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Wall Upgrades for Energy Retrofits: A Techno-Economic Study

November 2022

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Executive Summary

Nearly 70% of all existing residential housing stock was built before 1992, when the U.S. Department of Energy (DOE) Building Energy Codes Program was established[1]. Nearly half of those pre-energy code houses have little to no insulation in the walls[2] and have very high air leakage rates of 10 or more air changes per hour at 50 pascals of pressure (ACH_{50}). These deficiencies result in wasted energy and wasted money, especially in colder climates. There is a significant need for cost-effective, reliable retrofit methods for these homes that include air, moisture, and vapor controls, all of which are considered standard new construction practices under modern energy codes. Well-tested and documented wall retrofit systems can help to achieve substantial energy savings and also improve durability, comfort, health, and resilience.

In 2018, DOE's Building Technologies Office awarded Pacific Northwest National Laboratory, Oak Ridge National Laboratory, and the University of Minnesota funding to complete a 3-year project to compare a range of residential wall retrofit systems that prioritize affordability, durability, and energy savings potential. In addition to these core criteria, the ease-of-construction and the wide-scale applicability of the solutions also were considered.

In this project, the research team identified, constructed, tested, simulated, and analyzed the feasibility and economics of 16 wall retrofit assemblies (14 test configurations and 2 baseline configurations). The overall study included the following activities (bullet items refer to components of Figure ES.1 according to color coding):

- A comprehensive literature review of traditional and innovative retrofit wall solutions
- An expert advisory committee that provided feedback on key performance criteria
- Specific choices for wall candidates based on the research plan
- An in situ experiment that included an evaluation of ease-of-construction, observations of material sourcing, thermal and hygrothermal performance monitoring, and data analysis to calibrate/validate simulations
- Thermal and hygrothermal simulations
- Whole building energy modeling to determine potential energy savings on a per house level, focused particularly on cold climates, but extrapolated to all U.S. climate zones
- An economic assessment that included real contractor bids for labor and materials, as well as basic economic outputs including internal rate of return and simple payback
- A techno-economic model that was developed to provide an assessment of the technologies' market penetration potential.

[1] Livingston, O., Elliott, D., Cole, P., & Bartlett, R. (2014). *Building Energy Codes Program : National Benefits Assessment* (Issue March).
[2] National Renewable Energy Laboratory. (2019). *ResStock*. Data Viewer: National Baseline (EFS V2). https://resstock.nrel.gov/dataviewer/efs_v2_base#building-characteristics

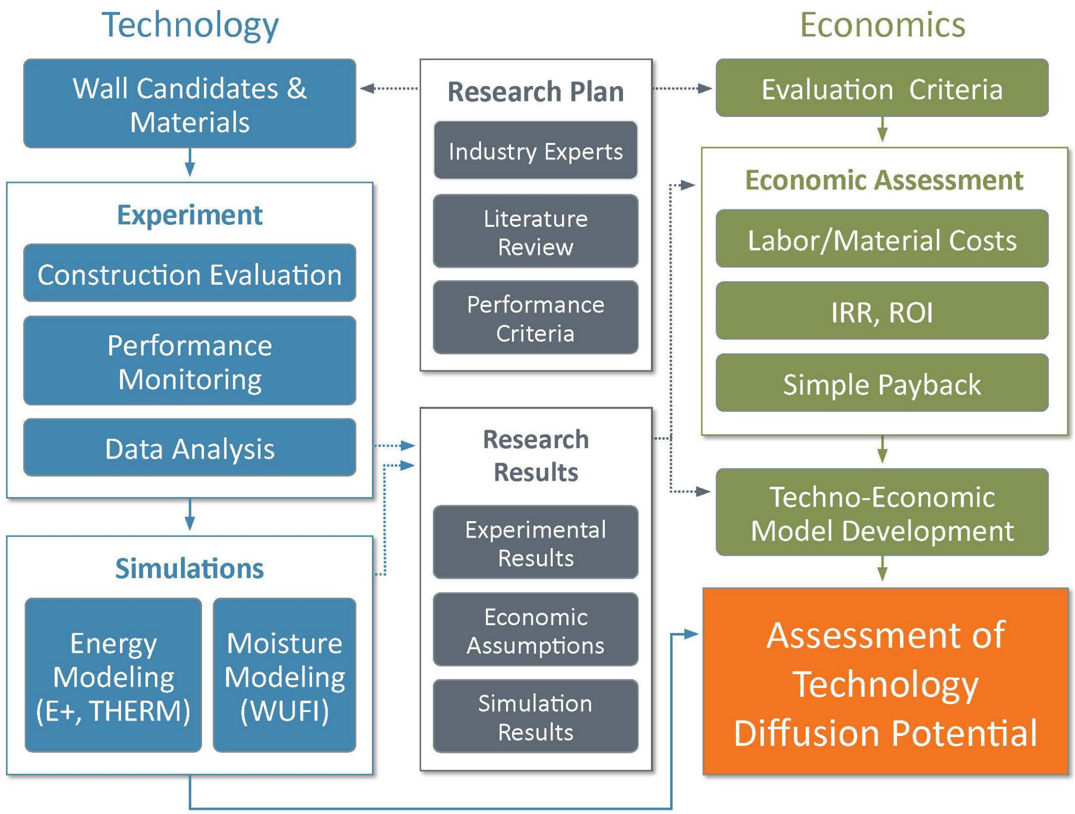

Figure ES.1. Project Flowchart

Target performance criteria and key research goals were based on input from industry experts and the literature review. Priorities included low air infiltration, constructability, affordability, ease of control layer installation, speedy installation, and wide-scale applicability. The team also chose a variety of thermal performance levels (not just "deep energy" retrofits for cold climates) as well as a variety of cladding treatments. This included retaining the existing cladding, to covering it, to complete removal and replacement. Table ES-1 lists the retrofit wall assemblies chosen for testing in the University of Minnesota's Cloquet Residential Research Facility (CRRF). Phase 1 walls were built in 2019 and Phase 2 walls were built the following year.

Table ES.1. Identifiers (ID) and Descriptions of 14 Test Wall Configurations and 2 Baselines

ID	Phase 1 Wall Description	ID	Phase 2 Wall Description
A	Baseline 1 – Typical uninsulated, circa 1950	I	Baseline 2 – Typical uninsulated, circa 1950
B	Drill-and-Fill Cellulose (dense-pack)	J	Drill-and-Fill Fiberglass (FG) (proprietary FG, high-density)
C	Injected Cavity Foam (proprietary cc-spu)	K	FG Batt + Interior Polyiso
D	Pre-Fab Exterior Expanded Polystyrene (EPS) (panel w/struts)	L	Drill-and-Fill FG + Exterior Polyiso
E	Drill-and-Fill Cellulose + Exterior XPS	M	Pre-Fab Exterior EPS/EIFS Panel System
F	Drill-and-fill Cellulose + Vacuum Insulated Panel (VIP)/Vinyl Siding	N	Pre-Fab Exterior Polyiso/Vinyl Block System
G	Exterior Mineral Fiber Board	O	Drill-and-Fill FG + Exterior FG Board
H	Exterior Graphite-Impregnated EPS (GPS) Structural Panel System	P	FG Batt + XPS + Oriented Strand Board (OSB) (thermal break shear wall)

Experiment and Constructability

Prototypes of each wall upgrade configuration were installed and instrumented on a test building in climate zone 7 (CZ-7) at the CRRF. Data gathered during the in situ testing then were used to validate energy and moisture models for simulating performance of the test assemblies in other climate zones. The exercise of building each baseline and test wall provided insight into the impacts and opportunities presented by different configurations.

Key findings included:

1. The simple geometry of the test walls provides limited insight into real-world constructability challenges.
2. Thicker walls require more time and effort to trim, detail and transition to openings, foundation, and soffits.
3. Fewer installation operations save time and effort.
4. Layers that can perform multiple duties (serve as multiple control layers, for instance) save time and effort.
5. Prefabricated components can sometimes provide predictability and efficiency to offset their cost premiums or save build time overall.

Some findings are more complex and specific. Walls that provide higher R-values without substantially increasing the thickness provide unique advantages. On the other hand, wall products that cannot easily be field modified create challenges.

Wall configurations installed over the top of existing exterior finishes were not always advantageous because air and water control layers were necessary. Adding a compressible fiberglass panel to fill between the existing finish and the new finish seemed to work well but increased time-on-task.

Prefabricated systems that incorporate necessary air and water control layers may have an advantage as all-purpose solutions but tended to be both thick and expensive. Drill-and-fill approaches were straightforward and fast because the existing siding did not have to be demolished and disposed of. Even when installed from the outside, insulation could be blown in through strategically located holes drilled into the sheathing, exposed by removing (and later replacing) just a few courses of siding.

Hygrothermal Modeling Results

Hygrothermal modeling is an important indicator of wall assembly moisture performance but is limited to ideal conditions; simulated results may not perfectly correlate with real-world performance due to field variations, construction errors, damage, and non-standard conditions. Hygrothermal simulations were carried out using WUFI Pro (Version 6.4) in all eight climate zones to understand the impact of the retrofit systems on moisture performance/durability. The material layer with the worst performance was taken to represent each test wall. The mold index was calculated in accordance with standard ANSI/ASHRAE 160-2016, Criteria for Moisture-Control Design Analysis in Buildings[1] to determine moisture durability for each

[1] ASHRAE. (2016). ANSI/ASHRAE Standard 160-2016: Criteria for Moisture-Control Design Analysis in Buildings. ASHRAE.

assembly. ASHRAE Standard 160 test method yields mold indices from 0 to 6; values of 3 and above indicate moisture vulnerability.

The resulting mold index was less than 3 for most walls in most climate zones; care should be taken for both Wall B (drill-and-fill cellulose) and Wall J (drill-and-fill fiberglass) in Subarctic, Very Cold and Marine climates. Note that if an added biocide were to be assumed for cellulose (per manufacturer) Wall B would potentially perform very similarly to Wall J—the same drill-and-fill method, but with fiberglass fill instead of cellulose, which results in fewer climate zones of concern for mold. In that case, as for Wall J, Wall B's sheathing would be the component most at risk of mold, rather than the cavity fill.

A third drill-and-fill (only) upgrade used closed cell injected foam (Wall C), with good moisture performance due to the relatively low permeability of the cavity fill foam—effectively preventing moisture from passing through the wall to locations cold enough to cause condensation.

The other two walls using drill-and-fill cellulose exhibited good moisture performance. Wall E also included an exterior layer of EPS continuous insulation, maintaining higher temperatures within the cavity and thus reducing the likelihood of condensation. Wall K included a 1-in. layer of polyisocyanurate on the interior side of the wall; the foil facing has very low permeability, successfully preventing the transport of moisture-laden air into the wall cavity.

This result is sensitive to the input assumptions for these materials and to air flow across the insulation materials, which in this case was assumed to be zero. In follow-on work, the team hopes to model the wall assemblies with a variety of air flow paths that may occur in real-world situations to further stress the wall assemblies.

Energy Modeling Results

A two-story, single family prototype building—originally defined to support building energy code development—was used to benchmark energy savings in each U.S. climate zone. To capture the conditions of the largest number of homes in the United States, the most frequent building characteristics (e.g., attic insulation level, window specifications, foundation insulation, etc.) were extracted from ResStock data and applied to the prototype model, intended to represent a typical home constructed in the mid-1950s.

Energy modeling results showed that the climate zones with the highest potential for retrofit savings are those which are heating-dominated (i.e., Cold and Very Cold climate designations) with heating and cooling energy use intensity (EUI) savings due to the wall retrofits alone ranging from 21.5% to 38.2%.

The various test configurations were specifically designed by the researchers to meet the loads of cold and very cold climates. Builders and homeowners in other climate zones may choose to modify the insulation levels to meet the "sweet spot" for matching thermal performance to load at the lowest cost. Results confirm that the highest potential for energy savings can be realized by first step interventions: adding insulation and/or air sealing where none exists. For all climate zones both thermal and air leakage improvements beyond these first step interventions produce diminishing effects on wall energy performance, confirming the importance of addressing the "low hanging fruit" in wall retrofits, meaning that retrofits do not necessarily need to be "deep" or invasive to significantly improve energy performance.

Economic Results

As with any other home improvement project, appearance, added value, and availability are compelling attributes for an energy upgrade. Use-driven rationale specific to energy upgrades typically focuses on occupant comfort, building durability, resilience, and conservation of finite energy resources. Even though energy savings translate very directly to utility dollar savings, the ability of an energy upgrade to offset some of its own cost should not be taken to imply that financial metrics are an appropriate single decision point. But when comparing competing methods for achieving other goals, financial metrics are useful differentiators.

Labor and Material costs were estimated for the 14 prototype walls and adjusted for sample locations throughout the U.S. according to standard industry practice. Cost data was combined with simulated energy cost savings using standard economic assumptions to yield internal rate of return (IRR) and simple payback.

Because this study focuses on cold climates, two representative cities are highlighted: Chicago, Illinois, and Burlington, Vermont. The five wall assemblies with the lowest per square foot installed costs (walls J, B, K, N, and C) were associated with paybacks of less than 10 years and IRRs in excess of 15%. Among the wall upgrades in this study, lower cost wall upgrades pay back faster, despite producing modest energy savings.

In addition to the traditional financial metrics described above, a market adoption analysis method was adapted from Fleiter et al. (2012)[1] and Hanes et al. (2019)[2] for use in this study and includes results from all other study categories of this project—material and labor costs, simulated energy cost savings over a 30-year life, simulated moisture performance, and relevant qualitative observations from the process of constructing the test walls, including ease and speed of installation, number of discrete process required, and availability of materials and equipment. Project team members with expertise in residential construction industry developed categories of attributes and assigned these categories weights based on the perceived importance of the attribute. Team members also assigned scores for each wall in each attribute category to reflect its performance or suitability for each attribute. Results then are normalized to fall between 0 and 1; scores closer to 1 indicate higher suitability within the priorities of the analysis design. Resulting adoption scores are specific to these wall upgrades and provide composite “ranking” useful for decision making. The results shown here illustrate the practicality and flexibility of this analysis method, which can easily be modified by decision makers to include the attributes most important in a particular region or for a specific situation; the user’s weighting choices reflect hierarchies of personal focus.

Section 6.4 Techno-Economic Modeling reports further details of the analysis methodology and resultant scores for all walls in four representative cold climates.

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[1] Fleiter, T., Hirzel, S., & Worrell, E. (2012). The characteristics of energy-efficiency measures – a neglected dimension. *Energy Policy*, *51*, 502–513. https://doi.org/10.1016/j.enpol.2012.08.054
[2] Hanes, R., Carpenter, A., Riddle, M., Graziano, D. J., & Cresko, J. (2019). Quantifying adoption rates and energy savings over time for advanced energy-efficient manufacturing technologies. *Journal of Cleaner Production*, *232*, 925–939. https://doi.org/10.1016/j.jclepro.2019.04.366

Overall Results and Conclusions

Up to 30% of existing homes in the United States have no cavity insulation and leaky construction. The retrofit interventions studied in this project provide many options for contractors and homeowners looking to save large quantities of energy, while increasing comfort and building durability. For the two climate zones of most concern—Cold and Very Cold—Table ES.2 provides a range of qualitative and quantitative metrics for assessing the full range of wall upgrade configurations tested, simulated, and analyzed. Cells with darker shades indicate better results, lighter shades are less good. Although the 4-ft. x 7-ft. geometry of the test wall does not reflect the range of complications one would likely encounter in the "real world," the construction exercise at the CRRF test site provided a consistent set of observations to compare the relative level of effort and complexities associated with each wall assembly included in the study.

Comparing the constructability metrics side-by-side against the pricing and the thermal and moisture performance allows a global perspective to that required by a contractor-homeowner team when making informed decisions. While it's intuitive that the best energy performers also are likely to be among the most expensive, it's also true that lowest first-cost solutions tend to have better financial results. Careful examination of all outcomes allows discernment between superficially similar options in the "middle of the pack" as well as the context to "mix and match." For instance, drill-and-fill approaches can be done from the interior or exterior and can use cellulose, fiberglass, or foam and can be done as the only intervention or in combination with one of many types of rigid insulation installed on either the inside or outside. ft^2

Table ES.2. Summary of Test Wall Results for CZ-5 and CZ-6.

		Construction / Performance							Economics Chicago					Economics Burlington				
ID	**Name**	**Materials Acquisition**	**# Operations**	**Installation SPEED**	**Installation EASE**	**Added thickness, in.**	**Moisture Risk by CZ**	**Assembly R-Value (eff)**	**Energy Cost Savings, %**	**EUI Savings, %**	**Cost $/ft^2 Wall**	**IRR**	**Simple Payback**	**Energy Cost Savings, %**	**EUI Savings, %**	**Cost $/ft^2 Wall**	**IRR**	**Simple Payback**
B	Drill-and-Fill Cellulose (dense-pack)	1	2	1	1	0	4C 5 6 7 8	14.2	18%	21%	$2	22%	5	18%	22%	$2	36%	3
C	Injected Cavity Foam (proprietary cc-spu)	X	2	2	1	0		19.5	22%	26%	$6	7%	13	22%	27%	$6	12%	8
D	Pre-Fab Exterior EPS (panel w/struts)	3	3	1	2	5.3		24.8	29%	35%	$20	0%	31	30%	36%	$21	3%	19
E	Drill-and-Fill Cellulose + Exterior XPS	1	5	3	3	2.5		28.4	30%	36%	$19	0%	28	31%	37%	$19	4%	17

		Construction / Performance							Economics Chicago					Economics Burlington				
ID	Name	Materials Acquisition	# Operations	Installation SPEED	Installation EASE	Added thickness, in.	Moisture Risk by CZ	Assembly R-Value (eff)	Energy Cost Savings, %	EUI Savings, %	Cost $/ft^2 Wall	IRR	Simple Payback	Energy Cost Savings, %	EUI Savings, %	Cost $/ft^2 Wall	IRR	Simple Payback
F	Drill-and-Fill Cellulose + VIP/Vinyl Siding	X	4	3	2	0.5		25.5	29%	36%	$14	2%	22	31%	36%	$14	6%	13
G	Exterior Mineral Fiber Board	3	3	2	3	5.3		22.9	29%	35%	$18	1%	27	30%	36%	$18	4%	16
H	Exterior GPS Structural Panel System	3	4	3	2	7		28.5	30%	36%	$22	-1%	32	31%	37%	$22	3%	20
J	Drill-and-Fill Fiberglass (proprietary FG, high-dens)	2	2	1	1	0	4C 7 8	16.5	21%	25%	$2	25%	4	22%	26%	$2	42%	2
K	Fiberglass Batt + Interior Polyiso	1	4	2	3	1		20.6	20%	24%	$5	9%	10	21%	24%	$5	16%	6
L	Drill-and-Fill FG + Exterior Polyiso	1	5	3	3	1.5		22.8	29%	35%	$14	2%	22	30%	36%	$15	6%	13
M	Pre-Fab Exterior EPS/EIFS Panel System	4	3	2	2	5.8		27.2	30%	36%	$45	-5%	67	31%	37%	$45	-2%	41
N	Pre-Fab Exterior Polyiso/Vinyl Block System	X	2	1	2	4		27.6	29%	36%	$5	13%	8	31%	37%	$5	22%	5
O	Drill-and-Fill FG + Exterior FG Board	3	4	2	3	3.3		25.2	29%	36%	$17	1%	25	31%	36%	$17	5%	15
P	FG Batt + XPS + OSB (thermal break shear wall)	1	6	4	4	0.8		18.9	28%	34%	$16	1%	25	29%	35%	$16	5%	15

Two tested wall upgrades for energy retrofits can likely be accomplished for about $2/ft^2 of wall:

- B – Drill-and-Fill Cellulose (high-density)
- J – Dense-Pack FG.

Three more walls were priced at between $4.50 and $6.50/ft^2 of wall:

- K – Fiberglass Batt + Interior Polyiso
- N – Pre-fab Exterior Polyiso/Vinyl Block System
- C – Injected Cavity Foam (proprietary cc-spu).

All five of these lower cost approaches leave the exterior siding in place, although walls B, C, and J require that a few courses of siding be removed to provide access for each stud cavity to be filled with blown insulation. Patching the sheathing and control layers and replacing and touching up the siding are tasks well within the skill set of most residential contractors. Wall N leaves siding in place but wraps it in weather-resistive barrier with taped edges and then builds up the new prefab wall in front of the old wall. Wall K leaves the siding untouched because all work is done on the inside of the house. However, the disturbance to the homeowner might not make sense unless they are already undertaking a major interior remodel.

Walls B, J, and C presume the existing home's stud cavities are completely empty. Drill-and-fill is not an option when walls are already filled will insulation, no matter how inadequate.

These five methods (i.e., B, J, K, N, and C) all provide energy savings although not all of them bring the existing building up to the current prescriptive energy code minimum for enclosure insulation. Based on hygrothermal simulations most of the methods provide appropriate moisture performance; only walls B and J may potentially be less moisture resilient in the Marine, Very Cold, and Subarctic climates.

Finally, four of these five wall upgrades (B, C, J, and K) do not result in new exterior siding, unique among the 14 tested walls. This keeps costs low when an energy upgrade is the only goal. The cost of the siding is included as a necessary component in the energy upgrade pricing of wall N and all others, so the intrinsic value of this new exterior finish should reasonably be accounted for by decision makers. In fact, if a homeowner had already budgeted for and committed to a re-siding project, the opportunity cost these other walls should be calculated as a separate line item for transparency.

Ultimately, both first cost and long-term energy savings contribute to a calculation to determine whether a builder recommends—or a homeowner chooses—a particular retrofit. In Cold and Very Cold climates, the five wall upgrades listed above—B, J, K, N and C—all provide payback of 13 years or less, and impressive IRRs ranging from 12% to 42% in cold climates. Moisture performance improvements to walls B and J and potential cost reductions (as a result of faster installation due to increased exposure or lower first cost due to market penetration) for walls C, K, and N would seem to warrant the most attention.

In the prefabricated wall category the manufacturer provided a unit cost for wall N that reflects the necessary profit margin if the wall – currently a prototype – were to be widely adopted. Wall H is more of a concept than a prototype, so had to be built up in layers on site; the cost reflects that complexity and no attempt was made to predict the price for a widely available factory-built version in the retail market. Wall M is currently in the marketplace at small scale at a somewhat introductory price; increased demand is likely to result in lower pricing.

Emerging products are relatively untested in the market, and the cost estimates are associated with a high degree of uncertainty. Two other innovative wall upgrades yielded promising adoption scores and appear to be ripe for market growth/introduction. Wall D [Pre-Fab Exterior EPS (panel w/struts)] is new to the market, and Wall F (Drill-and-Fill Cellulose + VIP/Vinyl Siding) is not yet commercially available. As with Wall N, both shift some of the labor associated with high-R walls into a factory setting, potentially streamlining on-site execution. Both received high marks from the University of Minnesota installation team for speed and ease. An important caveat for decision-making is to fine-tune the energy performance to the local climate conditions according to the law of diminishing returns. These test walls were designed for cold and very cold climates. That level of performance may not be necessary in milder conditions; configurations that are easily modifiable to incrementally reduce both R-value and cost should be strong contenders for market acceptance.

The large amount of wall area in a house combined with the complexities of connecting to the foundation and soffits, and detailing around each window, door and mechanical penetration, means that a wall upgrade can be materials-intensive and labor-complex. Finding additional advantages is therefore key, like coordinating with other improvement projects such as re-siding, window replacement, or remodeling. The cost and financial return of walls that result in new siding may not be directly comparable to walls in which the siding is not upgraded. Another opportunity is to add a new performance goal such as improved shear strength or fire resilience, in areas impacted by increased weather events or wildfire risk. These approaches can add perspective to the high first cost of these major undertakings.

Three of the tested walls are prototypical so accurately pricing both labor and materials is challenging. But both IRR and simple payback are very sensitive to first costs, so improvements that translate to labor or product cost savings are likely to have a strong positive effect.

The overarching issue is that in today's market, first-costs are too large, and projected annual energy cost savings too small, to make the time and trouble of the most intensive wall upgrades the first and easiest answer for the typical homeowner. The hefty price tag of these "deep energy retrofits" is likely to be acceptable to only a very committed subset of homeowners.

But this research confirms that even modest interventions can make a substantial difference, and careful planning can ensure good performance as well as good return on investment. DOE's Advanced Building Construction (ABC)[1] Initiative aims to help drive down the cost of these novel options to be more cost competitive with traditional techniques by making installation quicker and therefore less expensive. Ideally, some of these exterior wall retrofit solutions would also add resale value. And of course, a good wall upgrade improves occupant comfort, reduces operational carbon footprint, and decreases dependence on fossil fuels. Financial return should not be the only—or even primary—decision point.

This project provided insight into a great deal of future work to drill down or expand on understanding, leading to stronger, more reliable recommendations.

[1] https://advancedbuildingconstruction.org/

Experiment and Construction:

- Adding cooling equipment to the CRRF to validate performance in summer conditions.
- Further study of the impact of installation cost due to construction complexities and adding. thickness to walls
- What main installation challenge can prefabricated products solve?

Hygrothermal Modeling:

- Test, simulate more “drill-and-fill” products, due to condensation risk.
- Are there more expedient ways to ensure higher cavity temperatures?
- Should IRC Section R702.7 Vapor Retarders[1] apply to retrofits?
- Testing to simulate breaches to understand the impact of leaks.

Energy Modeling:

- Fine tune wall upgrade recommendations for CZ 1 through 4.
- Align air leakage modeling assumptions reliably with whole building examples.
- Examine the impact of air leakage improvement for retrofits versus new construction.

Techno-Economics:

- Use the detailed pricing developed in this project to design hypothetical wall upgrades to test new combinations of continuous insulation plus drill-and-fill, fine-tuned for other climate zones.
- Develop an Adoption Matrix worksheet or app with user flexibility for customization.
- Identify additional homeowner values (e.g. resiliency) to boost adoption of wall upgrades.
- Re-survey prefab and proprietary products for improvements, new contenders.
- Determine the existing housing needs and impacts with respect to sustainability, climate change, carbon footprint, and future energy costs.

[1] ICC. (2018). *International Residential Code*. https://codes.iccsafe.org/content/IRC2018P4

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Acronyms and Abbreviations

ASHRAE	American Society of Heating Refrigerating and Air-Conditioning Engineers
CRRF	Cloquet Residential Research Facility
CZ	climate zone
DAS	data acquisition system
DOE	U.S. Department of Energy
EEM	energy efficiency measure
EIFS	exterior insulated finish systems
EPS	expanded polystyrene
EUI	energy use intensity
GPS	graphite polystyrene
IRR	internal rate of return
HVAC	heating, ventilation, and air-conditioning
LAM	liquid applied membrane
NPV	net present value
ORNL	Oak Ridge National Laboratory
OSB	oriented strand board
polyiso	polyisocyanurate
PNNL	Pacific Northwest National Laboratory
ROI	return on investment
R-value	a measure of thermal resistance: $(ft^2 \cdot °F \cdot h)$ / BTU
UMN	University of Minnesota
VIP	vacuum insulated panel
WRB	weather-resistant barrier
XPS	extruded polystyrene

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1.0 Introduction

In the United States, 39% of total energy is consumed by the building sector, and half of that total by residential buildings (EIA 2018). Current energy codes for new homes result in relatively high performance through a combination of tight building envelopes; mechanical ventilation and efficient heating, ventilation, and air conditioning (HVAC) equipment; adequate airflow; and moisture control. These systems work together to create energy-efficient homes that also include measures to manage moisture and indoor pollutants. Older homes, built before 1992 when the U.S. Department of Energy (DOE) established its Residential Building Energy Codes program, represent approximately 68% of the residential building stock in the country (USCB 2017). These older homes often have significant air leakage, inadequate insulation, and inefficient windows. Homes with little to no air sealing or insulation have heating and cooling losses that can account for a substantial portion of utility bills. Done correctly, deep energy retrofits can significantly increase the energy performance of a home's thermal envelope, decrease indoor pollutants, increase homeowner comfort, and improve durability, thus extending the useful life of the building.

The DOE Building Technology Office collaborates with stakeholders in the building industry to improve energy efficiency in new and existing buildings. DOE's Residential Buildings Integration program sponsors this research as part of a larger research portfolio aimed at reducing energy use intensity in residential buildings that can serve as robust examples to encourage practices that will substantially improve energy performance across the entire sector.

Older homes often have significant air leakage, inadequate insulation, and inefficient windows. Windows and walls slowly deteriorate over time; unlike appliances or HVAC deterioration of windows and walls is not always obvious. Even when thermal, moisture, and infiltration issues with a home's façade are recognized, the path toward resolving issues is often fraught with technological, financial, and social challenges. Additionally, both problems and solutions will typically vary by region, climate zone, and type of construction.

In support of DOE's move toward transformational, whole-building upgrades and enclosure solutions, Pacific Northwest National Laboratory (PNNL), Oak Ridge National Laboratory (ORNL), and the University of Minnesota (UMN) have partnered and collaborated with leading building science researchers and home performance entities to itemize and characterize technical and economic barriers to facade retrofits in an effort to identify market-viable façade solutions and opportunities for an actionable plan to transform the market.

This project is comprised of an experimental study, a simulation study, and a market analysis and techno-economic study undertaken to examine comprehensive energy retrofits of residential enclosures that include both traditional and innovative wall upgrades to result in durable, energy efficient, and marketable energy retrofit strategies. The goal of this study is to advance the state of knowledge regarding reliable, cost-effective, high-performing wall configurations for energy retrofits and to characterize the viable market, identify barriers to uptake, analyze economic opportunities, and develop documentation specifically aimed to overcome technical and market barriers associated with adoption.

1.1 Project Team

1.1.1 Pacific Northwest National Laboratory

The following PNNL staff led and conducted the research for this project (Figure 1-1).

Cheryn Metzger
Co-PI, Project Manager

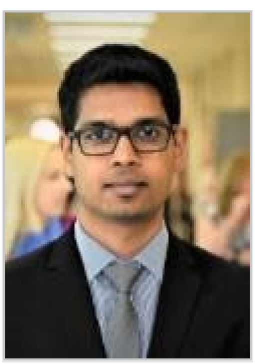
Jian Zhang
Co-PI, Energy Modeling

Philip Jenson
Assistant Project Manager

Chrissi Antonopoulos
Techno-Economic Analysis

Sumitrra Ganguli
Techno-Economic Analysis

Travis Ashley
Data Analysis/Management



Harshil Nagda
Energy Modeling

Tyler Pilet
Energy Modeling, Documentation

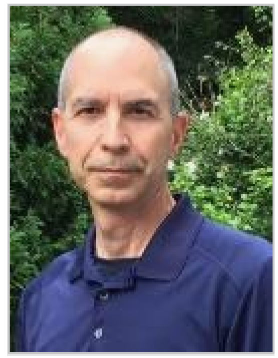
Patti Gunderson
Review, Documentation

Figure 1-1. Pacific Northwest National Laboratory Research Team

1.1.2 Oak Ridge National Laboratory

The following ORNL staff participated in the research and performed the hygrothermal simulation for this project (Figure 1-2).

Andrè Desjarlais
ORNL Project Management

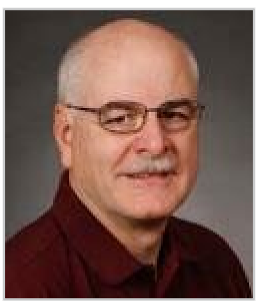


Anthony Aldykiewicz
Hygrothermal Modeling

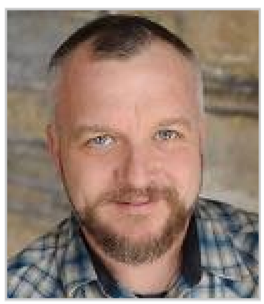
Figure 1-2. Oak Ridge National Lab Research Team

1.1.3 University of Minnesota

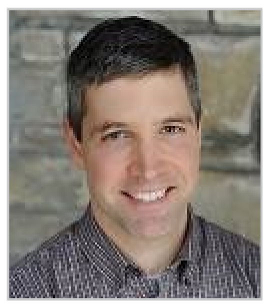
The following UMN staff participated in the research and performed specimen construction and lab testing for this project (Figure 1-3).



Pat Huelman
UMN Project Management



Garret Mosiman
Field Research Lead



Rolf Jacobson
Field Research Support

Fatih Evren
Data Acquisition

Figure 1-3 University of Minnesota Research Team

1.2 Research Questions

The primary research questions associated with this study are:

1. What types of construction challenges are present in retrofit wall approaches? Do these challenges impact viability in the retrofit market?
2. Under what circumstances does it make sense to retrofit walls over the existing cladding? Are there approaches that show ability to scale in the marketplace?
3. What is the thermal and moisture performance of different wall retrofit approaches, and how does performance vary between climates?

4. To what extent do cost factors such as high material and labor costs, long payback periods and low internal rate of return impact the economic viability of wall retrofit approaches? Are there advancements on the horizon that indicate better prospects for the economics of particular wall solutions?
5. Is there a clear path for reducing installation costs substantially or in the near-term for any of these wall solutions?

Secondary research questions include the following:

1. What are the best methods and metrics for comparing similar wall retrofit strategies?
2. Can solutions be usefully categorized for presentation to by insulation type? By installation complexity? By cost or return on investment (ROI)?

2.0 Experimental Design

This section provides background information on the study design, experimental approach, and criteria.

2.1 Literature Review

A comprehensive literature review was conducted in early 2019 to explore various innovative insulation materials, context and background for the planned experimentation, simulation approaches, and techno-economic analysis, including an examination of the anticipated use of final conclusions and recommendations by builders and building owners who were the constituents of the project (Antonopoulos et al. 2019).

The literature review provides an overview of the thermal and moisture performance of typical wall assemblies, identifies relevant research, and summarizes current practices for exterior wall retrofits for existing homes, focusing on retrofit applications to the exterior side of a wall assembly. Retrofit wall assemblies that can be applied over existing siding for reduced installation costs were of particular interest.

Findings from the literature review provided important context for the experimental plan, including a range of wall retrofit assemblies and innovative materials and methods being developed or tested by others and methods for monitoring wall performance and simulating building performance based on those results.

2.2 Advisory Committee

The research team engaged with leading thermal enclosure experts from industry, academia, national laboratories, state and federal program administrators, and other research organizations throughout the duration of this project. In the first advisory committee meeting (held on April 19, 2019, in Arlington Virginia), 27 experts (see the Acknowledgements section) plus the project team, helped identify and characterize candidate wall retrofit assemblies, and informed the research plan.

These leading researchers and innovators shared information and experience, collaborated on the development of the research methodology, identified test wall criteria, and reviewed and commented on results. Table 2-1 and Table 2-2 list the top voting results for the two primary questions:

1. What are the most important criteria that should be considered when choosing wall assemblies to be tested?
2. Which wall assemblies should the project focus on for in situ testing?

Results from the first advisory committee meeting are published in an expert meeting report (Antonopoulos, Baechler, et al. 2019). Subsequent advisory committee meetings took place on December 9, 2019; June 24, 2020; January 20, 2021; and July 12, 2021. No reports were published for the other meetings.

Table 2-1. Criteria Voting Outcome Voting Outcomes

Criteria	Description	Expert Meeting Votes
Air infiltration	Amount of air leakage measured by air changes per hour?	23
Constructability	How "fool proof" is this assembly to install?	22
Cost/ft^2 (labor)	Labor cost	18
Control layers	Speed, complexity - Easy, Intermediate, Hard? Applied on-site or prefabricated?	16
Time to install	How long does the assembly take to install?	14
Cost/ ft^2	Material cost?	13
Service life	How long is the expected life of this assembly?	13
Disaster resilience	Does this wall assembly improve resistance to other risks (e.g., earthquake, flood, pest, fire and wind)?	11
Roof, foundation interfaces	Is detailing easy, medium, hard at roof/wall & foundation/wall intersections?	10
Embodied energy	Does the assembly have a life-cycle cost analysis? Is there improved performance from a sustainability perspective?	10

Table 2-2. Wall Assembly Voting Outcomes

Wall Assembly Name	Expert Meeting Votes
Exterior Rigid Insulation	16
European Panels	16
Foam Panel with Plastic Struts	16
Minimally Invasive Cavity Spray Foam	15
Nail Base Retrofit Insulation Panels	14
Canadian Composite Concrete Material	13
Insulated Vacuum Panel Siding	13
Three-Dimensional Printed Skins: On-Site or Off-Site	10

Wall Retrofit Assembly Selection Criteria

Based on the voting exercise, the advisory committee determined that the following criteria were the most important to consider when choosing wall assemblies to study:

- Air infiltration
- Constructability
- Cost
- Ease of control layer installation
- Time to install.

In addition to those criteria, the team consulted with DOE to determine that wide-scale applicability should be considered as criteria as well. Last, while the original project focused only on “deep” energy retrofits and only on solutions that would be applied over cladding, the results of the initial advisory committee meeting showed that all levels of retrofits should be considered. Ultimately the test matrix included both solutions in which the cladding was removed and solutions for which the existing cladding was retained.

2.3 Wall Retrofit Systems

Taking into consideration all the inputs and research questions, the following 14 wall retrofit systems and two baseline walls (described in Section 5.1 Methodology) were chosen for inclusion in this study. All walls are framed with 2 x4-in. (nominal) studs, 16-in. on center, with gypsum board on the interior. Table 2-3 shows the summary of each wall layer. For more details on each wall layer, see Appendix A.

Table 2-3. Test Matrix Wall Systems Chosen for Inclusion in this Study

ID	Wall Name, R-assembly, hr-ft^2-F/Btu	Wall Layers
A	Baseline 1 R- 4.2	• Gypsum board with one coat of vapor retarder paint/primer (to represent several layers of interior paint over time) • Cavity – empty • Sheathing – 1- x 6-in. spruce/pine/fir (SPF) boards • Asphalt-impregnated building paper • Bevel cedar siding with one coat of oil base primer, one coat of vapor retarder paint, and one coat of latex paint (to represent several layers of exterior paint over time)
B	Drill-and-Fill Cellulose (dense-pack) R-14.2	• Gypsum board with one coat of vapor retarder paint/primer • Cavity – dense-pack cellulose • Sheathing – 1- x 6-in. SPF • Asphalt-impregnated building paper • Bevel cedar siding with two coats oil-based paint
C	Injected Cavity Foam (proprietary cc-spu) R19.5	• Gypsum board with one coat of vapor retarder paint/primer • Cavity – high-density, closed-cell spray foam • Sheathing – 1- x 6-in. SPF boards • Asphalt-impregnated building paper • Bevel cedar siding with two coats oil-based paint
D	Pre-Fab Expanded Polystyrene (EPS) (panel w/struts) R-24.8	• Gypsum board with one coat of vapor retarder paint/primer • Cavity – empty • Sheathing – 1- x 6-in. SPF boards • Asphalt-impregnated building paper • Bevel cedar siding with two coats of oil-based paint • Compressible fiberglass with spunbonded polyolefin weather-resistant barrier (WRB) • 4.5-in. EPS panels with built-in drainage channels • Vinyl siding
E	Drill-and-Fill Cellulose + Exterior Extruded Polystyrene (XPS) R-28.4	• Gypsum board with one coat of vapor retarder paint/primer • Cavity – dense-pack cellulose • Sheathing – 1- x 6-in. SPF boards • Spunbonded polyolefin WRB 2-in. XPS • 1- x 4-in. SPF furring strips with XPS between • Vinyl siding
F	Drill-and-Fill Cellulose + VIP/Vinyl Siding R-25.5	• Gypsum board with one coat of vapor retarder paint/primer • Cavity – dense-pack cellulose • Sheathing – 1- x 6-in. SPF boards • Spunbonded polyolefin WRB • VIP Vinyl Siding

ID	Wall Name, R-assembly, hr-ft^2-F/Btu	Wall Layers
G	Exterior Mineral Fiber Board R-22.9	• Gypsum board with one coat of vapor retarder paint/primer • Cavity – empty • Sheathing – 1- x 6-in. SPF boards • Asphalt-impregnated building paper • Bevel cedar siding with two coats of oil-based paint • Liquid applied membrane • 4-in. mineral wool board • 1- x 4-in. SPF furring strips • Fiber cement lap siding
H	Exterior Graphite-Impregnated EPS (GPS) Structural Panel System R-28.5	• Gypsum board with one coat of vapor retarder paint/primer • Cavity – empty • Sheathing – 1- x 6-in. SPF boards • Asphalt-impregnated building paper • Bevel cedar siding with two coats of oil-based paint • Compressible fiberglass panel • Oriented strand board (OSB) panel • Fully adhered membrane • 4¼-in. GPS • 1- x 4-in. SPF furring strips • Metal siding
I	Baseline 2	• Gypsum board with one coat of vapor retarder paint/primer • Cavity – empty • Sheathing – 1- x 6-in. SPF boards • Asphalt-impregnated building paper • Bevel cedar siding with two coats of oil-based paint
J	Drill-and-Fill Fiberglass (proprietary FG, high-dens) R-16.5	• Gypsum board with one coat of vapor retarder paint/primer • Cavity – dense-pack fiberglass • Sheathing – 1- x 6-in. SPF boards • Asphalt-impregnated building paper • Bevel cedar siding with two coats of oil-based paint
K	Fiberglass Batt + Interior Polyiso R-20.6	• Gypsum board with one coat of vapor retarder paint/primer • 1-in. foil-faced polyiso foam board • Cavity – R-13 FG batt • Sheathing – 1- x 6-in. SPF boards • Asphalt-impregnated building paper • Bevel cedar siding with two coats of oil-based paint
L	Drill-and-Fill FG + Exterior Polyiso R-22.8	• Gypsum board with one coat of vapor retarder paint/primer • Cavity – dense-pack FG • Sheathing – 1- x 6-in. SPF boards • Spunbonded polyolefin WRB 1-in. foil-faced polyiso foam board • 1- x 4-in. SPF furring strips • Wood composite lap siding
M	Pre-Fab Exterior EPS/EIFS Panel System R-27.2	• Gypsum board with one coat of vapor retarder paint/primer • Cavity – empty • Sheathing – 1- x 6-in. SPF boards • Liquid applied membrane • 6-in. EPS foam panel
N	Pre-Fab Exterior Polyiso/Vinyl Block	• Gypsum board with one coat of vapor retarder paint/primer • Cavity – empty

ID	Wall Name, R-assembly, hr-ft^2-F/Btu	Wall Layers
	System R-27.6	• Sheathing – 1- x 6-in. SPF boards • Asphalt-impregnated building paper • Bevel cedar siding with two coats of oil-based paint • Spunbonded polyolefin WRB • 4-in. prefabricated polyisocyanurate foam blocks with vinyl skin
O	Drill-and-Fill FG + Exterior FG Board R-25.2	• Gypsum board with one coat of vapor retarder paint/primer • Cavity – empty • Sheathing – 1- x 6-in. SPF boards • Asphalt-impregnated building paper • Bevel cedar siding with two coats oil-based paint • Spunbonded polyolefin WRB 2-in. mineral fiber board • 1- x 4-in. SPF furring strips • Fiber cement lap siding
P	FG Batt + XPS + OSB (thermal break shear wall) R-18.9	• Gypsum board with one coat of vapor retarder paint/primer • Cavity – R-13 fiberglass batt • 1-in. XPS foam board • OSB sheathing • Spunbonded polyolefin WRB • Vinyl siding

3.0 In Situ Experiment

3.1 Background

In situ testing is valuable for several reasons. First, it provides the opportunity to purchase goods in the local market, which is a useful touchstone for product availability and cost estimating. Second, it allows the research staff to work with the materials to determine construction challenges and identify opportunities for streamlining processes or refining details.

Finally, real-time measurements of local weather conditions combined with performance data gathered from the walls such as heat flux, temperature, relative humidity, and moisture content allows energy modelers to refine inputs and calibrate their simulation tools for accuracy. Once results are confirmed, these wall characteristics can be reliably extrapolated to other climate zones for consistent energy modeling.

The experimental portion of this project was carried out by UMN at the Cloquet Residential Research Facility (CRRF). This research building (Figure 3-1) is located on the Cloquet Forestry Center near Cloquet, Minnesota, which is approximately 20 miles west of Duluth and in Climate Zone 7. The CRRF was constructed by the UMN in 1997 with funding from Saint Gobain and CertainTeed Corporation to evaluate long-term, cold-climate performance of full-scale building enclosure assemblies.

Figure 3-1. CRRF in Climate Zone (CZ) 7

The CRRF building is oriented along an east-west axis to maximize its northern and southern exposures. It sits on a full basement with 12 independent above-grade test bays protected by two end guard bays (Figure 3-2). These test bays are also thermally isolated from the two basement test bays. Eight test bays (1 to 4 and 9 to 12) were selected to conduct in situ testing of the wall energy upgrades for this project, with two 4- x 7-ft wall assemblies installed in the exterior wall of each bay on both the north and the south exposures.

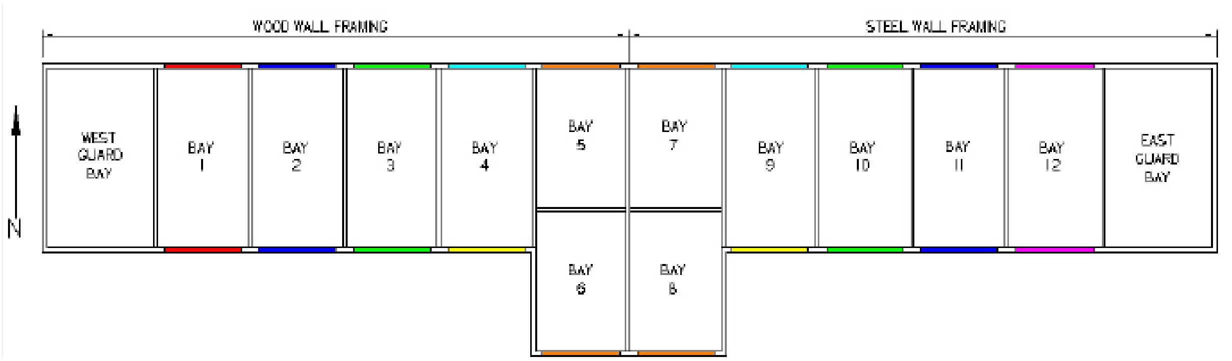


Figure 3-2 Floorplan of the CRRF. Central bays not used; two test walls on each exposure of each bay.

3.2 Overall Approach

Phase 1 retrofit test walls were installed in December of 2019 in Bays 1 through 4. Phase 2 used Bays 9 through 12 and the test walls were installed in December 2020. The middle bays (5 through 8) were not used for this project but the extension of Bays 6 and 8 do provide some morning and afternoon shading of the south walls of Bays 4 and 9, respectively. Each test bay has a north and south facing wall opening that is approximately 8-ft wide by 7-ft high. These test openings were divided vertically in half to support two different test panels, each approximately 4-ft wide by 7-ft high. Each test panel was mirrored on both the north and south orientation.

Panels were carefully sealed into the building's rough opening. In Phase 2 of this project, a receiver sleeve was added around each test panel opening and the test panels then were sealed to the receiver. This simplified the installation and will aid in future removal of individual test panels.

Each test panel has three wall cavities at approximately 16-in. on center to represent older wood-frame construction. The center cavity of each test panel was a true 16-in. on center and was designated as the test cavity (Figure 3-3). All of the monitoring sensors were placed in this center test cavity.

The wall cavities on each side of the test cavity were designed as guard cavities. They received the same insulation treatment to mitigate any differential horizontal heat flows between the test and guard cavities. The vertical heat flow was not as well controlled although the rim joist under the test opening was insulated as was the header above the test opening. Retrofit wall configurations with uninsulated test cavities and exterior insulation treatments were further guarded with a 3-in. XPS block at both the top and bottom of the test cavity to reduce diagonal heat transfer at the top and bottom. Both horizontal and vertical moisture flows between the test panels and test opening were controlled with the use of low permeability membrane tapes.

Figure 3-3 All Monitoring Sensors are Within the Center Test Cavity. Wall cavities on each side are guard cavities.

3.3 Base-Case Wall Preparation

Once the team had determined the base-case wall for in situ testing, the UMN team built 16 identical reference walls (Figure 3-4) for each phase as described in Table 2-3 and Appendix A. The exterior finish was selected to represent an older house with several coats of oil-based paints. The interior finish was selected to represent an older home with heavy drywall or plaster and several coats of paint.

Figure 3-4 Exterior View of CRRF Test Bays Showing Baseline Wall Construction Without the Exterior Cladding Applied

3.4 Data Acquisition System (DAS)

The DAS for the in situ experiment was based on the Campbell Scientific CR-1000X datalogger. The centrally located logger collected data from modules located in each test bay. Temperature, relative humidity, and heat flux signals were captured with Temp-120 and Volt-116 modules, respectively. There was one AM-16/32 module per test bay that collected moisture content data. The dataloggers were connected to a Sierra RV-50X cellular modem for data transmission to the UMN, ORNL, and PNNL staff.

Each test cavity had between 15 and 20 sensors depending on the wall treatment. These sensors included multiple sensor types and multiple locations. The sensor types and models installed in wall assemblies are in Table 3-1. The primary sensor array was located along a line through the wall section traversing the center of the width and height of the test cavity. In addition to the center line sensor array, there were secondary temperature and relative humidity sensors on the interior surface of the sheathing located approximately 6 inches from the top and bottom of the test cavity. The mapping for sensors built into the walls is shown in cross-section schematics for each wall type, located in Appendix E.

Table 3-1. Sensors Installed in the Wall Assembly for Performance Data Collection

Sensor Type	Sensor Model
Temperature	Omega Type-T thermocouples
Relative Humidity	Honeywell HIH-4000
Heat Flux	FluxTeq PHFS-09e
Moisture Content	Brass nails (shaft coated with enamel paint)

Following is a generalized description of the locations for each of the sensor types. Temperature sensors were installed on the interior and exterior surfaces of the drywall, interior and exterior surfaces of the sheathing, and the exterior surface of the siding. A relative humidity sensor was placed on the cavity-side surface of the drywall along with the interior and exterior surfaces of the sheathing. The heat flux plate was located on the interior surface of the drywall. The insulated moisture content pins were inserted from the cavity side to measure the moisture content of the interior and exterior surfaces of the pine sheathing as well as the middle of the cedar siding. In the cases where a cavity insulation was to be installed a protective cap was placed over the moisture content pins.

All sensor wires were run horizontally through a sealed opening into the guard cavity and then out to the test bay modules through a sealed block (Figure 3-5 and Figure 3-6).

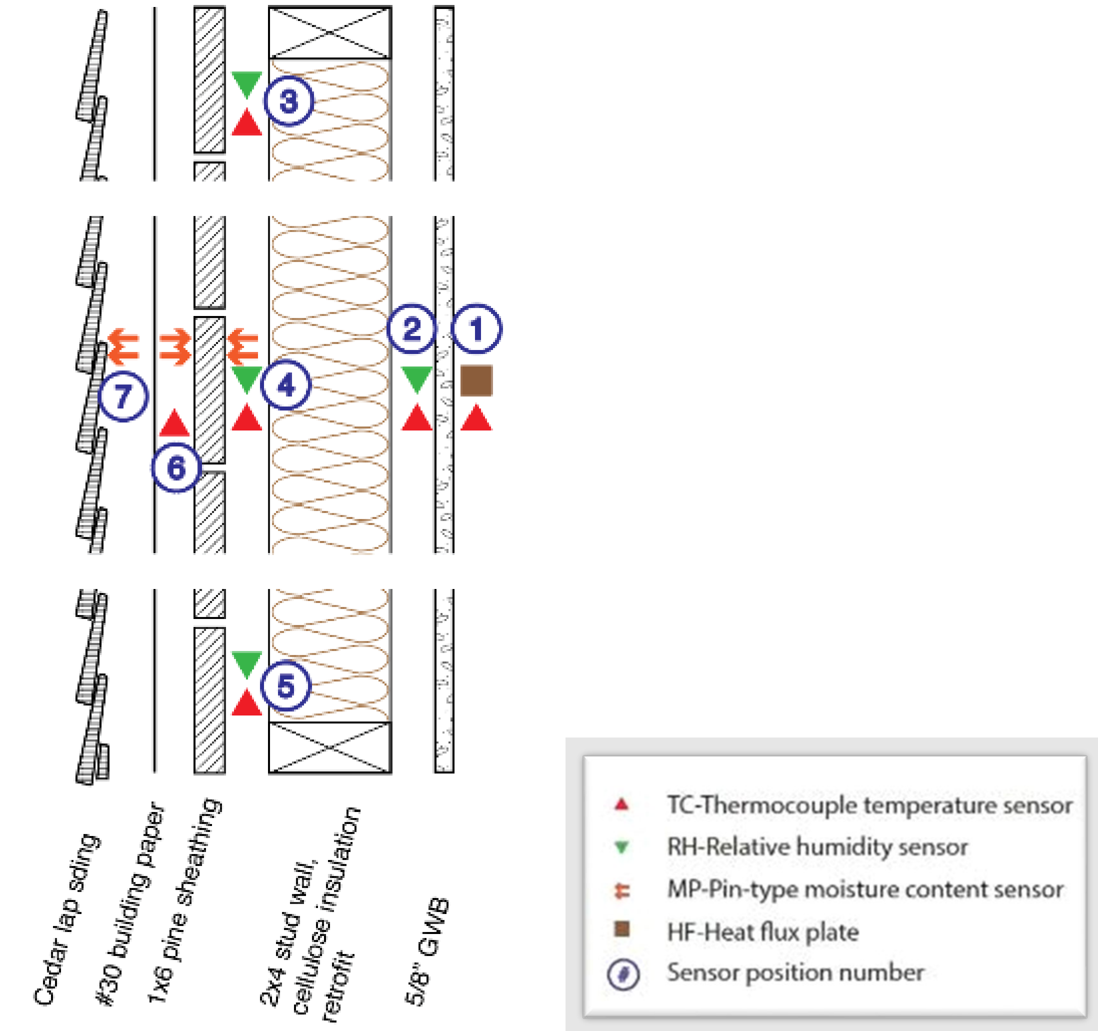


Figure 3-5. Example Test Wall Sensor Layout at the CRRF Test Facility

The DAS also was set up to collect interior and exterior boundary conditions. The interior temperature and relative humidity were measured in each test bay and recorded on the DAS. In Phase 1, the outside temperature, humidity, wind speed, and precipitation conditions were gathered from local weather stations.[1] For Phase 2, a weather station was added to the CRRF with temperature, relative humidity, wind speed and direction, rain gauge, and horizontal pyranometer. Also, two Campbell Scientific pyranometers (CS-320) were used to measure solar radiation of the vertical wall surface on both the north and south exposure. An additional six vertical pyranometers were added in Phase 2. Two of these were added to determine the impact of shading on the test walls in Bays 4 and 9.

[1] Using wunderground.com station KMCO

Figure 3-6 Example Sensor Installation in Wall A – Base-Case

3.5 Air Tightness Calibration

It is well documented that air leakage can significantly affect the thermal and moisture performance of a wall system. So it was critical to make sure that each of the 32 base-case walls (the substrate that represents the exiting conditions) had a similar overall air leakage rate across the assembly. To accomplish this, a gasket seal was installed along all four edges of the inner drywall panels and between the test cavity and guard cavities. This concentrates interior-side leakage through a single electrical outlet box placed in the test cavity. Once the base-case test panels were completed and installed, they were allowed to equilibrate with the controlled indoor conditions for at least several weeks. For this equilibration period and throughout the in situ experiment the indoor conditions were maintained at 70°F and 40% relative humidity. Fans were used to ensure good mixing and uniform conditions.

When panels were at equilibrium, the team performed an air leakage test on each test wall using the empty electrical cut-out in the drywall panel. The air test was conducted using a Micro Leakage Meter manufactured by The Energy Conservatory with a 50 Pascal (Pa) pressure difference between the test bay and the outdoors. Using these baselines one wall was set as the target. An electrical box was used to create a custom orifice, installed with an airtight gasket, and then successively larger holes were drilled in that electrical box to achieve the same leakage as previously measured. Airtight gasketed electrical boxes were then installed in all other walls, and then, to make sure the starting conditions of each test configuration were uniform, each box was drilled up to the size necessary to meet the air leakage target of the initial wall.

3.6 Constructability Notes

All retrofit test walls were installed into the CRRF test facility by UMN research staff. Qualified technicians installed all blown-in cellulose and fiberglass for walls B, E, F, L, and O and manufacturers' representatives installed the proprietary insulation for walls J (drill-and-fill fiberglass) and C (injected cavity spray foam). Complete narrative construction assessments for each wall type are included below. Tabular ratings for three criteria—Material Acquisition, Installation Ease, and Installation Speed—are described in detail in Constructability Assessment, Section 3.7.

General observations from the construction exercise:

- For wall treatments which left existing cladding in place and added new exterior insulation and finishes over the top:
  - Consider IRC guidance in IECC Section R703 *Exterior Covering*
  - Most solutions included a new air and WRB or liquid-applied membrane (LAM) over the existing cladding
  - Some solutions included a compressible layer of fiberglass paneling installed over the old cladding prior to installation of the wall upgrade to:
    - Provide some leveling assistance and support for the new layers
    - Suppress convection and minimize wind wash
    - Provide an opportunity for water to drain should it get behind the new treatment at existing windows, doors, and other wall penetrations.
- For drill-and-fill approaches:
  - Complete sealing of the WRB over the holes used for blowing in or injecting the insulation is necessary. If initial siding removal reveals an air and water barrier is missing entirely, the contractor and owner should discuss complete siding replacement to provide air and water protection.
  - The careful removal and replacement of one or more courses of the existing siding requires care and final touch-up for nails and seams.
  - Drill-and-fill approaches are possible where cavities are entirely empty (up to 30% of existing homes have little to no insulation in the walls (National Renewable Energy Laboratory 2019).

Wall A: Base-Case Wall #1

As this is the base-case wall, no assessment is provided. A photograph of this assembly is shown in Figure 3-6.

Wall B: Drill-and-Fill Cellulose

A qualified installer drilled these wall cavities from the exterior and filled with cellulose as is typical in the weatherization and retrofit market. The siding was removed in two locations—just below mid-point and near the top of the cavity—and holes were drilled through the building paper and sheathing. The cellulose was installed with a long flexible tube to achieve a high density between 3.5 to 4.0 lb/ft^3. throughout the cavity. Holes in the sheathing were sealed with spray foam, tape was used to repair the building paper, and the siding was replaced. This is a standard application used currently, and with a trained and experienced crew, it should be very straightforward. Trained crews with proper equipment for this type of application are widely available, allowing for competitive pricing and fast, straightforward installation. Photographs of this installation are shown in Figure 3-7. The drill-and-fill process shown in these photographs is similar to that used for Wall E and Wall F.

a) Cellulose insulation contractor with completed drill-and-fill, prior to hole sealing and cladding reinstall.

b) Holes in sheathing sealed with spray foam; foam subsequently cut flush with for siding reinstallation.

Figure 3-7. Photographs of the Drill-and-Fill Cellulose Installation

Wall C: Injected Cavity Foam (proprietary cc-spu)

This wall upgrade is a proprietary low-rise, closed-cell polyurethane foam installed from the interior by the manufacturer's representatives, who managed all formulation and installation techniques. The liquid foam was injected through very small holes in the drywall for each cavity. Infrared imaging was used to ensure the cavities were completely filled. The holes in the drywall were sealed by the closed cell spu foam. Drywall holes are patched, taped, mudded, sanded, primed, and painted. This treatment requires a trained crew with specialized equipment and the proprietary product is not yet widely available. However, the install for this wall upgrade was relatively fast and easily accomplished. Repair of the interior finishes would be necessary.

Wall D: Pre-Fab Exterior EPS (panel w/struts)

This wall treatment (Figure 3-8) used a commercially available EPS insulation product that includes built-in drainage capabilities and an embedded structural ladder for fastening to the existing framing. A low-density fiberglass panel was installed over the existing siding to remove the air channels that would be created between the existing lapped siding and the rigid EPS board. A housewrap was stretched over and secured with cap nails and taped to panel edges to provide a new air and water control layer.

a) Interstitial Compressible Fiberglass b) Installed EPS Panels

Figure 3-8. Photographs of Wall D Installation

The first 2-in. EPS panel was installed to the existing wall with screws using the integral fastening ladder. Then, a second 2½-in. panel was installed with screws to the previous panel using the integral fastening ladder. Uniform ladder spacing made it easy to connect the two panels. Finally, the vinyl siding was installed with screws to the integral fastening ladder in the second panel. This proprietary product is commercially available, although not necessarily in all regions. While this treatment is straightforward, it requires several steps. With this base case wall system (pine cladding over 1- x 6-in. board sheathing), these panels could be screwed to the existing siding and sheathing (approximately 1-in. to 1½-in. of wood). However, in other applications it may be necessary to match up the integral fastening ladder with the house framing. Uniform ladder spacing made it easy to connect the two panels and install the siding. While two layers of the proprietary EPS panel with struts was installed to achieve the target R-values for cold and very cold climates, the manufacturer recommends a single layer over cavity insulation as the most efficient and economical approach, and that level of thermal improvement is likely to be sufficient in several U.S. climate zones. The manufacturer is currently developing version 2.0 of this product.

Wall E: Drill-and-fill Cellulose + Exterior XPS

In this wall treatment (Figure 3-9), a layer of exterior continuous insulation was added to the dense-pack cellulose described in Wall B. The cedar lap siding and building paper were removed and a house wrap was installed with cap nails and taped at panel edges as a new air and water control layer. This was followed by a 2” layer of XPS insulation installed using minimal cap nails to hold in place until the 1” x4 ” furring strips were screwed through insulation layer and securely fastened to framing.

c) 2-in. XPS Layer with Furring Strips.

d) Backer XPS to Support Vinyl Siding.

Figure 3-9. Photographs of Wall E Installation

A $^3/_4$-in. XPS insulation was placed between the furring strips and tacked in place with cap nails to support the vinyl siding that was installed with typical fasteners to the furring strips. This well-vetted treatment was quite simple and easy to install though it involves several steps and layers, including removal of the existing siding.

The step requiring some the most planning and care is locating and fastening the furring strips for strategic connection to framing. However, furring strips and typical low-weight claddings could potentially be fastened to the $^3/_4$-in. sheathing only, using the guidance of IRC Table 703.3.3 *Optional Siding Attachment Schedule for Fasteners where no Stud Penetration Necessary*.

Wall F: Drill-and-Fill Cellulose + Vacuum Insulated Panel (VIP)/Vinyl Siding

This prototype composite product consists of double-six vinyl siding with thin VIPs adhered to the backside, within a thin frame of EPS foam to protect the VIPs and provide safe nailing locations. Similar to Wall E, this retrofit configuration started with removal of the siding and building paper, installation of dense-pack cellulose, and a new house wrap air and water control layer. Then courses of the VIP/vinyl siding were installed with appropriate fasteners to the sheathing. (Figure 3-10) Compared to separate layers of rigid foam insulation and siding the installation of this treatment was simple and straightforward. The VIPs are 18-in. long by 12-in. high to match the height of double-six siding. Their thickness is variable to mate with the vinyl siding profile but averages about 1-in. The siding panel is designed so the VIP panels will butt tightly between siding panels, both top-to-bottom and side-to-side. However, this tight tolerance made it challenging to engage the bottom hook of the siding into the upper receiver of the previous siding piece. A slightly more compressible foam between the VIP panels might help.

a) Close Up: VIP-Integrated Siding. b) Installed VIP Siding

Figure 3-10. Photographs of Wall F Installation

The lightweight siding could be fastened to the framing or directly to the ¾-in. sheathing per IRC Table 703.3.3 Optional Siding Attachment Schedule for Fasteners where no Stud Penetration Necessary. The 4-ft. x 7-ft. panel in the test building does not present the complexities of a real building. A VIP cannot be cut or punctured without losing the vacuum (the provisional patent invention is still in development and to be tested). When the panel size does not fit the wall section, a piece of traditional insulation (either expanded polystyrene or polyisocyanurate) of the same thickness and size can be used as a replacement. Custom-fitting such pieces on site may amount to a thermal bridge of between 10% and 25%.

Wall G: Exterior Mineral Fiber Board

This wall upgrade (Figure 3-11) started with a brush application of a vapor permeable LAM over the existing lapped siding to provide a robust water control layer. A 2-in. thick mineral wool panel was installed using minimal cap nails to hold the panel in place followed by a half-height panel of the second layer of 2-in. mineral wool installed at the bottom to make sure the seams were staggered; 1-in. x 4-in. furring strips were fastened to the framing at the bottom only, holding both insulation layers in place. The remaining second layer of 2-in. mineral wool panels were inserted behind the furring strips all the way to the top of the wall where the furring strips were adjusted to be straight and plumb and secured to the framing with screws. Then, screws were added in between and used to ratchet the furring strip to address bowing. Finally, a semi-rigid fiberglass panel was installed between the furring strips as an insect screen for drainage and drying. Fiber-cement siding was fastened to the furring strips using normal installation techniques. The installation of this treatment is straightforward but is complex and time-consuming.

a) Liquid Applied Membrane (left, green).

b) Mineral Fiber Panels and Furring Strips.

Figure 3-11. Photographs of Wall G Installation

The LAM was somewhat challenging to install to the cedar siding at the target thickness, and there was a tendency for small shrinkage cracks at the siding seams. A spray application would have worked better. The other remaining layers are simple enough, although attention is needed to compress the mineral wool while maintaining an even, flat, and plumb plane with the furring strips; however, screws do allow for easy adjustment. Because of the increased weight of the fiber-cement siding, the furring strips were fastened directly over and into the stud framing; identifying and marking the framing locations adds time and effort.

Wall H: Exterior GPS Structural Panel System

This wall upgrade was envisioned to be an off-site fabricated panel custom-fit to the specification and measurements of the existing building and then brought to the site to be installed on the existing wall using a preinstalled engineered clip system securely fastened to the structure. However, this panel is not commercially available, so the wall was built on-site in layers over the existing wall (Figure 3-12). A 1½-in. structural OSB sheet was fastened with screws to the wall framing and covered with a fully-adhered (peel and stick) membrane. The first layer of $2^1/_8$-in. graphite polystyrene (GPS) was installed with minimal cap nails to hold it in place. A second layer of $2^1/_8$ in. GPS was installed with 1-in. x 4-in. furring strips was fastened with screws to the structural OSB panel. A semi-rigid fiberglass panel was used between the furring strips as an insect screen and to provide drainage and drying. Finally, metal panel siding was fastened with screws and washers to the furring strips. Because of the weight of the complete panel system, the OSB must be securely fastened into the framing. Identification and marking of the framing members adds time and complexity to this installation. In this case, the interstitial layer over the existing cladding (compressible fiberglass panel) was not an issue as the stiffness of the OSB panel made it easy to keep it flat and plumb. Installation of the remaining layers was quite straightforward. This wall could have been site-built using a single layer of ¾-in. OSB.

a) Wall H Structural OSB   b) Installed GPS

Figure 3-12. Photographs of Wall H Installation

Wall I: Base-Case Wall #2

As this is the base-case wall, no assessment is provided.

Wall J: Drill-and-Fill Fiberglass (proprietary FG, high-dens)

A qualified installer drilled the walls and filled the cavity with blown-in fiberglass from the exterior similar to what would be done in the weatherization and retrofit market (Figure 3-13). The cedar siding was removed in one location near the middle of the cavities. Holes were drilled through the building paper and sheathing near mid-wall for each wall cavity. Fiberglass insulation was installed with a flexible tube to ensure a minimum density of 1.5 lb/ft^3 (~R-3.7/in.) throughout the cavity. The holes in the sheathing were sealed with a spray polyurethane foam, a piece of building paper was used to repair the water control layer and the siding was replaced. This is a standard application in use so trained crews with proper equipment and skills should be widely available, allowing for competitive pricing and fast, straightforward installation. This drill-and-fill process also was used for Wall I and Wall O.

Figure 3-13. Photograph of Wall H Installation

Wall K: Fiberglass Batt + Interior Polyiso

This wall was selected as an upgrade that could be installed by the homeowner during an interior remodel. The interior drywall was removed and an unfaced R-13 fiberglass batt was carefully installed in the existing cavity. Then a 1-in. foil-faced polyiso foam insulation board was installed over the studs on the room side. The foam board was sealed against air infiltration and new drywall was installed. A sealant was used around the electrical box. Sealant and tape could replace the drywall gasket to ensure the air seal. Longer drywall screws provide adequate purchase to framing through the 1-in. foam. Installation was relatively easy and fast.

Wall L: Drill-and-Fill FG + Exterior Polyiso

This wall upgrade started with drill-and-fill fiberglass like Wall J, but the existing siding and building paper were removed and the holes in the sheathing for the blown-in FG were sealed with one-part polyurethane spray foam. Next, a WRB was applied with cap nails, then a 1-in. foil-faced layer of polyiso was installed over the WRB with 1-in. x 4-in. furring strips over the foam fastened to the studs with long screws. A prefinished lap wood composite siding was fastened to the furring strips. Siding removal and the remaining two operations are pretty straightforward though it does require multiple operations. Ideally the exterior furring strips should be fastened to the studs so driving screws through the insulation and sheathing can be tricky. However, with only 1 in. of insulation it is relatively easily achieved.

Wall M: Pre-Fab Exterior EPS/EIFS Panel System

This wall upgrade is a 6-in. thick panel of EPS foam finished on all six sides with a stucco material. The building's existing siding and building paper were removed and a coat of LAM was applied using a paint roller. Then all sheathing gaps and nail holes were filled with a proprietary caulk (see Figure 3-14a), which was lightly tooled into the surface, followed by a second coat of membrane applied by roller. The prefinished EIFS panel was fixed in place using a gun-grade adhesive. A temporary shelf at the bottom edge of the test panel supported the weight of the panel as the adhesive cured (see Figure 3-14b). The shelf supports were removed approximately 24 hours later. It is the understanding of the team that a rack-mount attachment is under development for this system; however, it was not available for use at the time of this testing. As a prefabricated system, this should be fairly easy and straightforward. However, with board sheathing as the building's existing condition, there were many seams and nail holes that required filling for the liquid membrane application step. Wood sheathing panels, such as OSB and plywood would be easier to cover with a roller, and spray application would work with any sheathing substrates. The installation of the panel with adhesive was straightforward and very quick. It is unknown how the developer's proposed rack mounting system might affect installation.

Wall N: Pre-Fab Exterior Polyiso/Vinyl Block System

This prefabricated system of foam blocks faced with vinyl siding did not require removal of the existing siding. Instead, the existing exterior was prepared with a layer of WRB installed over the top and sealed at the edges with WRB tape to serve as a new air and back-up water control layer. Installation begins at the bottom with a starter strip or rail. Each lightweight block engages the previous course in tongue-and groove fashion and the assembly is screwed to the framing through the upper flange. The sides used a cap strip that resembles a deep J-channel. The installation of this system was generally very straightforward. Care was required to make sure the tongue-and-groove joints were fully seated. The majority of the installation time was spent engaging the trim pieces with their receiver. The system as delivered is prototypical so this issue may be resolved in the future. The finished look resembles typical vinyl siding. The blocks were loaned to the project, and when dismantled, they came apart quickly, easily, and without damage for packaging and shipping back to the manufacturer. Except for the custom-cut pieces these blocks could be re-used. Photographs of the polyiso blocks and the wall upgrade during installation are shown in Figure 3-15.

a) Caulking the Pre-Existing Sheathing.

b) Installed EIFS Panel.

Figure 3-14. Photographs of Wall M Installation

Wall O: Drill-and-Fill FG + Exterior FG Board

This wall upgrade starts with the dense-pack cellulose installed by removing two courses of siding as was described for Wall J. The siding was replaced but touch up was not required, and a sheet of housewrap was draped over it and secured at the top. The 2-in. semi-rigid fiberglass boards were installed starting at the bottom and temporarily secured using two cap nails per piece. Then 1- x 4-in. furring strips were installed over the panels and fastened to framing with washer-head screws. A fiber cement siding was installed on the furring strips. The installation of this treatment is pretty straightforward but does involve multiple layers and steps. The most challenging aspect of this method was the compressibility of the rigid fiberglass panels, especially at the edges. This problem can be mitigated with screws (advancing or retreating them as necessary to keep panels plumb and level) and may be minimized on larger expanses of wall.

c) Close-Up: Wall N Polyiso Blocks.

d) Installing Wall N Test Panels.

Figure 3-15. Photographs of Wall N Installation

Wall P: FG Batt + XPS + OSB (thermal break shear wall)

This wall upgrade was developed to provide a combined structural and thermal upgrade, presuming that additional desirable performance features may constitute a tipping point for a positive decision. The first step was to remove existing siding, building paper, and sheathing. Next, an unfaced R-13 fiberglass batt was installed in the existing cavity followed by a 1-in. XPS board insulation installed over the studs. A ¾-in. OSB sheet is installed over the XPS and fastened securely to the studs as a shear plate using 4-in. screws. WRB was installed using cap nails followed by a typical installation of vinyl siding. This wall treatment is somewhat involved but improves structural and energy performance. The installation was a bit challenging in our test case because the sheathing on the test building had been previously taped to the framing on the base-case wall, not an uncommonly encountered situation. Once the sheathing was removed, the remainder of the installation was pretty straightforward although time consuming.

3.7 Constructability Assessment

The UMN team provided a qualitative assessment for five constructability attributes for each of the wall treatments: 1) ease of material acquisition, 2) simplicity and ease of installation, 3) overall speed for installation, 4) number of discrete operations required, and 5) the added wall thickness.

Material acquisition focused on the availability of the material, trained contractor or proprietary installation equipment at the time of the project. It ranged from being readily available in the local market, to products that were only available from limited building material supply outlets or manufacturers, to some novel products that are not available in the marketplace at this time. The techno-economic analysis (Section 7.0) attempts to identify factors that relate to product adoption and determine a likely aggregate adoption score that may indicate the future availability of each wall system.

Simplicity and ease of installation include the level of skill required and the availability of equipment that might be needed to properly install the wall upgrade. Some wall upgrades were very simple and straightforward, while others required multiple steps or were more complex to execute. For Wall H, the Exterior GPS Structural Panel System, the installation ease was initially listed as “uncertain” as it currently is not available in a prefabricated form. Instead, “several layers or steps” describes the process of constructing the wall on-site. The complexity of the ultimate product as pre-fabricated is unknown at this time. If a crane or other mechanical lift is required for installation this could increase complexity, which can only be overcome by process savings associated with other aspects of the wall solution.

Overall speed of installation is a fairly intuitive metric to assess the comparative speed of the installation of the wall upgrade for these test panels. Speeds ranged from quite fast to slow or uncertain. This subjective assessment came from the exercise of building and installing the test walls and did not consider complexities associated with whole-house projects.

Number of operations is a metric used to indicate the unique steps, layers, or processes required to complete each wall upgrade. In general, an operation is limited to a single trade (though a trade may do multiple operations) and represents a particular layer or a clear chronological step from one type of operation to another. However, in the case of the drill-and-fill cavity insulation, the siding removal (first step) and siding replacement (last step) are counted as a single operation because the same skill or trade would be used for both. Likewise, multi-layer insulation wall upgrades are counted as a single operation since they would be done at the same time by the same trade. It is important to note that not all operations are similar in complexity or time. For instance, the installation of a house wrap or a fiberglass batt might be much simpler and quicker than the installation of two insulation layers that are overlaid and fastened with furring strips.

The *added wall thickness* was a quantitative value for the total finished thickness less the original base case wall thickness. When discussing wall upgrades a common concern is how the additional thickness can be integrated with existing features such as windows and overhangs. This thickness is generally added to the exterior of the wall. However, for Wall K, 1-in of insulation was added to the interior.

It is critical to understand that these qualitative and relative assessments are based on the experience of the UMN team in building and installing each of these wall upgrades on a 4- × 7-ft base-case wall. This assessment only represents these small, clean wall segments without openings, corners, or other architectural elements. No attempt has been made to assess how these wall upgrades would scale up to a whole house installation. Furthermore, because each wall upgrade was built only twice (one north and one south exposure) it is not clear how the learning curve with time and experience might impact the assessment provided. Presumably an actual bid from a contractor would include those considerations.

Table 3-2, below, shows the key for the qualitative assessments used by the construction team. The darker colors indicate advantages or positive outcomes; paler colors indicate challenges. Table 3-3 aggregates some of the most important logistical features perceived to affect adoption in the marketplace.

Table 3-2. Construction Assessment Key

	Material Acquisition	Installation Ease	Installation Speed	# Operations	Added thickness
1	Readily avail to contractor	Very easy; straightforward	Very fast	2	0-1 in.
2	Avail at most BMS	Moderately easy	Somewhat fast	3-4	1.5-4 in.
3	Available at some BMS	Several layers or steps	Somewhat slow	5	4.5-5 in.
4	Avail from Manufacturer	Moderately difficult	Quite slow	6	≥ 5 in.
X	Not currently avail	Uncertain at this time	Uncertain at this time	n/a	n/a

Table 3-3. Qualitative Constructability Assessments of Each Test Wall

ID	Description	Material Acquisition	Installation EASE	Installation SPEED	# Operations	Added thickness
B	Drill-and-Fill Cellulose (dense-pack)	1	1	1	2	0 in.
C	Injected Cavity Foam (proprietary cc-spu)	X	1	2	2	0 in.
D	Pre-Fab Exterior EPS[2] (panel w/struts)	3	2	1	3	5.25 in.
E	Drill-and-Fill Cellulose + Exterior XPS	1	3	3	5	2.5 in.
F	Drill-and-Fill Cellulose + VIP/Vinyl Siding	X	2	3	4	0.5 in.
G	Exterior Mineral Fiber Board[2]	3	3	2	3	5.25 in.
H	Exterior GPS Structural Panel System	3	2	3	4	7 in.
J	Drill-and-Fill Fiberglass (proprietary, high-density)	2	1	1	2	0 in.
K	Fiberglass Batt + Interior Polyiso	1	3	2	4	1 in.
L	Drill-and-Fill FG + Exterior Polyiso	1	3	3	5	1.5 in.
M	Pre-Fab Exterior EPS/EIFs Panel System	4	2	2	3	5.75 in.
N	Pre-Fab Exterior Polyiso/Vinyl Block System	X	2	1	2	4 in.
O	Drill-and-Fill FG + Exterior FG Board[3]	3	3	2	4	3.25 in.
P	FG Batt + XPS + OSB (thermal break shear wall)	1	4	4	6	0.75 in.

[1] BMS refers to Building Materials Supply outlets such as big-box chains or large local or national lumber stores
[2] Two layers of exterior continuous insulation, optimized for cold climate. Good results might be achieved with a single layer in other climate zones.
[3] Dense semi-rigid fiberglass board was difficult to source

3.8 Constructability Takeaways

Table 3-3 was developed to capture primary constructability issues, score individual methods by a repeatable metric, and present competing solutions side-by-side for direct comparison. Darker green indicates better results; a quick visual scan identifies Walls B and J are good performers by most metrics. The drill-and-fill method is straightforward and not very disruptive.

However, decision-makers may determine that they value some attributes more than others or they may identify a particular category (or a particular score in a category) that would constitute a no-go decision point. For instance, Wall C, Injected Cavity Foam, scores nearly as well as Walls B and J except in the category of Material Acquisition, but the proprietary spray foam is not yet widely available in the marketplace. However, once it penetrates the market, it has the advantage of being injectable into the cavity from the interior via drilled holes—no need to completely demolish the exterior or interior finish—while offering the higher R-value and lower permeability associated with traditional spray foam. Overcoming the availability issue makes this solution a strong contender.

Wall thickness is a potentially significant issue. Even for the test building, thicker walls required more attention to detail at the top, bottom, and edge connections. This challenge compounds greatly in real-world conditions. Actual houses have numerous service penetrations and orthogonal interfaces with window and door trim or framing that can be particularly challenging. Walls B and J stand out in this category because the drill-and-fill method does not increase wall thickness and can be accomplished without touching existing wall interfaces—just removal and replacement of strategic courses of existing siding. Solutions that provide higher R-values without substantially increasing overall wall thickness provide constructability advantages. Three-quarters to one inch of exterior continuous insulation has proven to be a relatively easy "add" to most houses built since the mid-20th century—existing casing and trim protrusions are often deep enough that no additional trim or "boxing out" is required. Such complexities are often cited by builders as a barrier. PNNL (Cort, Antonopoulos, Gilbride, Hefty, & Tidwell, 2022) and several of the collaborators on this project are currently engaged in a field demonstration which identifies the regions and existing conditions where a 1-inch exterior continuous insulation solution captures the bulk of available wall upgrade savings while maintaining or improving moisture durability and maximizing constructability. (Pacific Northwest National Laboratory, 2022)

The exercise of building each baseline wall and the 14 test wall assemblies provided insights into the relative degree of difficulty that novel—or even just slightly unusual—approaches may represent. The number of operations involved in the installation process is a telling metric. Each layer that can perform multiple duties saves the crew time, effort and even distraction. The 4 × 7-ft walls for the test building were geometrically simple and straightforward compared to the complexities of an entire house that has windows and doors, service penetrations, inside and outside corners, and connections to foundations and soffits. Prefabricated products that incorporate means of fastening and pre-measuring (Walls D, F, M, and N) provide a degree of predictability and efficiency that could offset at least a portion of their cost premiums.

The research team had anticipated that wall configurations which left the existing exterior finish in place and intact would always be advantageous. However, this was not necessarily the case, because oftentimes new air and water control layers were necessary. The solution of a compressible fiberglass panel seemed to work, but definitely increased the time-on-task. Alternate (i.e., faster, cheaper) methods of dealing with the interface between existing cladding and the wall upgrade should be explored. A prefabricated system that incorporates necessary air and water control may be advantageous. Direct comparisons of all attributes of wall upgrades targeted for particular outcomes are further explored in Section 7.2.

4.0 Hygrothermal Modeling

Hygrothermal modeling is used to evaluate the condensation potential, moisture content, drying capacity of the assembly, potential for mold growth, and freeze-thaw damage. The purpose of performing the hygrothermal modeling is to verify that the proposed energy-efficiency retrofit measures do not create a durability issue.

4.1 Introduction

WUFI® is one of the most commonly used hygrothermal simulation tools in the building industry (Antretter et al. 2011; Arena & Mantha 2013; Lepage et al. 2013; Lepage & Lstiburek 2013). WUFI® is an acronym for Wärme Und Feuchte Instationär, which is German for heat and moisture transiency. The WUFI model is based on a state-of-the-art understanding of the physics regarding sorption and suction isotherms, vapor diffusion, liquid transport, and phase changes. The model is well documented and has been validated by many comparisons between calculated and field performance data.

The use of transient hygrothermal models for moisture control is well established in the building industry in its codes, standards, and building insulation design principles. Building envelopes should be designed to naturally shed liquid water and to minimize its entry. Building envelopes should also be constructed to facilitate vapor transport so that moisture does not accumulate within the building envelope and lead to mold growth and other failure mechanisms.

Fourteen retrofit walls were constructed at the CRRF test facility. Each of the retrofit wall upgrades were installed over a baseline wall designed to represent the "typical" 1950s type wood frame construction. Two baseline walls served as an experimental control for the climatic conditions experienced by that subset of walls. Hygrothermal simulations for each wall configuration were compared with the experimental data using WUFI Pro 6.4 (Fraunhofer IBP 2019), followed by a national-scale hygrothermal analysis to explore wall hygrothermal performance in all other U.S. climate zones to expand the applicability of this study for practitioners throughout the United States.

4.2 Material Properties

Before creating a model of assembly performance, the thermal and vapor-related physical properties of the wall materials were characterized. Test specimens were transported from UMN to ORNL where the measurements were made in accordance with the following relevant ASTM standards:

- The thermal conductivity was measured in accordance with ASTM C518, "*Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus*" (ASTM 2017).
- The vapor transmission rate was measured in accordance with ASTM E96, "*Standard Test Methods for Water Vapor Transmission of Materials*" (ASTM 2016).

The tested material properties are tabulated in Appendix B. The material properties were compared to those in the WUFI materials database, and modifications were made accordingly. In some cases, there were no material properties present within WUFI, so a material property was created from test data (e.g., VIP-integrated vinyl siding).

4.3 Validation Study

Each assembly simulation was validated using two months of field data during cold winter months, including ambient temperature, ambient relative humidity, wind speed, wind direction, rain, solar loads, panel temperature, panel relative humidity, moisture content and heat flux. Simulations were compared to the measured values from the test panels, including south and north orientations. Figure 4-1 shows the simulation results compared to the measured values of temperature and relative humidity for wall assembly A. The dashed box in the section view schematic corresponds to the graphed sensor response.

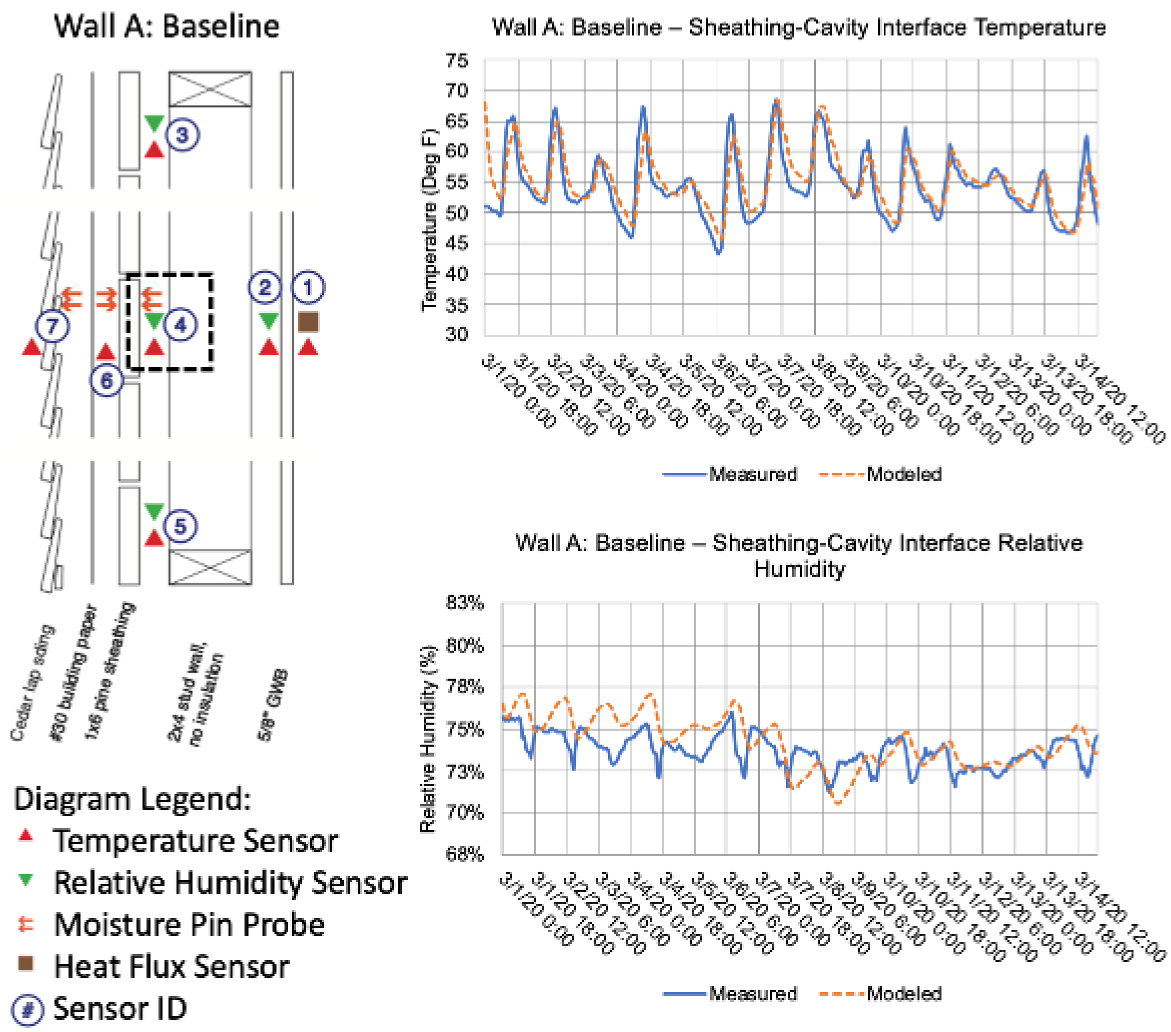


Figure 4-1. Sample Hygrothermal Benchmarking Results for Wall A (example)

Overall results show good agreement between the predicted relative humidity and temperatures compared to the measured values, in most cases. To measure the quality of the prediction, the mean absolute error was calculated for each simulation for both north and south orientations. The variation between measured and simulated values was less pronounced for the north orientation compared to the south orientation. For the north orientation, the mean absolute errors for temperature and relative humidity were between 0.7 and 13.3°F and 0.6 and 21.3%, respectively. The variation in mean absolute errors for temperature and relative humidity for the south orientation were 0.5 and 13.0°F and 0.6 and 27.4%, respectively.

4.4 Simulation Study

Following the validation study, hygrothermal simulations of all wall assemblies were carried out in the eight Building America climate zones to understand the impact of the retrofit wall upgrades on moisture performance/durability for representative cities throughout the United States. These simulations indicate hygrothermal performance under prescribed conditions per the test protocol. Conclusions about the moisture resilience of a particular wall should be based not only on generalized simulation results like those shown below but also with respect to local details such as nearby vegetation, building self-shading, and patterns of wind-driven rain.

The necessary input data for simulation include the composition of the examined component, its orientation and inclination, and the initial conditions and the time period of interest. The material parameters and the climatic conditions can be selected from the embedded databases or the actual data can be input if their hygrothermal properties have been measured.

Simulations were carried out in accordance with standard ANSI/ASHRAE 160-2016: Criteria for Moisture-Control Design Analysis in Buildings (ASHRAE 2016). The initial moisture content for the assemblies was established by using the moisture content of the base-case wall simulated for a service period of 3 years to represent the initial moisture content for the pre-existing envelope elements (reference building/base-case) in the retrofit construction. All newly installed retrofit wall components were assumed to be at an initial relative humidity of 80% at simulation start.

The mold index measured in accordance with ASHRAE 160 was used as an indicator of moisture durability. ASHRAE 160 uses the VTT model developed by Viitanen and Ojanen (Viitanen & Ojanen 2007) to calculate a mold index for materials that make up the building envelope. ASHRAE has adopted this scale for Table 6.1.1: four groups with respect to moisture sensitivity. It is the role of the researcher to categorize each unique material according to this table: resistant, medium resistant, sensitive or very sensitive. The distinction between the groups is apparent at temperatures higher than 44.6°F—temperatures commonly found within wood-framed walls during most seasons. Resistant materials require a relative humidity of 85% or greater to support mold growth, and sensitive materials will support mold growth at relative humidity of 80% or higher.

According to ASHRAE 160, the mold index takes on a value between 0 and 6, and "In order to minimize problems associated with mold growth on the surfaces of components of building envelope assemblies, the mold index shall not exceed a value of three (3.00)." Figure 4-2 shows an example mold index calculation as a function of time for the southern exposure of Wall J in the Cold climate zone. This calculation was performed for both surfaces of all substrate materials except for weather resistive barriers (which do not support mold growth) and framing. Where only diffusion is simulated (not bulk water intrusion), the sheathing layers (e.g., OSB, plywood) will reach the 20% threshold before the studs because of the greater moisture storage capacity of the framing members compared to the sheathing materials.

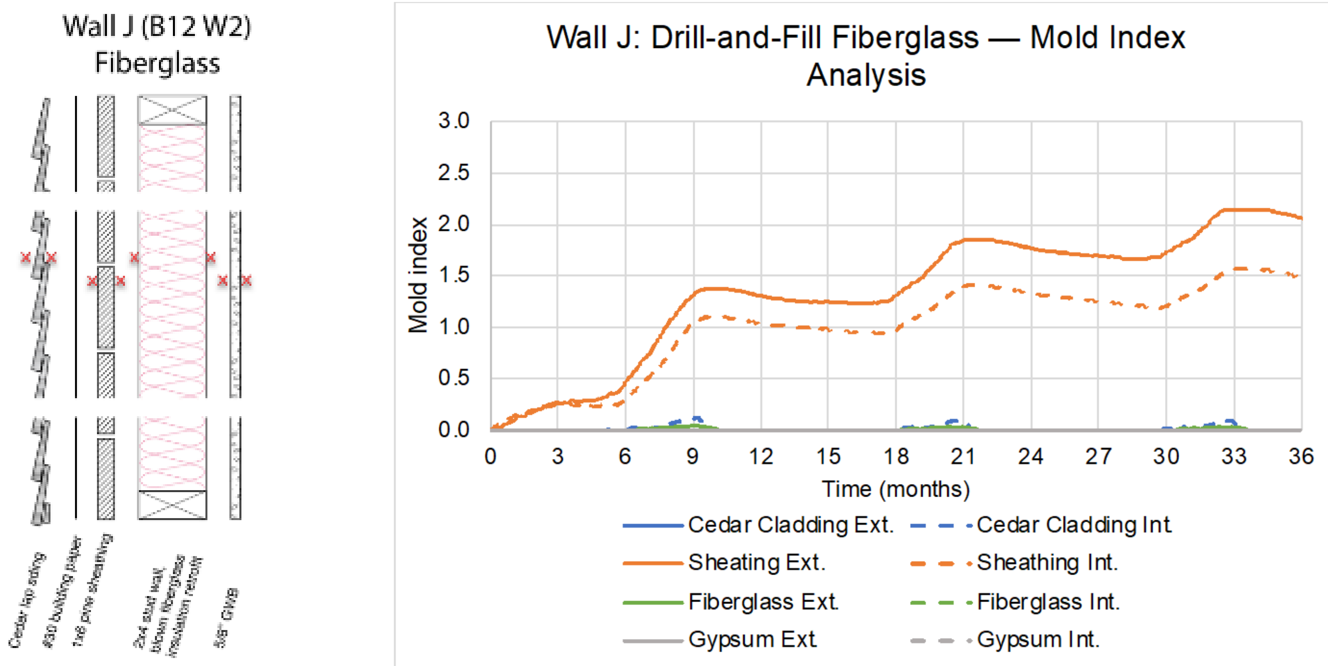


Figure 4-2. Sample Layer-by-Layer Time Series; Wall J, Cold Climate, Southern Exposure

Unless other construction layers show excessive mold indices, simulating studs or framing members is not necessary.[1] For both interior and exterior surfaces of all simulated layers in this example (Figure 4-2, Wall J) the mold index is less than 3.

This calculation was carried out for the base-case and all 14 of the tested wall assemblies for both northern and southern exposures. Using the VTT model in WUFI the mold index is calculated for all surfaces within each wall. The surface with the worst performance is then used as the representative value for the entire wall assembly. In the matrix of results (Table 4-1) orange highlighting designates a mold index of 3 or more which indicates potential susceptibility to mold growth due to high moisture levels and less capability to dry out diurnally or seasonally. Outputs are shown for both southern and northern exposures. These hygrothermal simulations indicate that most test wall assemblies in most climate zones are not susceptible to mold, but that care should be taken for walls B and J in Subarctic, Very Cold and Marine climates.

[1] Framing lumber is relatively large volumetrically and therefore can safely store much more water vapor than the exterior sheathing or other, thinner, construction materials. In cold climates, the studs typically are warmer than the exterior sheathing so the vapor pressure difference between the building interior and the exterior side of the stud is smaller than the vapor pressure difference between the building interior and the exterior sheathing.

Table 4-1. Representative Mold Indices Computed for All Simulated Walls Across All Building America Climate Zones for Southern and Northern Wall Exposures

	Shaded indicates mold index ≥ 3	Subarctic	Very Cold	Cold	Mixed humid	Mixed dry	Hot humid	Hot dry	Marine	Subarctic	Very Cold	Cold	Mixed humid	Mixed dry	Hot humid	Hot dry	Marine
ID	Wall Name/ Description	Southern Wall Exposures								Northern Wall Exposures							
A	Base Case 1	0.5	0.8	0.5	0.1	0.2	0.0	0.0	1.5	0.5	1.3	0.8	0.7	0.6	0.3	0.0	2.4
B	Drill-and-Fill Cellulose (dense-pack)	3.6	3.7	3.2	1.8	2.4	0.3	0.1	3.6	3.7	3.8	3.5	3.5	2.7	2.4	0.6	3.7
C	Injected Cavity Foam proprietary cc-spu)	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.3	0.3	0.1	0.4	0.0	0.3	0.0	0.3
D	Pre-Fab Exterior EPS (panel w/struts)	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.1	0.1	0.6	0.0	0.0	0.0	0.1
E	Drill-and-Fill Cellulose + Exterior XPS	0.3	0.5	0.4	0.3	0.4	0.2	0.1	1.1	0.3	0.5	0.5	0.7	0.5	0.3	0.1	1.3
F	Drill-and-Fill Cellulose + VIP/Vinyl Siding	0.3	0.3	0.2	0.1	0.2	0.1	0.0	0.7	0.3	0.3	0.3	0.3	0.3	0.1	0.1	0.6
G	Exterior Mineral Fiber Board	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.1
H	Exterior GPS Structural Panel System	1.4	1.3	1.1	0.7	0.9	0.4	0.6	1.0	1.5	1.3	1.1	0.8	1.0	0.5	0.7	1.0
I	Base Case 2	0.5	0.8	0.5	0.1	0.2	0.0	0.0	1.5	0.5	1.2	0.8	0.7	0.6	0.3	0.1	2.4
J	Drill-and-Fill Fiberglass (proprietary FG, high-density)	2.9	3.0	2.2	0.4	0.4	0.1	0.0	3.0	3.2	3.2	2.8	2.6	1.3	1.2	0.0	3.3
K	Fiberglass Batt + Interior Polyiso	1.3	1.8	0.6	0.1	0.1	0.1	0.0	2.5	2.4	2.7	1.6	1.6	0.5	0.7	0.0	2.8
L	Drill-and-Fill FG + Exterior Polyiso	0.5	0.6	0.1	0.1	0.1	0.1	0.0	1.3	1.2	1.4	0.4	0.6	0.2	0.3	0.0	2.1
M	Pre-Fab Exterior EPS/EIFs Panel System	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0
N	Pre-Fab Exterior Polyiso/Vinyl Block System	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.1
O	Drill-and-Fill FG + Exterior FG Board	0.3	0.4	0.2	0.1	0.1	0.1	0.0	0.9	0.4	0.5	0.3	0.4	0.2	0.1	0.0	1.1
P	FG Batt + XPS + OSB (Thermal Break Shear Wall)	0.3	0.5	0.0	0.7	0.1	0.1	0.0	1.2	0.6	1.1	0.3	1.1	0.1	1.1	0.0	1.2

At this time, only drill-and-fill fiberglass (Wall J, three of the eight climate zones) and drill-and-fill cellulose (Wall B, five of the eight climate zones) were determined to have a mold index greater than 3 and only in the absence of added exterior insulation. The addition of exterior insulation shifts the temperature gradient toward the outside of the envelope, thereby preventing condensation within the stud cavity by keeping temperatures more reliably above dewpoint. As noted in Section 3.8, drill-and-fill approaches are straightforward, resulting in speed and cost advantages. This wall upgrade is popular and has been successfully used for decades; their limited thermal improvement still captures a large portion of available wall upgrade savings. Nevertheless, their simulated potential for moisture risk in certain regions warrants caution.

The third drill-and-fill approach (Wall C) uses an injected proprietary closed cell foam in the cavity and shows almost no sensitivity to moisture. This highlights the fact that moisture control within and through walls relates to two different drivers. Closed cell foam provides protection through its very low permeability, retarding the passage of water vapor from inside the building into materials beyond the layer of foam. Wall K also benefits from resistance to winter moisture drive. The 1-in. layer of polyiso with foil facing has very low permeability, thus successfully preventing the transport of moisture-laden air into the wall cavity. In cold conditions, low temperatures still exist within the fiberglass insulation, but there is much less water vapor present and at risk of condensation.

Walls B and J use cavity fill insulations that are quite permeable, and the temperature gradient becomes the important aspect: water vapor is transported quite freely through the wall layers in response to the vapor drive (typically from inside to outside during the winter, and from outside to inside during warm summer periods). A fully vapor-open wall is generally safe when conditions make this a temporary condition—such as where ambient relative humidity is low, where the moisture remains in a vapor state (rather than as liquid water) due to higher temperatures, and when diurnal and seasonal changes allow ample opportunity for drying, even if some condensation does occur. However, in cold climates the temperatures within the wall may drop below dewpoint on a regular basis and for longer periods, condensing liquid water out of the air in locations of sensitive materials within the wall.

Figure 4-3 illustrates the mold indices associated with each of the layers of concern within Walls B and J for northern and southern exposures. Eight strata including both inside and outside faces of each substrate were simulated. Only the higher value was reported for each pair. These walls perform well in Mixed Dry, Hot Humid, and Hot Dry climates so those three results are not shown in Figure 4-3 for either wall. For both Wall B and Wall J, the sheathing (orange bar) is a weak point, demonstrating mold indices >3 in the challenging climates. As previously described, there are a greater number of sensitive conditions for northern exposures.

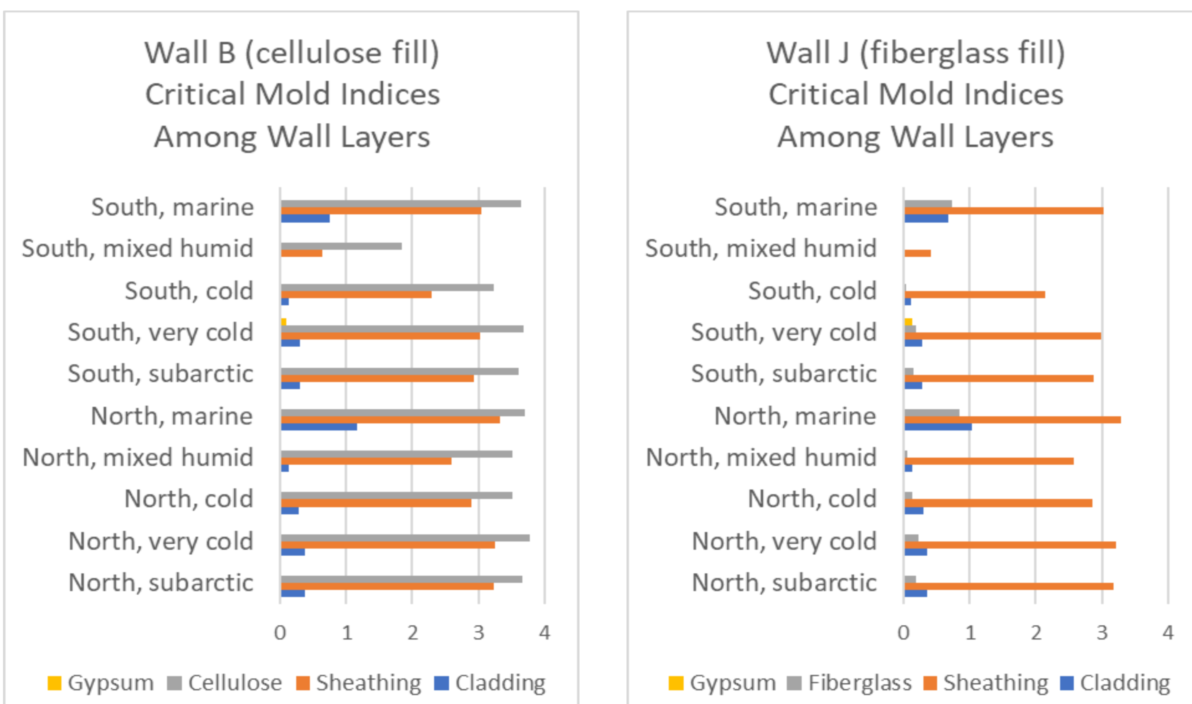


Figure 4-3. Mold Index: Differences Among Wall Layers, Drill-and-Fill Walls B and J

For Wall B, the cellulose fill (grey bar) is even more problematic than the sheathing. Cellulose was assigned a moisture sensitivity classification of “very sensitive” for untreated wood, based on traditional characteristics. Modern cellulose fill insulation often includes biocides that potentially could allow a classification of “resistant” in Table 6.1.1 of ASHRAE Standard 160, similar to fiberglass. Practitioners should contact the manufacturer of the product they intend to install for guidance regarding mold sensitivity.

Performance differences are also related to local patterns of precipitation, ambient humidity, and opportunities for drying. Walls with northern exposures are typically worse moisture performers than walls facing other directions; this is related particularly to diurnal and seasonal opportunities for drying as a result of direct solar radiation. The difference between simulated mold indices for southern and northern exposures for each wall upgrade is shown in Table 4-2 (delta = north to south). Darker shading indicates larger variations between the mold indices associated with northern versus southern exposures. Conclusions about the moisture resilience of a particular wall should be based not only on generalized simulation results like those shown below but also with respect to local details such as nearby vegetation, building self-shading, and patterns of wind-driven rain. Assumptions regarding interior conditions of the building (temperature and relative humidity due to setpoints and human activity) also impact performance.

Table 4-2. Differences in Mold Indices (northern–southern exposure) for Simulated Test Walls

	Magnitude of Difference (delta) Between Northern and Southern Mold Indices	Subarctic	Very Cold	Cold	Mixed Humid	Mixed Dry	Hot Humid	Hot Dry	Marine
ID	Designation	Mold Index by Climate Zone							
A	Base Case 1	0.1	0.5	0.4	0.6	0.4	0.3	0.0	0.9
B	Drill-and-Fill Cellulose (dense-pack)	0.1	0.1	0.3	1.7	0.3	2.1	0.5	0.1
C	Injected Cavity Foam (proprietary cc-spu)	0.1	0.1	0.1	0.4	0.0	0.3	0.0	0.1
D	Pre-Fab Exterior EPS (panel w/struts)	0.0	0.0	0.0	0.6	0.0	0.0	0.0	-0.1
E	Drill-and-Fill Cellulose + Exterior XPS	0.0	0.0	0.1	0.4	0.2	0.1	0.0	0.2
F	Drill-and-Fill Cellulose + VIP/Vinyl Siding	0.0	0.0	0.1	0.2	0.0	0.0	0.0	-0.1
G	Exterior Mineral Fiber Board	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
H	Exterior GPS Structural Panel System	0.1	0.0	0.1	0.1	0.1	0.1	0.2	0.0
I	Base Case 2	0.1	0.5	0.4	0.6	0.4	0.3	0.1	0.9
J	Drill-and-Fill Fiberglass (proprietary FG, high-density)	0.3	0.2	0.7	2.2	0.9	1.1	0.0	0.3
K	Fiberglass Batt + Interior Polyiso	1.1	0.8	1.0	1.4	0.4	0.7	0.0	0.4
L	Drill-and-Fill FG + Exterior Polyiso	0.6	0.8	0.2	0.5	0.1	0.3	0.0	0.7
M	Pre-Fab Exterior EPS/EIFS Panel System	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0
N	Pre-Fab Exterior Polyiso/Vinyl Block System	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
O	Drill-and-Fill FG + Exterior FG Board	0.1	0.1	0.1	0.3	0.1	0.1	0.0	0.3
P	FG Batt + XPS + OSB (Thermal Break Shear Wall)	0.3	0.5	0.3	0.3	0.1	1.0	0.0	-0.1

4.5 Hygrothermal Modeling Conclusions

Results from the hygrothermal analysis carried out in this study show good agreement with relative humidity and temperature results from field measurements. The full-range simulation results show that most wall upgrades have good moisture performance in most climate zones as indicated by the low mold indices.

For all climate zones all but two of the walls had mold index calculations (mold indices) less than 3, which indicates no risk of mold growth or support of mold growth in accordance with ASHRAE 160. Mold indices greater than 3 in two simulated wall upgrades (Walls B and J) were limited to a subset of climate zones. Neither wall had exterior continuous insulation or vapor resistant layers on the inside to prevent transport of moisture-laden air into the cavity and exterior material layers, where cold temperatures could potentially cause condensation. In general, the addition of exterior insulation, especially with moisture-tolerant materials (Walls E and L, respectively), improve the hygrothermal performance of the wall assembly by pushing the point of condensation to the exterior side of the sheathing. Wall K adds an interior layer of polyiso to a wall with fiberglass batts in the stud cavities—the foil facing of the polyiso layer provides an interior vapor resistant layer to achieve good moisture results.

As a result, in the absence of leaks behind the insulation layer or between the insulation layer and sheathing, the hygrothermal performance of the majority of these walls should be very good. There is little or no risk of moisture performance problems. Moisture resilience is a notable durability metric that can serve as a partial proxy for useful service life.

The next step should be to evaluate moisture performance of wall assemblies introducing moisture sources/sinks behind the continuous insulation or between the continuous insulation and exterior sheathing to understand the impact of leaks on the moisture performance. Additional study of retrofit strategies that provide interior vapor retarders is warranted.

5.0 Energy Modeling

In situ laboratory and field evaluations of building envelope assemblies are expensive, and it is difficult to control environmental conditions, especially for multiple climates. In the past decade, software programs to simulate building energy performance have become more robust and are widely accepted by industry and the research community (Dentz & Podorson 2014; Lepage & Lstiburek 2013).

Whole-building energy modeling tools are used to capture annual energy cost savings quickly and accurately for simulated buildings by calculating energy consumption on an hourly basis, accounting for all energy interactions between indoor and outdoor environmental conditions, building envelope, HVAC system, lighting, service water heating, other appliances and equipment, and occupant behavior. EnergyPlus—a free, open-source and cross platform building energy simulation tool developed by the DOE Building Technology Office—was used for this research project.

5.1 Methodology

5.1.1 DOE Prototype Building Model

To support the DOE Building Energy Codes Program, PNNL developed a set of representative Prototype Building Models[1] of national residential new construction to quantify the energy performance for evaluation of, and proposed changes to, energy codes (Mendon et al. 2012, 2015a; Xie et al. 2018). Because this project is focused on retrofits of existing homes that may be anywhere from two decades to a century old, the DOE prototype models were modified to represent the target existing building stock that may benefit from the wall retrofits. The inputs for targeted representative existing buildings were taken from the ResStock database published by the National Renewal Energy Laboratory (Wilson et al. 2017),[2] a large-scale housing stock database developed using public and private data sources, statistical sampling, and detailed building simulations. Figure 5-1 is a representation of the prototype building used for modeling in this study.

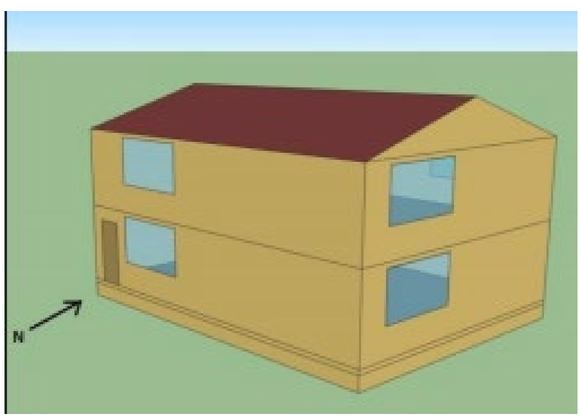


Figure 5-1. Modeled Single-Family Residential Prototype Building (Mendon et al. 2015b)

[1] DOE and PNNL. 2020. Prototype Building Models, Richland, WA, Pacific Northwest National Laboratory. Available at https://www.energycodes.gov/prototype-building-models.
[2] Wilson, Eric, et al. 2017. Energy Efficiency Potential in the U. S. Single-Family Housing Stock. Available at https://www.nrel.gov/buildings/resstock.html.

The residential prototype in this study begins with a single-family reference building with two-stories and approx. 2,400 ft^2 gross floor area. The total opaque wall area is 2,160 ft^2 with a total window area 355 ft^2 for a window-to-wall ratio of 14%. Details about the original model are from work by Mendon, et al. 2012. To capture the conditions of the largest number of homes in the United States, the most frequent building characteristics were extracted from ResStock data and applied to the prototype model. ResStock-motivated modifications to the baseline prototype model for this project include the following:

- *Foundation*: Slab-on-grade
- *Walls*: Wood-framed 2-in. x 4-in. studs @16 in. on-center with no insulation
- *Ceiling*: R-30 ceiling insulation with vented attic
- *Heating system*: Electric resistance, centrally ducted system for hot-humid climates; 80% AFUE natural gas, centrally ducted system for all other climates
- *Cooling System*: Centrally ducted, direct expansion, SEER 10
- *Ducting*: All inside conditioned space
- *Domestic hot water, storage*: Electricity for hot-humid climates; natural gas for all other climates
- *Windows*: Single-pane glass at U-1.22 Btu/h-ft^2-F and SHGC-0.39 for hot-humid and mixed-humid climates; Double-pane glass at U-0.62 Btu/h-ft^2-F and SHGC-0.39 for all other climates
- *Whole-home infiltration rate*: 15 air changes per hour at 50 pascals of pressure (ACH_{50})
- *Setpoints:* 72°F for heating and 75°F for cooling.

A complete listing of energy modeling inputs for all final wall layers (existing and new) for each configuration is provided in Appendix A

5.1.2 Two-Dimensional Wall Layer Modeling

The modified reference model and 14 variation buildings—one with each of the 14 wall retrofit options applied—were modeled using EnergyPlus v.8.6 (U.S. Department of Energy 2016). Each of these baselines were then modeled in all climate zones in the United States. A typical residential building with a single thermostat and a forced-air furnace and air-conditioning system is typically treated as a single-zone HVAC system and the heat balance represents a "well-stirred" model for a zone. In single-family homes, certain detailed energy flow characteristics, such as infiltration through the wall cracks (potential mass flow of moisture and air, and phase changes of moisture) and three-dimensional conductive and convective heat flow through walls, are not easily captured. Kośny and Kossecka, and Kośny et al. illustrated the difference in the thermal performance calculated using a simplified one-dimensional model of heat transfer compared to a multi-dimensional model capturing the effects of thermal bridging (Kosny et al. 2006; Kośny & Kossecka 2002).

Because EnergyPlus uses a simplified one-dimensional calculation approach for conduction heat transfer through the building envelope the multi-dimensionality of thermal bridging was captured by applying THERM, a two-dimensional conduction heat-transfer analysis program developed by Lawrence Berkeley National Laboratory (Vidanovic et al. 2021). A THERM model was developed for each wall section using the as-built construction schematic and the thermal properties of the wall assemblies to develop an overall section U-value for input into EnergyPlus. Two example outputs of the THERM simulations are shown in Figure 5-2.

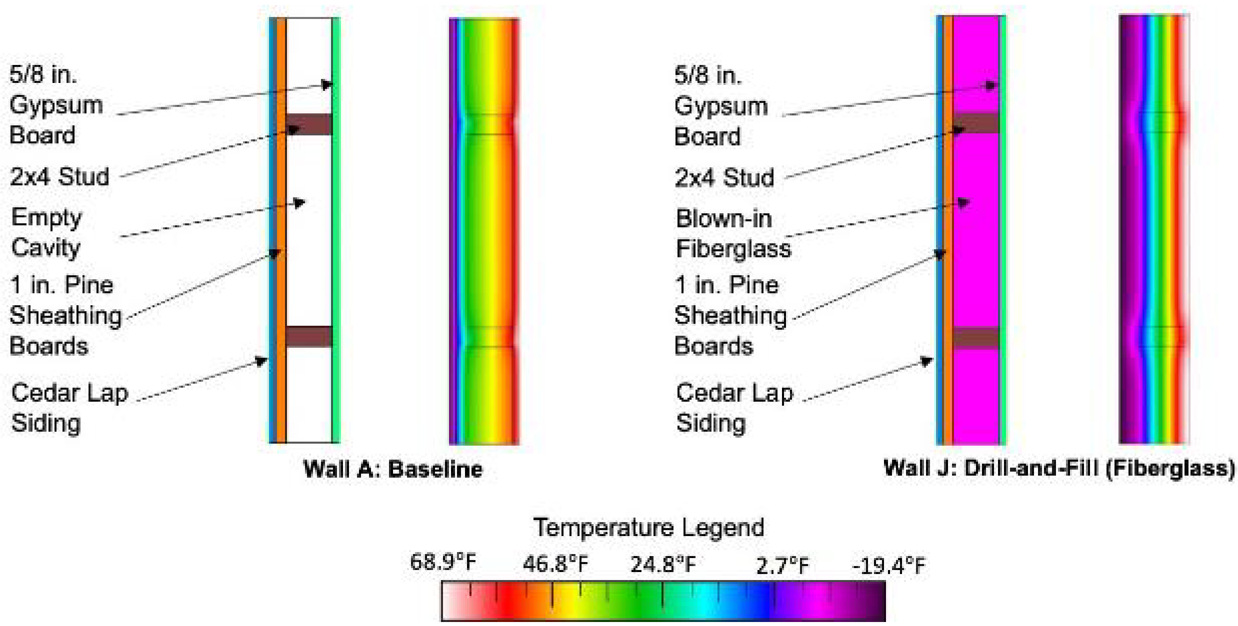


Figure 5-2. Sample Views of Two Wall Assemblies Modeled in THERM to Capture the Impact of Thermal Bridging

5.2 Results and Analysis

5.2.1 Model Benchmarking and Climatic Data

To use energy modeling to analyze test wall performance on a national scale, it's necessary to compare modeled results against measured data for a sampled location and calibrate the simulation to match actual performance, if they diverge. All 14 test wall assemblies plus the two baselines were constructed and instrumented with sensors at the CRRF test facility (i.e., a very cold climate).

Climate data were gathered from an on-site weather station and from a local weather station 0.5 miles away. A sample plot of the site's dry bulb temperature from both sources for the year 2020 is shown in Figure 5-3, compared to the historical TMY3 data (DOE 2021) from the local Cloquet airport weather station (Cloquet AWOS 726558) (The Weather Company 2021). Site-based monitoring is preferred because of the specificity and granularity of the data obtained.

From Figure 5-3, the hourly comparison between the on-site weather station and TMY3 dry bulb temperatures can be seen for the benchmarking period. While weather was measured on-site, the weather data logger experienced unexpected but occasional disruptions. During these times, data from the local airport weather station were used to fill in the gaps. If both local real-time sources were out of service, TMY3 values were used. While this figure displays dry bulb temperature, site instruments also measured relative humidity, wind speed, wind direction, cloud cover, global horizontal irradiance, and diffuse horizontal irradiance. Wet bulb temperature, dew point temperature, and direct normal irradiance were computed from these data by the EnergyPlus Weather Data converter. Metrics that were not measured and could not be computed were defaulted to TMY3 values.

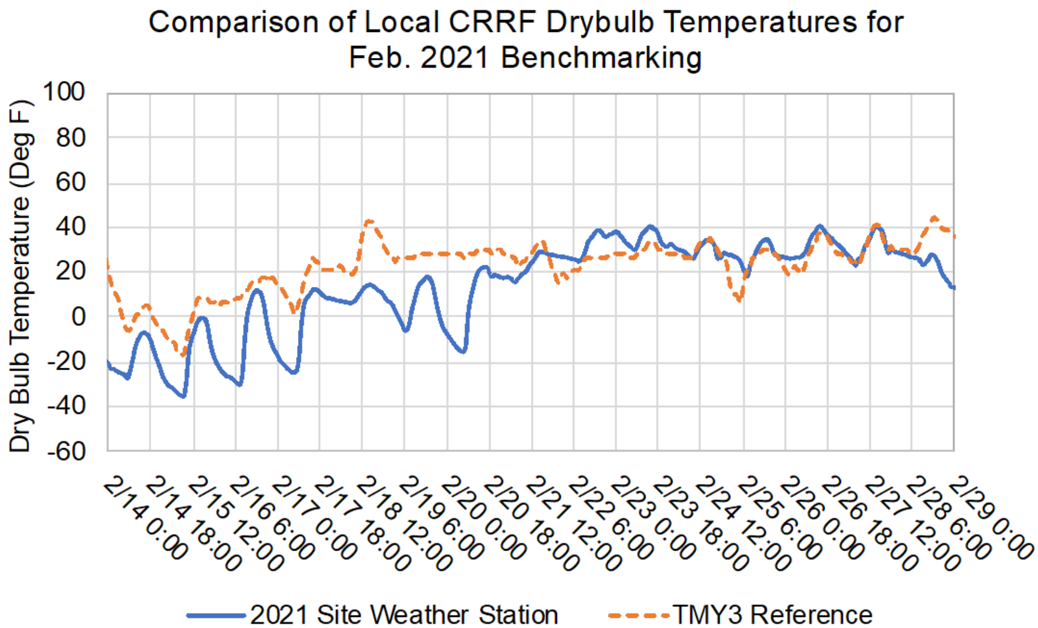
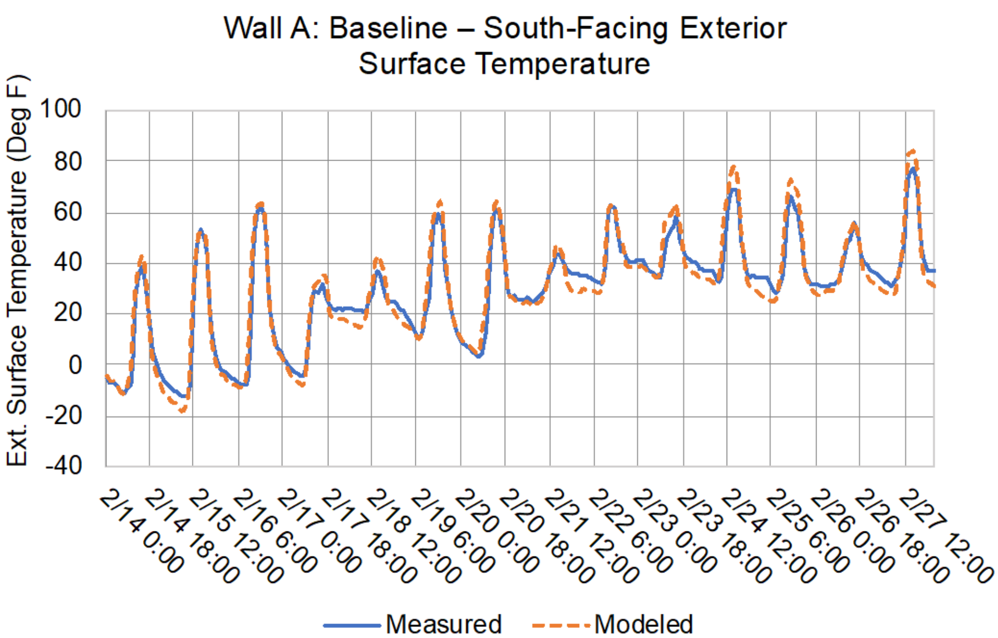


Figure 5-3. Sources for Dry Bulb Temperature Data Compared: On-Site Weather Station and TMY3 Weather File Values

Figure 5-4 and Figure 5-5 provide two examples comparing the exterior surface temperature and interior surface heat flux values for Wall A and Wall J, respectively. These comparisons indicated appropriate congruence with the simulation results and therefore required no calibration in the modeled input values. The general trends of the measured data appear to be captured by the energy models, thus confirming use of the modeled assembly values for both surface temperature and heat flux. All benchmarked values exhibited similar congruence across all walls, thus requiring no calibration to any of the modeled assemblies.



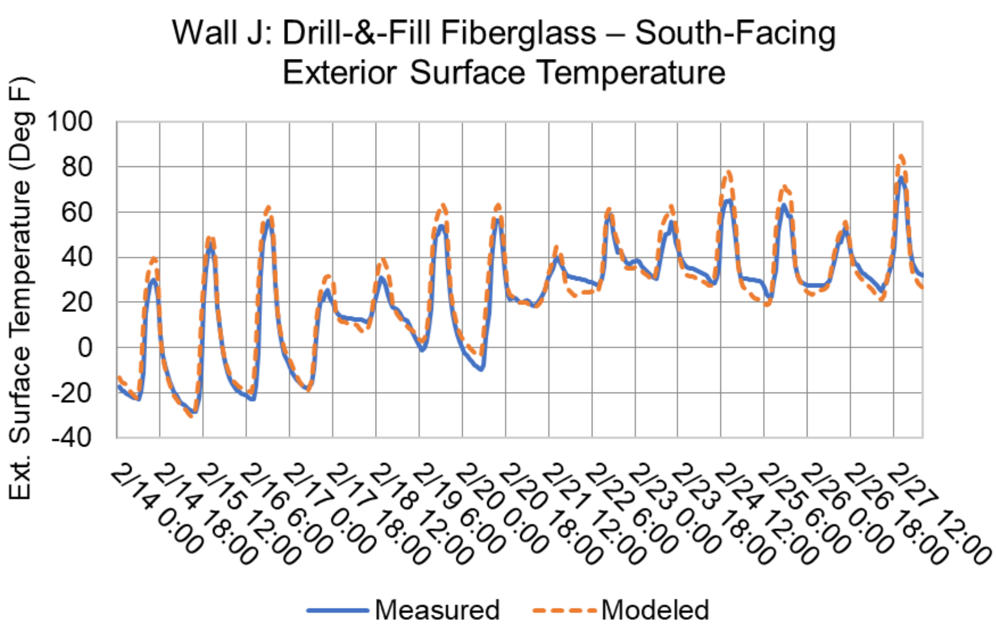


Figure 5-4. Energy Modeling Outputs of Exterior Surface Temperatures (Wall A top, Wall J bottom) Compared to Measured Experimental Data

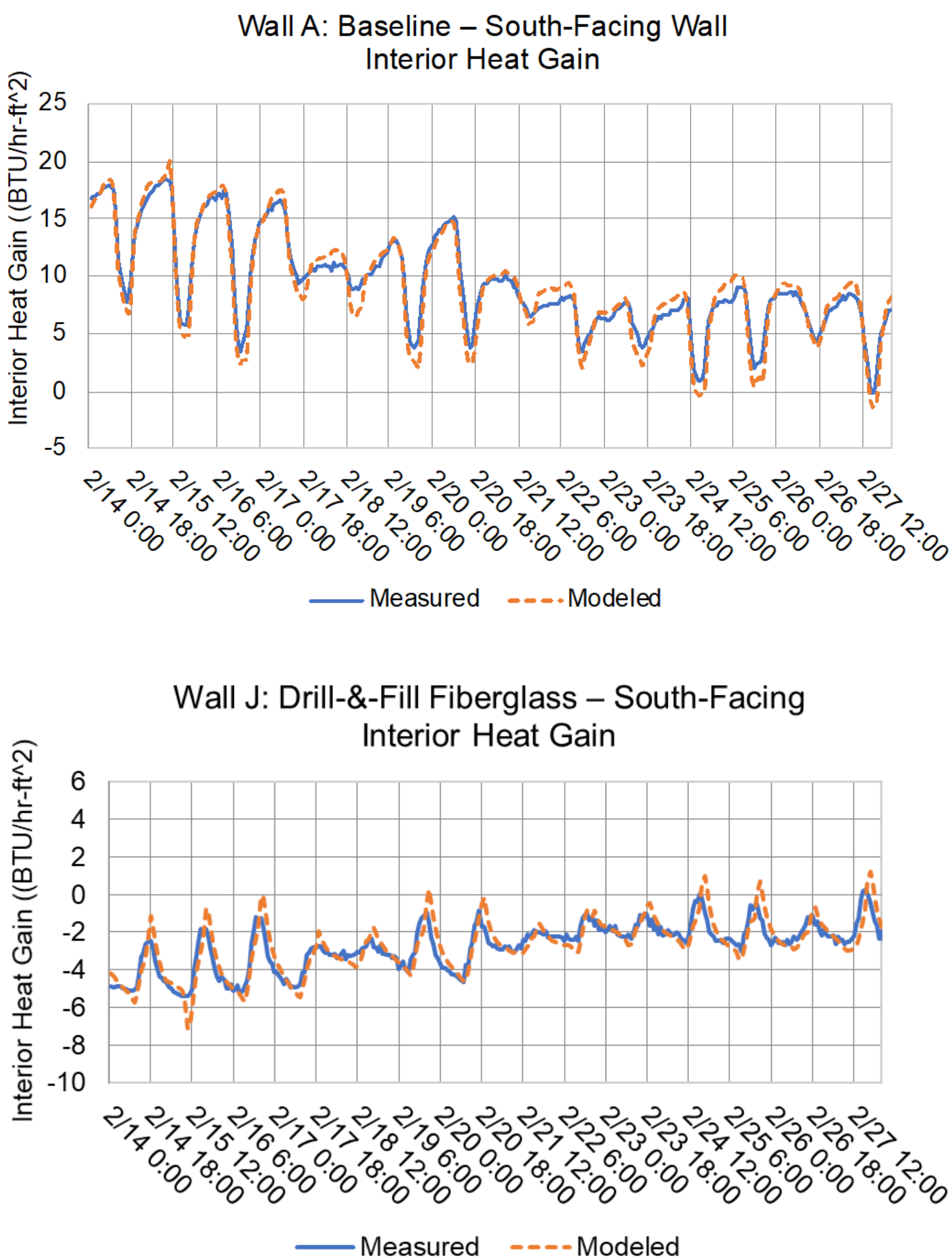


Figure 5-5. Energy Modeling Outputs of Interior Surface Heat Gain (Wall A top, Wall J bottom) Compared to Measured Experimental Data

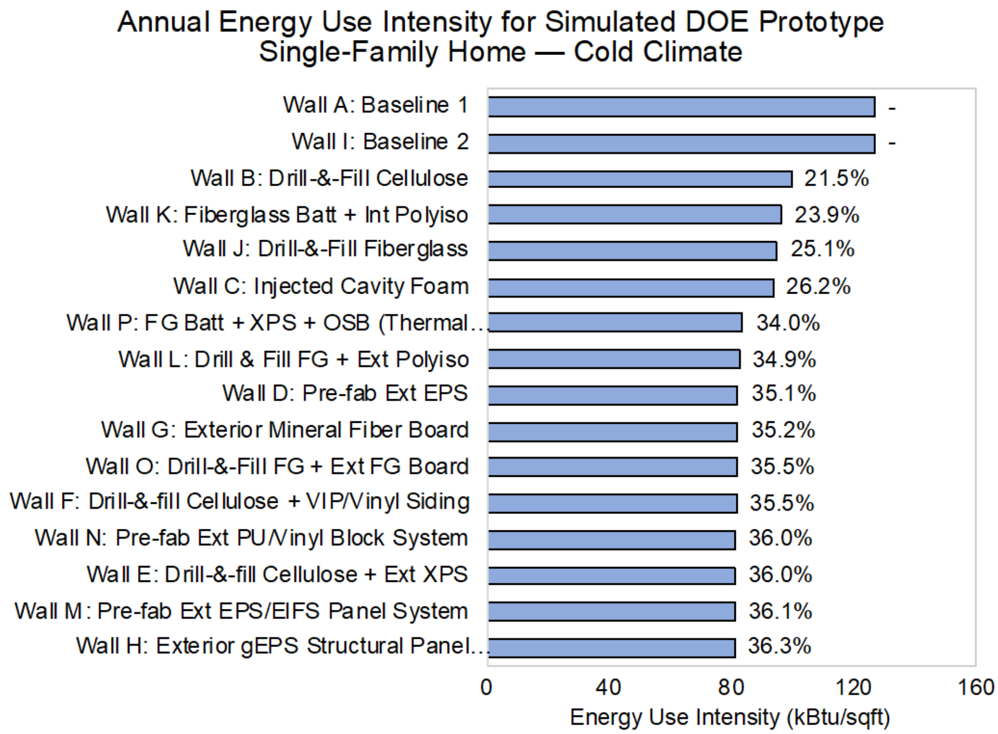
5.2.2 National Savings Analysis

All 15 test wall assemblies were updated in EnergyPlus using benchmarked values according to the methodology described previously. Simulations were run to explore the energy performance of the assemblies in eight representative cities, selected from the Building America climate zones (Baechler et al. 2015). To represent each of the Building America climate zones, the following representative cities were simulated:

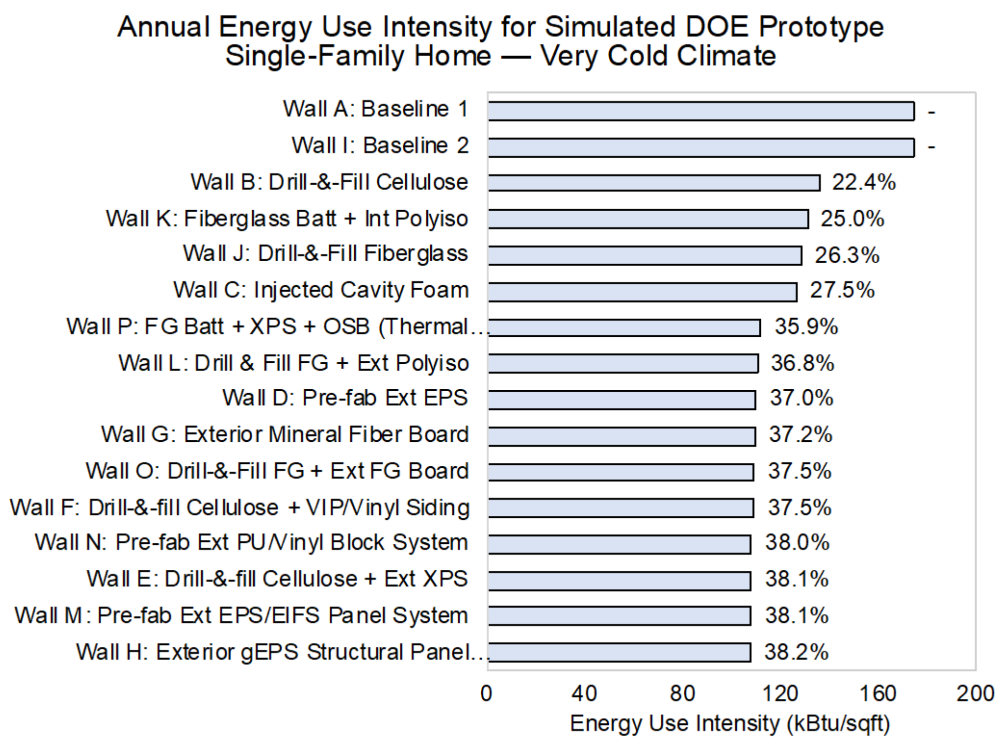
- *Hot Humid*: Miami, Florida
- *Hot Dry*: Phoenix, Arizona
- *Mixed-Dry*: Albuquerque, Minnesota
- *Mixed Humid*: Baltimore, Maryland
- *Marine*: Salem, Oregon
- *Cold*: Chicago, Illinois
- *Very Cold*: Duluth, Minnesota
- *Subarctic*: Fairbanks, Alaska.

Whole-building energy usage simulation for 120 energy models were used in the techno-economic analysis to develop several methods to characterize potential investment outcomes. Simulated energy use intensity and percentage energy savings are displayed for the Building America cold and very cold climates in this section—the regions of the United States that are the focus of this study. Results at a national scale can be found in Appendix C.

Figure 5-6 shows the simulated whole-home energy use index (EUI) values for all test walls for the cold and very cold climates. For all wall retrofits simulated, savings ranged from 21.5% to 38.2% across both climate zones, which appears to correlate with increased assembly overall R-value and improved air sealing. In addition to these savings, performance of the simulated assemblies appears to be stratified into groupings vaguely related to construction method (i.e., baseline, cavity retrofit only, and exterior insulation alone or combined with cavity fill.



a) Simulated Whole-Home Energy Use (EUI) for All Test Walls, Cold Climate.



b) Simulated Whole-Home Energy Use (EUI) for All Test Walls, Very Cold Climate.

Figure 5-6. Simulated EUI for a) Cold Climates and b) Very Cold Climates for the DOE Prototype Home

5.2.3 Impact of Air Sealing vs Insulation

Savings due to the wall upgrades are anticipated to be affected by two main factors: the thermal resistance of the envelope, which is discussed in the previous section, and infiltration or exfiltration through the envelope (air leakage into or out of the building).

For each wall assembly's whole-home air leakage, values were estimated based on the material and location of the air barrier layer in the wall, as well as the insulation type. Wall impact on whole-building air leakage was modeled as the following:

- *Baseline walls*: 15 ACH_{50} (based upon ResStock data)
- *Dense-packed cellulose*: 14 ACH_{50} (Walls B, K)
- *Closed-cell*[1] *spray foam and dense-packed fiberglass*: 13 ACH_{50}[2] (Walls C, J)
- *Spun-bonded polyolefin layers, peel-and-stick membranes, or liquid-applied layers*: 10 ACH_{50} (Walls D, E, F, G, H, J, M, N, O, P)

These air leakage improvements were based on experience and expert judgement, with an eye to conservatism. Because modern energy codes require 3 to 5 ACH_{50}, these simulated values are not likely to overwhelm the benefits of the improved thermal envelope. To be conservative, no wall upgrade was assigned an improved air infiltration value lower than 10 ACH_{50}, even though the case could be made that LAM or peel-and-stick membranes typically provide much lower infiltration rates in new construction and could also do so in certain retrofit applications.

Wall systems that add top-to-bottom exterior air barriers (e.g., WRB and LAM) improve a larger portion of the opaque envelope than drill-and-fill methods, which are limited to the stud cavity. These nuances are not captured in the following parametric study; all models assumed the wall upgrade impacted 66% of the total envelope surface. Future work is recommended to characterize the degree of air-infiltration improvement possible more precisely with real-world retrofits using different materials and applications.

To determine the relative impact of air leakage improvements and thermal resistance improvements, each wall was modeled twice for the select climate—once with the noted air leakage improvement and baseline insulation level, and once with baseline air leakage level and insulation improvement. Figure 5-7 shows the EUI impact of reduced air leakage in comparison to increased thermal resistance for the very cold climate (Duluth, Minnesota). For the retrofits studied, the thermal improvements consistently provide greater energy savings than the leakage improvements, though both are substantial.

[1] The spray foam initially examined for air tightness was >94% open cell by volume. The injected foam product ultimately installed in Wall C was a closed cell spray foam, expected to provide more robust air sealing. The lower permeability could reduce air infiltration even more and improve both energy savings and return on investment.

[2] The research team recognizes that Wall J, Drill-And-Fill Fiberglass (Proprietary FG, High-Density), is likely to have similar air leakage improvement to drill-and-fill cellulose, both of which have less than the Wall C: Injected Cavity Foam (Proprietary cc-spu), which has closed-cell foam insulation. Adjustments will be made in future work.

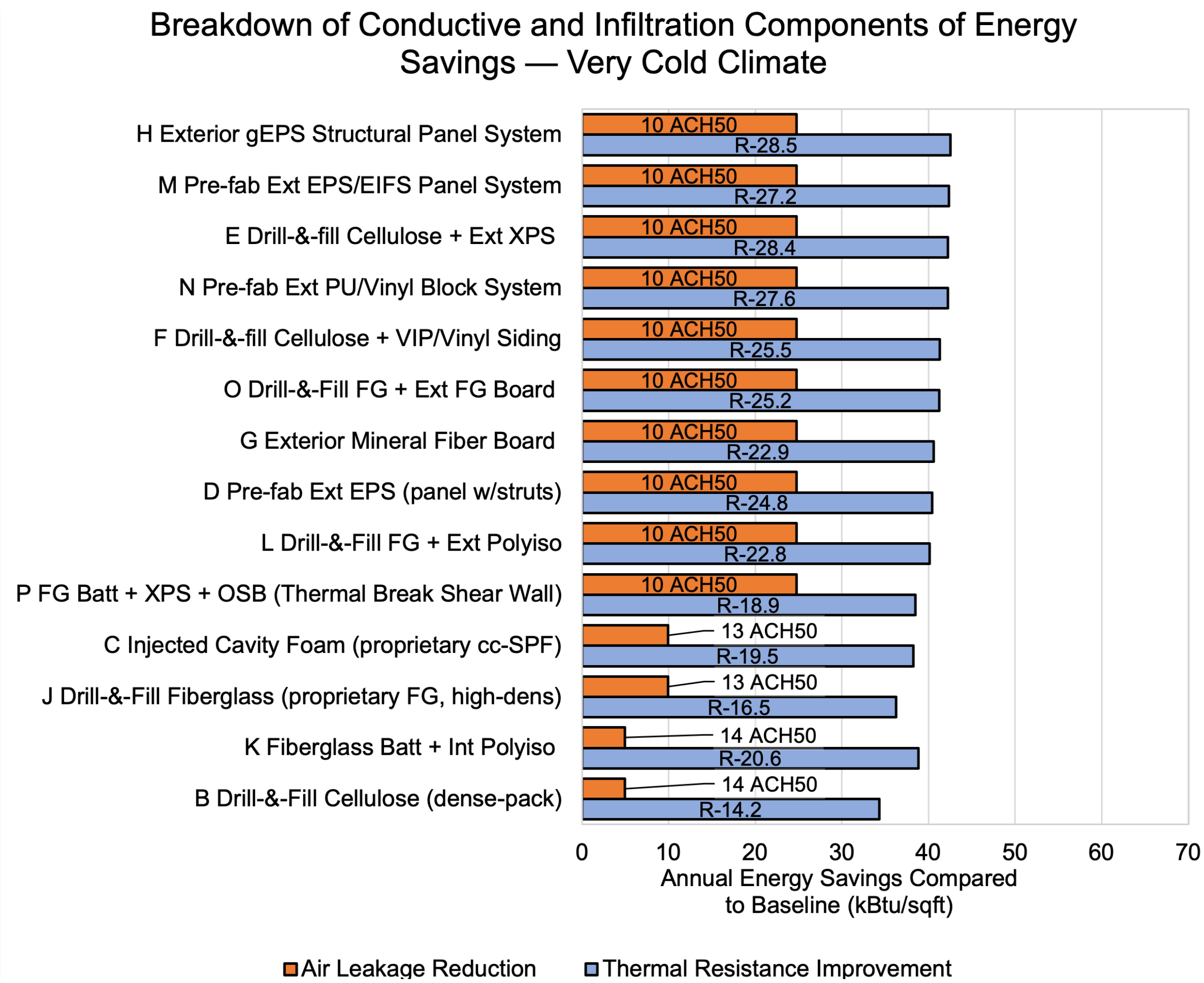


Figure 5-7. Comparison of the Relative Contributions of Air Leakage Reduction and Insulation Improvements on Annual Energy Savings

Installation is key to energy performance improvements for any wall retrofit. Just as thermal bridging reduces the value of robust insulation, poor air sealing leaves savings on the table.

This finding indicates that even for retrofit walls with modest insulation improvements, deliberate reductions in wall leakage can vastly improve energy performance. A comparison of this for Walls C and P is shown in Figure 5-7. The two walls have very similar simulated thermal performance ($R_{assembly}$ = 19.5 and 18.9, respectively), but wall P has about 23% lower infiltration and provides substantially larger energy cost savings.

Results also confirm the diminishing returns of increasingly high R-value retrofits. This trend typically applies to air leakage improvements, as well, although this is less clearly illustrated due to the incremental assumptions shown here. These two interventions (improved insulation and improved air sealing) are at different locations on the improvement curve, however. Figure 5-7 clearly shows that doubling the thermal improvement of a wall retrofit from R-14.2 effective (Wall B) to R-28.5 effective (Wall H) yields only about a 25% energy performance advantage. By contrast, choosing a wall retrofit with a leakage rate of 10 ACH_{50} versus one with 14 ACH_{50} (a 30% reduction between the two candidate retrofits) produces nearly a fourfold improvement in energy performance.

The air sealing improvements modeled for each wall type are conservative. As a reminder, modern energy codes require 5 ACH_{50} for CZ-0 through CZ-2 and 3 ACH_{50} for CZ-3 through CZ-8. These very low code-mandated leakage rates would be difficult to achieve in a retrofit situation because not all areas of the envelope are physically available, as they are in new construction. Nevertheless, it confirms the commonly held belief that any exterior or interior upgrade to an existing building should include an effort to air seal all exposed areas.

Both results suggest the importance of addressing the “low hanging fruit” in wall retrofits, meaning that retrofits do not necessarily need to be a “deep” or invasive to significantly improve energy performance, and some strategies can perform double duty by adding thermal resistance and also reducing leakage.

5.3 Energy Modeling Conclusions

In this study, the energy savings of 14 different retrofit wall assemblies were explored via a prototype single-family home energy model. This model was benchmarked with experimental data sourced from the in situ experiment at the Cloquet Residential Research Facility in northern Minnesota, which is in the DOE cold climate zone. The reference model represented mid-20^{th} century wood-frame construction, and the research wall configurations then were simulated across all climate zones to evaluate the range of savings potential for each of the candidate assemblies.

The climate zones with the highest potential for retrofit savings are those that are heating-dominated (i.e., Building America’s cold and very cold climates). This is in part because the effective assembly R-values of the test configurations were specifically designed by the researchers to meet the needs of cold and very cold climates. Simulated whole-home energy savings on an EUI basis for the full range of the 14 wall upgrades studied were as follows:

- 7.9% to 38.2% range across all climate zones
- 17% to 34% average inclusive of all climate zones
- 21.5% to 36.3% for the Cold climate zone
- 22.4% to 38.2% for the Very Cold climate zone.

Relative R-value improvements between the tested and simulated methods created less overall performance variation than did air leakage improvements. Both categories of improvements produce diminishing effects on wall energy performance, confirming the value of matching thermal performance to load conditions. This means that the highest potential for energy savings can be realized by first step interventions: adding insulation where no insulation exists; adding air sealing where no air sealing exists. Low cost retrofit strategies that moderately improve thermal performance and air sealing can have a large positive effect.

6.0 Economic Analysis

Economic performance of each wall includes complete material and installation costs for all components associated with the wall retrofits, as well as the financial impact from the simulated performance of each wall, calculated as energy cost savings compared to the baseline. Cost stacks are presented for labor, materials, and energy savings. Two typical investment metrics are also presented: internal rate of return (IRR) and simple payback; both are defined in Section 6.4.1.1. To integrate technical performance into the analysis, a techno-economic model is developed which identifies the market opportunity for each wall system based on both economic and technical performance factors. The traditional economic analysis is presented first, followed by the techno-economic modeling method and results.

6.1 Cost Data

Cost data were derived from three sources: 1) cost estimator Earth Advantage in Portland, Oregon; 2) RS Means Residential Cost Databook, 2020;[1] 3) detailed production and loaded pricing costs directly from manufacturers, and/or research partner teams.[2] Depending on the level of the technology, the current state of industry knowledge, and the local availability of products or proprietary equipment, pricing was adjusted based on research team members' expert knowledge. All modifications are explained in the narrative and footnotes. As industry conditions change practitioners may perceive different levels of complexity and opportunity, and products may infiltrate the market at different rates and to different levels than assumed here, any of which may result in different real-world pricing. Additionally, cost estimations were accomplished in different phases of the COVID-19 pandemic and thus are potentially inconsistent and not necessarily reflective of a settled construction market.

Each wall system was reduced to individual material layers that could be costed separately then summed to provide a total cost estimate. Material and labor costs were tallied separately. Table 6-1 provides an example of the retrofit layer designations for Wall H. Layers 1–7, representing the base case (the existing wall), are not shown here. Similar details for all test walls are included in Appendix A.

Information from the RS Means 2020 Residential Construction Cost Databook was used to supplement when information from the cost estimator was incomplete or fell substantially outside the expectations of the research team.

For experimental systems or approaches, such as Walls M and N that are prefabricated and not currently available in the marketplace, PNNL worked directly with manufacturers and research teams to estimate costs. Table 6-2 provides a breakdown of costing sources for each wall system.

[1] RS Means produces comprehensive cost data for the construction industry including detailed labor, material, and component costs along with typical task times and markups to allow accurate estimation of all types of construction projects. The Residential Construction issue is designed for homeowners, contractors, estimators, architects, and engineers and includes regional indexing to allow for local price adjustment.

[2] Manufacturers of tested prototype materials and components provided planned or calculated pricing for their as-yet un-marketed products and were interviewed about the assumptions regarding material availability, factory tool-up requirements, and anticipated market penetration to achieve target pricing. Characterization of these assumptions are included in the pricing discussions throughout this section.

Table 6-1. Example Wall Layer Designations for Costing

Exterior GPS/Metal Structural Panel System (Wall H)			
Layer	Generic label	Specific material	Detailed Description
8	Interfacial layer	Compressible fiberglass over existing cladding	$^{5}/_{8}$-in. semi-rigid fiberglass panel @ 19 bags of 2-ft x 4-ft sheets in bag of 16
9	OSB panel	Structural OSB panel	1-½ in. (two-layer laminate of ¾ in.) OSB panel @ 158 4- x 8-ft sheets or 79 4-ft x8-ft sheets
10	FAM WRB	Fully-adhered membrane	60 mil @ 2334.5 ft^2
11	Exterior GPS foam	GPS	2-$^{1}/_{8}$-in. GPS foam board (Type IX - 25 PSI) @ 79 4-ft x 8-ft sheets
12	Exterior GPS foam	GPS	2$^{1}/_{8}$ in. GPS foam board (Type IX - 25 PSI) @ 79 4-ft x 8-ft sheets
13	Furring strips	1- x 4-in. furring strips	¾-in. SPF boards at studs @ 2,334.5 board ft
14	Metal siding panel	Metal ribbed vertical siding	26 gage metal roofing panel - 48 panels @ 20 ft x 3 ft

Table 6-2. Material and Labor Costing Sources for Each Wall System.

ID	Wall Name	Cost Data Source(s)
B	Drill-and-Fill Cellulose (dense-pack)	Cost Estimator, RS Means
C	Injected Cavity Foam (proprietary cc-spu)	Manufacturer[a]
D	Pre-Fab Exterior EPS (panel w/struts)	Cost Estimator, RS Means
E	Drill-and-Fill Cellulose + Exterior XPS	Cost Estimator, RS Means
F	Drill-and-Fill Cellulose + VIP/Vinyl Siding	Cost Estimator, Manufacturer[a]
G	Exterior Mineral Fiber Board	Cost Estimator
H	Exterior GPS Structural Panel System	Cost Estimator
J	Drill-and-Fill Fiberglass (proprietary FG, high-density)	Cost Estimator, RS Means
K	Fiberglass Batt + Interior Polyiso	Cost Estimator, RS Means
L	Drill-and-Fill FG + Exterior Polyiso	Cost Estimator, RS Means
M	Pre-Fab Exterior EPS/EIFS Panel System	Manufacturer[a]
N	Pre-Fab Exterior Polyiso/Vinyl Block System	Manufacturer[a]
O	Drill-and-Fill FG + Exterior FG Board	Cost Estimator, RS Means
P	FG Batt + XPS + OSB (thermal break shear wall)	Cost Estimator, RS Means

[a] Manufacturers of wall upgrade materials or components with limited availability or which have not yet fully entered the market (C, F, M, N) shared conjectural pricing for their proprietary products. This is highly dependent on assumptions of supply chain and market conditions that are beyond the scope of this research; greater uncertainty is associated with these cost estimates compared to more traditional, widely available materials.

6.1.1 Cost Estimator Approach

Earth Advantage, a local non-profit organization and construction cost estimator in Portland, Oregon, provided material and labor costs for each wall studied. Earth Advantage's ties to the local residential building industry include workforce training and building certification programs. These activities put Earth Advantage regularly in the field, giving them access to a variety of local contractors familiar with advanced building science approaches and principles. This connection was imperative to determining fair market costs associated with experimental approaches and installation techniques for materials not commonly used for exterior wall retrofits.

For each of the 14 test wall configurations Earth Advantage provided itemized wall layer details to three different local contractors. Contractors were asked to bid as if these were actual projects, using current material and labor pricing, but with traditional contractor markups (despite the pressures of the pandemic). Using this uniform information, each of these contractors produced separate estimates for both material and labor costs, including demolition, if necessary. Upon review of the cost summaries, the research team determined that estimates from one contractor were much higher than the other two and did not seem realistic based on the team's construction experience and industry knowledge. When compared to RS Means, this set of estimates did not appear to consistently align with real-market values. The results from this contractor were determined to be outliers and removed from consideration. The remaining two labor and material estimates were averaged to develop each wall configuration's total estimated cost for use in the economic analysis.

6.1.2 RS Means and Manufacturer/Research Team Cost Data

PNNL and the cost estimator reached out directly to manufacturers for help with cost estimates for prototype or novel wall systems. For products that have either limited availability or have not yet fully entered the market, manufacturers shared conjectural pricing that is highly dependent on assumptions of supply chain and market conditions, which are beyond the scope of this research. Additionally, contractor estimates of labor for novel materials and methods are likely to be somewhat speculative and subject to the natural conservatism of the industry.

It is reasonable to assume these costs will not perfectly predict the eventual market pricing once the products and installation approaches are commercialized and widely adopted. In some cases, such as Walls C and N, the entire cost of the wall upgrade was developed by the manufacturer and research team, using reasonable comparisons to other materials and methods with known price ranges and sometimes applying a hypothetical multiplier to account for the novel nature of the newer approach.

For a final reality check, PNNL also referenced costs from the RS Means Residential Cost Databook from 2020. Typical data sourced from RS Means included costs for removal of cladding and sheathing, along with drywall installation and repairs. RS Means also was used as a touchstone when pricing from the cost estimator seemed unrealistic.

Additionally, RS Means regional indices were used to translate costs from Portland, Oregon, to other regions throughout the country. Regions chosen matched the analyses conducted in the energy models. Two cities are presented here, corresponding to the cold and very cold climates: Chicago, Illinois, and Burlington, Vermont. Results for representative locations in all other climate zones can be found in Appendix E.

6.1.3 Adjustments to Siding Costs

For each wall of the test matrix a siding material was identified as the final layer of the wall system. In some cases (B, C, J, and K), the treatment was a cavity-only application that did not require additional siding. In other cases, the siding was integrated with the insulation in a panelized approach to retrofits. In cases in which new siding material was needed, the research team specified a variety of materials including vinyl, fiber cement, stucco, and metal. Some of these were deliberate choices to support a secondary performance goal, as in the case of fiber cement siding paired with mineral wool to result in a retrofit wall that is recommended by some entities to be resistant to wildfire. The choice and associated cost of siding varies dramatically and is almost solely based on the preference of the consumer. For example, vinyl siding is significantly cheaper than stucco, but stucco might have more curb appeal to certain consumers. To control for siding costs, the cost analysis assumes vinyl siding for all wall systems that factored siding as a separate layer to the construction process (i.e., not cavity fill only or panelized systems with integrated insulation/siding). This limits the cost difference to the wall structure and control layers for comparison of the performance-related aspects. Table 6-3 presents mean average siding costs for materials and labor collected from the cost estimator ($\$/ft^2$ of opaque wall area). For the economic analysis, vinyl siding at $\$7.58/ft^2$ of wall was assumed for every wall type for which siding was applied as a separate layer. This improves comparability by limiting the cost variation between walls to the subset of components that directly affect energy performance.[1]

Table 6-3. Reported Siding Material and Labor Costs ($\$/ft^2$ of wall area) in Portland, Oregon, for a Typical 2,400 ft^2 Home (2,160 ft^2 wall area)

Siding Material*	Mean Material Costs	Mean Labor Costs	Mean Total Cost
Vinyl Siding	$1.39	$6.19	$7.58
Metal Siding Panel	$1.60	$6.71	$8.31
EIFS Panel	$2.48	$7.69	$10.17
Fiber Cement Siding	$1.60	$7.74	$9.34
Wood Composite Siding	$2.06	$8.26	$10.32
* Does not apply to walls B, C, J, K			

6.1.4 Limitations to Cost Data

There are a number of limitations associated with the cost data that should be noted.

First, this study was completed in two phases, the first in 2019 and the second in 2020. There is an inherent variation associated with costing construction projects over multiple years, related to changes in the consumer price index (which is a measure of inflation), contractor approaches, workforce issues, and other factors. An additional complexity for this project is that the first year of costs were derived before the advent of the COVID-19 pandemic, and the second-year costs were derived after COVID-19 had disrupted the market, including the availability and costs of many construction materials, which had large impacts on the construction sector in general. Therefore, direct comparisons between walls in Phase 1 (A-H) and Phase 2 (J-P) should be made with caution, using caveats described throughout this section.

Second, four different manufacturers and/or research entities provided cost data for wall systems, materials and/or approaches that are not currently available on the market, and there

[1] Where non-embedded furring strips were part of a wall's base assembly, labor and material costs for a backing layer (filling the void between the furring strips) of the exterior continuous insulation should technically be included because a solid substrate would be necessary to support the thin vinyl cladding. Even in these cases only the siding cost was adjusted. For simplicity, neither the first cost of the thin layer of added insulation (negative impact) nor the simulated thermal improvement of that thin insulation layer (positive impact) were adjusted. The added first costs would be offset to some degree by slightly better thermal performance, but both are small in comparison to other aspects of the calculation.

is no way to make sure all used the same methods to assess future market conditions or product adoption, which would directly relate to final retail pricing. Additionally, it is difficult to compare speculative costs for experimental systems with costs that are estimated by a contractor using known market products and processes. Wall systems that include manufacturer/researcher-derived costs include Walls C, F, M, and N.

Third, many wall systems analyzed here include cost data derived from additional, ancillary sources. While all pricing here used vetted knowledge and methods, there still may be inconsistencies that are not captured in the final presentation. Readers are encouraged to reference their own knowledge of local construction practices and trends to determine the cost and value of a particular wall retrofit for their own needs.

Finally, existing geometries have a major impact on the complexity of any particular wall upgrade. For the buildings with soffits, gable overhangs, and window and door trim projections that are deep enough to allow the new materials to fit without edge exposure, detailing is fairly standard. However, any required additional trim, non-standard cladding channels and caps, or boxing-out of windows required to accommodate the new wall thickness would increase both material and labor costs. Because of the wide range of variation in existing conditions, no attempt has been made to capture these costs. The “total added thickness” metric described in Section 3.7 was included to alert decision makers of this potential extra effort.

6.2 Total First Costs, Material, and Labor Compared

Material, labor, and energy costs are presented here in absolute dollar values, matched to the energy modeling analysis for two cities representing the Building America Cold and Very Cold climate zones, aligning to the objectives of the overall experiment. Because costs vary significantly between regions, results are presented by city as opposed to climate zone: two cities in the cold climate: Chicago, Illinois, (IECC CZ-5A) and Burlington, Vermont (IECC CZ-6A). Additional cities representing all climate zones are presented in Appendix E. Energy costs were matched to the cities using regional data for natural gas and electricity. In addition to labor, materials, and energy costs, simple payback, and IRR were calculated to assess the viability of the initial investment.

Total costs for labor and materials ($\$/ft^2$ of opaque wall area) in Chicago and Burlington are presented in Table 6-4 with ranking (least to most expensive) in the far-right column. RS Means cost indices were applied to account for regional cost differences between cities. In all but two cases, labor costs represent a majority of the total cost. The walls with high labor costs might be indicative of opportunities for cost compression. Full descriptions of each wall’s layers and components are presented in Appendix B.

Table 6-4. Material, Labor, and Total Costs by Square Foot of Opaque Wall Area for Each Wall in Chicago, Illinois, and Burlington Vermont

		Chicago Illinois (USD)			Burlington, Vermont (USD)			
Title	Wall Description	Labor Cost ($/ft^2)	Material Cost ($/ft^2)	Total Cost ($/ft^2)	Labor Cost ($/ft^2)	Material Cost ($/ft^2)	Total Cost ($/ft^2)	Rank (1 = least expensive)
Wall B	Drill-and-Fill Cellulose (dense-pack)	1.45	0.40	1.85	1.46	0.41	1.87	1
Wall C	Injected Cavity Foam (proprietary cc-spu) *	2.16*	4.16*	6.32*	2.20*	4.20*	6.40*	5*
Wall D	Pre-Fab Exterior EPS (panel w/struts)	13.42	6.95	20.37	13.55	7.02	20.57	12
Wall E	Drill-and-Fill Cellulose + Exterior XPS	14.88	4.08	18.95	15.02	4.12	19.14	11
Wall F	Drill-and-Fill Cellulose + VIP/Vinyl Siding*	11.37*	3.00*	14.38*	11.49*	3.03*	14.52*	6*
Wall G	Exterior Mineral Fiber Board	11.74	6.09	17.82	11.86	6.15	18.00	10
Wall H	Exterior GPS Structural Panel System	14.99	6.94	21.93	15.14	7.01	22.15	13
Wall J	Drill-and-Fill FG (proprietary FG, high-density)	1.45	0.40	1.85	1.46	0.41	1.87	2
Wall K	Fiberglass Batt + Interior Polyisoº	3.78 º	0.82 º	4.60 º	3.82 º	0.83 º	4.64 º	3 º
Wall L	Drill-and-Fill FG + Exterior Polyiso	12.05	2.33	14.38	12.17	2.36	14.53	7
Wall M	Pre-Fab Exterior EPS/EIFS Panel System*	22.50*	22.50*	45.00*	22.73*	22.73*	45.45*	14*
Wall N	Pre-Fab Exterior Polyiso/Vinyl Block System+*	1.50+*	3.56+*	5.06+*	1.52+*	3.60+*	5.11+*	4+*
Wall O	Drill-and-Fill FG + Exterior FG Board	11.87	4.66	16.53	11.99	4.71	16.70	9
Wall P	FG Batt + XPS + OSB (thermal break shear wall)	13.17	2.75	15.92	13.31	2.77	16.08	8

*Manufacturers of wall upgrade materials or components with limited availability or which have not yet fully entered the market (C, F, M, N) shared conjectural pricing for their proprietary products. This is highly dependent on assumptions of supply chain and market conditions that are beyond the scope of this research; greater uncertainty is associated with these cost estimates compared to more traditional, widely available materials.
+Costs for Wall N assume the block system is manufactured in volume.
ºWall K was assumed to exploit the opportunity of a full interior gut rehab. It was presumed that the interior drywall was already removed, and the wall cavities already filled with fiberglass batt insulation. Pricing accounts for the additional material and labor associated only with the polyiso foam board.

Wall M, the prefabricated panel system with exterior EPS and an EIFS finish, is intended to be prefabricated off-site and installed with all components integrated into one panel. There is significant opportunity for cost compression of this wall system for both labor and materials. Wall M is not yet commercially available and is an outlier in this analysis, due to the fact that both labor and material costs are currently assumed by the manufacturer to be high. Wall D, the prefabricated EPS insulation panel system with integrated installation struts at typical framing intervals, is now on the market. Initially, installation of Wall D required many steps, which is the source of the higher labor costs, but the manufacturer has redesigned this product to improve installation speed and reduce cost. Additionally, Wall D is envisioned as a single layer, not two as installed in this study. The one-layer system is likely to provide thermal performance more appropriately tuned to CZ 3–5, which could improve the economic calculations and adoption score. Walls H and E (Exterior GPS Structural Panel System and Drill-and-Fill Cellulose + Exterior XPS, respectively) also have higher labor costs, due to complex installation regimes. But Wall H is a site-fabricated version of a wall panel system envisioned as a factory panelized product. Similar to Wall M, off-site manufacturing offers some economies of scale and a level of quality control that may provide cost compression opportunities. The high labor cost of Wall E is due to the several steps associated with adding insulation to both the cavity and the exterior plane of the building and removing existing cladding and later adding new cladding. This is a fairly typical approach to deep energy retrofits in the last decade or more.

6.3 Energy Cost Savings

Residential electricity and natural gas prices were updated for each state, based on published annual market rates available through the U.S. Energy Information Administration (EIA 2020, 2021). Natural gas prices trend marginally lower in Illinois and higher in Vermont than the U.S. average. Electricity prices in Chicago are approximately 10% less than the national average, and in Burlington are about 30% higher than the national average. Special pricing, such as time of use, was not considered; taxes and fees were not included. This pricing was then combined with the energy simulation results from Section 5.2 to estimate total energy costs for the 1950’s era reference building and all test configurations for fair comparison to baseline. No attempt was made to calibrate to average current building utility costs.

Energy cost savings for Chicago and Burlington are presented in Figure 6-2. Cost savings potential is relatively high in colder climates; in areas that also have high energy prices, such as Burlington, the potential for savings is even higher. In Chicago, the savings range from nearly $26,000 to almost $44,000 over a 30-year time period. In Burlington, cost savings potential ranges from over $43,000 to more than $73,000 over a 30-year period. The large difference in cost savings potential between Burlington and Chicago is associated with Vermont’s substantially higher costs of electricity and gas.

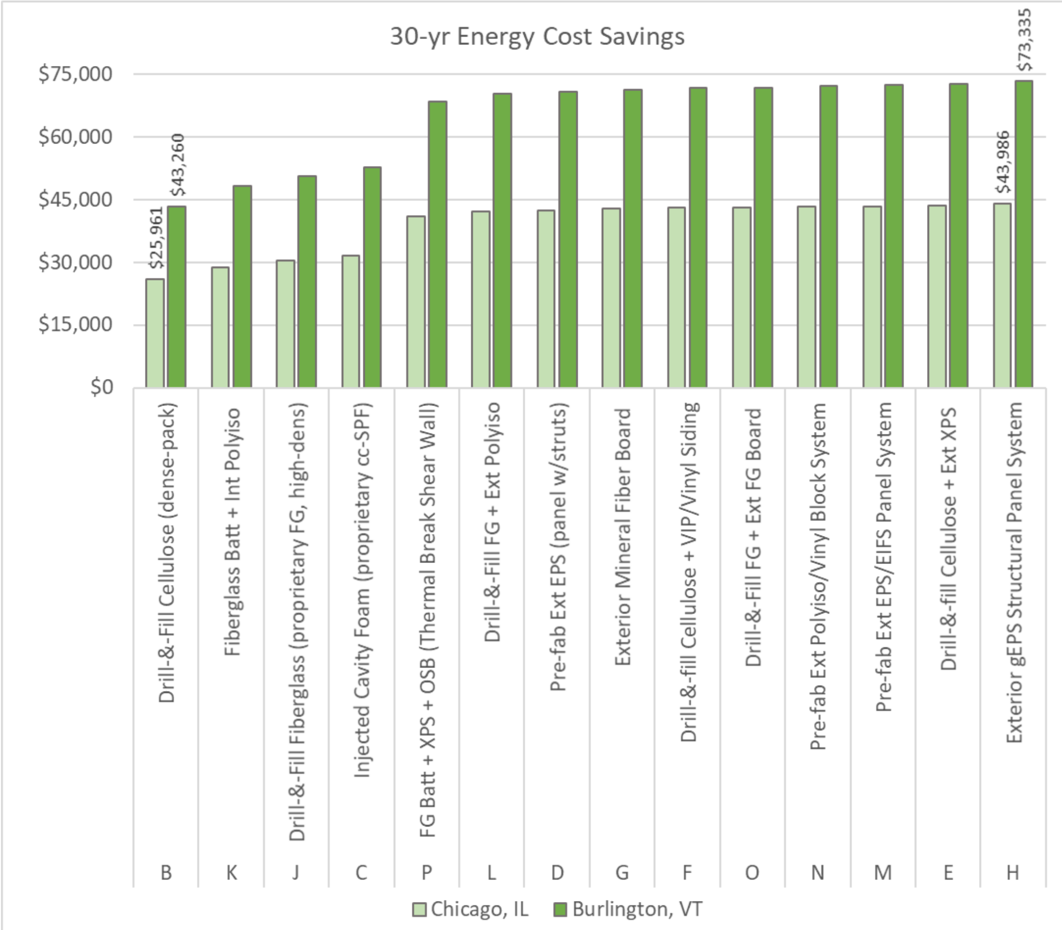


Figure 6-1. Energy Cost Savings for All Walls Over a 30-Year Time Horizon – Cold Climates

One illustration of economic value compares walls by considering the energy savings and initial investment as a ratio of 30-year energy cost savings potential compared to the initial cost investment: ($_{savings}$)/($_{first\ cost}$). Table 6-6 presents this ratio, ordered by highest ratio. Higher values indicate a better investment-to-savings opportunity for that wall system. For each climate zone, the walls with the most energy cost savings and lower material/labor costs are likely the most viable options for retrofits. As noted above, Burlington has high energy prices (30% higher than the national average), which yields even higher ratios than for Chicago that has lower energy prices (10% below the national average).

Table 6-5. Energy Cost Savings as a Multiple of First Costs for Chicago, Illinois

		30-yr Energy Cost Savings to Total Cost Ratio	
ID	**Wall Description**	**Chicago, Illinois**	**Burlington, Vermont**
J	Drill-and-Fill Fiberglass (proprietary FG, high-dens)	7.6	12.7
B	Drill-and-Fill Cellulose (dense-pack)	6.5	10.8
N	Pre-Fab Exterior Polyiso/Vinyl Block System	4.0	6.6
K	Fiberglass Batt + Interior Polyiso	2.9	4.9
C	Injected Cavity Foam (proprietary cc-SPF)	2.3	3.9

ID	Wall Description	30-yr Energy Cost Savings to Total Cost Ratio Chicago, Illinois	Burlington, Vermont
F	Drill-and-Fill Cellulose + VIP/Vinyl Siding	1.4	2.3
L	Drill-and-Fill FG + Exterior Polyiso	1.4	2.3
O	Drill-and-Fill FG + Exterior FG Board	1.2	2.0
P	FG Batt + XPS + OSB (thermal break shear wall)	1.2	2.0
G	Exterior Mineral Fiber Board	1.1	1.9
E	Drill-and-Fill Cellulose + Exterior XPS	1.1	1.8
D	Pre-Fab Exterior EPS (panel w/struts)	1.0	1.6
H	Exterior GPS Structural Panel System	0.9	1.5
M	Pre-Fab Exterior EPS/EIFS Panel System	0.4	0.7

Note: Baseline wall is modeled as circa 1950's with no cavity insulation and high leakage rate of 15 ACH

Table 6-5 presents two common investment metrics—IRR (%) and simple payback (years)—for each wall system in Chicago, Illinois, and Burlington, Vermont, ordered by highest IRR. Detailed discussion of these calculations can be found in Section 6.4. Additionally, the walls are ranked—best return on investment to worst—similar to the cost data. Walls with high payback (e.g., more years of energy savings are needed to earn back the cost of the retrofit) and negative IRR (indicating a net-loss investment) are not cost effective. Wall rankings according to simple payback yield a similar order to the ranking exercise for first cost. The lowest-cost walls tend to pay back in the shortest amount of time, considering energy savings and other economic inputs. The ranking order is the same for both cities.

Table 6-6. IRR and Simple Payback Period for Cold Climate Cities, All Walls

ID	Wall Description	Chicago IRR (%)	Chicago Payback (years)	Burlington IRR (%)	Burlington Payback (years)
J	Drill-and-Fill Fiberglass (proprietary FG, high-density)	25%	4	42%	2
B	Drill-and-Fill Cellulose (dense-pack)	22%	5	36%	3
N	Pre-Fab Exterior Polyiso/Vinyl Block System	13%	8	22%	5
K	Fiberglass Batt + Interior Polyiso	9%	10	16%	6
C	Injected Cavity Foam (proprietary cc-SPF)	7%	13	12%	8
F	Drill-and-Fill Cellulose + VIP/Vinyl Siding	2%	22	6%	13
L	Drill-and-Fill FG + Exterior Polyiso	2%	22	6%	13
O	Drill-and-Fill FG + Exterior FG Board	1%	25	5%	15
P	FG Batt + XPS + OSB (thermal break shear wall)	1%	25	5%	15
G	Exterior Mineral Fiber Board	1%	27	4%	16
E	Drill-and-Fill Cellulose + Exterior XPS	0%	28	4%	17
D	Pre-Fab EPS (panel w/struts)	0%	31	3%	19
H	Exterior GPS Structural Panel System	-1%	32	3%	20
M	Pre-Fab Exterior EPS/EIFS Panel System	-5%	67	-2%	41

6.4 Techno-Economic Modeling

To expand on the economic analysis in Section 6.2, researchers developed a techno-economic model to assess market penetration potential. The method for establishing model input was derived from previous studies (Fleiter et al. 2012; Hanes et al. 2019). An “adoption” matrix for each of the wall assemblies was created based on key features identified in the literature as drivers for the adoption of energy efficiency technology systems. Scores were assigned to each attribute, with higher scores implying greater benefit or more desirable features and thus faster adoption. Details and demonstration of that methodology in the context of a retrofit wall system follows.

6.4.1 Techno-Economic Modeling Methodology

The method used to develop the techno-economic model included developing discrete metrics that would influence the market to adopt or expand the presence of wall systems in retrofit projects: “market diffusion potential.” The resulting metrics were categorized into a matrix, in which each attribute was weighted, and a final adoption score calculated. The adoption matrix used in this exercise was adapted from precursor studies by Fleiter et al. (2012) and Hanes et al. (2019). In both studies, the goal was to develop a matrix of characteristics used to understand what drives energy efficiency measure (EEM) adoption and apply the matrix to a market diffusion model. Their developed classification scheme has implications for designing a method to analyze practitioners’ adoption of EEMs. Because their study focused on EEM manufacturing, their framework was adapted to be considered for residential wall retrofits. Most importantly, their process aids in understanding what drives the adoption process (i.e., by itemizing attributes that are likely to cause certain EEMs to diffuse faster than others). Fleiter and Hanes (2012) chose the following five criteria to assess and select useful attributes from the broad number of EEM and innovation characteristics proposed in the literature.

1. *Relevance*: The chosen characteristics should directly and compellingly affect whether the EEMs are adopted in the marketplace.
2. *Applicability*: The characteristics should be sufficiently general to allow the characterization of very different EEMs.
3. *Specificity*: The characteristics should remain specific enough to be evaluated as concrete and objectively as possible.
4. *Independence*: To increase the comparability among EEMs, the characteristics should not depend on the adopting firm or other contextual factors but rather be related to distinct features intrinsic to the EEMs.
5. *Distinctness*: The characteristics should not overlap and should be distinct from each other.

Based on these specifications, they developed the following general structure to characterize an EEM (Figure 6-2).

Characteristics		Attributes			
Relative advantage	Internal rate of return	Low (< 10%)	Medium (10 - 30%)	High (> 30%)	
	Payback period	Very long (>8 years)	Long (5-8 years)	Medium (2-4 years)	Short (<2 years)
	Initial expenditure	High (> 10% of invest budget)	Medium (0.5-10% of invest. budget)	Low (<0.5% of invest. budget)	
	Non-energy benefits	Negative	None	Small	Large
Technical context	Distance to core process	Close (Core process)	Distant (Ancilliary process)		
	Type of modification	Technology substitution	Technology replacement	Technology add-on	Organizational measure
	Scope of impact	System (system-wide effects)	Component (local effects)		
	Lifetime	Long (>20 years)	Medium (5-20 years)	Short (<5 years)	Not relevant
Information context	Transaction costs	High (> 50% of in. expenditure)	Medium (10–50% of in. expenditure)	Low (< 10% of in. expenditure)	
	Knowledge for planning and implementation	Technology expert	Engineering personnel	Maintenance personnel	
	Diffusion progress	Incubation (0%)	Take-off (<15%)	Saturation (>85%)	Linear (15-85%)
	Sectoral applicability	Process related	Cross-cutting		
		Lower adoption rate			Higher adoption rate

Figure 6-2. Classification Scheme for EEMs (Fleiter et al. 2012)

Each category in this matrix is expected to influence a market actor's decision whether or not to adopt an advanced energy efficient technology. For instance:

- Relative advantage includes economic and other monetary benefits.
- Technical context includes characteristics that have a bearing on the risk of adopting a specific technology and the difficulties involved in implementing a new technology within the market.
- Information context includes characteristics that reflect the amount of knowledge or training required to successfully implement the technology.

Researchers developed a scoring matrix based on the referenced classification system but with a focus on residential wall assemblies intended for retrofit use. In the absence of an adoption matrix precedent for EEMs in the residential space, reliance was placed on 1) published information from the literature for features that were specific to the adoption of residential wall assemblies, 2) metrics developed using inputs from the experiment and modeling activities conducted throughout the 3-year study, and 3) the experience, knowledge, and training of the expert researchers on the project team and the Advisory Group.

Within these categories, clustering methods were used for each attribute's range of performance data to develop bins—logical groupings—and assign a representative value from an appropriate range to each attribute in the context of every wall type and climate zone combination. Then each attribute category was weighted according to its perceived importance with respect to adoption of retrofit wall technologies. Together, these elements constitute a global calculation for a custom adoption score for every wall in each specific climate zone. Using the approach developed by Fleiter, we have discretized the characteristic ratings space. For quantitative characteristics, relying on the use of discrete ratings maintains comparability across technologies and across sets of technologies. The bins create maximum and minimum values for each characteristic rating that apply regardless of the technology, and the categories' weight assignments relate to real-world constraints and opportunities. Each category in the matrix (Figure 6-2) is discussed in detail below.

6.4.1.1 Relative Advantage

Internal Rate of Return

IRR is a method of calculating the rate of return of an investment, which is independent of external factors such as the risk-free rate, inflation, the cost of capital, or financial risk.

IRR is the discount rate at which the net present value (NPV) of the future cash flow is equal to the initial investment; that is, it is the rate of return at which the investment breaks even.

The higher an IRR, the more desirable an investment is to undertake. IRR is uniform for investments of varying types and, as such, can be used to rank multiple prospective investments or projects on a relatively even basis.

The calculation used to determine IRR is:

$$IRR = \Sigma_{t=1}^{\mathrm{t=T}} \frac{C_t}{(1+IRR)^t} - C_0 \quad (1)$$

Where C_t is the first cost (Material Cost and Labor Cost) and C_0 is the amount of energy cost savings in each year (going from year 0 to year 30).

The analysis was carried out over a 30-year period to correspond to the typical home mortgage term.

For the matrix, a clustering analysis was performed for each wall system to bin IRRs and a value of High, Medium, Low, and Very Low (best to worst moving from left to right) was assigned to this metric for each of the wall systems. Higher IRRs are preferred.

Net Present Value

NPV is the sum of the present values of the cash inflows and outflows; that is, R_t computed over a 30-year period at a discount rate of *i*. A positive NPV means the investment is worthwhile, an NPV of 0 means the inflows equal the outflows, and a negative NPV means the investment is not good for the investor.

$$NPV(i,T) = \Sigma_{t=1}^{\mathrm{t=T}} \frac{R_t}{(1+i)^t} \quad (2)$$

The discount rate *(i)* used in these calculations was 7% (National Academy of Sciences et al. 2010). The analysis was carried out over a 30-year period.

For the matrix, a clustering analysis was performed for each wall system for NPVs across CZ-5 and CZ-6 and a value of High, Medium, Low and Very Low (best to worst moving from left to right) was assigned to this metric for each of the wall systems. Higher NPVs are preferred.

Payback Period

Payback period refers to the amount of time it takes to recover the cost of an investment. The desirability of an investment is directly related to its payback period; shorter paybacks represent more attractive investments. Simple payback does not include the cost of money and is therefore somewhat limited. Nevertheless, it is a commonly used metric in residential construction. Payback was computed as follows:

$$Payback\ Period = \frac{(Material\ Cost + Labor\ Cost)}{Energy\ Savings\ in\ Year\ 1} = \frac{First\ Cost}{Energy\ Savings\ in\ Year\ 1} \tag{3}$$

For the matrix, a clustering analysis was performed for each wall system for payback period across CZ-5 and CZ-6 and a value of Very Long, Long, Medium, Short (worst to best moving from left to right) was assigned to this metric for each of the wall systems. Lower simple payback periods are preferred.

Material Cost

The material cost is all non-labor costs associated with each wall assembly. Inputs for this characteristic are the result of estimates provided by Earth Advantage for each wall type and adjusted by location indices using the 2020 Residential Costs guide with RS Means Data.

For the matrix, a clustering analysis was performed for each wall system for material costs across CZ-4 through CZ-7 and a value of Very High, High, Medium, Low (worst to best moving from left to right). A lower first cost for materials is preferred.

Labor Cost

The number of labor hours to completely install each wall retrofit is based on estimates provided by Earth Advantage for each wall type and per-unit pricing was adjusted by location indices using the 2020 Residential Costs guide with RS Means Data.

For the matrix, visual clusters were used to assign discrete values to “labor cost” for each climate zone for each wall type: Very High, High, Medium, Low (worst to best moving from left to right). A corresponding numerical value for each assignment (1–4) was used to quantify these assignments. A lower labor cost is preferred.

6.4.1.2 Technical Context

Ease of Installation

For this characteristic, the input comes directly from the constructability index developed by the UMN when constructing and installing test walls at the CRRF. Numerical assignments reflect the qualitative values: Very Easy (=5), Moderately Easy (=4), Several Layers or Steps (=3), Moderately Difficult (=2), Uncertain at this Time (=1).

For the matrix: Visual clusters were used to assign discrete values to “east of installation” for each climate zone for each wall type: Very Easy, Moderately Easy, Several Layers or Steps, Moderately Difficult, Uncertain at this Time (best to worst moving from left to right). Easy installation is preferred.

Scope of Impact – I (Energy Savings)

The energy savings for each wall system in each climate zone over a 30-year period was integrated from the energy modeling activity.

For the matrix, a clustering analysis was performed for each wall system for energy savings across cold and very cold climate zones and a value of value of High, Medium, Low and Very Low (best to worst moving from left to right) was assigned. Higher savings are preferred.

Scope of Impact – II (Mold Index)

The mold risk index in each climate zone, determined by the hygrothermal modeling activity, was integrated. This is a binary variable that is treated as a pass or a fail.

For the matrix, because this is a binary variable that is treated as a pass or a fail, a value greater than 3 (increased risk of mold) was assigned a value of 0 and a value less than 3 (not susceptible to mold) was assigned a value of 1.

6.4.1.3 Information Context

Workforce Knowledge Requirement

Overall Speed of Installation from the UMN constructability analysis was used as a proxy. We assumed that walls that are easier or faster to install can translate into a more efficient training process for the workforce.

For the matrix, input into the constructability index (overall “Speed of Installation”) developed by UMN was used with values of very fast (=5), somewhat fast (=4), somewhat slow (=3), quite slow (=2), uncertain at this time (=1). Faster installation times (which imply the ability for less-skilled workers to successfully perform the task) are preferred.

Transaction Costs

Material Acquisition from the UMN constructability analysis was used as a proxy. We assumed that materials that are readily available locally can translate into greater advantages to contractors when they make recommendations to their clients and can contribute to more efficient scheduling and the avoidance of costly delays.

For the matrix, readily available to contractor (=5), available at most building material stores (BMS) (=4), available at certain BMS (=3), available from manufacturer (=2), not available at this time (=1).

Note: For any individual metric, high attribute assignment values equate to more desirable outcomes and low assigned values equate to less desirable outcomes. For instance:

- A high first cost is “bad” as opposed to a low first cost; hence, a high first cost gets an assignment of 1,

- A high number of years for simple payback gets an assignment of 1 because a slow payback time is disadvantageous. A faster payback time would be preferable and would be assigned a higher value.
- A high IRR indicates a larger return on investment on a percentage basis, so a higher IRR is "good" and would be assigned a value of 3.

Following these qualitative valuations of the ordered outcomes within each attribute category, each individual attribute was assigned a weight corresponding to its relative importance in the adoption scheme. Some of these weight assignments were driven by the precursor methodology (Hanes et al. 2019) and others were informed by our own perceptions based on expert knowledge and experience in the building industry and the residential construction market. Attribute weights for the resultant matrix sum to 1 (100%). Figure 6-3 shows the score ranges and final weight assignments for each of these characteristics.

Relative Advantage						Weights
IRR	High (=4)	Medium (=3)	Low (=2)	Very Low (=1)		0.6
NPV	High (=4)	Medium (=3)	Low (=2)	Very Low (=1)		0.6
Payback Period	Very High (=1)	High (=2)	Medium (=3)	Low (=4)		0.1
Material Cost	Very High (=1)	High (=2)	Medium (=3)	Low (=4)		0.12
Labor Cost	Very High (=1)	High (=2)	Medium (=3)	Low (=4)		0.12
Technical Context						
Ease of Installation (UofM)	Very Easy (=5)	Moderately Easy (=4)	Several Layers/steps (=3)	Moderately difficult (=2)	Uncertain at this time (=1)	0.15
Scope of Impact I – **Energy Savings**	High (=4)	Medium (=3)	Low (=2)	Very Low (=1)		0.15
Scope of Impact – II – **Mold Index**	Low (<3) (=1)			High (>3) (=0)		0.09
Information Context						
Workforce Knowledge Requirement (Speed of Installation)	Very Fast (=5)	Somewhat Fast (=4)	Somewhat Slow (=3)	Quite Slow (=2)	Uncertain at this time (=1)	0.1
Transaction Costs (Material Acquisition)	Readily available (=5)	Available at most BMS (=4)	Available at certain BMS (=3)	Available from manufacturer (=2)	Not available at this time (=1)	0.05

Figure 6-3. Technology Adoption Matrix with Qualitative Valuations and Weight Assignments

The technology adoption scores (S_k) were then calculated as a weighted average of normalized characteristic ratings.

$$S_k = \Sigma_c w_c \left(\frac{r_{ck}}{r_c^{max}}\right) \quad (4)$$

where:

w_c is the characteristic weight that quantifies the relative importance of each technology characteristic to the overall adoption rate,

r_{ck} is the rating for technology k and characteristic c, and

r_c^{max} is the maximum possible value of r_{ck}.

Based on these characterizations, the adoption scores were calculated for each wall system in all climate zones. The adoption scores have been normalized to be bounded between 0 and 1. Scores closer to 1 indicate faster anticipated adoption based on these assumptions. Walls that are already commonly used for energy retrofits will naturally have higher scores, reflecting their current serviceability and/or popularity.

6.4.2 Summary of Adoption Scores

Figure 6-5 shows the adoption scores for the cold and very cold climates (CZs 5A, 5B, 6A, and 6B) for each of the wall systems, grouped into four tiers associated with first cost and arranged from best (upper left) to worst (lower right). The project team's methodology is based on ranked attribute categories that reflect known practical, technical, energy performance, and cost expectations in the residential construction market, with scorings for each wall's ability to meet each metric.

For these test walls lower first cost tracks quite well with better financial outcomes, despite producing more modest energy savings. Not surprisingly, the two lowest cost walls have the highest adoption scores; first cost is heavily weighted in the adoption matrix developed for this project. Walls with the highest adoption scores also tend to be the most traditional and thinnest, and involve the least disruption, which is consistent with the priorities developed in the adoption method. Scores closer to 1 indicate faster adoption based on these categorizations and indicate which technologies have the best chance for market uptake, based on these assumptions. Not surprisingly, Wall B and Wall K have high adoption scores which is due to the fact that these technologies are already available in the market and widely used. In these cases, the adoption score more accurately describes the technology's potential for deeper market penetration or the potential to capture more market share.

The prototypical wall upgrades with the highest adoptions scores in each cost tier would seem to be good candidates for improved market penetration, with targeted improvements. Wall N, a prefabricated product not yet available in the market, also shows promise, due to the low cost of the technology and opportunity for easy installation. Walls J, C, F, L, and O also show significant potential as a result of the modeling exercise.

The cost estimation portion of this study demonstrated that the bulk of any wall's cost is typically labor, and walls with multiple layers (i.e., both cavity fill and exterior treatments) require many installation steps, accounting for higher labor costs.

First Cost Tier	Adoption Score		
1 <$2 per ft^2	**Location**	**B: Drill-&-Fill Cellulose (dense-pack)**	**J: Drill-&-Fill Fiberglass (proprietary FG, high-dens)**
	Baltimore, MD	0.90	0.97
	Alberquerque, NM	0.91	0.89
	Salem, OR	0.94	0.85
	Chicago, IL	0.90	0.89
	Boise, ID	0.90	0.89
	Burlington, VT	0.94	0.98
	Helena, MT	0.94	0.93

First Cost Tier	Location	K: Fiberglass Batt + Int Polyiso	N: Pre-fab Ext PU/Vinyl Block System	C: Injected Cavity Foam (proprietary cc-SPF)
2 $4.50 to $6.50 per ft^2	Baltimore, MD	0.84	0.90	0.85
	Alberquerque, NM	0.84	0.85	0.80
	Salem, OR	0.84	0.89	0.85
	Chicago, IL	0.92	0.93	0.89
	Boise, ID	0.84	0.85	0.80
	Burlington, VT	0.92	0.91	0.89
	Helena, MT	0.88	0.86	0.87

First Cost Tier	Location	F: Drill-&-fill Cellulose + VIP/Vinyl Siding	L: Drill-&-Fill FG + Ext Polyiso	P: FG Batt + XPS + OSB (Thermal Break Shear Wall)	O: Drill-&-Fill FG + Ext FG Board
3 $14.500 to $22 per ft^2	Baltimore, MD	0.75	0.84	0.78	0.81
	Alberquerque, NM	0.69	0.71	0.64	0.69
	Salem, OR	0.77	0.76	0.70	0.74
	Chicago, IL	0.82	0.84	0.78	0.81
	Boise, ID	0.86	0.71	0.64	0.69
	Burlington, VT	0.76	0.86	0.81	0.84
	Helena, MT	0.82	0.80	0.71	0.74

First Cost Tier	Location	G: Exterior Mineral Fiber Board	E: Drill-&-fill Cellulose + Ext XPS	D: Pre-fab Ext EPS (panel w/struts)	H: Exterior gEPS Structural Panel System
3 $14.500 to $22 per ft^2	Baltimore, MD	0.70	0.69	0.65	0.64
	Alberquerque, NM	0.62	0.63	0.65	0.58
	Salem, OR	0.65	0.66	0.67	0.62
	Chicago, IL	0.71	0.74	0.75	0.66
	Boise, ID	0.67	0.66	0.68	0.62
	Burlington, VT	0.81	0.80	0.79	0.74
	Helena, MT	0.75	0.74	0.75	0.70

First Cost Tier	Location	M: Pre-fab Ext EPS/EIFS Panel System
4 ~$45 per ft^2	Baltimore, MD	0.60
	Alberquerque, NM	0.50
	Salem, OR	0.56
	Chicago, IL	0.60
	Boise, ID	0.53
	Burlington, VT	0.65
	Helena, MT	0.56

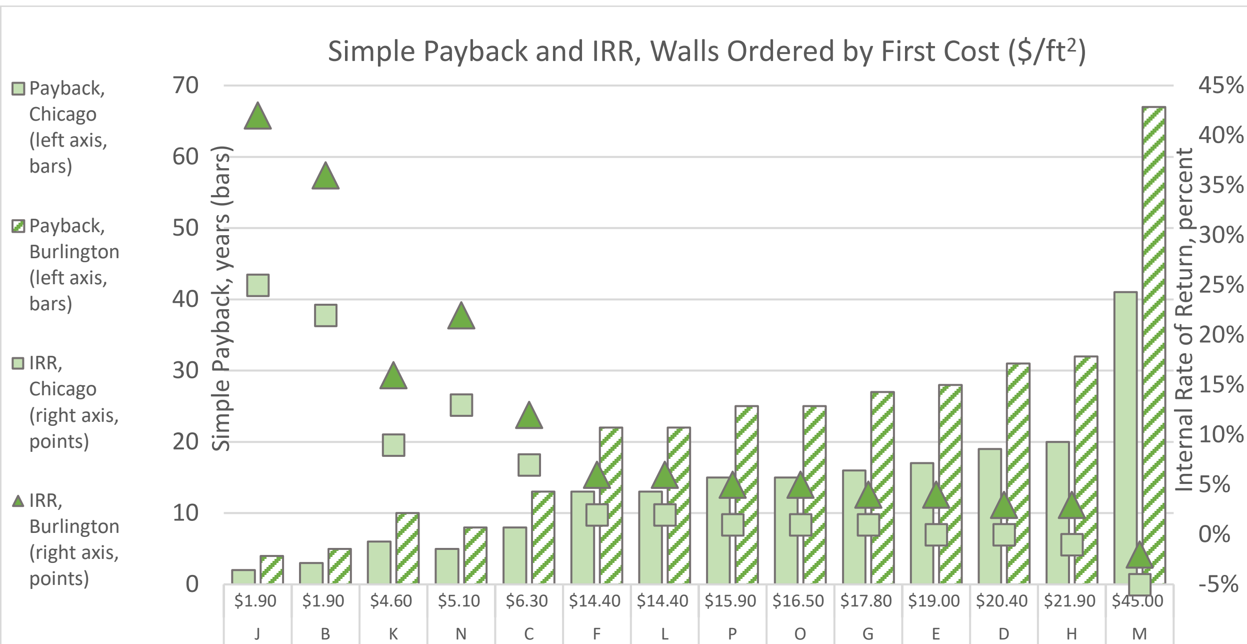
Figure 6-4. Adoption Scores for All Candidate Wall Assemblies. Grouped according to first cost for the two Cold Climate locations (Chicago, Illinois, and Burlington, Vermont)

6.5 Techno-Economic Conclusions

Figure 6-6 highlights the strong relationship between low first cost and good return on investment, two metrics that are especially compelling for homeowners.

Walls J and B are the two least expensive walls (and also the most common in the current market) and provide excellent IRR and very quick payback. The next set of three walls—K, N and C—also show reasonably low first cost ($4.50 to $6.50/ft^2) as well as good IRR (8% to 23%) and a simple payback of under 13 years (the construction industry often uses a 10-year payback as the indicator of a worthwhile energy conservation measure).

Of the three walls in this second tier, two (Walls N and C) are experimental in nature and not yet commercially available, highlighting the opportunity for new technologies and approaches to disrupt the market. Wall K takes advantage of an already-planned interior remodel to add an interior layer of polyiso, so some costs are attributed to the primary remodeling activity and not included in the reported cost of the energy upgrade, illustrating the value of combining projects.



	$1.90 J	$1.90 B	$4.60 K	$5.10 N	$6.30 C	$14.40 F	$14.40 L	$15.90 P	$16.50 O	$17.80 G	$19.00 E	$20.40 D	$21.90 H	$45.00 M
Payback, Chicago (left axis, bars)	2	3	6	5	8	13	13	15	15	16	17	19	20	41
Payback, Burlington (left axis, bars)	4	5	10	8	13	22	22	25	25	27	28	31	32	67
IRR, Chicago (right axis, points)	25%	22%	9%	13%	7%	2%	2%	1%	1%	1%	0%	0%	-1%	-5%
IRR, Burlington (right axis, points)	42%	36%	16%	22%	12%	6%	6%	5%	5%	4%	4%	3%	3%	-2%

Figure 6-5. Internal Rate of Return (%) and Simple Payback (years) for Chicago and Burlington. Ordered by installation cost ($/ft^2) of the wall upgrades.

The same can be said of the complexity associated with some of the multi-step or innovative walls in the study—thicker walls and novel configurations that require more installation time with respect to complex details and connections will naturally be more costly, at least initially. Walls with panelized, thicker, or multiple insulation layers also typically have higher materials costs. Prefabricated wall upgrades may have intensely designed component properties and some labor steps shifted from the site into the factory, affecting the cost of the product.

Conversely, the highest cost walls in this study are also likely to yield the highest energy savings because they provide the most improvement to insulation and air sealing capability. Table 6-7 shows the total 30-year energy savings of the 14 test walls ordered from least to most expensive and includes the labor-to-total cost ratio (a single set of cost columns represents both Chicago and Burlington because the differences are small and few). For nearly all walls labor cost dominates total cost; for the set, higher first cost typically correlates with higher energy savings. Orange borders in Table 6-7 indicate the ranges of four natural first-cost bins.

Table 6-7. Comparison of All Wall Upgrades: Cost versus Savings. Ordered from least to most expensive, including labor-to-total cost ratio.

				Chicago, IL	Burlington, VT
ID	**Wall Description**	**Total Cost**	**Labor-to-Total Cost Ratio**	**30-yr Energy Savings**	**30-yr Energy Savings**
B	Drill-and-Fill Cellulose (dense-pack)	$1.85	0.78	$25,961	$43,260
J	Drill-and-Fill Fiberglass (proprietary FG, high-dens)	$1.85	0.78	$30,322	$50,565
K	Fiberglass Batt + Interior Polyiso	$4.60	0.82	$28,894	$48,238
N	Pre-Fab Exterior PI/Vinyl Block System	$5.06	0.30	$43,279	$72,344
C	Injected Cavity Foam (proprietary cc-spu)	$6.32	0.34	$31,600	$52,728
F	Drill-and-Fill Cellulose + VIP/Vinyl Siding	$14.37	0.79	$43,017	$71,726
L	Drill-and-Fill FG + Exterior Polyiso	$14.38	0.84	$42,227	$70,385
P	FG Batt + XPS + OSB (thermal break shear wall)	$15.92	0.83	$41,088	$68,480
O	Drill-and-Fill FG + Exterior FG Board	$16.53	0.72	$43,047	$71,763
G	Exterior Mineral Fiber Board	$17.83	0.66	$42,783	$71,292
E	Drill-and-Fill Cellulose + Exterior XPS	$18.96	0.78	$43,608	$72,729
D	Pre-Fab Exterior EPS (panel w/struts)	$20.37	0.66	$42,517	$70,865
H	Exterior GPS Structural Panel System	$21.93	0.68	$43,986	$73,335
M	Pre-Fab Exterior EPS/EIFS Panel System	$45.00	0.50	$43,411	$72,556

The two lowest cost solutions, Walls B and J (Drill-and-Fill Cellulose and Fiberglass, respectively), are potentially already optimized for both materials and labor. Walls N (Pre-Fabricated Exterior Polyiso /Vinyl Block System) and C (Injected Cavity Foam (proprietary cc-SPU) in the second tier are notable exceptions. The small labor-to-total cost ratio may indicate that the technology has successfully reduced labor costs to near ideal or more likely has shifted a portion of them to the product-embedded costs in the factory. In either case, the potential for improved investment now seems to hinge on reduction of materials (product) cost. Note that costing for Wall N was provided by the manufacturer and presumes the block system is manufactured and sold in volume; however, it is not yet available in the market.

These results imply that the remaining nine wall upgrades would become better investments if their labor costs could be reduced, and those with the largest ratio of labor cost to total cost would benefit the most. (Table 6-7)

The adoption scores from the techno-economic study bolster these conclusions. Walls B and J are already the lowest cost wall upgrades and best investments, with fairly standard materials and methods. Their high adoption scores likely indicate their potential for deeper market penetration.

Walls N and C are prototypes with high adoption scores, indicating potential for market penetration.

Walls K, L, and P all have labor to total cost ratios of 0.8 or higher. Based on their adoption scores, Walls F and L would seem to be the best candidates for labor cost compression based on this techno-economic analysis. Of these two, Wall F Drill-and-Fill Cellulose + VIP/Vinyl Siding is currently under development and so has genuine potential to respond to market drivers of change.

Wall B	
Chicago, IL	0.90
Boise, ID	0.90
Burlington, VT	0.94
Helena, MT	0.94

Wall K	
Chicago, IL	0.92
Boise, ID	0.84
Burlington, VT	0.92
Helena, MT	0.88

Wall N	
Chicago, IL	0.93
Boise, ID	0.85
Burlington, VT	0.91
Helena, MT	0.86

Wall J	
Chicago, IL	0.89
Boise, ID	0.89
Burlington, VT	0.98
Helena, MT	0.93

Wall C	
Chicago, IL	0.89
Boise, ID	0.80
Burlington, VT	0.89
Helena, MT	0.87

Wall F	
Chicago, IL	0.82
Boise, ID	0.86
Burlington, VT	0.76
Helena, MT	0.82

Wall L	
Chicago, IL	0.84
Boise, ID	0.71
Burlington, VT	0.86
Helena, MT	0.80

Wall O	
Chicago, IL	0.80
Boise, ID	0.69
Burlington, VT	0.84
Helena, MT	0.74

Wall P	
Chicago, IL	0.78
Boise, ID	0.64
Burlington, VT	0.81
Helena, MT	0.71

Wall D	
Chicago, IL	0.75
Boise, ID	0.68
Burlington, VT	0.79
Helena, MT	0.75

Wall E	
Chicago, IL	0.74
Boise, ID	0.66
Burlington, VT	0.80
Helena, MT	0.74

Wall G	
Chicago, IL	0.71
Boise, ID	0.67
Burlington, VT	0.81
Helena, MT	0.75

Wall H	
Chicago, IL	0.66
Boise, ID	0.62
Burlington, VT	0.74
Helena, MT	0.70

Wall M	
Chicago, IL	0.60
Boise, ID	0.53
Burlington, VT	0.65
Helena, MT	0.56

Figure 6-6. Wall Adoption Scores of All 14 Wall Upgrades for Four Cold Climate Locations

Future techno-economic work could include application of the detailed pricing information and the adoption score matrix to new combinations of materials and approaches. Continued development and calibration of the novel adoption matrix/scoring methodology may be warranted.

7.0 Project Summary

In the United States, 39% of total energy is consumed by the building sector and 20% of that total by residential buildings (EIA 2018). Sixty-eight percent of residential building stock in the country was built before 1992, and these houses have significant air leakage, inadequate insulation, and inefficient windows. This project explored wall upgrades across a broad range of practical and performance metrics with the goal of identifying opportunities for retrofitting existing buildings to substantially reduce heating and cooling loads in underperforming homes across the United States, but especially in cold climates.

The work included expert industry input, experimentation, simulation, and market analysis to identify, explore, and analyze 12 promising wall upgrade configurations in addition to two baseline assemblies. Wide adoption in the marketplace—and thus deep impact on energy use—must necessarily capture the attention of builders and consumers. A successful wall upgrade will provide a cost-effective, constructable, durable, energy-efficient, and marketable strategy.

This section discusses issues of general interest based on the project's initial research questions (Section 7.1) and includes focused examinations of subsets of wall upgrades with similar components, goals or conditions (Section 7.2).

7.1 Research Questions – Construction, Performance, and Economics

The primary research questions posed in this study are discussed below, with general responses derived from project results:

- *What types of construction challenges are present in retrofit wall approaches? Do these challenges impact viability in the retrofit market?*

  Materials acquisition, especially of novel materials, can be challenging given the flux of construction markets. Some novel materials also require specialized training and/or equipment for application. Lack of local competition can keep prices high. In general, wall upgrades are challenging due to their geometric complexity, which include inside and outside corners, connection to the existing wall and to the soffit and foundation, and treatment of windows and mechanical penetrations. All require preparation, time, skill, and care. The 4-ft x 7-ft test walls on the CRRF did not present adequate complexity to fully examine these challenges. Recent constrictions of the skilled labor pool make the possibility of factory-fabrication of panelized wall even more relevant. Prefabrication methods could potentially lower cost while increasing quality and consistency, but regional availability could be a bottleneck, especially as transportation prices increase due to fuel cost.

- *Under what circumstances does it make sense to retrofit walls over the existing cladding? Are there approaches that show ability to scale in the marketplace?*

  The ability to encapsulate hazardous materials (lead, asbestos) and leave them in place is tempting; no attempt was made in this analysis to determine costs or ROIs in comparison to the cost and liability of hazardous waste removal, or whether abandoning-in-place is an allowed solution in any particular location or situation.

Nevertheless, leaving existing siding in place avoids the mess and noise of demolition as well as the need to dispose of construction materials in the landfill. In most cases where existing siding was left in place and covered by these wall upgrades, a compressible layer of fiberglass paneling was applied as a leveler and air/water control layer. This step requires additional material and is time consuming, which adds cost. Factory panelized solutions, especially with an attached hanger system, could resolve this issue, but the test walls considered are still considered novel and therefore expensive and not widely available. Recent exploration of wall upgrade systems that follow the European “EnergieSprong” approach (this project, New York State Energy Research and Development Authority, Rocky Mountain Institute) may help to identify good candidates and introduce them to the market. Additional skilled labor pressures may hasten adoption of solutions which shift some of the construction activities to a factory setting..

- *What is the thermal and moisture performance of different wall retrofit approaches? How does performance vary between climates?*

  Monitoring of the test walls in cold climates and subsequent simulations of the configurations in all climate zones indicates that most walls are capable of providing adequate moisture and thermal performance. Performance and simulation data, along with techno-economic analysis, can be found in Appendix E for all test wall configurations and all climate zones. See Section 7.2 for comparisons of logical subsets of wall upgrade approaches. This project identified ample wall types for good moisture performance in every climate zone. As expected, walls lacking exterior continuous insulation (B Drill-and-Fill Cellulose (dense-pack), J Drill-and-Fill Fiberglass (dense-pack)) may require special consideration if installed in climates which experience low winter temperatures that may allow condensation within the wall cavity. As discussed in Section 4.4, with further research cellulose could well be reclassified as less moisture sensitive due to added biocides, which may then result in mold indices for Wall B nearly identical to Wall J. Walls that incorporate inexpensive interior vapor retarders (Walls C and N) are promising solutions.

- *To what extent do cost factors such as high material and labor costs, long payback periods and low IRRs impact the economic viability of wall retrofit approaches? Are there advancements on the horizon that indicate better prospects for the economics of particular wall solutions?*

  Economic inputs such as material, labor, and energy costs drive the results directly, but first cost had the strongest relationship to both IRR and simple payback. Decreases in material and labor costs and increases in energy costs result in major improvements of simple payback and IRR. The correlation between higher energy savings and positive economic metrics is less direct because more thermally robust walls also have higher material and labor costs. Walls that include novel materials, unusual installations, or both, have high relative first costs for both materials and labor that likely make their ROI unappealing to homeowners. The economic analysis and adoption score exercise indicate that wall upgrades with high labor cost to total cost ratios are ripe for price compression of a scale which may put their IRR or simple paybacks within ranges consumers expect. One prototype Wall, F Drill-and-Fill Cellulose + VIP/Vinyl Siding, seems to meet most of the metrics that indicate a good opportunity for market diffusion due to the possibility for cost compression.

Because these test walls were designed to meet cold-climate needs, extrapolation to regions with lower heating demands is interesting but not dispositive. Designers in regions with more cooling degree days are likely to choose different insulation and control layer types or quantities, likely at lower cost, and this will improve economic viability for those regions.

7.2 Wall Upgrade Comparisons

Secondary research questions focused on methods to critically judge and compare the many wall upgrades tested and simulated in the study:

- What are the best methods and metrics for comparing similar wall retrofit strategies?
- How best to categorize and group the wide range of solutions? By insulation type? By installation complexity? By cost or ROI?

While the protype wall upgrades were installed and tested in CZ 7, the economic indicators in this discussion will focus on CZ 5 and CZ 6 because they represent the vast majority of the existing housing stock in colder climates that can benefit from the interventions included in this study. Results for the full range of researched walls in all climate zones can be found in Appendix A. Schematics and full descriptions of the configuration details and construction notes can be found in Section 3.0. Non-economic indicators are valid for all locations.

This section provides discussion of various logical subsets of tested wall upgrades. In each section, the first matrix highlights the construction and performance attributes of each wall in the comparison category which are not climate zone-specific, except for some small variations in moisture risk and IECC energy code compliance, noted for each wall type.

Economic indicators for these groupings of interest are presented next, specifically for CZ 5 and CZ 6 to represent the cold climate that is the primary focus of this research. Although most IECC prescriptive residential building requirements for these two climate zones are nearly identical, the two regions do represent somewhat different climate conditions (loads), especially for heating, and this affects their respective energy savings. Economic inputs for CZ 5 and CZ 6 are also different since representative cities typically have different local labor and materials pricing. See Section 6.0 for further details.

Note that for the first matrix of each comparison category, a “no” answer in the “Variations” section is considered to potentially reduce cost or complexity. A “yes” answer in the “Added Value” section is expected to be advantageous, perhaps justifying larger first cost or less advantageous return on investment. Throughout the matrices, darker green shading indicates a better relative outcome, whether subjective, observed, measured, calculated, or simulated.

7.2.1 Leave Exterior Finish Intact

Four wall upgrades left the existing exterior finish intact. Three upgrade methods add insulation to the presumably empty wall cavity using the drill-and-fill method, and one installs a layer of rigid insulation at the inside face of the home’s exterior walls, assuming the opportunity to coordinate with a major interior remodel.

All four wall upgrades (Figure 7-1) can be accomplished relatively quickly and avoid the cost, disruption, and time associated with removing and replacing siding as well as saving the fuel that would be required for transportation for disposal, and even saving space in the landfill.

ALL CLIMATE ZONES		Variations			Added Value				Construction						Performance		
ID	Wall Name/ Description	Siding Removed	Novel Materials	Novel Installation	Improved Shear (e.g. wind, earthquake)	Fire protection / Noise control	New Ext Finish	Leave/encapsulate hazardous materials	Materials Acquisition	# Operations	Speed of Installation	Ease of Installation	Added thick-ness, in.	Moisture Risk by CZ	Effective R-Value (assembly)	Meets or Beats in CZ 2021 IECC
B	Drill-&-Fill Cellulose (dense-pack)	N*	N	N	N	N	N	Y	1	2	1	1	0	4C, 5, 6, 7, 8	14.2	0-2
C	Injected Cavity Foam (proprietary cc-spu)	N	Y	Y	N	N	N	Y	X	2	2	1	0		19.5	0-3
J	Drill-&-Fill Fiberglass (proprietary FG, high-dens)	N*	N	N	N	N	N	Y	2	2	1	1	0	4C, 7, 8	16.5	0-2
K	Fiberglass Batt + Int Polyiso	N	N	Y	N	N	N	Y	1	4	2	3	1		20.6	0-3

Figure 7-1. Summary Details of Construction, Performance and Other Attributes for Wall Upgrades that Leave the Existing Siding in Place

An asterisk under "Siding Removed" (N*) indicates that only a few courses of siding were removed (to drill a hole to feed the blown-in or injected insulation into the stud cavity) and later replaced, after the sheathing and WRB were patched.

The cavity-fill only solutions (Walls B, J, and C) were among the fastest and simplest approaches tested, and of these three only the low-expansion injected foam (Wall C) was considered somewhat novel. The very low permeability of the closed cell injected foam of Wall C provided moisture resilience that was not evident in Walls B and J (caution is suggested in Marine, Very cold, and Subarctic regions).

Wall K with fiberglass batt installed from the inside and a layer of interior polyiso also provides good moisture resilience by retarding vapor transport, similar to Wall C. It also has simple paybacks and IRRs in Chicago of 10 years and 9%, respectively, and in Burlington of 6 years and 16%, respectively, despite four separate installation operations and a relatively low designation of "3" for installation ease (1 = "very easy").

A modification to Wall K could be to leave the drywall in place and hire an insulation contractor to drill-and-fill cellulose, fiberglass, or injected foam. The layer of polyiso would then go over the top of the existing drywall and a new layer of drywall would be installed. The time and mess of drywall removal would be avoided and could offset the higher cost of the drill-and-fill approach. The thermal performance of the wall would slightly increase by the R-value of the extra layer of drywall, about R-0.5. Eventually, improvements in directing the flow of injected foam could allow insulation of the rim band area between the first and second floors. This treatment requires only very small holes. If done very near the exterior perimeter of the ceiling the new layers of polyiso and drywall would cover these access points without the need for patching.

All four wall upgrades are among the lowest cost options tested and provide energy cost savings of about 20% on average, with positive IRRs and simple payback periods of from 2 to 13 years (Figure 7-2). Most are expected to have adequate moisture performance based on simulation results, but none are thermally robust enough to bring a home's opaque envelope up to IECC 2021 performance standards. While meeting current energy code typically is not a requirement for retrofit projects, it is of interest considering that the 2021 IECC requirements have been designed to contribute to energy reduction targets associated with global warming.

		Economics Chicago						Economics Burlington					
ID	Wall Name/ Description	Energy Cost Savings, %	EUI Savings, %	Cost $/sf Wall	Cost Bin ($3/sf, $13/sf)	IRR	Simple Payback	Energy Cost Savings, %	EUI Savings, %	Cost $/sf Wall	Cost Bin ($3/sf, $13/sf)	IRR	Simple Payback
B	Drill-&-Fill Cellulose (dense-pack)	18%	21%	$2	1	22%	5	18%	22%	$2	1	36%	3
C	Injected Cavity Foam (proprietary cc-spu)	22%	26%	$6	2	7%	13	22%	27%	$6	2	12%	8
J	Drill-&-Fill Fiberglass (proprietary FG, high-dens)	21%	25%	$2	2	25%	4	22%	26%	$2	2	42%	2
K	Fiberglass Batt + Int Polyiso	20%	24%	$5	1	9%	10	21%	24%	$5	1	16%	6

Figure 7-2. Economic Results for CZ 5 (left) and CZ 6 (right) for Wall Upgrades that Leave the Existing Siding in Place

7.2.2 New Siding and Added Exterior Insulation (Built-up Systems)

The seven wall upgrades in this category all had the added value of brand-new siding—an aesthetic improvement that might appeal to homeowners looking for a facelift. If a homeowner is already planning a re-siding project, the addition of an energy upgrade to the walls is an opportunity that should not be ignored. The wall upgrades described here already include the cost of new cladding. Coordinating new wall insulation with new cladding can ease the pain of the price tag for either project alone. Because the labor for the energy upgrade overlaps the labor for the re-siding effort, there is a combined cost advantage.

7.2.2.1 New Siding and Exterior Insulation Only, Installed Over Old Siding

Two of the wall upgrades left the existing siding in place (Figure 7-3) and then covered them with new material, including new cladding.

		Variations			Added Value				Construction						Performance		
ID	Wall Name/ Description	Siding Removed	Novel Materials	Novel Installation	Improved Shear (e.g. wind, earthquake)	Fire protection / Noise control	New Ext Finish	Leave/encapsulate hazardous materials	Materials Acquisition	# Operations	Speed of Installation	Ease of Installation	Added thickness, in.	Moisture Risk by CZ	Effective R-Value (assembly)	Meets or Beats in CZ 2021 IECC
D	Pre-fab Ext EPS (panel w/struts)	N	N	N	N	N	Y	Y	3	3	1	2	5.25		24.8	all
G	Exterior Mineral Fiber Board	N	N	N	N	Y	Y	Y	3	3	2	3	5.25		22.9	all

Figure 7-3. Construction and Performance Summaries (all climate zones) for Wall Upgrades Using Exterior Insulation Only and New Siding Over the Existing Siding

For Wall D, a compressible layer of fiberglass panel was installed over the existing siding as a leveler and air and water control layer, followed by exterior continuous insulation (4½ in. of EPS); Wall G: did not require the interstitial compressible fiberglass layer because the mineral wool (2¾ in. of mineral fiber board) served that purpose on its own. Both Walls D and G got new siding. One advantage of this approach is the ability to abandon existing materials in place, encapsulating them behind the new wall layers, and avoid the cost, disruption, and time associated with removing and disposing of siding, as well as saving the fuel that would be required for transportation. Encapsulation also prevents disturbance of sensitive or potentially hazardous materials such as lead and asbestos.

The Wall G mineral fiber board insulative sheathing combined with fiber cement siding meets fire resiliency practices suggested by defensible space experts, possibly increasing the allure of this solution for homeowners in the wildland-urban interface. The pricing below was normalized to vinyl siding, but fiber cement would command a premium of about $0.50 more per square foot installed.

EPS and mineral wool are standard materials in the industry, but the COVID-19 pandemic created challenges in sourcing the products. Additionally, the tested EPS panel was a proprietary product with an embedded structural ladder and drainage channels. A similar result could have been achieved at a lower price with two layers of construction-grade EPS foam plastic insulated sheathing from a building supply store. The proprietary EPS product with the integrated fastening system offered some installation advantages over plain EPS sheathing fastened with screws and is evidently being re-design to improve installation speed.

Both of these walls provide good moisture and energy performance, but both were fairly expensive, at \$18–\$21/ft^2 of wall area. For both, about 70% of the total cost was labor, due to somewhat novel techniques. High labor/material cost ratios have previously been noted as opportunities for cost compression, which could improve market adoption. Both upgrades improve thermal performance beyond the IECC-2021 prescriptive requirements (Figure 7-4).

		Economics Chicago						Economics Burlington					
ID	Wall Name/ Description	Energy Cost Savings, %	EUI Savings, %	Cost $/sf Wall	Cost Bin ($3/sf, $13/sf)	IRR	Simple Payback	Energy Cost Savings, %	EUI Savings, %	Cost $/sf Wall	Cost Bin ($3/sf, $13/sf)	IRR	Simple Payback
D	Pre-fab Ext EPS (panel w/struts)	29%	35%	$20	4	0%	31	30%	36%	$21	4	3%	19
G	Exterior Mineral Fiber Board	29%	35%	$18	4	1%	27	30%	36%	$18	4	4%	16

Figure 7-4. CZ-5 (L) and CZ-6 (R) Economic Summaries for Wall Upgrades Using New Siding and Exterior Insulation Installed Over Old Siding

7.2.2.2 New Siding and Exterior Insulation *Plus Cavity Fill*, Installed Over Old Siding

Wall upgrades that use both cavity fill and exterior insulation are high performers but at the price of complexity because of the many operations involved in the dual approaches. Of course, there is also the cost of double the insulation. All but one in this subset of wall upgrades offer final assembly thermal resistance of between R-20 and R-30, and most avoid novel materials and methods, putting them within the existing skillset of most framing and insulating crews (Figure 7-5). Although this subset of wall upgrades is among the more expensive, because of the high thermal performance, most have positive (though modest) IRRs of up to 2% in Chicago and 6% in Burlington. Their paybacks are from 22 to 28 years in Chicago and 13 to 17 years in Burlington. (Figure 7-6)

A notable exception is the VIP-integrated siding in combination with drill-and-fill cellulose (Wall F). It scored reasonably well for installation speed and had among the least number of operations within this subset. It also was judged by the UMN research team to be easier to install than its competitors in the subset. Among these five configurations, it has the lowest first-cost at about $\$12/ft^2$ and the shortest simple payback period of about 10 years. It has a unique advantage (barring methods that rely solely on drill-and-fill) of adding only ½ in. to the thickness of the wall. This is likely to vastly reduce complexities with connections to soffits and foundations and trimming around windows and doors. Unfortunately, the product cannot be cut in the field and fill-in must be accomplished using siding backed with traditional foam insulation, leaving thermal bridges in many locations. As a relatively new and somewhat novel product, VIP-integrated siding could turn into an excellent choice should it undergo modest improvement in cost, flexibility, and availability.

One modification to Wall P would be to use a drill-and-fill cavity insulation and install the foam layer and the ¾-in. OSB over the existing sheathing to avoid the time and mess of removal and disposal.

		Variations			Added Value				Construction					Performance		
ID	Wall Name/ Description	Siding Removed	Novel Materials	Novel Installation	Improved Shear (e.g. wind, earthquake)	Fire protection / Noise control	New Ext Finish	Leave/encapsulate hazardous materials	Materials Acquisition	# Operations	Speed of Installation	Ease of Installation	Added thickness, in.	Moisture Risk by CZ	Effective R-Value (assembly)	Meets or Beats in CZ 2021 IECC
E	Drill-&-fill Cellulose + Ext XPS	Y	N	N	N	N	Y	N	1	5	3	3	2.5		28.4	all
F	Drill-&-fill Cellulose + VIP/Vinyl Siding	Y	Y	N	N	N	Y	N	X	4	3	2	0.5		25.5	all
L	Drill-&-Fill FG + Ext Polyiso	Y	N	N	N	N	Y	N	1	5	3	3	1.5		22.8	all
O	Drill-&-Fill FG + Ext FG Board	N	N	Y	N	N	Y	Y	3	4	2	3	3.25		25.2	all
P	FG Batt + XPS + OSB (Thermal Break Shear Wall)	N	N	Y	Y	N	Y	N	1	6	4	4	0.75		18.9	0-3

Figure 7-5. Construction and Performance Summaries (all climate zones) for Wall Upgrades Using Exterior Insulation Plus Added Cavity Fill and New Siding Over the Existing Siding

ID	Wall Name/ Description	Economics Chicago: Energy Cost Savings, %	EUI Savings, %	Cost $/sf Wall	Cost Bin ($3/sf, $13/sf)	IRR	Simple Payback	Economics Burlington: Energy Cost Savings, %	EUI Savings, %	Cost $/sf Wall	Cost Bin ($3/sf, $13/sf)	IRR	Simple Payback
E	Drill-&-fill Cellulose + Ext XPS	30%	36%	$19	3	0%	28	31%	37%	$19	3	4%	17
F	Drill-&-fill Cellulose + VIP/Vinyl Siding	29%	36%	$14	3	2%	22	31%	36%	$14	3	6%	13
L	Drill-&-Fill FG + Ext Polyiso	29%	35%	$14	3	2%	22	30%	36%	$15	3	6%	13
O	Drill-&-Fill FG + Ext FG Board	29%	36%	$17	3	1%	25	31%	36%	$17	3	5%	15
P	FG Batt + XPS + OSB (Thermal Break Shear Wall)	28%	34%	$16	3	1%	25	29%	35%	$16	3	5%	15

Figure 7-6. CZ-5 (L) and CZ-6 (R) Economic Summaries for Wall Upgrades Using Exterior Insulation Plus Added Cavity Fill and New Siding Over the Existing Siding

7.2.3 Prefabricated Exterior Panel Systems

Transitioning a large portion of wall upgrade construction activities to a controlled factory environment allows automation of some production aspects while prioritizing skilled trades for the on-site, problem-solving tasks of installing and connecting the panels to the existing structure. Factory panelization may eventually improve speed, consistency, and quality, while potentially also reducing cost (Figure 7-7 and Figure 7-8). As with the previous set of walls, these upgrades include the cost and the value of new exterior cladding.

The monolithic nature of preconstructed wall panels and the likelihood that the system includes preinstalled hangers (i.e., with supports that likely could be preinstalled on the subject building) mean that detailed prep-work of the building's existing finish may be reduced, as well as time and disruption to the homeowner. These are legitimate advantages to which it is hard to assign a dollar value.

		Variations			Added Value				Construction						Performance		
ID	Wall Name/ Description	Siding Removed	Novel Materials	Novel Installation	Improved Shear (e.g. wind, earthquake)	Fire protection / Noise control	New Ext Finish	Leave/encapsulate hazardous materials	Materials Acquisition	# Operations	Speed of Installation	Ease of Installation	Added thickness, in.	Moisture Risk by CZ	Effective R-Value (assembly)	Meets or Beats in CZ 2021 IECC
H	Exterior gEPS Structural Panel System	N	Y	Y	N	N	Y	Y	3	4	3	2	7		28.5	all
M	Pre-fab Ext EPS/EIFS Panel System	N	Y	Y	N	N	Y	N	4	3	2	2	5.75		27.2	all
N	Pre-fab Ext PU/Vinyl Block System	N	Y	N	N	N	Y	Y	X	2	1	2	4		27.6	all

Figure 7-7. Construction and Performance Summaries (all climate zones) for Wall Upgrades Using Prefabricated Exterior Panels

		Economics Chicago						Economics Burlington					
ID	Wall Name/ Description	Energy Cost Savings, %	EUI Savings, %	Cost $/sf Wall	Cost Bin ($3/sf, $13/sf)	IRR	Simple Payback	Energy Cost Savings, %	EUI Savings, %	Cost $/sf Wall	Cost Bin ($3/sf, $13/sf)	IRR	Simple Payback
H	Exterior gEPS Structural Panel System	30%	36%	$22	4	-1%	32	31%	37%	$22	4	3%	20
M	Pre-fab Ext EPS/EIFS Panel System	30%	36%	$45	4	-5%	67	31%	37%	$45	4	-2%	41
N	Pre-fab Ext PU/Vinyl Block System	29%	36%	$5	4	13%	8	31%	37%	$5	4	22%	5

Figure 7-8. CZ-5 (L) and CZ-6 (R) Economic Summaries for Wall Upgrades Using Prefabricated Exterior Panels

Factory wall panelization is not yet the norm, even for traditional materials and methods. For the wall upgrade approaches studied in this study that are relatively new and use novel materials or products, the cost exercise was necessarily inexact and speculative. Natural industry conservatism resulted in very high labor cost estimates. Two of the three prefabricated exterior panels in this subset are the most expensive walls studied and have the longest simple payback periods combined with negative IRRs. Without compelling additional advantages or large improvements in cost, homeowners and builders are unlikely to consider these solutions.

The three prefabricated walls are, however, the most thermally robust. Only Wall E, Drill-and-Fill Cellulose + Exterior XPS, is in the same ballpark, with thermal resistance of the whole wall assembly at R-28.4. The next best performers are ~R-25. Again, as designed, these walls are not likely to be considered for Climate Zones 0 through 4 because much of the insulation cost is not recouped with commensurate energy savings. One strong advantage may be the ability to fine tune the thermal performance to achieve the thinnest possible wall upgrade to maximize economic return and minimize on-site installation complexities.

In this subset Wall N was the standout—a prefabricated system of vinyl-covered foam blocks that are smaller than traditional sheathing panels, stack together snugly with a tongue-and-groove profile and take advantage of custom hangers and channels to keep them in place and tight. The final effect looks very much like traditional vinyl siding, though the blocks themselves are quite thick. This system is a good example of the vagaries associated with attempting to accurately price products that have not been marketed yet and are not commercially available. Installers do not have the hands-on experience to bid labor commensurate with the expected needs—the product's unique nature may provoke industry conservatism. Additionally, the unit price of these products is genuinely unknown because they are pre-market prototypes. For both labor and materials, the initial cost exercise yielded a figure that put this solution near the top for pricing and near the bottom for economic return. Upon reflection, the team decided to ask the manufacturer what a profitable price for the product would be if it were to be manufactured in volume. Additionally, the labor prices were adjusted in light of the very positive construction scores the product received from the crew who installed the test walls at CRRF.

To be fair, the economic analysis could be similarly modified for the two other wall upgrades in this subset. One of them, Wall H, is more of a concept than a prototype, so had to be built up in layers on-site. The cost reflects that complexity, which is outside the scope of the planned prototype. The other, Wall M, is a product that is actually in the marketplace but at small scale. So while it has a legitimate price associated with it, increased demand could substantially reduce that product cost.

8.0 Conclusions

As described in the Project Summary, most wall configurations studied can provide good or even excellent energy performance in cold climates (CZ 5 and 6). Additionally, most walls can be used safely in cold climates, offering reasonable thermal and moisture control. Note that because this research focused on cold climates, the project's additional thermal, moisture, and economic analysis for climate zones 0-4 and 7-8 is of interest but is not fine-tuned. These regions are included in general discussion and simulation; energy modeling and techno-economic results are provided in the appendices. Designers in regions with more cooling degree days are likely to choose different insulation and control layer types or quantities to meet region-specific thermal and moisture needs, which may change the economic viability of each wall retrofit. However, because other home improvement projects do not typically pay for themselves, a strong case can be made that economic return should be secondary to subjective advantages such as comfort, quiet, updated curb appeal, and reduced strain on the energy grid.

8.1 Project Findings

This comprehensive analysis was performed on 14 wall upgrades, ranging from solutions already widely used in the industry to less common, more complex configurations, and several prototype systems. All wall upgrades were measured and simulated in the same ways:

1. Constructability (construction and installation in the CRRF test facility: materials acquisition, number of installation operations, installation speed, installation ease, and added wall thickness)
2. Durability (simulated moisture risk: mold index per ASHRAE Standard 160)
3. Energy performance (calculated assembly R-value; energy models calibrated using measured heat flux, surface temperatures, and moisture content)
4. Investment outcomes (energy cost savings, local utility rates, local labor and materials pricing; calculation of internal rate of return and simple payback)

Results were then presented in two novel ways for easy comparison:

1. A color-coded matrix with incremental ratings in each category, allowing quick visual comparison of chosen priorities.
2. An adoption score methodology using wall ratings and attribute weightings to determine a normalized adoption score.

The goal was to provide accurate data and wide-ranging context for stakeholders to make informed choices based on their personal priorities; no effort was made to identify a single overall winner, and in fact that is an impossibility given the diverse priorities of the various stakeholders.

Nevertheless, there is ample evidence that drill-and-fill approaches[1] (Wall B, Dense-Pack Cellulose and Wall J, Dense-Pack Fiberglass) provide low first cost, minimum disruption, high

[1] The baseline wall was presumed to have completely empty stud cavities. Drill-and-fill is generally not an option when walls are already filled will insulation, no matter how inadequate.

availability, and good investment return. Unfortunately, in certain climates these methods may present moisture risks.[1]

Adding a layer of exterior continuous insulation addresses that risk while providing even greater energy savings. This addition is also likely to improve occupant comfort by reducing interior surface temperature deviations and even reducing noise transmittance. However, these improvements come at added cost and reduced IRR. A less expensive approach to moisture management is the addition of an interior vapor retarder.

But a wide range of other home improvements are not expected to “pay for themselves.” The intrinsic benefits of an energy upgrade may reasonably warrant higher cost and greater disruption. Within this top tier of economic performers, two of the proprietary upgrades, Wall N – Pre-Fabricated Exterior Polyiso/Vinyl Block System and Wall C – Injected Cavity Foam, were more expensive but provided greater R-value. With deep enough market penetration, these walls could be contenders on economic outcomes, as well.

As with drill-and-fill methods, the above methods leave the exterior siding in place, which is considered a major cost saver. On the other hand, of these four high economic performers, only Wall N results in completely new siding. The analysis did not consider this synergy but capturing the value of re-siding—typically an expensive home improvement project undertaken for primarily aesthetic reasons—would markedly improve the IRR for Wall N and reduce the perceived first cost by providing dual advantages. Re-siding without improving thermal and infiltration performance is a missed opportunity.

Without having to account for the cost of new siding, at approximately \$7.50/ft^2 of wall, the remaining wall upgrades would all have lower actual energy upgrade prices, higher IRRs, and faster payback times. Additionally, prototype configurations identified by the adoption score methodology could well experience future price reductions that would also improve their economic outcomes.

Ultimately, a complex range of considerations including comfort, performance, first cost, constructability, aesthetics, and long-term energy savings inform a determination whether a builder recommends—or a homeowner chooses—a particular retrofit, according to their personal priorities. The discussion in Section 7.2 itemizes several pertinent characteristics in tabular form for comparison. These include whether or not the wall upgrade required siding removal, included novel materials or installation methods, added performance attributes like strength or fire resistance or additional noise control, included a new exterior finish, and left or encapsulated hazardous materials associated with the existing assembly.

8.2 Limitations

An important caveat for economic decision making is the need to fine-tune the energy performance to the local climate conditions according to the law of diminishing returns. These test walls were designed for cold and very cold climates; the very high performance of some of these walls may not be needed in milder conditions. Most are easily modifiable to reduce both R-value and cost incrementally for climates with fewer heating degree days.

[1] This may change with more materials research under ASHRAE Standard 160 to credit cellulose with moisture-resistant additives.

The large amount of wall area in a house combined with the complexities of connecting to the foundation and soffits, and detailing around each window, door, and mechanical penetration, means that a wall upgrade can be materials-intensive and labor-complex. Finding additional advantages is therefore key, such as coordinating with other improvement projects such as re-siding, window replacement, or remodeling. Another opportunity is to coordinate an effort to add a new performance goal such as improved shear strength or fire resilience in areas impacted by worsening and more frequent weather events and fire risk. These approaches can ameliorate the high first cost of these major undertakings.

Wall upgrades that include exterior insulation, whether alone or in combination with cavity fill, are excellent approaches to moisture durability and can often exceed energy code prescriptive targets even in CZ 7. Unfortunately, the number of construction operations more than doubles, substantially increasing labor costs; thicker walls also increase the complexity of making connections to the existing structure. Additionally, exterior rigid insulation materials tend to be expensive, and some are challenging to acquire in certain regions.

The overarching issue is that in today's market, first-costs are too large, and projected annual energy cost savings too small, to make the time and trouble of the most intensive wall upgrades the first and easiest answer for the typical homeowner. The hefty price tag of these "deep energy retrofits" is likely to be acceptable to only a very committed subset of homeowners. However, this research indicates that even modest interventions can make a substantial difference, and careful research can ensure good return on investment.

It should be noted that modifications to the envelope—for both heat flow resistance and air leakage—can affect indoor air quality. Many older buildings have excellent moisture control and good air quality simply due to their leaky nature. As leakage through the envelope is reduced, indoor air can become stagnant and moisture laden. Mechanical ventilation should be considered a part of any healthy home retrofit effort.

Finally, increased energy costs and/or a stronger focus on building energy efficiency as a response to climate change would certainly affect these economic metrics.

8.3 Opportunities for Future Research

Proposed next steps for the project include:

1. *Economic analysis updates*: The cost estimation exercise resulted in incremental labor and materials prices that should allow analysis of hypothetical combinations—multiple rigid insulative sheathing products, many different blown-in, sprayed-on, or injected insulations. Further investigation is warranted. Additionally, hypothetical configurations fine-tuned to the remaining climate zones could be simulated and analyzed. Further vetting of the categories and assumptions of the market adoption matrix may also be instructional: focus groups, industry interviews, or surveys may allow fine-tuning.
2. *Occupant comfort:* Although it was not in the official scope of the research, thermal comfort due to moderated surface temperatures is a genuine benefit that can be confirmed through measured and simulated data, if not fully quantified and valuated. Noise from outside is typically dampened by added insulation, especially continuous layers. Because the walls make up about 40% of the envelope, reduced infiltration rates are likely to improve energy performance while not being low enough to negatively affect indoor air quality and require additional mechanical ventilation, but each case should be validated before determining scope.

3. *Mold:* Simulations of two walls indicated potential for mold growth in a subset of climates. Future work should include study of various products used for “drill-and-fill” applications, because this approach does not guarantee prevention of low temperatures within the cavity, potentially allowing condensation and subsequent mold growth. Are there more expedient ways to add external continuous insulation to maintain higher cavity temperatures? Is current new construction guidance in IRC Section R702.7 Vapor Retarders applicable to retrofits? Testing that simulates breaches or construction errors should be explored to understand the impact of leaks on the moisture performance of these wall upgrades.
4. *Construction*: Construction complexities include window and door openings, mechanical penetrations, inside and outside corners, and connections to foundations and soffits. How best to address these challenges using prefabricated products? What is the real effect of very thick retrofit walls?
5. *Air leakage*: Confirm modeling assumptions and develop a reliable method to translate experimental values to whole building examples in combination with practitioner knowledge; air leakage improvement contributes substantially to energy savings. This should be understood in detail for the wide variety of materials, methods and climate zones studied, including variations in success for retrofits versus new construction.
6. *Existing hazardous materials*: Further research could determine ROIs that consider the cost and liability of hazardous waste removal, or whether abandoning-in-place is an allowed solution in any particular location or situation.
7. *Carbon footprint*: Carbon life-cycle implications will become more important with the advancement of climate change.
8. *Cooling Conditions*: Ideally, heat pump cooling capability could be added to the CRRF and the installed walls could undergo further monitoring followed by simulation validation.
9. *Follow up:* The pre-fab and proprietary products included in this study should be monitored. Have any been improved or are they undergoing improvements?

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Appendix A – Detailed Wall Layers

Table A.1. Detailed Wall Layer Information for Every Wall in This Study.

Wall A: Baseline 1			
Layer	Layer Label	Material	As-Built Specification
1	Exterior Finish	Paint (multiple coats)	Oil-based Primer; Latex Vapor Retarder Paint; Latex Topcoat (white)
2	Lap Siding	Cedar Lap Siding	1 x 8‘ (¾- x 7¼”) Inland Western Red Cedar
3	Building Paper	Asphalt Impregnated Paper	#30 Roofing Felt
4	Board Sheathing	Spruce/Pine Wood Sheathing	1" x 6" (¾” x 5-½") Spruce/Pine Boards
5	Empty Stud Cavity	Open Cavity	3½" Air Space
6	Drywall	Gypsum Board	$^{5}/_{8}$” Gypsum Board
7	Interior Finish	Vapor Retarder Paint	Latex Vapor Retarder Primer (white)
Wall B: Drill-and-Fill (Cellulose)			
Layer	Layer Label	Material	As-Built Specification
1	Exterior Finish	Paint (multiple coats)	Oil-based Primer; Latex Vapor Retarder Paint; Latex Topcoat (white)
2	Lap Siding	Cedar Lap Siding	1" x 8" (¾” x 7¼”) Inland Western Red Cedar
3	Building Paper	Asphalt Impregnated Paper	#30 Roofing Felt
4	Board Sheathing	Spruce/Pine Wood Sheathing	1" x 6" (¾” x 5½") Spruce/Pine Boards
5	Cavity Insulation	Blown-in Dense-Pack Cellulose	3½” at 3.5–4.0 lb/cf
6	Drywall	Gypsum Board	1$1^{5}/_{8}$” Gypsum Board
7	Interior Finish	Vapor Retarder Paint	Latex Vapor Retarder Primer (white)
Wall C: Minimally Invasive Cavity Spray Foam			
Layer	Layer Label	Material	As-Built Specification
1	Exterior Finish	Paint (multiple coats)	Oil-based Primer; Latex Vapor Retarder Paint; Latex Topcoat (white)
2	Lap Siding	Cedar Lap Siding	1" x 8" (¾” x 7¼”) Inland Western Red Cedar
3	Building Paper	Asphalt Impregnated Paper	#30 Roofing Felt
4	Board Sheathing	Spruce/Pine Wood Sheathing	1"x6" (¾” x 5-½") Spruce/Pine Boards
5	Cavity Insulation	Closed-Cell Spray Foam	Injected Closed-cell Spray Polyurethane Foam (CT)
6	Drywall	Gypsum Board	$^{5}/_{8}$” Gypsum Board
7	Interior Finish	Vapor Retarder Paint	Latex Vapor Retarder Primer (white)

Wall D: Exterior EPS Insulation			
Layer	Layer Label	Material	As-Built Specification
1	Lap Siding	Vinyl Lap Siding	CertainTeed Monogram; Double 5” Lap Siding (white)
2	Board Insulation	Manufactured Expanded Polystyrene (EPS) Panel	2½” InSoFast EPS Panel with Integrated Furring & Grooves on Both Sides)
3	Board Insulation	Manufactured Expanded Polystyrene (EPS) Panel	2” InSoFast EPS Panel with Integrated Furring & Grooves on Weather-Resistant Barrior (WRB) Side)
4	WRB	Spun-bonded Polyolefin	Tyvek House Wrap
5	Compressible Layer	Compressible Fiberglass Panel	$^5/_8$” Semi-rigid Fiberglass Panel
6	Exterior Finish	Paint (multiple coats)	Oil-Based Primer; Latex Vapor Retarder Paint; Latex Topcoat (white)
7	Lap Siding	Cedar Lap Siding	1" x 8" (¾” x 7¼”) Inland Western Red Cedar
8	Building Paper	Asphalt Impregnated Paper	#30 Roofing Felt
9	Board Sheathing	Spruce/Pine Wood Sheathing	1" x 6" (¾” x 5½") Spruce/Pine Boards
10	Empty Stud Cavity	Open Cavity	3½" Air Space
11	Drywall	Gypsum Board	$^5/_8$” Gypsum Board
12	Interior Finish	Vapor Retarder Paint	Latex Vapor Retarder Primer (white)

Wall E: Drill-and-Fill with Exterior XPS Insulation (Siding Removed)			
Layer	Layer Label	Material	As-Built Specification
1	Lap Siding	Vinyl Lap Siding	CertainTeed Monogram; Double 5” Lap Siding (white)
2	Furring Strip with Board Insulation Infill	Wood Furring Strip with Extruded Polystyrene (XPS) Foam Board	1" x 4" (¾” x 3½") SPF Boards at Studs with ¾” DOW XPS In-fill
3	Board Insulation	XPS Foam Board	2” DOW XPS Foam Board
4	Weather Resistive Barrier (WRB)	Spun-bonded Polyolefin	Tyvek House Wrap
5	Board Sheathing	Spruce/Pine Wood Sheathing	1" x 6" (¾” x 5-½") Spruce/Pine Boards
6	Cavity Insulation	Blown-in Dense-Pack Cellulose	3½” at 3.5-4.0 lb/cf
7	Drywall	Gypsum Board	$^5/_8$” Gypsum Board
8	Interior Finish	Vapor Retarder Paint	Latex Vapor Retarder Primer (white)

Wall F: Drill-and-Fill with Exterior VIP Siding (Siding Removed)			
Layer	Layer Label	Material	As-Built Specification
1	Lap Siding	Manufactured VIP Siding	Vacuum Insulated Panel Mounted to Vinyl Lap Siding (Brown)
2	WRB	Spun-bonded Polyolefin	Tyvek House Wrap
3	Board Sheathing	Spruce/Pine Wood Sheathing	1" x 6" (¾” x 5½") Spruce/Pine Boards
4	Cavity Insulation	Blown-in Dense-Pack Cellulose	3½” at 3.5–4.0 lb/cf
5	Drywall	Gypsum Board	$^5/_8$” Gypsum Board
6	Interior Finish	Vapor Retarder Paint	Latex Vapor Retarder Primer (white)

Wall G: Exterior Mineral Fiber Board Insulation			
Layer	Layer Label	Material	As-Built Specification
1	Lap Siding	Fiber Cement Lap Siding	James Hardie $^{5}/_{16}$" x 8.25" (white)
2	Furring Strips	Wood Furring Strips	1" x 4" (¾" x 3½") SPF Boards at Studs
3	Board Insulation	Mineral Wool Board	2" Rockwool Comfortboard; 80 at 8 lb/cf
4	Board Insulation	Mineral Wool Board	2" Rockwool Comfortboard; 80 at 8 lb/cf
5	WRB	LAM	Vapor Permeable Brush Applied Membrane
6	Exterior Finish	Paint (multiple coats)	Oil-based Primer; Latex Vapor Retarder Paint; Latex Topcoat; (white)
7	Lap Siding	Cedar Lap Siding	1" x 8" (¾" x 7¼") Inland Western Red Cedar
8	Building Paper	Asphalt Impregnated Paper	#30 Roofing Felt
9	Board Sheathing	Spruce/Pine Wood Sheathing	1" x 6" (¾" x 5½") Spruce/Pine Boards
10	Empty Stud Cavity	Open Cavity	3½" Air Space
11	Drywall	Gypsum Board	$^{5}/_{8}$" Gypsum Board
12	Interior Finish	Vapor Retarder Paint	Latex Vapor Retarder Primer (white)

Wall H: Exterior Structural Graphite EPS (GPS) Panel (Inspired by EnergieSprong)			
Layer	Layer Label	Material	As-Built Specification
1	Panel Siding	Metal Vertical Rib Siding Panel	26 ga. Classic Rib Metal Roofing Panel (white)
2	Furring Strips	Wood Furring Strips	1" x 4" (¾" x 3½") SPF Boards at Studs
3	Board Insulation	GPS Foam Board	2$^{1}/_{8}$" GPS Foam Board
4	Board Insulation	GPS Foam Board	2$^{1}/_{8}$" GPS Foam Board
5	WRB	Fully Adhered Membrane (FAM)	60mm Perm-a-Barrier
6	Structural Panel	OSB Panels	1½" (2 Layer Laminate of ¾") Huber Advantech OSB Panel
7	Compressible Layer	Compressible Fiberglass Panel	$^{5}/_{8}$" Semi-rigid Fiberglass Panel
8	Exterior Finish	Paint (multiple coats)	Oil-based Primer; Latex Vapor Retarder Paint; Latex Topcoat (white)
9	Lap Siding	Cedar Lap Siding	1" x 8" (¾" x 7¼") Inland Western Red Cedar
10	Building Paper	Asphalt Impregnated Paper	#30 Roofing Felt
11	Board Sheathing	Spruce/Pine Wood Sheathing	1" x 6" (¾" x 5½") Spruce/Pine Boards
12	Empty Stud Cavity	Open Cavity	3½" Air Space
13	Drywall	Gypsum Board	$^{5}/_{8}$" Gypsum Board
14	Interior Finish	Vapor Retarder Paint	Latex Vapor Retarder Primer (white)

Wall I: Baseline 2			
Layer	Layer Label	Material	As-Built Specification
1	Exterior Finish	Paint (multiple coats)	Oil-based Primer; Latex Vapor Retarder Paint; Latex Topcoat (white)
2	Lap Siding	Cedar Lap Siding	1" x 8" (¾" x 7¼") Inland Western Red Cedar
3	Building Paper	Asphalt Impregnated Paper	#30 Roofing Felt
4	Board Sheathing	Spruce/Pine Wood Sheathing	1" x 6" (¾" x 5½") Spruce/Pine Boards
5	Empty Stud Cavity	Open Cavity	3½" Air Space
6	Drywall	Gypsum Board	$^{5}/_{8}$" Gypsum Board
7	Interior Finish	Vapor Retarder Paint	Latex Vapor Retarder Primer (white)

Wall J: Drill-and-Fill (Fiberglass)			
Layer	Layer Label	Material	As-Built Specification
1	Exterior Finish	Paint (multiple coats)	Oil-based Primer; Latex Vapor Retarder Paint; Latex Topcoat (white)
2	Lap Siding	Cedar Lap Siding	1" x 8" (¾" x 7¼") Inland Western Red Cedar
3	Building Paper	Asphalt Impregnated Paper	#30 Roofing Felt
4	Board Sheathing	Spruce/Pine Wood Sheathing	1" x 6" (¾" x 5-½") Spruce/Pine Boards
5	Cavity Insulation	Blown-in Dense-pack Fiberglass	3½" JM Spider Blown-in Fiberglass (approx. 2 lb/cf)
6	Drywall	Gypsum Board	$^5/_8$" Gypsum Board
7	Interior Finish	Vapor Retarder Paint	Latex Vapor Retarder Primer (white)

Wall K: Interior Polyiso Insulation			
Layer	Layer Label	Material	As-Built Specification
1	Exterior Finish	Paint (multiple coats)	Oil-based Primer; Latex Vapor Retarder Paint; Latex Topcoat (white)
2	Lap Siding	Cedar Lap Siding	1" x 8" (¾" x 7¼") Inland Western Red Cedar
3	Building Paper	Asphalt Impregnated Paper	#30 Roofing Felt
4	Board Sheathing	Spruce/Pine Wood Sheathing	1" x 6" (¾ "x 5½") Spruce/Pine Boards
5	Cavity Insulation	Fiberglass Batt	3½" R-13 Fiberglass Batt
6	Board Insulation	Polyisocyanurate Foam Board	1" Thermax Foil-faced Polyisocyanurate
7	Drywall	Gypsum Board	$^5/_8$" Gypsum Board
8	Interior Finish	Vapor Retarder Paint	Latex Vapor Retarder Primer (white)

Wall L: Exterior Polyiso Insulation (Siding Removed)			
Layer	Layer Label	Material	As-Built Specification
1	Lap Siding	Wood Composite Lap Siding	LP Smartside 5/16"x8" (white)
2	Furring strips	Wood Furring Strips	1" x 4" (¾" x 3½") SPF Boards at Studs
3	Board Insulation	Polyisocyanurate Foam Board	1" Thermax Foil-faced Polyisocyanurate
4	WRB	Spun-bonded Polyolefin	Tyvek Water Resistive Barrier (Drain-Wrap)
5	Board Sheathing	Spruce/Pine Wood Sheathing	1" x 6" (¾" x 5½") Spruce/Pine Boards
6	Cavity Insulation	Blown-in Dense-pack Fiberglass	3½" JM Spider Blown-in Fiberglass (approx. 2 lb/cf)
7	Drywall	Gypsum Board	$^5/_8$" Gypsum Board
8	Interior Finish	Vapor Retarder Paint	Latex Vapor Retarder Primer (white)

Wall M: Realize EIFS Panel (Siding Removed)			
Layer	Layer Label	Material	As-Built Specification
1	Prefinished Insulation Panel	Manufactured EIFS EPS Foam Panel	6" EPS Foam Panel with Thin Stucco Finish
2	WRB	LAM	Tremco LAM
3	Board Sheathing	Spruce/Pine Wood Sheathing	1" x 6" (¾" x 5½") Spruce/Pine Boards
4	Empty Stud Cavity	Open Cavity	3½" Air Space
5	Drywall	Gypsum Board	$^5/_8$" Gypsum Board
6	Interior Finish	Vapor Retarder Paint	Latex Vapor Retarder Primer (white)

Wall N: ABC Fraunhofer Blocks			
Layer	Layer Label	Material	As-Built Specification
1	Prefinished Insulation Blocks	Manufactured Prefinished Polyurethane Foam Blocks	4" PolyIso Foam Blocks with Integral Finish
2	WRB	Spun-bonded Polyolefin	Tyvek WRB (Drain-Wrap)
3	Exterior Finish	Paint (multiple coats)	Oil-based Primer; Latex Vapor Retarder Paint; Latex Topcoat (white)
4	Lap Siding	Cedar Lap Siding	1" x 8" (¾" x 7¼") Inland Western Red Cedar
5	Building Paper	Asphalt Impregnated Paper	#30 Roofing Felt
6	Board Sheathing	Spruce/Pine Wood Sheathing	1" x 6" (¾" x 5½") Spruce/Pine Boards
7	Empty Stud Cavity	Open Cavity	3½" Air Space
8	Drywall	Gypsum Board	$^5/_8$" Gypsum Board
9	Interior Finish	Vapor Retarder Paint	Latex Vapor Retarder Primer (white)

Wall O: Exterior Fiberglass Board Insulation			
Layer	Layer Label	Material	As-Built Specification
1	Lap Siding	Fiber Cement Lap Siding	James Hardie 5/16" x 8.25" (white)
2	Furring Strips	Wood Furring Strips	1" x 4" (¾" x 3½") SPF Boards at Studs
3	Board Insulation	Mineral Fiber Board	2" O-C Mineral Fiber Drainage Board
4	WRB	Spun-Bonded Polyolefin	Tyvek Water Resistive Barrier (drain wrap)
5	Exterior Finish	Paint (multiple coats)	Oil-based Primer; Latex Vapor Retarder Paint; Latex Topcoat (white)
6	Lap Siding	Cedar Lap Siding	1" x 8" (¾" x 7¼") Inland Western Red Cedar
7	Building Paper	Asphalt Impregnated Paper	#30 Roofing Felt
8	Board Sheathing	Spruce/Pine Wood Sheathing	1" x 6" (¾" x 5½") Spruce/Pine Boards
9	Cavity Insulation	Blown-in Dense-pack Fiberglass	3½" JM Spider Blown-in Fiberglass (~2 lb/cf)
10	Drywall	Gypsum Board	$^5/_8$" Gypsum Board
11	Interior Finish	Vapor Retarder Paint	Latex Vapor Retarder Primer (white)

Wall P: Thermal Break Shear (Siding & Sheathing Removed)			
Layer	Layer Label	Material	As-Built Specification
1	Lap Siding	Vinyl Lap Siding	CertainTeed Monogram Double 5" Lap Siding (white)
2	WRB	Spun-bonded Polyolefin	Tyvek WRB (drain wrap)
3	Panel Sheathing	OSB Sheathing	¾" Oriented Strand Board
4	Board Insulation	XPS Foam Board	1" DOW XPS Foam Board
5	Cavity Insulation	Fiberglass Batt	3½" R-13 Fiberglass Batt
6	Drywall	Gypsum Board	$^5/_8$" Gypsum Board
7	Interior Finish	Vapor Retarder Paint	Latex Vapor Retarder Primer (white)

Appendix B – Laboratory Tested Material Properties

Table B.1. Thermal Properties Measured in Accordance with ASTM C518

Insulation	Thickness in	Density lb/ft^3	R-value, hr-ft^2-F/Btu-in
2-in. Expanded Polystyrene (EPS)	1.54	1.40	4.16
2.5-in. EPS	2.03	1.21	3.97
2-in. Graphite-Impregnated EPS	2.15	1.95	4.60
2-in. XPS	2.01	1.50	5.02
2-in. Mineral Wool	1.88	9.20	4.18
Dense-Packed Cellulose	3.50	3.50	3.50
Spray Foam	2.01	1.58	5.76
1 by 6-in. Wood Siding	0.77	27.1	1.53
⅝-in. Gypsum	0.62	43.7	2.81
¾-in. Oriented Strand Board	0.71	40.5	2.46
Wood Siding	0.80	26.0	1.79
Fiber Cement Siding	0.32	79.5	1.86
Fiberglass Compression Layer	0.50	3.83	4.52

Table B.2. Vapor Permeance Measured in Accordance with ASTM E96

Materials	Water vapor transmission				Permeance	
	g/h*m^2	grains/h*ft^2	g/s*Pa*m^2	perm	g/s*Pa*m	perm-in
1 x 6-in. Wood Siding	2.356	3.369	4.200×10^{-7}	7.735	8.411×10^{-9}	5.787
Gypsum Board	10.659	15.243	2.000×10^{-6}	34.999	3.110×10^{-8}	21.394
Gyp Board + Paint	2.457	3.514	4.616×10^{-7}	8.068	7.120×10^{-9}	4.962
#15 Felt	4.979	7.120	9.342×10^{-7}	16.348	6.202×10^{-10}	0.427
WRB	7.065	10.103	1.326×10^{-6}	23.199	1.189×10^{-10}	0.082
WRB + Liquid AVB Coating	3.227	4.615	6.056×10^{-7}	10.597	5.628×10^{-10}	0.387
AVB Membrane	0.006	0.008	1.069×10^{-9}	0.019	8.380×10^{-13}	0.001
1-in. Polyisocyanurate	0.025	0.036	4.929×10^{-9}	0.086	1.257×10^{-10}	0.086
Smart siding	0.661	0.945	1.380×10^{-7}	2.415	1.223×10^{-9}	
House Wrap with Liquid Weather Resistive Barrier	1.839	2.630	3.619×10^{-7}	6.332	9.924×10^{-11}	0.068

Appendix C – National Annual Energy Use Intensity (EUI) Results

Annual Energy Use Intensity for DOE Prototype Single-family Home — Phase 1 Walls

- Wall A: Baseline 1 (R-4.2)
- Wall B: Drill-&-Fill Cellulose (R-14.2)
- Wall C: Injected Cavity Foam (R-19.5)
- Wall D: Pre-fab Ext EPS (R-24.8)
- Wall E: Drill-&-fill Cellulose + Ext XPS (R-28.4)
- Wall F: Drill-&-fill Cellulose + VIP/Vinyl Siding (R-25.5)
- Wall G: Exterior Mineral Fiber Board (R-22.9)
- Wall H: Exterior gEPS Structural Panel System (R-28.5)

Percent EUI Savings Compared to Wall: A Baseline (R-4.2)

	Hot-Humid	Hot-Dry	Mixed-Dry	Mixed-Humid	Marine	Cold	Very Cold	Subarctic
Wall B: R-14.2	7.9%	16.1%	22.3%	20.8%	22.5%	21.5%	22.4%	22.4%
Wall C: R-19.5	9.4%	18.7%	26.5%	25.2%	27.0%	26.2%	27.5%	27.5%
Wall D: R-24.8	13.3%	24.3%	34.2%	33.5%	35.4%	35.1%	37.0%	36.9%
Wall E: R-28.4	13.3%	24.6%	35.0%	34.4%	36.3%	36.0%	38.1%	38.0%
Wall F: R-25.5	13.2%	24.4%	34.6%	33.9%	35.8%	35.5%	37.5%	37.5%
Wall G: R-22.9	13.7%	25.1%	34.6%	33.7%	35.9%	35.2%	37.2%	37.0%
Wall H: R-28.5	14.0%	25.7%	35.6%	34.7%	36.9%	36.3%	38.2%	38.1%

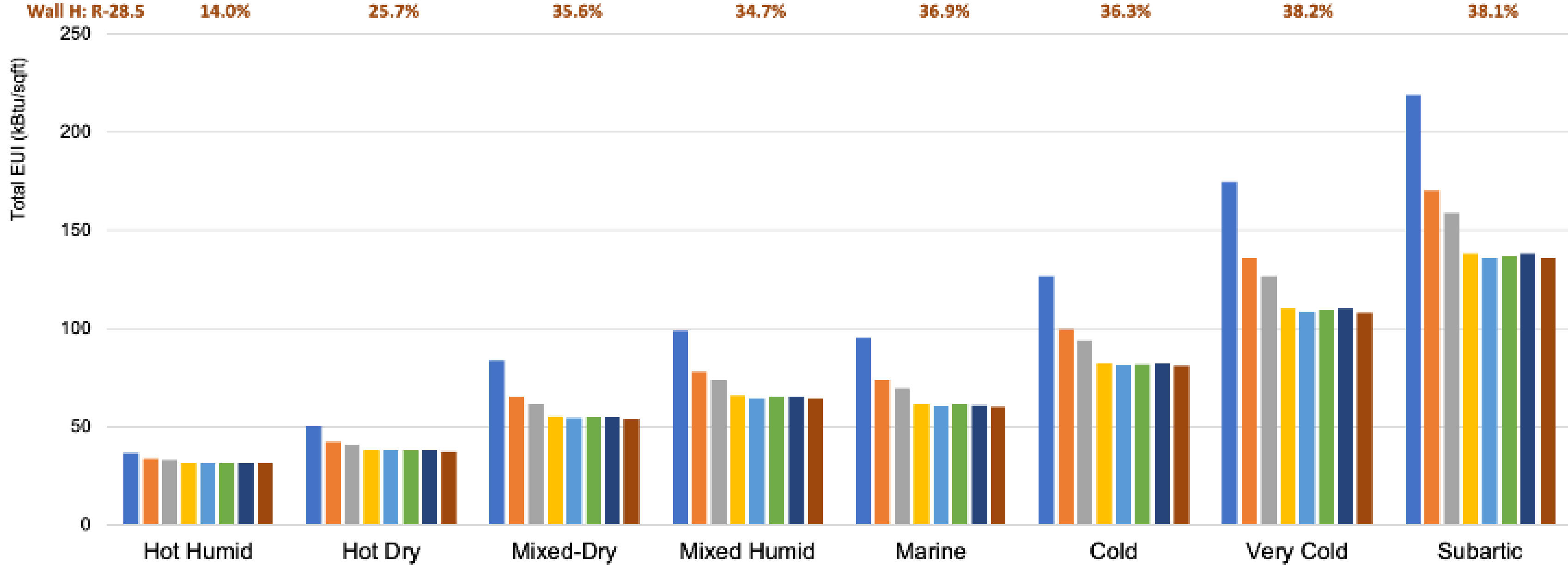
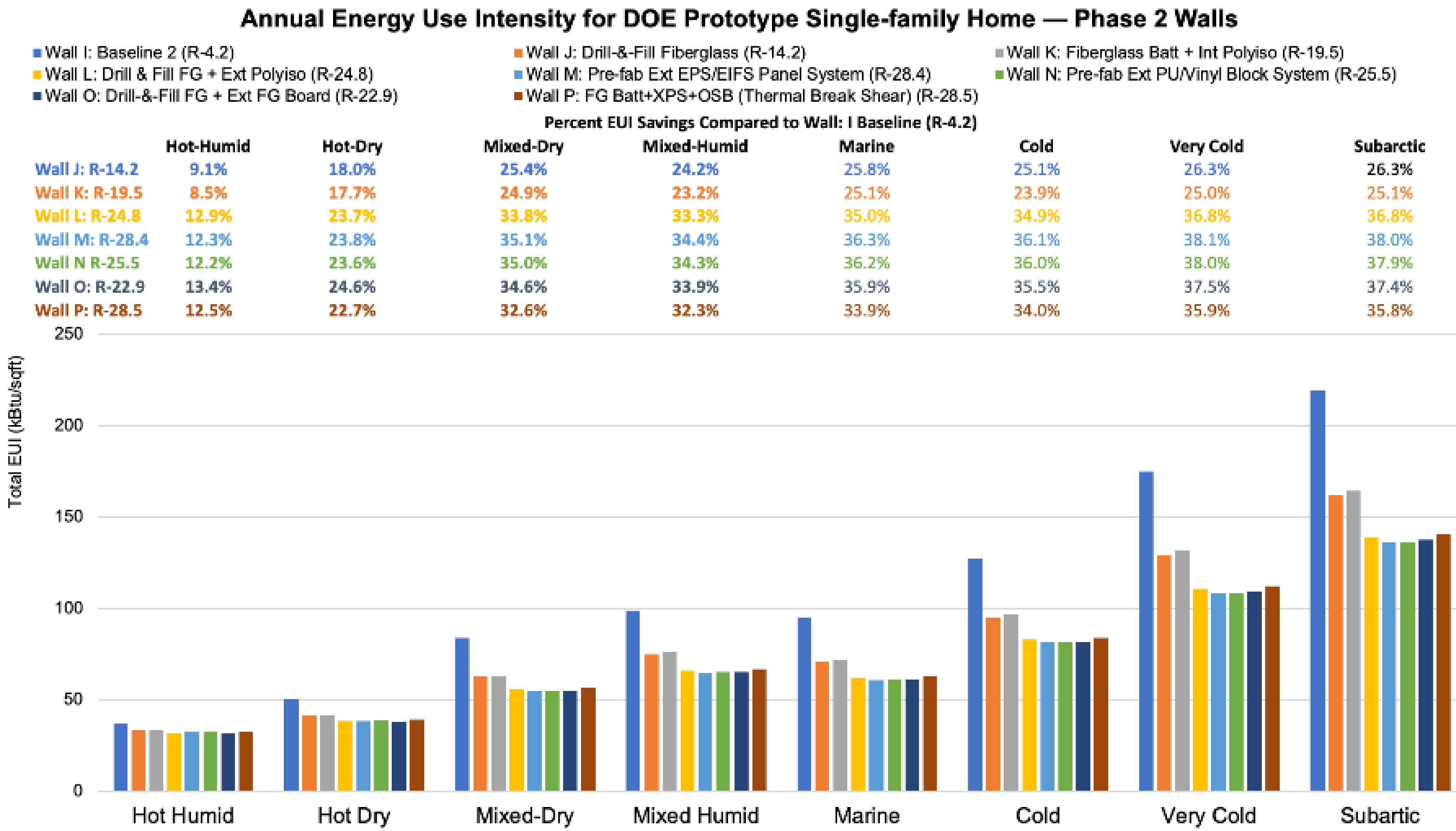


Figure C.1. Energy Use Intensities for the Modeled Residential Prototype Building with the Phase 1 Wall Assemblies



	Hot-Humid	Hot-Dry	Mixed-Dry	Mixed-Humid	Marine	Cold	Very Cold	Subarctic
Wall J: R-14.2	9.1%	18.0%	25.4%	24.2%	25.8%	25.1%	26.3%	26.3%
Wall K: R-19.5	8.5%	17.7%	24.9%	23.2%	25.1%	23.9%	25.0%	25.1%
Wall L: R-24.8	12.9%	23.7%	33.8%	33.3%	35.0%	34.9%	36.8%	36.8%
Wall M: R-28.4	12.3%	23.8%	35.1%	34.4%	36.3%	36.1%	38.1%	38.0%
Wall N R-25.5	12.2%	23.6%	35.0%	34.3%	36.2%	36.0%	38.0%	37.9%
Wall O: R-22.9	13.4%	24.6%	34.6%	33.9%	35.9%	35.5%	37.5%	37.4%
Wall P: R-28.5	12.5%	22.7%	32.6%	32.3%	33.9%	34.0%	35.9%	35.8%

Figure C.2. Energy Use Intensities for the Modeled Residential Prototype Building with the Phase 2 Wall Assemblies

Appendix D – Wall Construction Schematics

Figures in this appendix are cross sections of the walls with symbols that indicate the sensor installation location within the wall panel, as defined by the legend in Figure D.1.

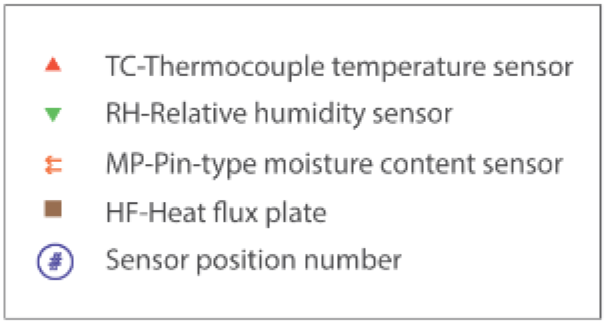


Figure D.1. Legend for wall cross sections in Figure D.2 through D.17

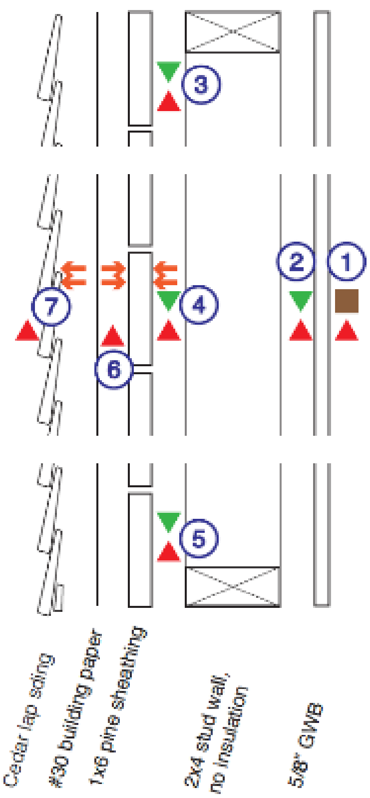
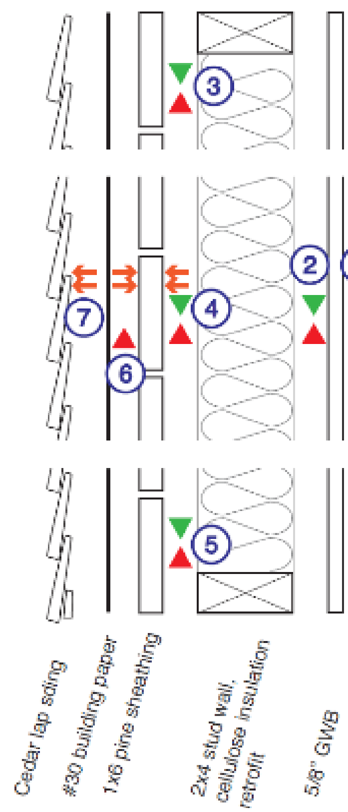
<table>
<tr><th>Construction Notes</th><th>Wall Cross-Section</th></tr>
<tr><td>Wall A: Base-Case Wall #1
Once the team had determined the base-case wall for in situ testing, the University of Minnesota team built 16 identical test walls for each phase. The test walls were constructed of 2- x 4 in. SPF wood studs with 1- x 6-in. pine board sheathing. The pine sheathing was loosely fit to reflect older construction. The sheathing was covered with a heavy #30 building paper lapped and stapled to the sheathing followed by 8-in. cedar lap siding finished with an oil base primer, vapor retarder primer, and a latex topcoat. This exterior finish was selected to represent an older house with several coats of oil-based paints. The test panel edges were wrapped with an air and vapor tight tape. Once the test panel was installed in the test opening and the sensor array was completed, an interior finish of $^{5}/_{8}$-in. gypsum board with a vapor retarder primer was added. The interior finish was selected to represent an older home with heavy drywall or plaster and several coats of paint.</td><td>

Figure D.2. Wall A: Baseline Wall</td></tr>
</table>

Wall B: Drill-and-Fill (Cellulose) The University of Minnesota team hired a qualified installer to drill-and-fill these walls cavities with cellulose from the exterior similar to what would be done in the weatherization and retrofit market. The siding was removed in two locations just below mid-point and near the top of the cavity and holes were drilled through the building paper and sheathing. The cellulose was installed with a long flexible tube ensuring a high density between 3.5 to 4.0 lb/ft^3 throughout the cavity. The holes in the sheathing were sealed with spray foam, tape was used to repair the building paper, and the siding was replaced.	 Figure D.1. Wall B: Drill-and-Fill (Cellulose).

Wall C: Minimally Invasive Cavity Spray Foam

This treatment is a proprietary closed-cell polyurethane foam installed from the interior by the manufacturer's representatives. They managed all formulation and installation techniques. The liquid foam was injected through very small holes in the drywall for each cavity. Infrared imaging was used to ensure the cavities were completely filled. The holes in the drywall were sealed by the ccSPU foam. In a typical application, these holes would be patched and painted.

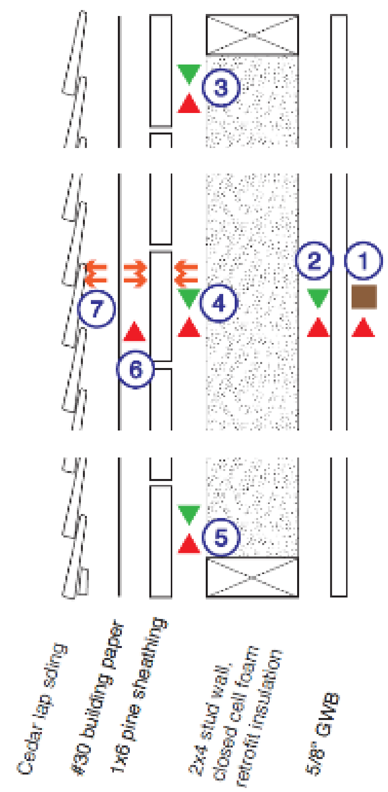


Figure D.4. Wall C: Minimally Invasive Cavity Spray Foam

Wall D: Exterior EPS

This wall treatment used a commercially available EPS insulation product that includes built-in drainage capabilities and an imbedded structural ladder for attachment. A low-density fiberglass panel was installed over the existing siding in an attempt to remove the air channels that would be created between the existing lapped siding and the rigid EPS board. A house wrap was stretched over this "squishy layer," secured with cap nails, and taped to panel edges to provide a new air and water control layer. The first 2-in. EPS panel was installed to the existing wall with screws using the integral fastening ladder. Then a second 2½-in. panel was installed with screws to the previous panel using the integral fastening ladder. Finally, the vinyl siding was installed with screws to the integral fastening ladder in the second panel.

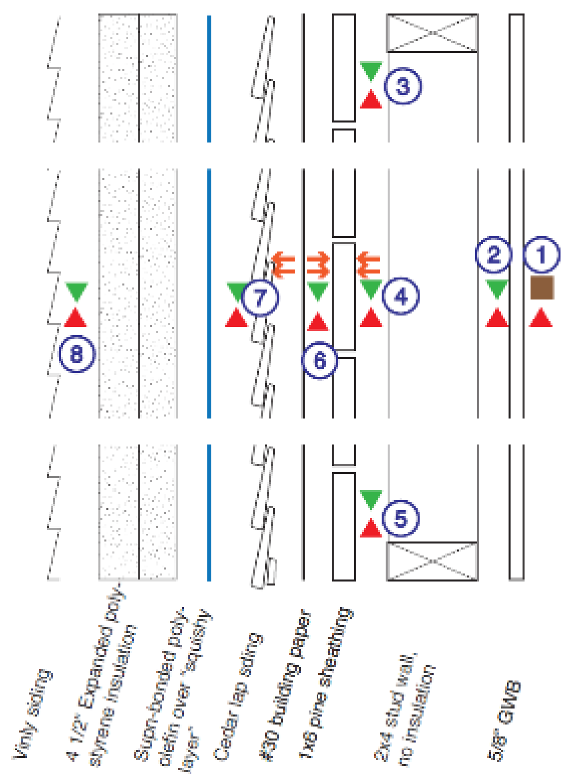


Figure D.5. Wall D: Exterior EPS Insulation

Wall E: Drill & Fill (Cellulose) w/ Exterior XPS (siding removed)

In this wall a dense-pack cellulose was installed as described in Wall B. However, the cedar lap siding and building paper were removed. A house wrap was installed with cap nails and taped at panel edges as a new air and water control layer. This was followed by a 2-in. layer of XPS insulation installed using minimal cap nails to hold in place until the 1- x 4-in. furring strips were screwed through insulation layer and securely fastened to framing. Finally, a ¾-in.” XPS insulation was placed between the furring strips and tacked in place with cap nails to support the vinyl siding that was installed with typical fasteners to the furring strips.

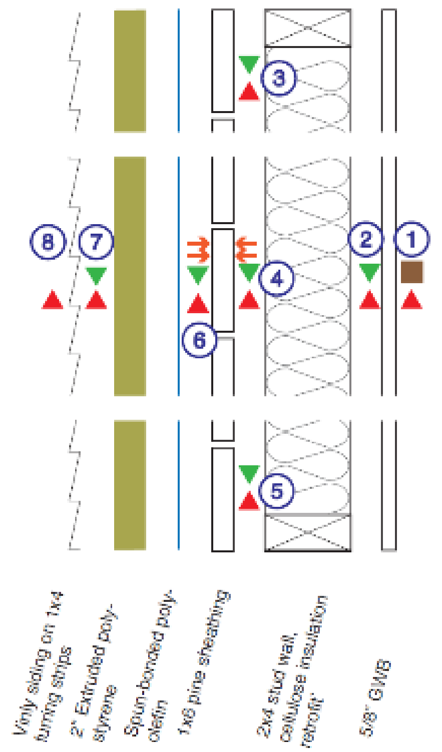


Figure D.6. Wall E: Drill-and-Fill with Exterior XPS Insulation (siding removed)

Wall F: Drill & Fill (cellulose) with Exterior VIP (siding removed)

Again, this wall treatment used the dense-pack cellulose installed as described in Wall B. The cedar lap siding and building paper were removed. A house wrap was installed with cap nails and taped at panel edges as a new air and water control layer. Then a VIP siding panel was installed with appropriate fasteners to the sheathing.

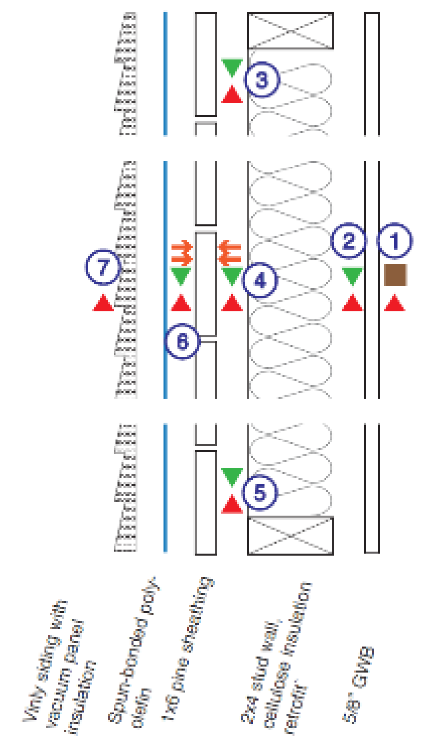
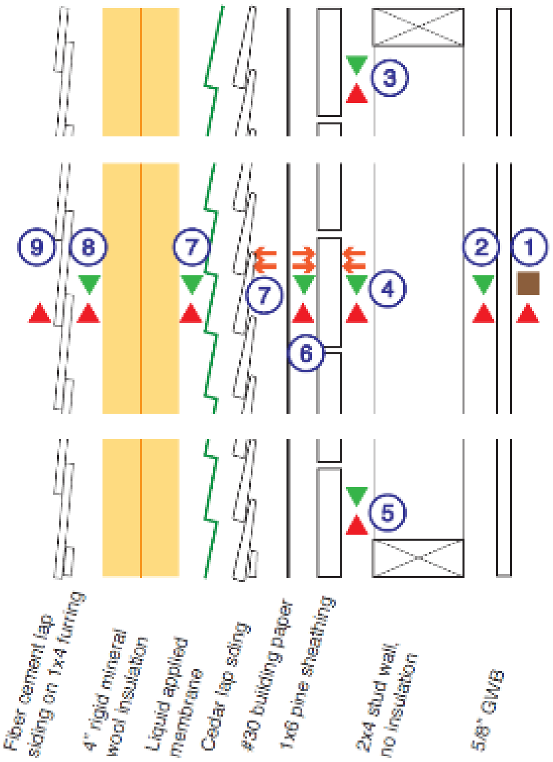


Figure D.7. Wall F: Drill-and-Fill with Exterior VIP Siding (siding removed)

Wall G: Exterior Mineral Fiber Board Insulation	
This wall treatment started with a brush application of a vapor permeable liquid applied membrane (LAM) over the existing lapped siding to provide a more robust water control layer. A 2-in. mineral wool panel was installed using minimal cap nails to hold in place. Then a half-height panel of the second layer of 2-in. mineral wool is installed at the bottom. This will ensure the seams are staggered. At this point the 1- x 4-in. furring strips are installed, but only fastened to the framing at the bottom. The remaining second layer of 2-in. mineral wool panels are slid behind furring strips. This is repeated to the top of the wall with the furring strips secured to the framing with screws. This helps to keep the furring strips straight and plumb. Finally, a semi-rigid fiberglass panel was used between the furring strips as an insect screen that will allow drainage and drying. Then fiber-cement siding was fastened to the furring strips using normal installation techniques.	 Figure D.8. Wall G: Exterior Mineral Fiber Board Insulation

Wall H: Exterior Structural GPS Panel (Inspired by EnergieSprong)

This wall treatment was envisioned to be an off-site fabricated panel. However, to keep the project moving the panel was installed in layers onto the existing wall. A low-density fiberglass panel was installed over existing siding to fill potential air voids between the existing lapped siding and the panel. A 1.5-in. structural OSB sheet was fastened with screws to the wall framing and covered with a fully adhered (peel and stick) membrane. The first layer of $2^{1}/_{8}$-in. graphite impregnated EPS was installed with minimal cap nails to hold in place. A second layer of $2^{1}/_{8}$-in. graphite impregnated EPS was installed also using limited cap nails. Then the 1- x 4-in. furring strips were fastened with screws to the structural OSB panel. A semi-rigid fiberglass panels was used between the furring strips as an insect screen that will allow drainage and drying. Finally, a metal panel siding was fastened with washered screws to the furring strips.

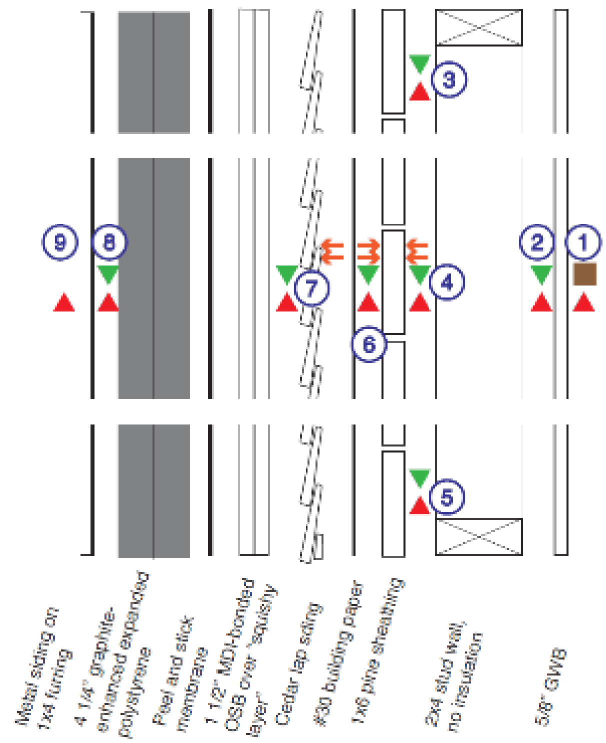


Figure D.9. Wall H: Exterior Structural GPS Panel (inspired by EnergieSprong)

Wall I: Base-Case Wall #2

The materials and construction for this assembly were presented in the discussion of the base-case wall preparation. This wall was reconstructed to serve as a control for Phase 2 testing.

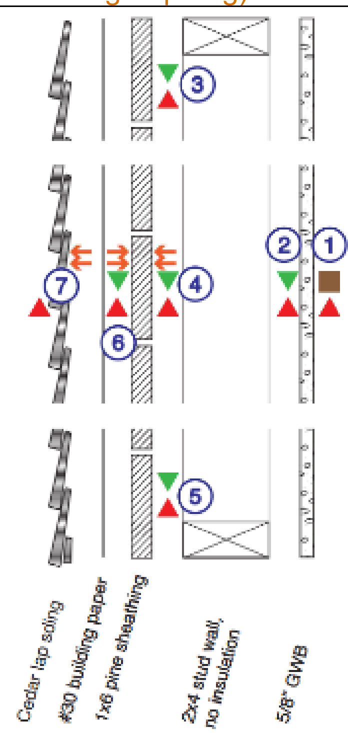


Figure D.10. Wall I: Baseline #2

Wall J: Drill-and-Fill (Fiberglass)

The University of Minnesota team hired a qualified installer to drill-and-fill these walls with blown-in fiberglass from the exterior similar to what would be done in the weatherization and retrofit market. The cedar siding was removed in one location near the middle of the cavities. One oval-shaped hole was drilled through the building paper and sheathing near mid-wall for each wall cavity. Fiberglass insulation was installed with a flexible tube to ensure a high density throughout the cavity. The contractor was aiming for a minimum density of 1.5 lb/ft^3. The holes in the sheathing were sealed with a spray polyurethane foam, a piece of building paper was used to repair the water control layer, and the siding was replaced.

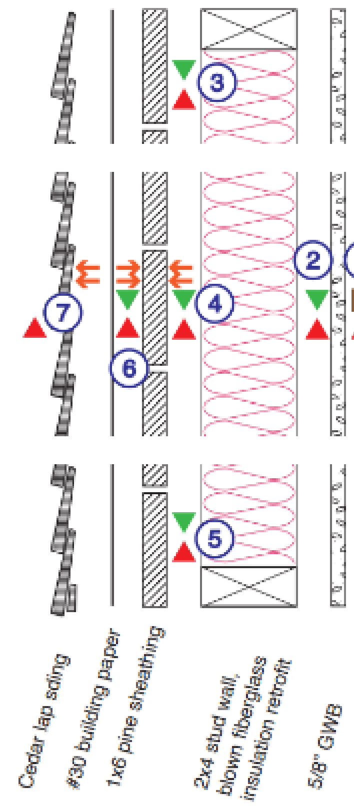


Figure D.11. Wall J: Drill-and-Fill (Fiberglass)

Wall K: Interior Polyiso Insulation w/ FG Batt

This wall treatment was selected to an upgrade that could be installed during an interior remodel. The interior drywall was removed and an unfaced R-13 fiberglass batt was carefully installed in the existing cavity. Then a 1-in. foil-faced polyiso foam insulation board was installed over the studs. The existing drywall gasket sealed against air infiltration. The drywall was reinstalled and a sealant was used to ensure air tightness at the electrical box. In a typical application, this would be new drywall.

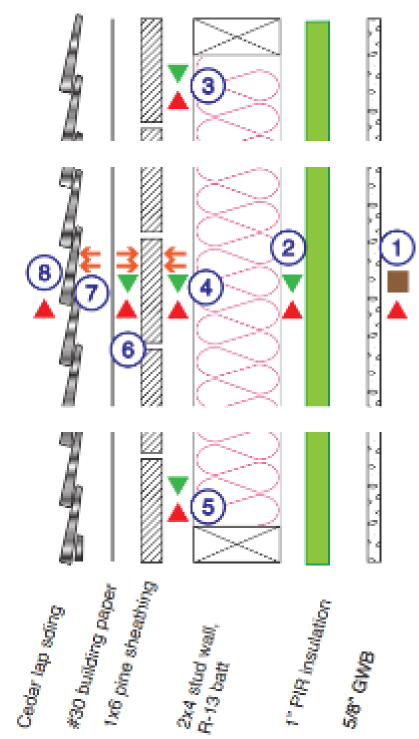


Figure D.2 Wall K: Interior Polyiso Insulation.

Wall L: Drill & Fill (Fiberglass) with Exterior Polyiso Insulation (siding removed)

For this wall a dense-pack fiberglass was installed as described in Wall J. However, the cedar lap siding and building paper were removed. The holes were filled with one-part polyurethane spray foam. Next, a house wrap was applied with cap nails. Then a 1-in. foil-faced polyiso board was installed over the house wrap with 1- x 4-in. furring strips over the foam fastened to the studs with long screws. A prefinished lap wood composite siding was fastened to the furring strips in a standard fashion.

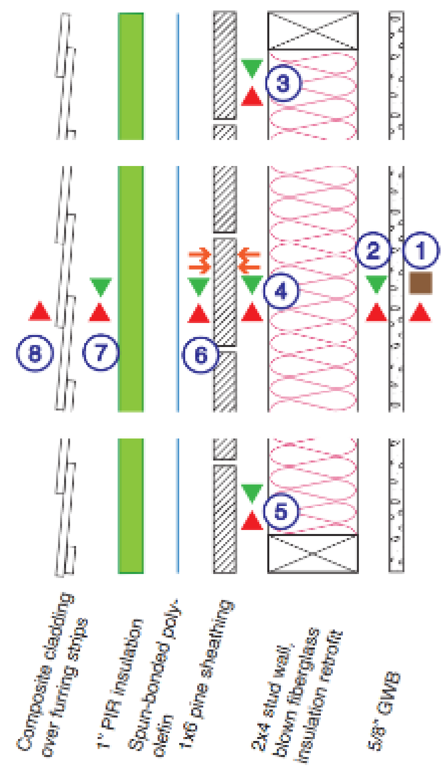


Figure D.13. Wall L: Exterior Polyiso Insulation (siding removed)

Wall M: Realize EIFS Panel (siding removed)

The treatment is a 6 in. piece of EPS foam finished on all six sides with a stucco material. For this prefabricated wall treatment, the existing siding and building paper were removed and a coat of liquid-applied membrane was applied using a paint roller. Then all sheathing gaps and nail holes were filled with a proprietary caulk, which was lightly tooled into the surface, followed by a second coat of membrane applied by roller. The prefinished EIFS panel was fixed in place using a gun-grade adhesive. A temporary shelf at the bottom edge of the test panel supported the weight of the panel as the adhesive cured. The shelf supports were removed approximately 24 hours later. It is the understanding of the team that a rack-mount attachment is under development for this system, however it was not available for use at the time of this testing.

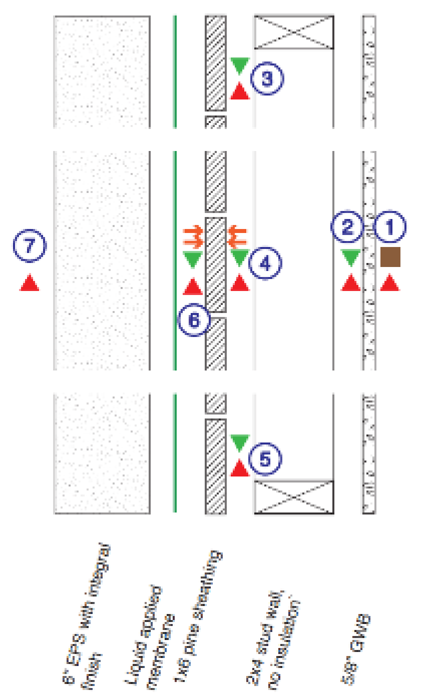


Figure D.14. Wall M: Realize EIFS Panel (siding removed)

Wall N: ABC Fraunhofer Blocks

For this prefabricated wall treatment, a house wrap was installed over the existing siding and sealed at the edges with house wrap tape to serve as a new air and back-up water control layer. A base plate was installed to receive the custom trim pieces for the top and both sides. Next a custom metal starter strip was installed to receive the first block, at the bottom edge. Then the foam blocks were installed using four screws per block. Subsequent blocks engage the block below with a large tongue-and-groove shape in the foam extrusion. The final step was to clip the L-section trim pieces into the receiver plates.

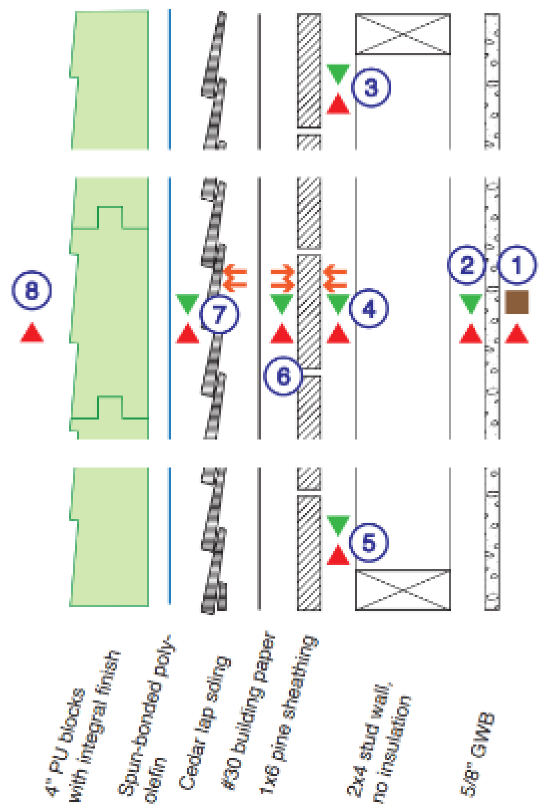


Figure D.15. Wall N: ABC Fraunhofer Blocks

Wall O: Drill & fill (Fiberglass) w/ Exterior Fiberglass Board Insulation

Again, this wall treatment uses dense-pack cellulose installed as described in Wall J. The siding was replaced, but touch up was not required, and sheet of house wrap was draped from the top of the panel. The 2-in. semi-rigid fiberglass boards were installed starting at the bottom and temporarily secured using two cap nails per piece. Then 1- x 4-in. furring strips were installed over the panels and fastened to framing with washer-head screws. A fiber cement siding was installed on the furring strips.

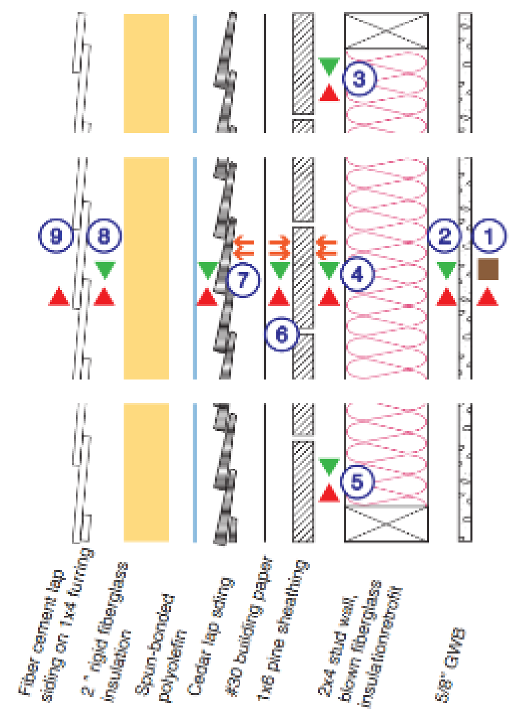
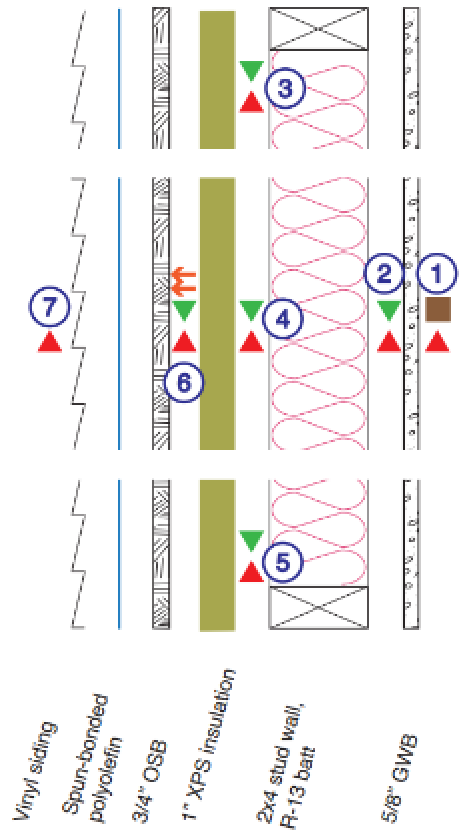


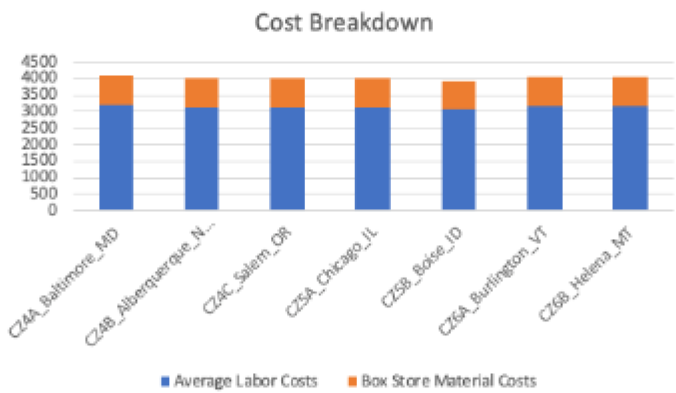
Figure D.16. Wall O: Exterior Fiberglass Board Insulation

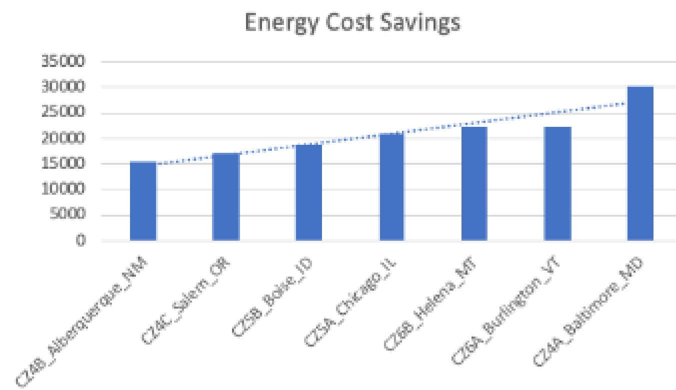
Wall P: Thermal Break Shield (siding and sheathing removed) This wall treatment was developed to provide a combined structural and thermal upgrade. The first step was to remove existing siding, building paper, and sheathing. Next, an unfaced R-13 fiberglass batt was installed in the existing cavity followed by a 1-in. XPS board insulation installed over the studs. A ¾-in. OSB sheet is installed over the XPS and fastened securely to the studs as a shear plate using 4-in. screws. Finally, a house wrap was installed using cap nails followed by a typical installation of vinyl siding.	 Figure D.17. Wall P: Thermal Break Shear Wall

Appendix E – Analysis by Wall Type for All Climate Zones

E.1 Wall B: Drill-and-Fill Cellulose (dense-pack)

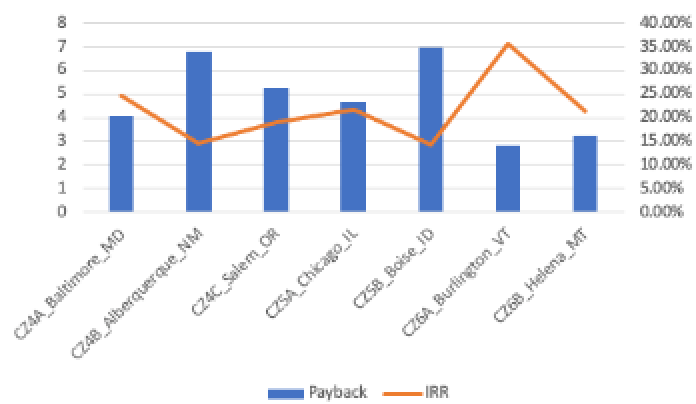
Wall B: Drill-&-Fill Cellulose (dense-pack)





Adoption Score

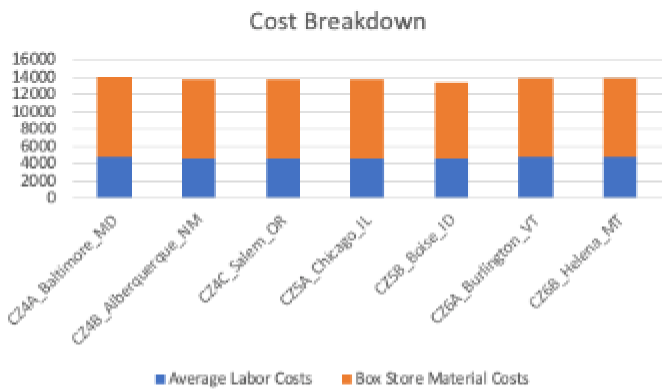
Wall B	
CZ4A_Baltimore_MD	0.900
CZ4B_Alberquerque_NM	0.910
CZ4C_Salem_OR	0.940
CZ5A_Chicago_IL	0.903
CZ5B_Boise_ID	0.900
CZ6A_Burlington_VT	0.940
CZ6B_Helena_MT	0.940



Location and Climate Zone	Payback	IRR
CZ4A Baltimore, MD	4	24.72%
CZ4B Albuquerque, NM	7	14.49%
CZ4C Salem, OR	5	18.94%
CZ5A Chicago, IL	5	21.56%
CZ5B Boise, ID	7	14.15%
CZ6A Burlington VT	3	35.67%
CZ6B Helena, MT	3	21.32%

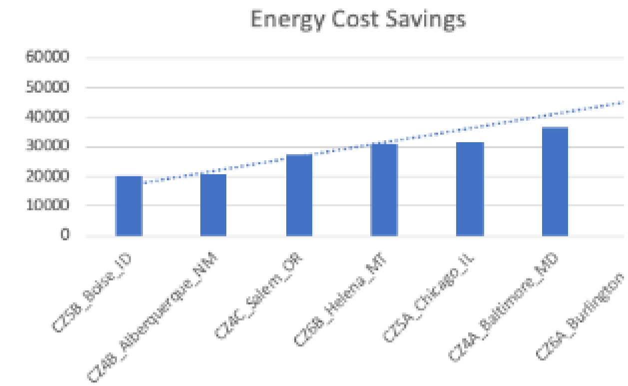
E.2 Wall C: Injected Cavity Foam (proprietary cc-spu)

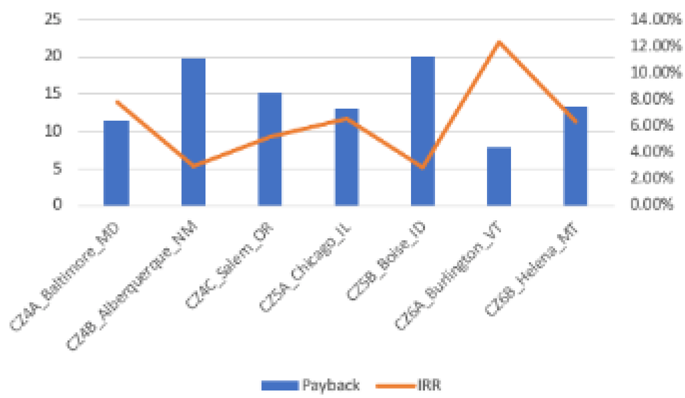
Wall C: Injected Cavity Foam (proprietary cc-spu)



Adoption Score

Wall C	
CZ4A_Baltimore_MD	0.848
CZ4B_Alberquerque_NM	0.795
CZ4C_Salem_OR	0.848
CZ5A_Chicago_IL	0.885
CZ5B_Boise_ID	0.795
CZ6A_Burlington_VT	0.885
CZ6B_Helena_MT	0.865

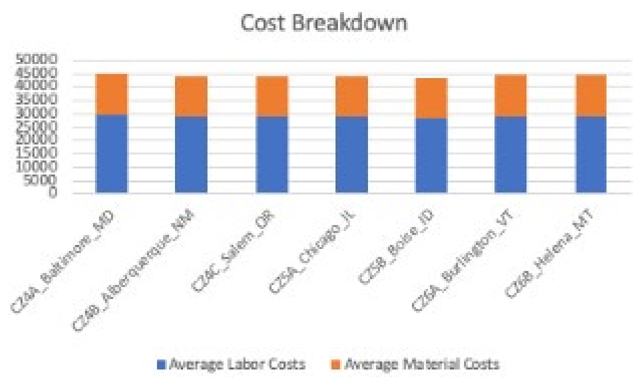


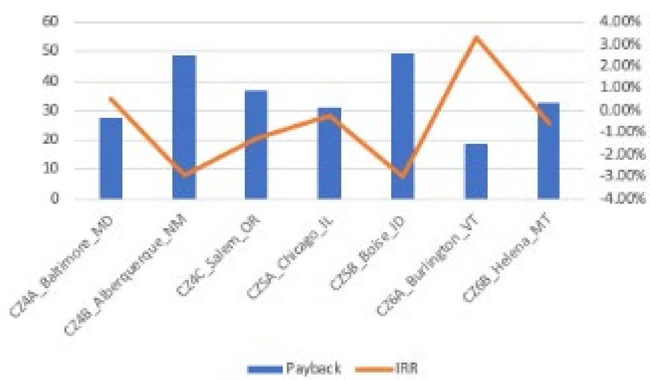


Location and Climate Zone	Payback	IRR
CZ4A_Baltimore, MD	11	7.84%
CZ4B_Alberquerque, NM	20	2.94%
CZ4C_Salem, OR	15	5.18%
CZ5A_Chicago, IL	13	6.54%
CZ5B_Boise, ID	20	2.84%
CZ6A_Burlington, VT	8	12.31%
CZ6B_Helena, MT	13	6.29%

E.3 Wall D: Prefab Exterior EPS (panel with struts)

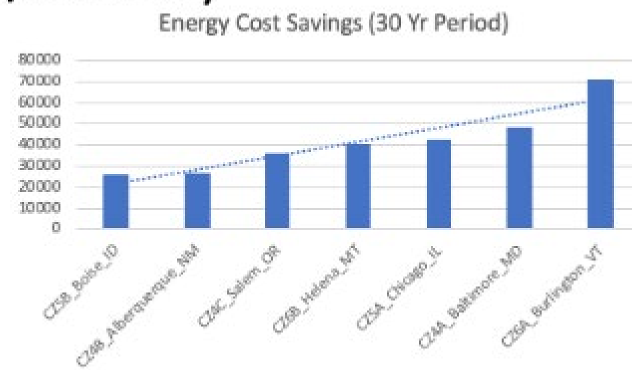
Wall D: Pre-fab Ext EPS (panel w/struts)





Adoption Score

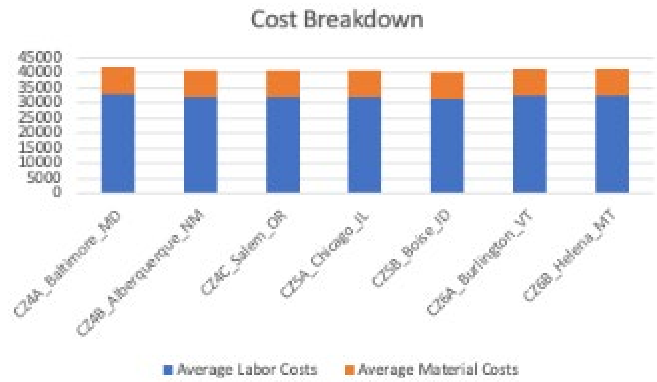
Wall D	
CZ4A_Baltimore_MD	0.645
CZ4B_Alberquerque_NM	0.645
CZ4C_Salem_OR	0.670
CZ5A_Chicago_IL	0.745
CZ5B_Boise_ID	0.683
CZ6A_Burlington_VT	0.785
CZ6B_Helena_MT	0.745

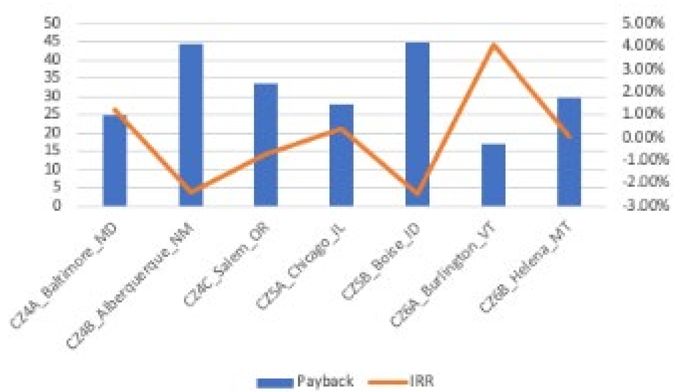


Location and Climate Zone	Payback	IRR
CZ4A_Baltimore_MD	28	0.54%
CZ4B_Alberquerque_NM	49	-2.92%
CZ4C_Salem_OR	37	-1.27%
CZ5A_Chicago_IL	31	-0.23%
CZ5B_Boise_ID	50	-2.97%
CZ6A_Burlington_VT	19	3.31%
CZ6B_Helena_MT	33	-0.59%

E.4 Wall: E. Drill-and-Fill Cellulose + Exterior EPS

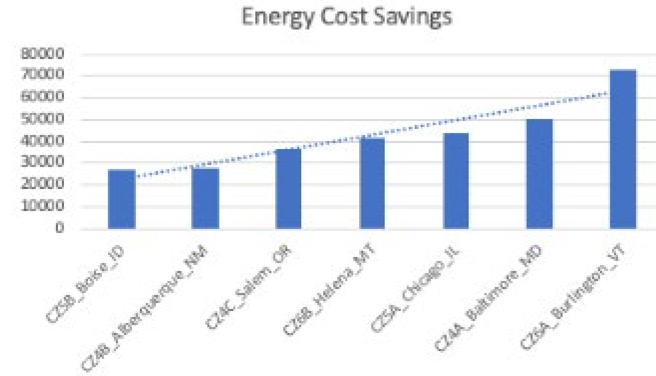
Wall E: Drill-&-fill Cellulose + Ext EPS





Adoption Score

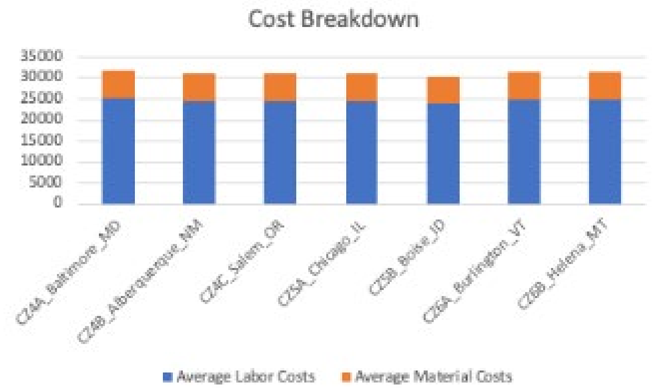
Wall E	
CZ4A_Baltimore_MD	0.690
CZ4B_Alberquerque_NM	0.625
CZ4C_Salem_OR	0.658
CZ5A_Chicago_IL	0.740
CZ5B_Boise_ID	0.663
CZ6A_Burlington_VT	0.795
CZ6B_Helena_MT	0.740

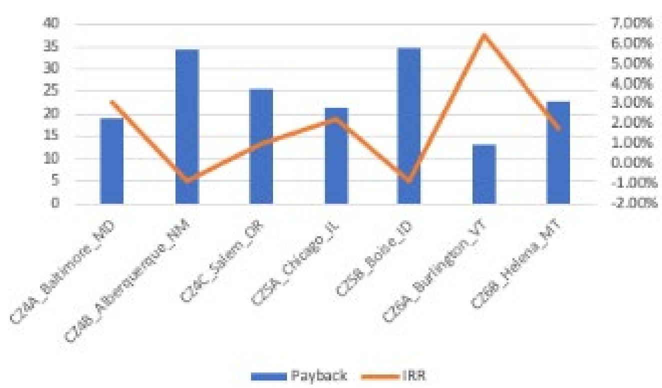


Location and Climate Zone	Payback	IRR
CZ4A_Baltimore_MD	25	1.21%
CZ4B_Alberquerque_NM	45	-2.39%
CZ4C_Salem_OR	33	-0.69%
CZ5A_Chicago_IL	28	0.41%
CZ5B_Boise_ID	45	-2.43%
CZ6A_Burlington_VT	17	4.11%
CZ6B_Helena_MT	30	0.04%

E.5 Wall F: Drill-and-Fill Cellulose + VIP/Vinyl Siding

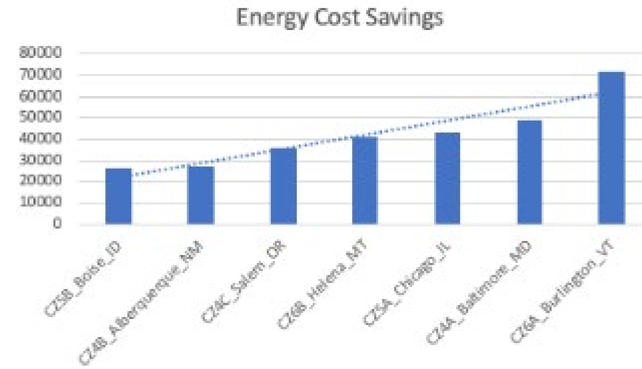
Wall F: Drill-&-fill Cellulose + VIP/Vinyl Siding





Adoption Score

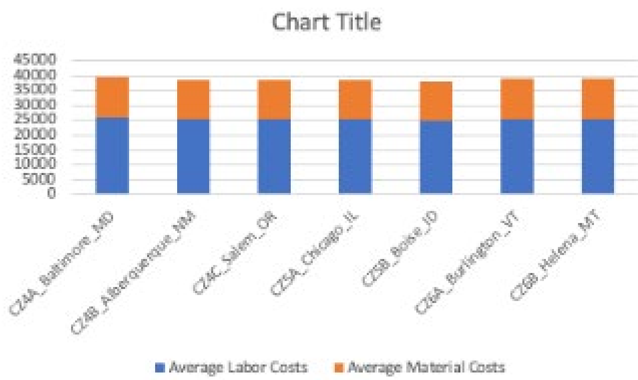
	Wall F
CZ4A_Baltimore_MD	0.745
CZ4B_Alberquerque_NM	0.690
CZ4C_Salem_OR	0.768
CZ5A_Chicago_IL	0.820
CZ5B_Boise_ID	0.863
CZ6A_Burlington_VT	0.760
CZ6B_Helena_MT	0.820



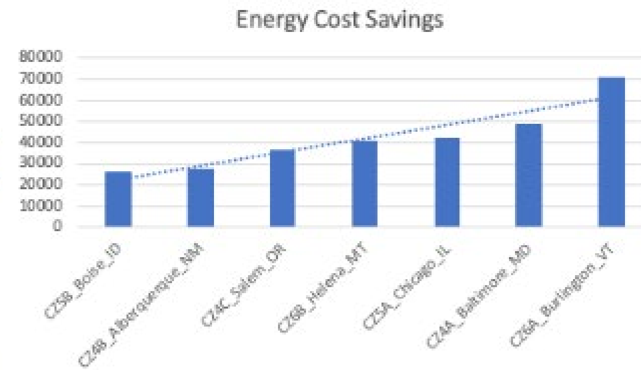
Location and Climate Zone	Payback	IRR
CZ4A_Baltimore_MD	19	3.14%
CZ4B_Alberquerque_NM	34	-0.84%
CZ4C_Salem_OR	26	1.03%
CZ5A_Chicago_IL	22	2.24%
CZ5B_Boise_ID	35	-0.89%
CZ6A_Burlington_VT	13	6.45%
CZ6B_Helena_MT	23	1.83%

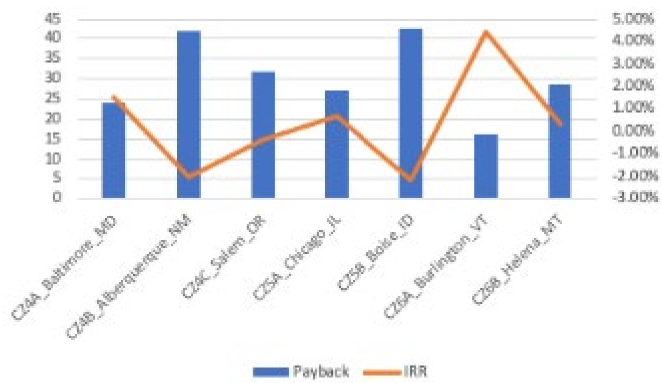
E.6 Wall G: External Mineral Fiber Board

Wall G: Exterior Mineral Fiber Board



Adoption Score	
Wall G	
CZ4A_Baltimore_MD	0.700
CZ4B_Alberquerque_NM	0.620
CZ4C_Salem_OR	0.645
CZ5A_Chicago_IL	0.713
CZ5B_Boise_ID	0.673
CZ6A_Burlington_VT	0.805
CZ6B_Helena_MT	0.750

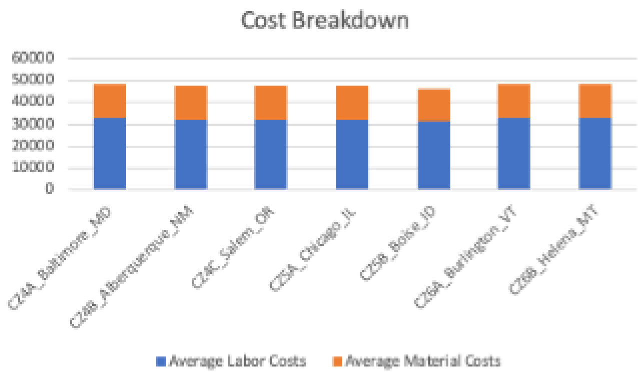




Location and Climate Zone	Payback	IRR
CZ4A_Baltimore_MD	24	1.51%
CZ4B_Alberquerque_NM	42	-2.05%
CZ4C_Salem_OR	32	-0.35%
CZ5A_Chicago_IL	27	0.69%
CZ5B_Boise_ID	43	-2.12%
CZ6A_Burlington_VT	16	4.45%
CZ6B_Helena_MT	29	0.32%

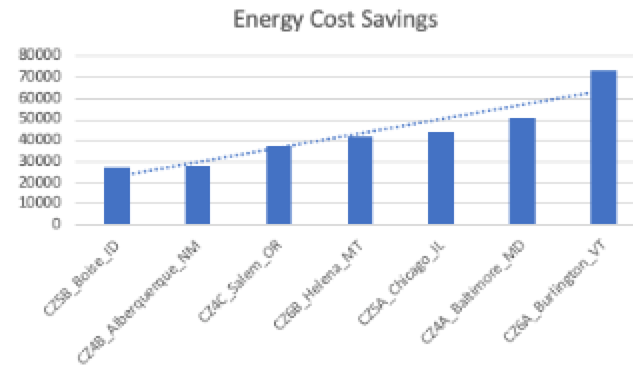
E.7 Wall H: Exterior GPS/Metal Structural Panel System

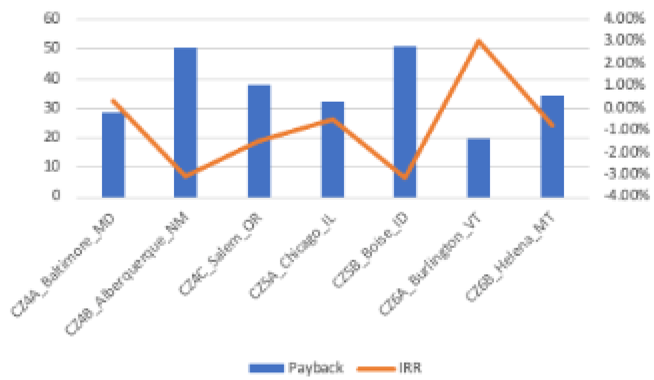
Wall H: Exterior gEPS/Metal Structural Panel System



Adoption Score

Wall H	
CZ4A_Baltimore_MD	0.635
CZ4B_Alberquerque_NM	0.580
CZ4C_Salem_OR	0.620
CZ5A_Chicago_IL	0.658
CZ5B_Boise_ID	0.618
CZ6A_Burlington_VT	0.735
CZ6B_Helena_MT	0.695

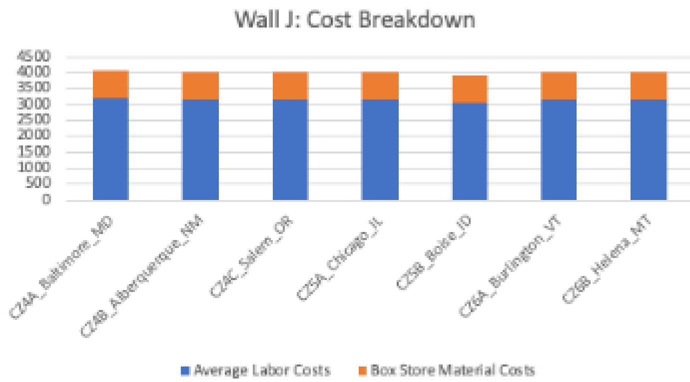




Location and Climate Zone	Payback	IRR
CZ4A_Baltimore_MD	29	0.30%
CZ4B_Alberquerque_NM	50	-3.06%
CZ4C_Salem_OR	38	-1.46%
CZ5A_Chicago_IL	32	-0.48%
CZ5B_Boise_ID	51	-3.12%
CZ6A_Burlington_VT	20	3.00%
CZ6B_Helena_MT	34	-0.81%

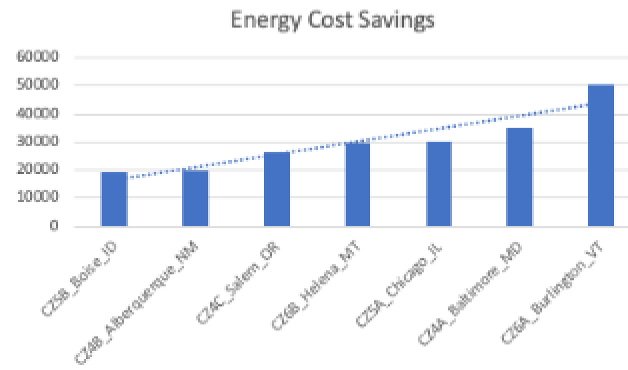
E.8 Wall J: Drill-and-Fill Fiberglass (proprietary fiberglass, high-density)

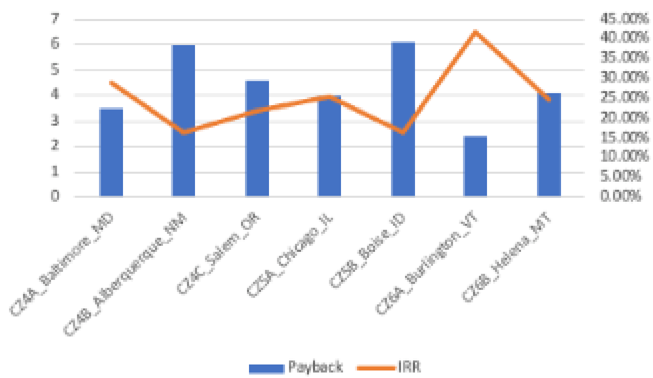
Wall J: Drill-&-Fill Fiberglass (proprietary FG, high-density)



Adoption Score

Wall J	
CZ4A_Baltimore_MD	0.965
CZ4B_Alberquerque_NM	0.890
CZ4C_Salem_OR	0.845
CZ5A_Chicago_IL	0.885
CZ5B_Boise_ID	0.890
CZ6A_Burlington_VT	0.980
CZ6B_Helena_MT	0.928

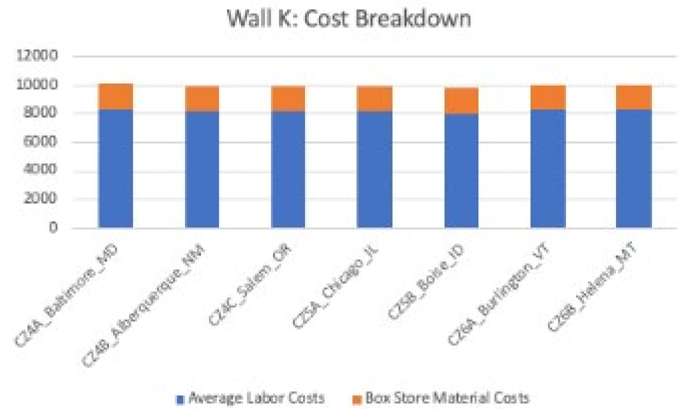




Location and Climate Zone	Payback	IRR
CZ4A_Baltimore_MD	3	28.71%
CZ4B_Alberquerque_NM	6	16.48%
CZ4C_Salem_OR	5	21.74%
CZ5A_Chicago_IL	4	25.23%
CZ5B_Boise_ID	6	16.23%
CZ6A_Burlington_VT	2	41.70%
CZ6B_Helena_MT	4	24.53%

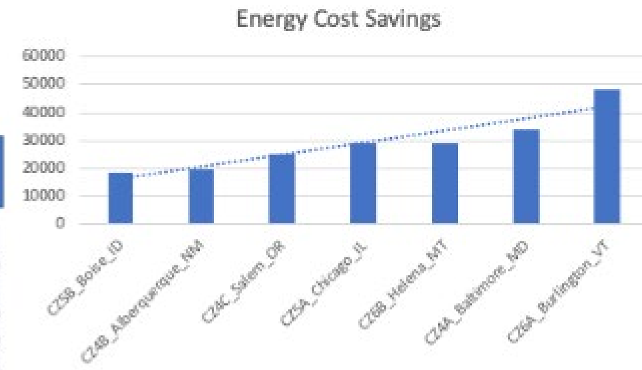
E.9 Wall K: Fiberglass Batt + Interior Polyiso

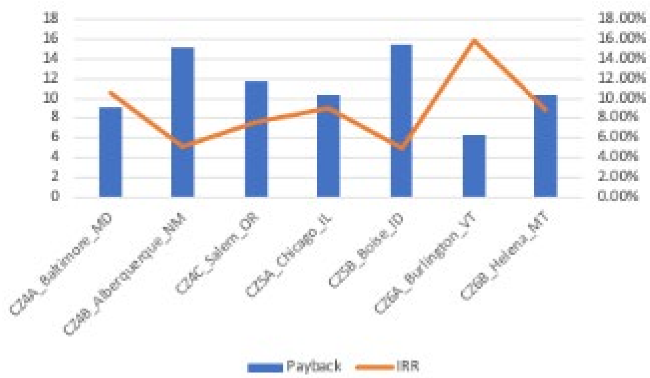
Wall K: Fiberglass Batt + Int Polyiso



Adoption Score

	Wall K
CZ4A_Baltimore_MD	0.840
CZ4B_Alberquerque_NM	0.840
CZ4C_Salem_OR	0.840
CZ5A_Chicago_IL	0.915
CZ5B_Boise_ID	0.840
CZ6A_Burlington_VT	0.915
CZ6B_Helena_MT	0.878

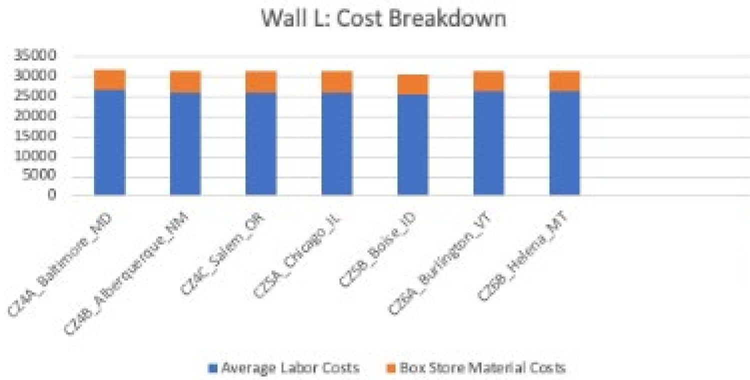




Location and Climate Zone	Payback	IRR
CZ4A_Baltimore_MD	9	10.56%
CZ4B_Alberquerque_NM	15	5.09%
CZ4C_Salem_OR	12	7.58%
CZ5A_Chicago_IL	10	8.94%
CZ5B_Boise_ID	15	4.93%
CZ6A_Burlington_VT	6	15.81%
CZ6B_Helena_MT	10	8.88%

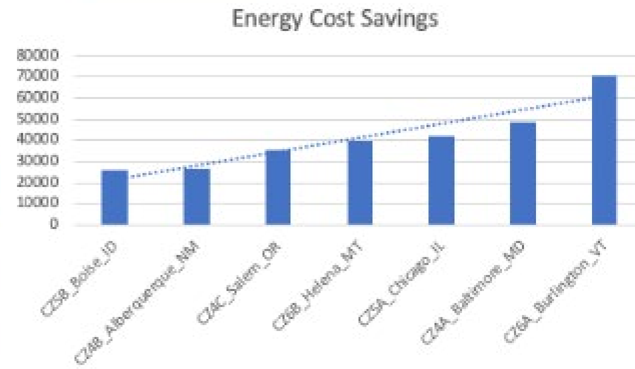
E.10 Wall L: Drill-and-Fill Fiberglass + Exterior Polyiso

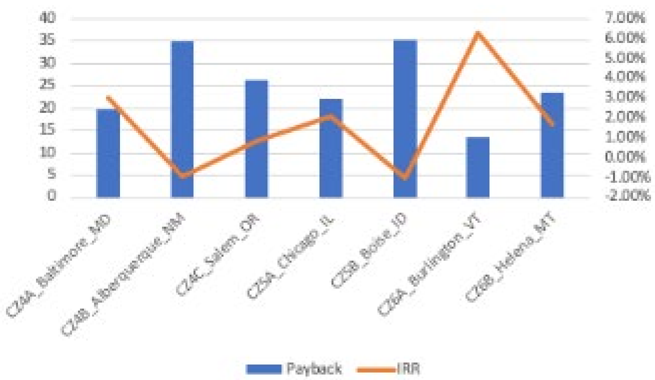
Wall L: Drill & Fill FG + Ext Polyiso



Adoption Score

Wall L	
CZ4A_Baltimore_MD	0.840
CZ4B_Alberquerque_NM	0.710
CZ4C_Salem_OR	0.763
CZ5A_Chicago_IL	0.840
CZ5B_Boise_ID	0.710
CZ6A_Burlington_VT	0.855
CZ6B_Helena_MT	0.803

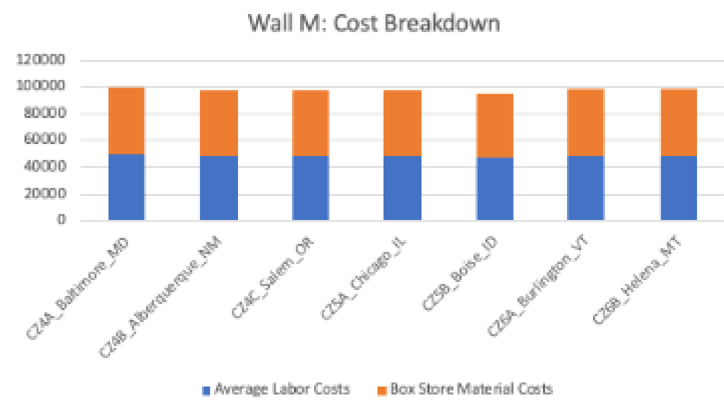


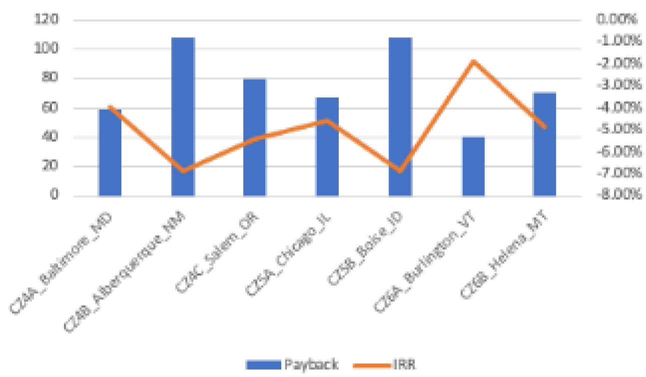


Location and Climate Zone	Payback	IRR
CZ4A_Baltimore_MD	20	2.98%
CZ4B_Alberquerque_NM	35	-0.99%
CZ4C_Salem_OR	26	0.87%
CZ5A_Chicago_IL	22	2.10%
CZ5B_Boise_ID	35	-1.03%
CZ6A_Burlington_VT	13	6.26%
CZ6B_Helena_MT	23	1.67%

E.11 Wall M: Prefab Exterior EPS/EIFS Panel System

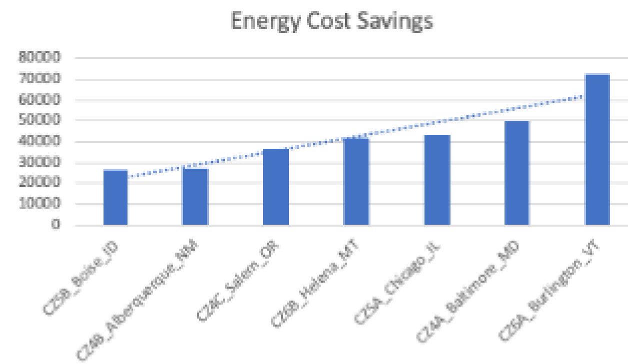
Wall M: Pre-fab Ext EPS/EIFS Panel System





Adoption Score

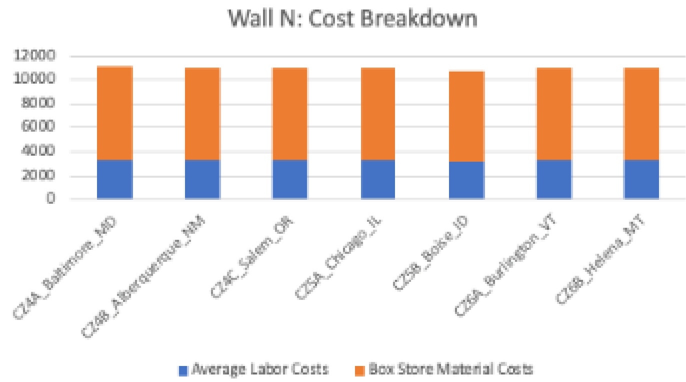
Wall M	
CZ4A_Baltimore_MD	0.600
CZ4B_Alberquerque_NM	0.500
CZ4C_Salem_OR	0.563
CZ5A_Chicago_IL	0.600
CZ5B_Boise_ID	0.525
CZ6A_Burlington_VT	0.645
CZ6B_Helena_MT	0.563



Location and Climate Zone	Payback	IRR
CZ4A_Baltimore_MD	60	-3.96%
CZ4B_Alberquerque_NM	108	-6.84%
CZ4C_Salem_OR	80	-5.42%
CZ5A_Chicago_IL	67	-4.58%
CZ5B_Boise_ID	108	-6.84%
CZ6A_Burlington_VT	41	-1.86%
CZ6B_Helena_MT	71	-4.84%

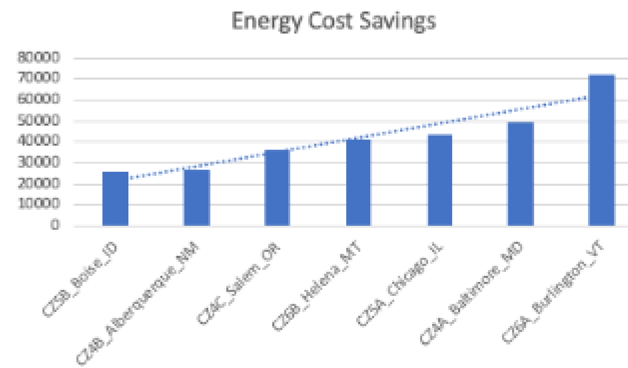
E.12 Wall N: Prefab Exterior polyiso/Vinyl Block System

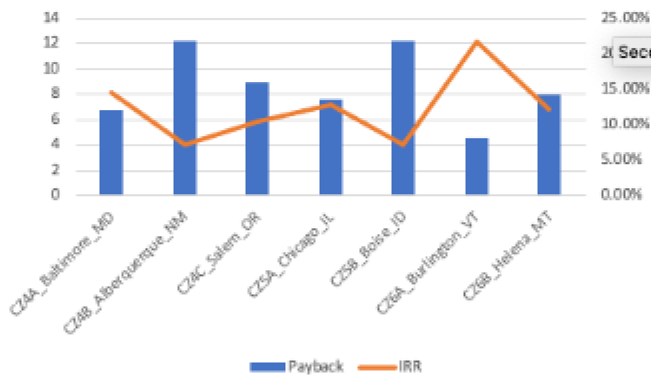
Wall N: Pre-fab Ext PU/Vinyl Block System



Adoption Score

	Wall N
CZ4A_Baltimore_MD	0.895
CZ4B_Alberquerque_NM	0.850
CZ4C_Salem_OR	0.888
CZ5A_Chicago_IL	0.925
CZ5B_Boise_ID	0.850
CZ6A_Burlington_VT	0.910
CZ6B_Helena_MT	0.858

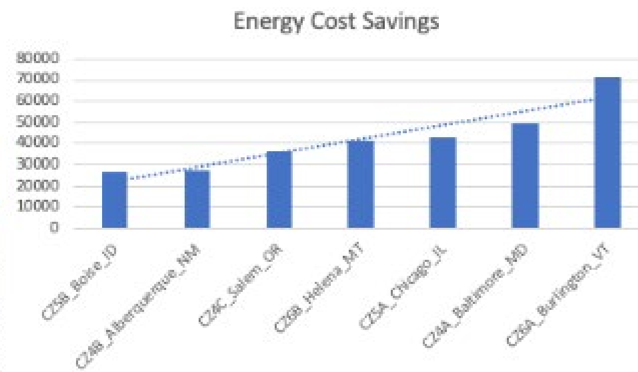




Location and Climate Zone	Payback	IRR
CZ4A_Baltimore_MD	7	14.62%
CZ4B_Alberquerque_NM	12	7.18%
CZ4C_Salem_OR	9	10.56%
CZ5A_Chicago_IL	8	12.83%
CZ5B_Boise_ID	12	7.17%
CZ6A_Burlington_VT	5	21.76%
CZ6B_Helena_MT	8	12.11%

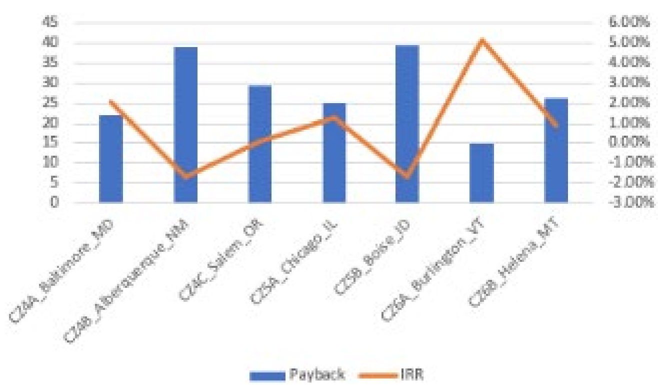
E.13 Wall O: Drill-and-Fill Fiberglass + Exterior Fiberglass FG Board

Wall O: Drill-&-Fill FG + Ext FG Board



Adoption Score

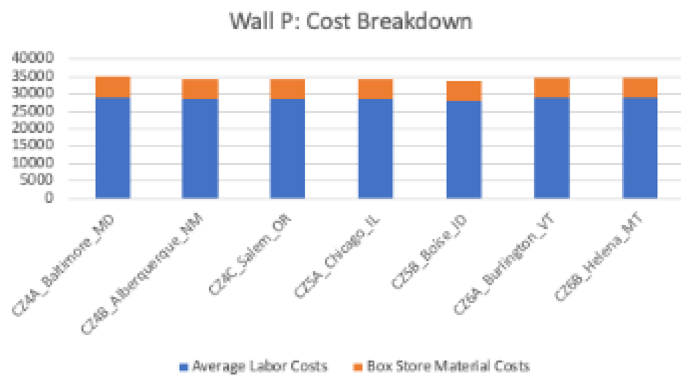
	Wall O
CZ4A_Baltimore_MD	0.805
CZ4B_Alberquerque_NM	0.690
CZ4C_Salem_OR	0.743
CZ5A_Chicago_IL	0.805
CZ5B_Boise_ID	0.690
CZ6A_Burlington_VT	0.835
CZ6B_Helena_MT	0.743

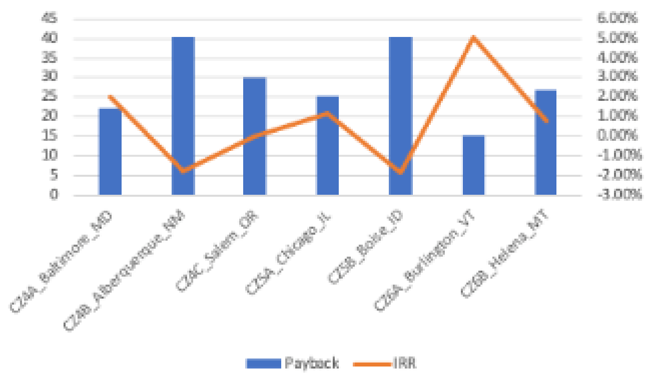


Location and Climate Zone	Payback	IRR
CZ4A_Baltimore_MD	22	2.09%
CZ4B_Alberquerque_NM	39	-1.64%
CZ4C_Salem_OR	29	0.12%
CZ5A_Chicago_IL	25	1.24%
CZ5B_Boise_ID	40	-1.70%
CZ6A_Burlington_VT	15	5.16%
CZ6B_Helena_MT	26	0.86%

E.14 Wall P: Fiberglass Batt + OSB (thermal break shear wall)

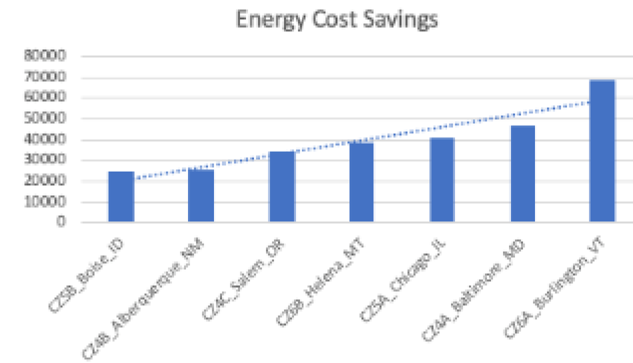
Wall P: FG Batt + XPS + OSB (Thermal Break Shear Wall)





Adoption Score

	Wall P
CZ4A_Baltimore_MD	0.775
CZ4B_Alberquerque_NM	0.635
CZ4C_Salem_OR	0.698
CZ5A_Chicago_IL	0.775
CZ5B_Boise_ID	0.635
CZ6A_Burlington_VT	0.805
CZ6B_Helena_MT	0.713



Location and Climate Zone	Payback	IRR
CZ4A_Baltimore_MD	22	2.00%
CZ4B_Alberquerque_NM	40	-1.82%
CZ4C_Salem_OR	30	-0.04%
CZ5A_Chicago_IL	25	1.18%
CZ5B_Boise_ID	41	-1.85%
CZ6A_Burlington_VT	15	5.08%
CZ6B_Helena_MT	27	0.75%

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