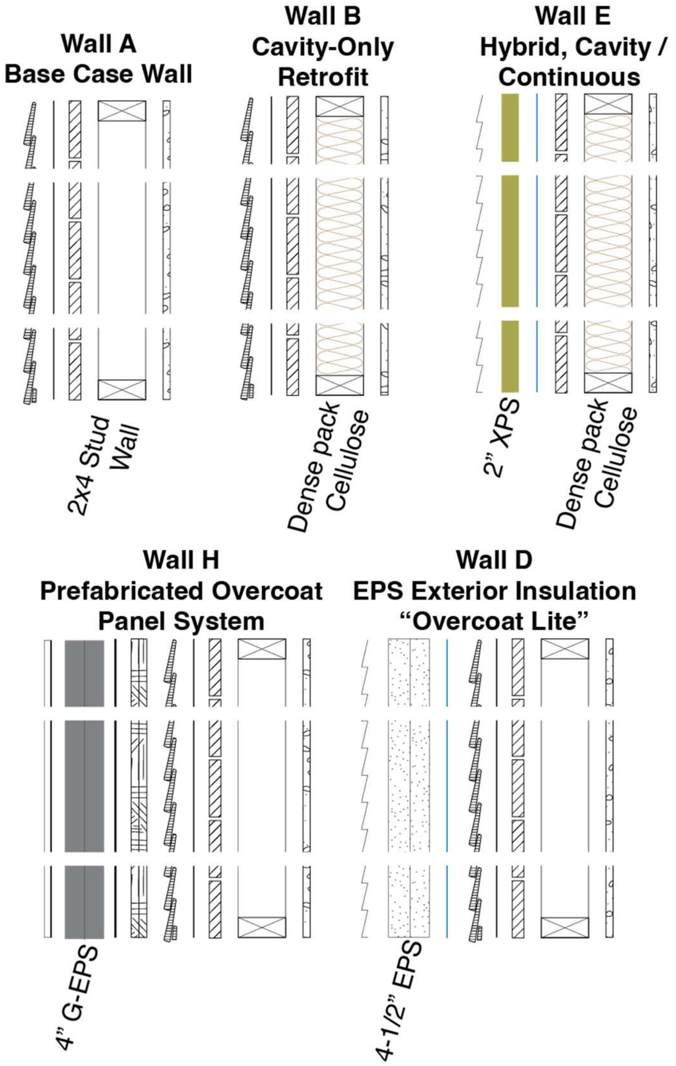


Figure 4. Select Assemblies Tested at Cloquet Residential Research Facility

Figure 5 clearly shows that cavity-only approaches (Cavity Only) cause the sheathing to become quite cold, nearly as cold as the outdoor air temperature. Meanwhile the two walls using only exterior insulation, Wall H and Wall D, maintain sheathing temperatures near indoor air temperature. This difference is important because materials that are cold tend to become wet, and once wetted tend to remain wet. This can be especially true when drying is limited in one or both directions. The hybrid approach (Wall E), similar to the uninsulated base case, shows sheathing temperatures between cavity-only and exterior-only approaches.

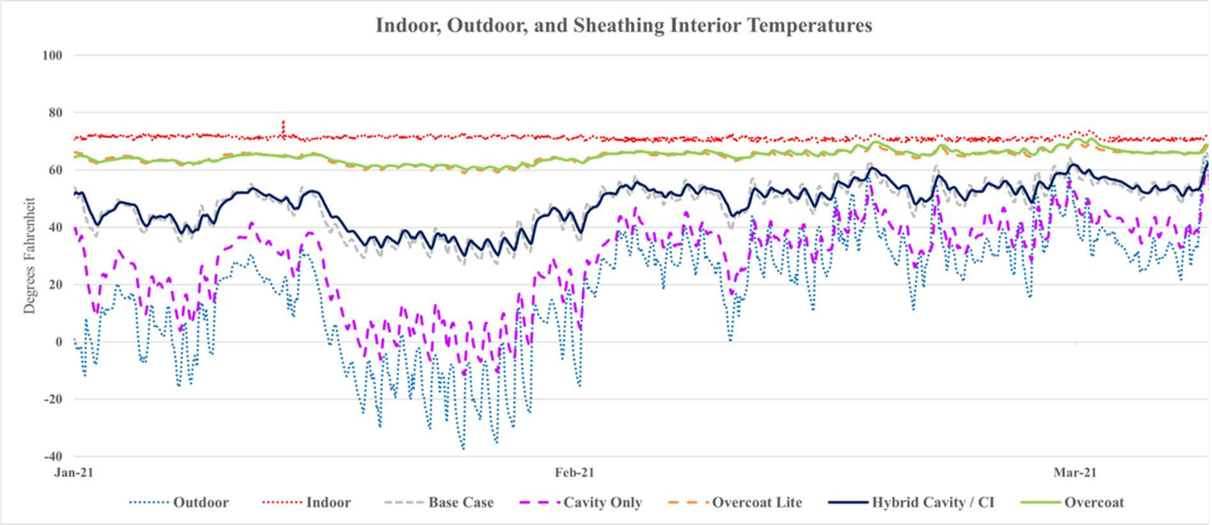


Figure 3. Temperature at Sheathing Interior

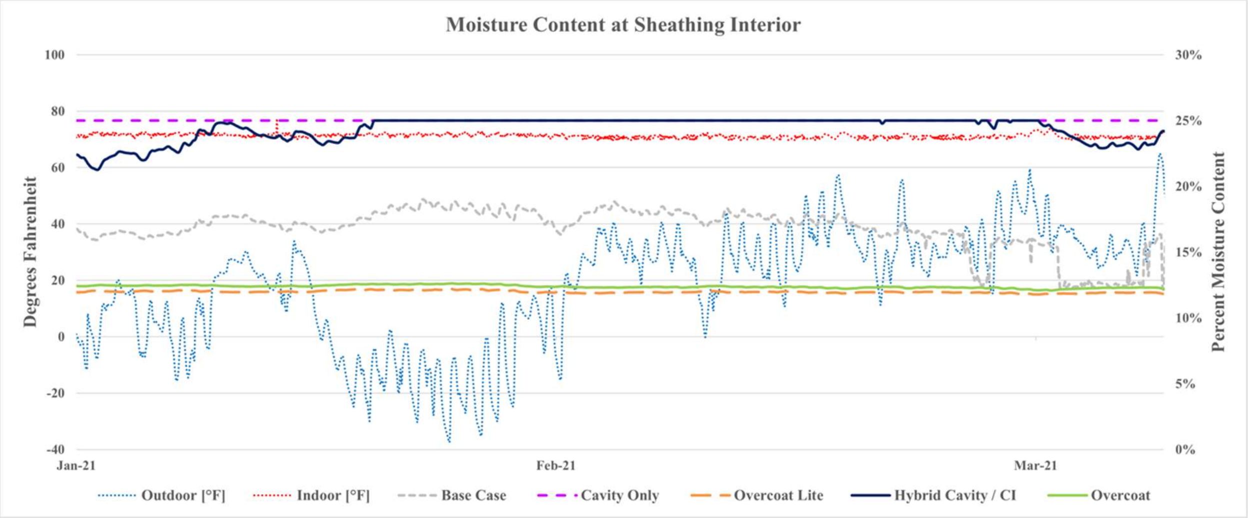


Figure 6. Moisture Content at Sheathing Interior

Figure 6 shows the moisture content of the sheathing. In this study, standard brass nails are used as moisture sensors and are integrated with a commercial data logger capable of measuring resistance through an integrated half-bridge circuit. Brass nails, 1.6 mm (1/16 inch) in diameter with a tip gap of 4 mm (0.15 inch), are inserted into the sheathing, with a spacing of 19 mm (3/4 inch) between two nails. The resistance of the wood is determined through the half-bridge circuits on the data logger with 4 V excitation voltage. Calibration processes are conducted in controlled test environments to develop Resistance-Moisture Content (MC) graphs for the setup. Species specific temperature correction is applied to the raw moisture content measurements (Evren et al. 2023). The apparatus design loses resolution at approximately 25% MC, which is near the fiber saturation point in any case. Values are capped at that level accordingly. Sustained moisture content above 18% or 20% should be considered as a high-risk moisture regime.

The base case wall moisture content increases after the start of the experiment and has a peak moisture content above 18% during the very cold weather shown on these graphs. The wall then dries significantly as the weather becomes warmer. By contrast, the Cavity Only wall shows sustained MC above 24%, only beginning to dry beyond the extent of the graph, during much warmer weather. The Hybrid wall does show high moisture content during and immediately after the coldest weather, but the duration of wetness is much less than the Cavity Only wall. By contrast, Walls D and H enjoy consistent, very low moisture contents around 12%. These graphs illustrate the inherent moisture safety of exterior insulation approaches, which both featured technologies utilize.

The Overcoat Panel System

Origin and Concept

One strategy that was studied is referred to here as the Overcoat Panel System (OPS). It is derived from a previous study by the UMN for the DOE Building America program on the Solid Panel Structural system (SPS) (Schirber et al. 2020). The original project studied an innovative construction method that employed a “studless” exterior structural wall system and utilized the principles of the so-called ‘Perfect Wall’ (Lstiburek 2007). The perfect wall consists of an arrangement of control layers - for air, water, vapor, and heat - which are applied to the exterior sheathing of the building shell, followed by cladding. This construction method keeps moisture sensitive materials entirely interior to the insulation layer, which results in their maintaining humidity and temperature conditions tightly coupled to indoor conditions. If water leaks or other moisture ingress into the wall assembly occurs, such walls are more able to dry effectively than walls where sensitive materials are tightly coupled to the outdoor environment or sandwiched between relatively impermeable layers.

The observed performance of the OPS leads to further exploration into the potential for large-scale deployment as a retrofit option for the aging multifamily housing stock in Minnesota. One precedent of this type of panelized exterior retrofit, Energiesprong, has been broadly deployed in the Netherlands, using a process for customized offsite production of retrofit façade panels that can be quickly applied to a building. A streamlined mechanical system upgrade is typically performed concurrently to ensure energy performance and minimize risks due to combustion safety and ventilation issues (Energiesprong 2022).

Based on the Energiesprong model, the OPS is designed to be fabricated off site. The first phase of construction involves the creation of a 3D model of the candidate building to enable the production of panels that precisely fit the building, and accommodate deviations from level, square, and/or plumb conditions that are common in existing buildings. This step often employs a 3D laser scanner which sends laser signals from a fixed point in space and records the time it takes for the signal to return to the scanner. The resulting model is called a point cloud. These point clouds can be further refined into 3D models of the whole building, and 2-dimensional drawings can be extracted that precisely locate features such as corners, windows, and penetrations. These drawings, in turn, are used by computer numeric controlled (CNC) machinery that cuts the panels precisely to fit the candidate building. Windows and doors would be factory installed and integrated with the air / water control layer. Insulation and furring strips would also be pre-installed, along with the cladding material. Complete panels could then be shipped to the job site and installed quickly with minimal disruption to occupants.

Selected Details

Figure 7 shows a diagram of the Overcoat Panel concept. It is constructed on an OSB structural panel, with a membrane applied to the OSB face for control of airflow, water, and vapor diffusion. This membrane has been envisioned and depicted as a peel-and-stick material, however, other options like structural panels with an integral control layer function, or liquid applied membranes are also appropriate. Rigid insulation is applied over the membrane. This layer could be fibrous insulation like rigid mineral wool, vacuum panels, or foam plastic. Furring strips are laid over the insulation and fastened back to the OSB using bolts and t-nuts or screws. The furring strips provide a fastening surface for the cladding and create an air gap between the insulation and cladding for drainage, ventilation, and to enhance drying potential. A wide variety of cladding materials could be used, including fiber-cement siding systems, wood, metal panels, or composites.

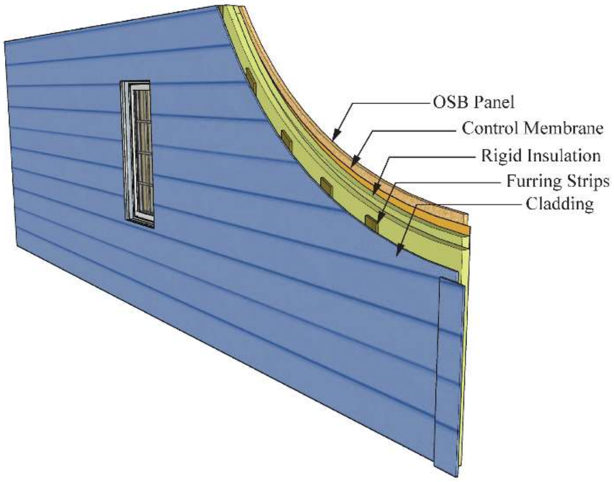


Figure 7. Overcoat Panel System Diagram

The continuity of air and thermal control layers is critical to ensure achieving the energy saving and moisture performance potential of the system. Therefore, panel connection joint details were carefully developed to ensure the continuity of these layers. Joints where panels meet in the field, or at inside and outside corners, can be handled in one of two ways: “open” connections, where the final connection is made by technicians in the field, or “blind” connections, where the control layers are connected by virtue of their geometry as one panel is placed against another. Figure 8 shows the outside corner connection using an open connection (left side), in which a supplemental strip of membrane would be field installed. The right side shows a blind connection at an outside corner.

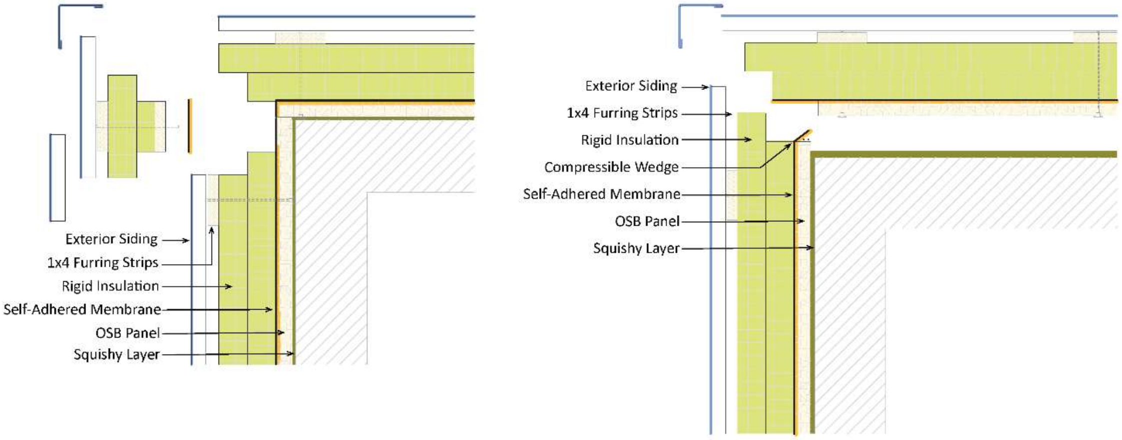


Figure 8. Open Corner Connection and Blind Corner Connection (Plan View)

For blind connections, air barrier continuity is the main challenge. A slight out-of-plane condition between the adjacent panels could lead to a gap between the adhesive (inner) side of one panel's membrane and the outer surface of its adjacent panel's membrane. This discontinuity could allow air leakage, which would compromise moisture and energy performance. For this reason, we recommend a compressible wedge or similar extrusion that pushes the membrane of one panel out of plane from itself and into the adjoining panel to ensure good adhesion, as can be seen on the right side of Figure 8. Staggered seams in the insulation layer serve to limit air leakage at joints and are common to both joint types.

Panels are installed using a linear "French cleat" device that is fastened to the building structure. A schematic drawing of the device is shown in the left side of Figure 9. This cleat transfers vertical and horizontal (wind) loads to the building structure. A small number of fasteners can be used to secure the panel to the cleat, if necessary.

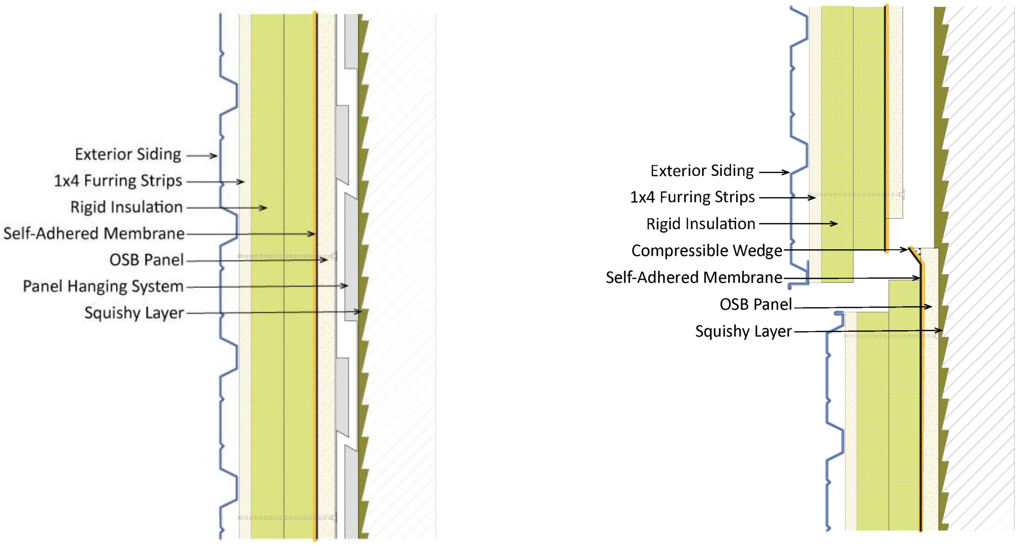


Figure 9. French Cleat Hanging System Diagram and Horizontal Panel Connection Detail Diagram (Section View)

Finally, building surfaces are often not flat and/or coplanar. The OPS is intended to be applied over most existing claddings to eliminate the cost of demolition. We propose a lightweight filler material between the back of the panel and the exterior surface to fill any gaps. This filler material, referred to colloquially as the "squishy layer" is compressible, and serves to limit air movement behind the panel. While the details for panel seams and terminations are designed to eliminate airflow that would bypass the thermal control layer, convective movement of air in this interstitial space could still compromise thermal or moisture performance. The material chosen should be able to drain any accumulated water down and out of the assembly. The right side of Figure 9 shows a horizontal panel seam connection installed over existing lap siding. The squishy layer fills the spaces between the irregular cladding surface and the back of the panel.

Retrofit solutions must also address foundations and roofs to ensure a high-performance outcome. The OPS is not designed for below grade use, however, foundations in existing buildings are commonly not insulated. Areas of the foundation wall that are above grade, and extending at least down to the frost line, can be significant sources of heat flow. We recommend that these walls be partially or fully excavated so that a waterproofing material can be applied to the foundation and rigid insulation (typically extruded polystyrene) applied over the waterproofing.

For pitched roofs, panels similar in construction to the OPS wall panel can be applied over the existing roof plane. This can be an especially attractive option if the attic includes occupied space since it ensures complete thermal control coverage at the roof plane. This approach is commonly referred to as a "chainsaw retrofit," since the existing soffits must be removed so that the control layers of the wall panels can be connected to the control layers in the roof panels. However, such panels will not have finish layers applied at the factory. After application of the panels, soffits can be either constructed on site, or prefabricated soffits can be attached. At that point, roof finish layers can be applied. Figure 10 shows this chainsaw retrofit application. The OPS presented here is not designed for flat roof applications, or for cases where attic floor insulation is desired. In these cases, a variety of methods are available to ensure control of air, water, vapor, and heat flow. These will often involve more traditional techniques.

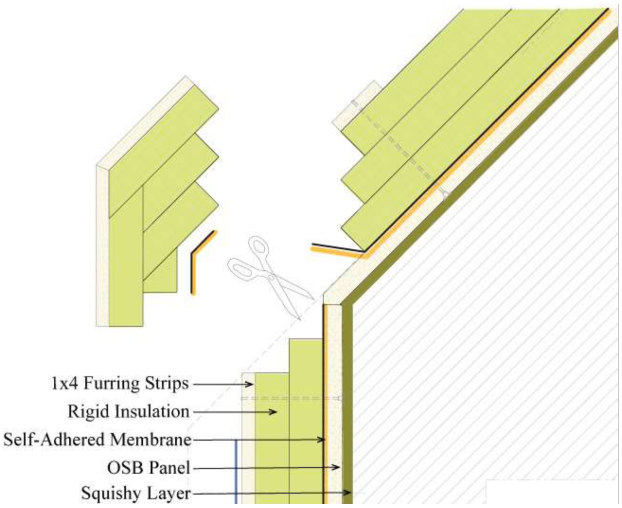


Figure 10. Chainsaw Retrofit Application Diagram (Section View)

Mechanical System

A critical concern with upgrades using the OPS is ventilation and combustion safety. In the Building America study (Schirber et al. 2020), it was found that airtightness levels of the single-family homes built under the project were routinely less than 1 ACH50, despite the project using inexperienced volunteer labor for installation of the air control layer. With proper detailing, it is anticipated that the OPS will be able to match this air control performance. Most retrofit candidate buildings have exhaust driven ventilation systems that would need to be upgraded to balanced systems with dedicated supply and exhaust. Additionally, many of the heating and hot water systems are atmospherically vented combustion equipment (furnaces, boilers, water heaters, etc.) and will also require replacement. These retrofits provide an opportunity for electrification and improved indoor air quality.

In keeping with the Energiesprong retrofit concept, minimal intrusion on building occupants during construction is an important goal. However, some interior work will obviously be required to address the decommissioning of this old equipment and substitution with new mechanical systems. Efforts are underway to commercialize individual unit “combi” systems to provide most or even all of these services in a self-contained, drop-in unit for the U.S. market. One such unit, produced by Danish manufacturer Systemair and already available in Europe, is the focus of a current DOE-funded research effort. Such systems could radically simplify the HVAC and domestic hot water upgrades and efficiency improvements associated with overcladding multifamily properties. For the time being, however, these systems are still on the horizon.

When considering indoor air quality (IAQ), with the common exceptions of intermittently and/or manually operated bath and range exhaust, no provision is made for intentional ventilation to meet standards such as ASHRAE 62.1 or 62.2. Additionally, these exhaust-only systems typically rely on enclosure air leakage to provide makeup air. One solution would be to install louvered trickle vents on the side of the unit to provide a source of make-up air for ventilation, but these can result in undesirable cold drafts and would reduce the energy savings potential of the retrofit. A better solution would be to temper the makeup air through an energy recovery ventilation system that supplies balanced ventilation to the building while minimizing the associated heat loss. This system would provide a low level of constant supply and exhaust. Constant exhaust sources would be located in both the bathroom(s) and the kitchen.

Energy Savings, Costs, and Payback

A number of energy models were developed to test potential energy savings, utility cost impacts, and carbon reductions from both the overcoat insulation system and recommended mechanical upgrades. The analysis was conducted using a DOE-2 energy model based on four candidate buildings as a representative sample. These buildings are the same properties used to investigate the costs for overcladding.

Installation of the OPS shows significant whole-building site energy savings, even accounting for the energy penalty associated with providing dedicated ventilation air. Savings are even more robust with the substitution of heat pumps for space conditioning, ranging from a EUI savings of 60 to 75 percent. EUI and cost savings are summarized in Table 1.

Table 1. Energy and cost savings (kBtu/ft^2/yr)

Building	Retrofit Type	Pre- EUI	Post- EUI	% Reduction
1	Overcoat +Ventilation	93	42	55%
	+ Heat pump conversion	93	23	75%
2	Overcoat + Ventilation	84	46	45%
	+ Heat pump conversion	84	23	73%
3	Overcoat + Ventilation	65	48	26%
	+ Heat pump conversion	64	26	60%
4	Overcoat + Ventilation	69	36	48%
	+ Heat pump conversion	70	21	70%

There are two challenges in providing a fair estimate of costs for the OPS and mechanical system upgrades: first, labor and material costs have dramatically increased over the past four years, and the market has been more volatile than is typical. Therefore, costs that have been calculated during this time, and are reflected here, are likely higher than what would be considered typical. Second, the costs for the OPS were derived during the PNNL study and reflect a bespoke site-built retrofit and not the highly mechanized Energiesprong retrofit process that is envisioned. In fact, no manufacturing capability for this type of panel currently exists in the U.S., though many projects are in development. Because of this, it is not possible to credibly speculate about savings that will flow from streamlining of processes, bulk material purchases, material optimization and minimization, and similar industrial optimization steps. Costs shown here should be considered as conservative, with substantial potential for cost reduction.

The cost of the OPS determined for the PNNL study was \$21/ft^2 enclosure area. Costs for mechanical system replacement determined for the Minnesota CARD study varied according to which system type was replaced. The maximum cost was determined to be \$25/ft^2 floor area.

Table 2 shows the costs for the OPS installation and mechanical system upgrades, along with the annual energy savings derived from energy models. These are used to calculate simple payback, which ranges from 22 years to 152 years. The clearest distinction between the buildings with relatively short paybacks and with long payback cases was the heating system. Both buildings with shorter paybacks in this sample used electric baseboard heat, therefore their absolute energy cost savings were substantially higher than the other two buildings, which used gas-fired heating equipment. This range in the simple payback results showcases the challenges with the return on investment when electrifying natural gas equipment.

Table 2. Costs and simple payback

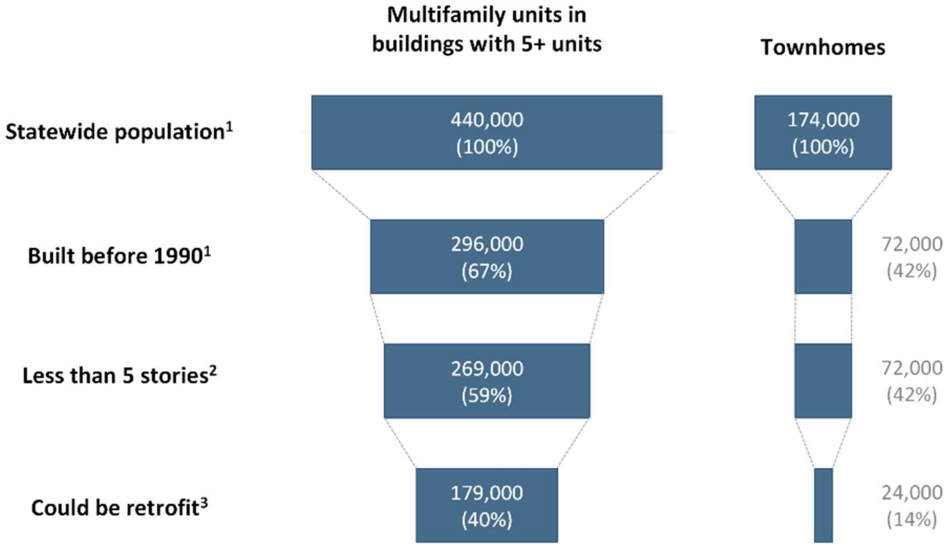
Building	Floor Area ft^2	Enclosure Area ft^2	OPS cost @ \$21/ft^2 enclosure	Mech cost @ \$25/ft^2 floor	Total Cost	Annual Energy Cost Savings	Simple Payback (years)
1	5,000	7,750	\$162,750	\$125,000	\$287,750	\$12,800	22
2	9,100	11,080	\$232,680	\$227,500	\$460,180	\$4,459	103
3	58,600	40,450	\$849,450	\$1,465,000	\$2,314,450	\$15,236	152
4	22,000	22,750	\$477,750	\$550,000	\$1,027,750	\$39,380	26

Potential Application Scale

A housing stock analysis was performed with a goal to estimate the proportion of Minnesota multifamily housing that could be retrofitted with the Overcoat system, as well as to identify key attributes of good (or poor) candidates for retrofit.

To conduct the analysis, we relied on a statistical sample of 120 properties identified in a prior CARD study that characterized 5+ unit multifamily housing and single-family-attached townhomes (Pigg et al. 2013). Because the Overcoat retrofit would be difficult to apply to taller properties without extensive assembly fire testing to meet requirements of NFPA 285, the characterization-study sample was filtered to include only properties that were four stories or less in height. Properties built in the 1990s or later were also eliminated, because these would likely already be reasonably well insulated. Publicly available imagery was then used to classify the 97 remaining properties as good or poor candidates for retrofit based on a visual review of the complexity of the facade, architectural features and other building aspects that might hinder retrofit. Finally, Census data was accessed to extrapolate the results to the latest estimates for the statewide population of townhomes and multifamily housing units.

The results suggest that about 40% of all multifamily housing units in Minnesota are in buildings that could be retrofitted with the Overcoat system as shown in Figure 11 (Mosiman et al. 2023) The number of townhomes that could be retrofit is much lower, because there are many fewer townhomes, and the ones that exist are likely to be newer and thus already well insulated. Additionally, fewer townhomes were deemed to be amenable to retrofit based on a visual review.



1. Source: 2015-2019 Census American Community Survey
2. Source: 2013 Minnesota Multifamily Rental Characterization Study
3. Based on visual review of Rental Characterization Study sample properties

Figure 11. Multifamily Units in Minnesota with Retrofit Potential

Approximately 179,000 multifamily units in Minnesota within 5+ unit buildings would make good candidates for the overcladding retrofit. Of those we estimate a 60/40 split between gas heated and electric resistance heated buildings. The average area per unit is about 900 ft^2 (Pigg et al. 2013). Savings per unit without a heat pump conversion are estimated to be 29,900 kBtu/yr. After converting either electric resistance or gas heat to heat pumps, savings increase to

48,400 kBtu/yr. In total, the technical savings potential could reach 5,348,000 MBtu/yr for Overcoat plus ventilation upgrades or 8,666,000 MBtu/yr in combination with a heat pump conversion. Broken out by fuel type, savings without a heat pump conversion is 790,000 kWh/yr and 29,000 therms, or with heat pumps installed, 1,120,000 kWh/yr and 47,000 therms. (Mosiman, 2023)

The recent NREL publication “U.S. Building Stock Characterization Study” (Reyna, 2022) provides a basis for estimating the national potential of the Overcoat system. The study identifies 243,000 multifamily buildings of five or more units with one to three levels, in the Cold / Very Cold region (including New England, the Midwest, the upper west coast, and mountainous areas) built before 1980. Assuming the same proportion of these are good candidates for retrofit as described above, 40%, or 97,200 buildings (777,600 units[1] in multifamily buildings) could be retrofitted with this system.

This vast population of buildings lends itself to another of the key components of the Energiesprong approach: demand aggregation. Since the manufacturing infrastructure does not exist, and will be costly to create, it is necessary to demonstrate to entrepreneurs and investors that a ready market exists for a system like Overcoat. By recruiting significant numbers of buildings who wish to move forward with enclosure retrofits, manufacturers can be assured of a durable market for their products.

“Overcoat Lite,” or the InSoFast system with Minnesota Weatherization

In 2022, UMN collaborated with the Weatherization Assistance Program (WAP) at the Minnesota Department of Commerce to secure a DOE grant that enables WAP to apply deep energy retrofits centered on exterior insulation, even if savings are not expected to meet typical program Savings to Investment Ratio (SIR) requirements. The project is titled “The Minnesota WRAP (Weather Resistive Advanced Prefab) Pilot Initiative. The technology chosen for these retrofits was studied in Cloquet, where it was known as Wall D. The technology is marketed commercially as InSoFast. It consists of EPS panels with ladderlike plastic “studs” embedded in the foam on sixteen-inch centers to facilitate attachment to the building, and enable cladding attachment. Figure 12 shows a typical panel design. The study wall included two layers, totaling 4-1/2” in thickness. During preparation for the deployment, InSoFast deployed a new design, a panel that achieves 3-3/4” thickness in one layer. It was determined that the labor savings from installing only one layer would be significant, while the energy penalty would be small, so that design was chosen.

The team is collecting pre- and post- retrofit heating energy use, along with pre- and post- blower door results to understand the energy benefit of the technique. In addition, we are instrumenting the walls to collect data on temperature and relative humidity at the sheathing, as well as sheathing moisture content to verify the overall moisture safety of the approach.

Figure 12 shows the application on the first house, completed in 2023. The home is one story with a basement, with a footprint of 1172 ft^2. Work proceeded as follows:

1. Removal of existing cladding, including soffits.
2. Extension of penetrating elements (gas meter, electric receptacles and lights, vents, etc.)

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[1] Number of units calculated based on a data set of 90 buildings with number of units ranging from 5 to 123 with an average of 25 units, a mode of 8 units, and a median of 13 units.

3. Application of new polyolefin housewrap, carefully sealing seams and connections to existing windows and doors to remain (windows had previously been replaced).
4. Trench around foundation to ~24 inches below finished grade
5. Application of InSoFast system, from below grade to within two inches of roof sheathing. The EPS is sealed to the sheathing at the top to prevent convective losses and held down from the roof sheathing to allow for attic ventilation from the soffit.
6. Application of new cladding

Figure 12. WRAP Installation in Progress (photo courtesy Paul Cole, SRC)

This is the first of six retrofits to be performed for this pilot. We anticipate that homes will be likely to be substantially airtight post-retrofit, thus the risk of indoor air quality problems, excessive humidity, or backdrafting of combustion appliances would be increased. For this reason, we included installation of an ERV as a baseline for these projects. In this case the home had been previously weatherized, including window and door replacement, spray foam at the rim, attic air sealing, and installation of cellulose in wall cavities. Therefore, the reduction in air leakage after the retrofit was only 4.6%, dropping from 1018 CFM50 to 971 CFM50.

Energy savings are currently unknown. The winter of 2023/2024 was much warmer than average, and so energy billing data are not comparable to the previous year. We will reevaluate pre-and post-retrofit energy use following the upcoming winter. Anecdotally, occupants report a significant increase in thermal comfort compared to previous winters in the home.

Monitored relative humidity at the sheathing has peaked at 66%, with a simultaneous temperature of around 72 °F. This yields a calculated equilibrium moisture content of around 12%, well below levels that would indicate a potential for moisture issues.

Project costs for all work related directly to the insulation retrofit (including extension electrical, plumbing, HVAC venting and gas service) were \$51,463. Installation of the ERV added \$3,592, bringing total project cost to \$55,055. On a square foot basis, all-inclusive costs are \$4.70/ft^2 gross wall area, and \$4.40/ft^2 when the ERV is excluded.

We are hoping to realize some cost savings on the remaining five projects due to contractor experience with the process. However, the Insofast system has been optimized for this application, and significant cost compression is unlikely. The remaining five projects will be completed during summer / fall of 2024, so the actual potential for labor savings is to be determined.

Conclusion

Retrofitting the vast number of older homes in the U.S. to achieve significant increases in energy performance without compromising indoor air quality or durability is a key element in the quest to achieve carbon neutrality. Yet, these buildings are notoriously difficult to upgrade in a cost-effective manner due to the unique characteristics of each building and inherent need for custom solutions for each home. This paper explores two solutions appropriate for single-family or low-rise multifamily buildings: one hypothetical prefabricated panel system, and one modular, site-fitted system currently in the marketplace. Both of these solutions have been experimentally verified to achieve significant reductions in energy use while maintaining the hygrothermal integrity of the enclosure. An additional benefit of these exterior approaches is the minimization of disruption to the home interior and the occupants.

Energy savings are significant, and R-value of the systems can be modulated to suit the needs of particular climates. Detailed analysis of the Overcoat Panel System showed EUI savings in four multifamily buildings in Minnesota ranging from 60%–75% when space conditioning was converted from gas combustion to electric heat pump, in addition to the OPS retrofit and balanced ventilation.

The challenge to widespread deployment with these approaches is cost. Simple payback for OPS ranged from 22 to 152 years, with the lower values achievable in homes heated with electric resistance. Homes using delivered fuels would also likely see shorter payback periods. But capital costs remain high. The InSoFast system appears to be more affordable, with costs of approximately \$5/ft^2, compared to OPS at \$21/ft^2, though the InSoFast figure does not include windows and doors, while OPS does. Even at this lower per-unit cost, the up-front cost is still out of reach for many homeowners. Labor savings and cost compression achievable through automation and prefabrication is the critical path to enable retrofitting this vast population of buildings to rabidly decarbonize the residential building sector. Due to the high capital costs and risk associated with the new industry, this will only occur through demand aggregation, assuring investors that there is a ready market for the new product.

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References

Architecture 2030. (n.d.). *Why the building sector?* Retrieved March 29, 2022, from https://architecture2030.org/why-the-building-sector/

Energiesprong. 2022. "*Energiesprong Explained*." energiesprong.org

EPA. 2022. *Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks*: 1990-2020. U.S. Environmental Protection Agency, EPA 430-P-22-001. https://www.epa.gov/ghgemissions/draft-inventory-us-greenhouse-gas-emissions-and-9 sinks-1990-2020.

Evren, F., G. Mosiman, P. Huelman, A. Desjarlais, and A. Aldykiewicz. 2023, Data Acquisition System Selection and Calibration of Resistive Moisture Content Measurements for Large-Scale Field Studies in Cold Climate Residential Building Envelope Performance. in *2023 ASHRAE Winter Conference.* ASHRAE Transactions, vol. 129, ASHRAE, pp. 676-684,

Livingston, O., D. Elliott, P. Cole, and R. Bartlett. 2014. *Building Energy Codes Program: National Benefits Assessment.* Prepared for the US Department of Energy

Lstiburek, J. "The perfect wall." *ASHRAE Journal*, vol. 49, no. 5, 2007, p. 74+

Mosiman, G., L. Kutschke, C. Jansen, and S. Pigg. 2023. *Project Overcoat: Investigation of a Process for Affordable High Performance Enclosure Upgrades for Multifamily Buildings.* Minneapolis, MN. Prepared for MN Department of Commerce, Division of Energy Resources.

National Renewable Energy Laboratory. 2019. *ResStock Data Viewer: National Baseline.* https://resstock.nrel.gov/dataviewer/efs_v2_base#building-characteristics

Pigg, S., J. LeZaks, K. Koski, I. Bensch and S. Kihm. 2013. "*Minnesota Multifamily Rental Characterization Study*," report prepared for the Minnesota Department of Commerce, Division of Energy Resources, Energy Center of Wisconsin, and Franklin Energy.

Reyna, J., E. Wilson, A. Parker, A. Satre-Meloy, A. Egerter, C. Bianchi, M. Praprost, A. Speake, et al. 2022. *U.S. Building Stock Characterization Study: A National Typology for Decarbonizing U.S. Buildings*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5500-83063. https://www.nrel.gov/docs/fy22osti/83063.pdf.

Schirber, T., R. Jacobson, G. Mosiman, D. Handeen, and P. Huelman. 2020. *Affordable Solid Panel "Perfect Wall" System*. St. Paul, MN. University of Minnesota NorthernSTAR Building America Partnership.