Assessing the Performance, Application, and Cost of Retrofit Wall Systems for Residential Buildings

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Abstract

According to the U.S. Department of Energy Windows and Building Envelope Research and Development Roadmap for Emerging Technologies, building envelope wall energy loss in the United States accounts for about 2 quads of energy annually, costing homeowners and occupants billions of dollars. Enclosure retrofits targeting these losses can save significant energy, reduce greenhouse gas emissions, and save occupants millions of dollars over time.

The Oak Ridge National Laboratory, Pacific Northwest National Laboratory, and the University of Minnesota have been conducting a 3-year study of residential retrofit wall systems. The researchers have identified, tested, and verified the hygrothermal performance of sixteen wall assemblies in retrofit applications. The approach to this study includes a comprehensive literature review, the involvement of an expert advisory group made up of thermal enclosure experts, small-scale experimental in-situ testing of the wall assemblies at the University of Minnesota's Cloquet Residential Research Facility, and energy and hygrothermal simulation of wall assemblies using EnergyPlus, THERM, and WUFI. Simulation and experimental results are then combined with an economic analysis to produce a techno-economic study of residential wall systems for deep energy retrofits.

This paper will summarize the findings of this research project and is intended for guiding architects and designers on how to retrofit existing residential wall assemblies without creating a durability issue. The audience will learn:

1. What building science experts feel are the best wall system to deploy when performing a deep energy retrofit.
2. How these wall systems perform when being tested in-situ in a cold climate.
3. How field testing and computer simulation of both the thermal and moisture performance of these wall assemblies compare.
4. How the costs of these systems compare to the benefits they derive.

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Introduction

In the United States, 39% of total energy is consumed by the building sector; 20% of that total is attributed to residential buildings (U.S. Energy Information Administration, 2018). Newly constructed homes built to meet modern energy codes incorporate a combination of tight, well-insulated building envelope components, high-performing windows, controlled mechanical ventilation, and other efficient components which deliver comfort, adequate airflow, and moisture control in addition to significantly lower energy consumption than ever before.

Older homes, built before 1992 when DOE's Building Energy Codes Program was established, represent approximately 68 percent of the residential building stock in the country (Livingston et al. 2014; U.S. Census Bureau 2017), often having significant air leakage and inadequate insulation. Homes with little to no air sealing or insulation have heating and cooling losses that can represent a substantial portion of utility bills.

The residential remodeling market continues to grow, amounting to $424 billion in 2017 (up 50 percent from 2010). In 2017, approximately 50 percent of home improvement projects included upgrades to mechanical and envelope systems in aging housing stock. This includes replacement of windows and doors; siding and roofing; heating, ventilation, and air-conditioning systems; and insulation. Approximately one in five homeowners have invested in energy efficiency retrofits (Joint Center for Housing Studies of Harvard University 2019). Even so, the number of existing residential buildings with little to no insulation is staggering. An estimated 34.5 million homes with wood studs have no wall insulation (National Renewable Energy Laboratory 2019), representing approximately 38 percent of existing single-family detached homes in the United States. Similarly, 71 percent of existing homes have air leakage rates of 10 or more air changes per hour at 50 pascals of pressure (ACH50), indicating a significant amount of air leakage through the building envelope.

There is a significant need for cost-effective methods of increasing wall insulation and reducing air infiltration for existing homes. In current practice, wall retrofits seldom include the air, moisture, and vapor controls that are considered best practices for high-performance new home construction, potentially creating problems that put the building materials or occupants at risk. Well-tested and documented retrofit wall systems can help to achieve substantial energy savings and improve home durability, comfort, health, and resilience. Done correctly, deep energy retrofits (DERs) can significantly improve the energy and air barrier performance of a home's thermal envelope, help manage indoor environmental pollutants, improve the building's aesthetics, and increase homeowner comfort.

The purpose of this three-year effort funded by the U.S. Department of Energy (DOE) was to identify high-performing wall retrofit systems and provide a real-world context for their thermal, moisture and economic performance to aid decision makers in balancing various goals for deep energy retrofits.

Industry Input and Literature Survey

As an initial step in this project, the research team invited experts from industry, academia, the national laboratories, and other research organizations to join an expert advisory committee and participate in an expert meeting to help identify and characterize candidate wall systems. The meeting was held on 19 April 2019 in Arlington Virginia and thirty-three experts were able to attend. A report summarizing this meeting was published (Antonopoulos et al. 2019a).

The objective of this meeting was to bring together leading researchers and innovators to review the research methodology and to encourage suggestions, information sharing, and collaboration. Outcomes would inform potential retrofit systems to be developed and tested. Specific topics that were discussed in detail including data characterization for proposed wall selections, wall selection for subsequent in-situ testing, and techno-economic study criteria.

The literature review was conducted and published in June 2019 and includes references and links for a variety of sources of relevant information. (Antonopoulos et al. 2019b).

This literature review provides an overview of the thermal and moisture performance of 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.

In addition to investigating wall assemblies, this literature review explored various innovative insulation materials, and provided background for a techno-economic analysis, and the use of such analyses in building construction. Finally, a review of literature on the modeling and simulation of hygrothermal wall assembly performance was presented.

Field Testing

Test Facility and Test Articles

The experimental portion of this project was carried out by the University of Minnesota at the Cloquet Residential Research Facility (CRRF). This research building is located on the Cloquet Forestry Center near Cloquet, Minnesota which is approximately 20 miles west of Duluth and in DOE Climate Zone 7.

The CRRF building is elongated along an east-west axis to maximize the northern and southern exposures. It sits on a full basement with twelve independent above-grade test bays protected by two end guard bays. The eight test bays (1 to 4 and 9 to 12) having both a north and south exposure were selected to conduct in-situ testing for this project. The CRRF is pictured in figure 1 and a schematic of the floor plan is depicted in Figure 2.

Figure 1: Cloquet Residential Research Facility (CRRF) was used for the in-situ testing of retrofit wall assemblies.

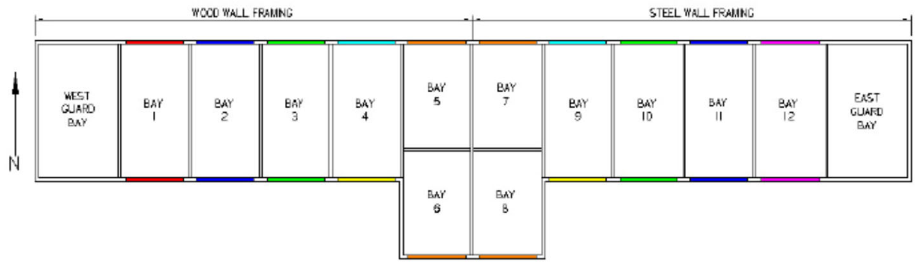


Figure 2: Floor plan of the CRRF.

Baseline Test Articles

Two series of in-situ experiments were conducted during this three-year project. The first series of test walls (Phase 1) were developed in response to the activities associated with the literature survey and the expert meeting, were deployed in the CRRF in December 2019, and were evaluated for two winter periods. After studying the results of these first tests, a second series of wall assemblies (Phase 2) were proposed by the research team in consultation with an Advisory Committee that oversaw the research project. These wall assemblies were installed in the CRRF in December 2020.

Phase 1 of this project was conducted in Bays 1 to 4 and Phase 2 used Bays 9 to 12. Each test bay has a north and south facing wall opening that is approximately 8' (2.44 m) wide and 7' (2.13 m) high. For this project, these test openings were divided in half to support two different test panels. Each test panel was mirrored on both the north and south orientation so eight pairs of wall assemblies were studied during each phase.

The test panels are approximately 4' (1.22 m) wide by 7' (2.13 m) high. Each test panel was divided into three wall cavities at approximately 16" (40.6 cm) on center (oc) to represent older wood-frame construction. The center cavity of each test panel was a true 16" (40.6 cm) oc and was designated as the test cavity. All the monitoring sensors were installed within this test cavity. The wall cavities on each side of the test cavity were designed as guard cavities. They received the exact same insulation treatment to mitigate any differential horizontal heat flows between the test and guard cavities. 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: Exterior view of baseline walls depicting cedar siding prior to wall retrofits.

To assess the impact of wall retrofits, a baseline wall assembly was designed and used as the starting point for each wall assembly and sixteen identical test walls were constructed for each Phase. The baseline test walls were constructed of 2x4 (38 mm x 89 mm) spruce, pine, and fir (SPF) wood studs with 1”x 6” (2.54 cm x 15.25 cm) pine board exterior 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” (20.3 cm) 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. Once the test panel was installed in the test opening and the instrumentation array was installed, an interior finish of 5/8” (1.59 cm) 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 coats of paint. Baseline walls from Phase 2 are shown in Figure 3.

Instrumentation

Depending on the specific construction, each test cavity had between 15 and 20 sensors installed. Temperature (type-T thermocouples), relative humidity (capacitance type), heat flux (heat flux transducers), and moisture content (brass nails coated with enamel) were deployed in each test panel. Generally, there was a temperature sensor 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 transducer was located on the interior surface of the drywall. The 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. A schematic of a typical instrumentation array is shown in Figure 4.

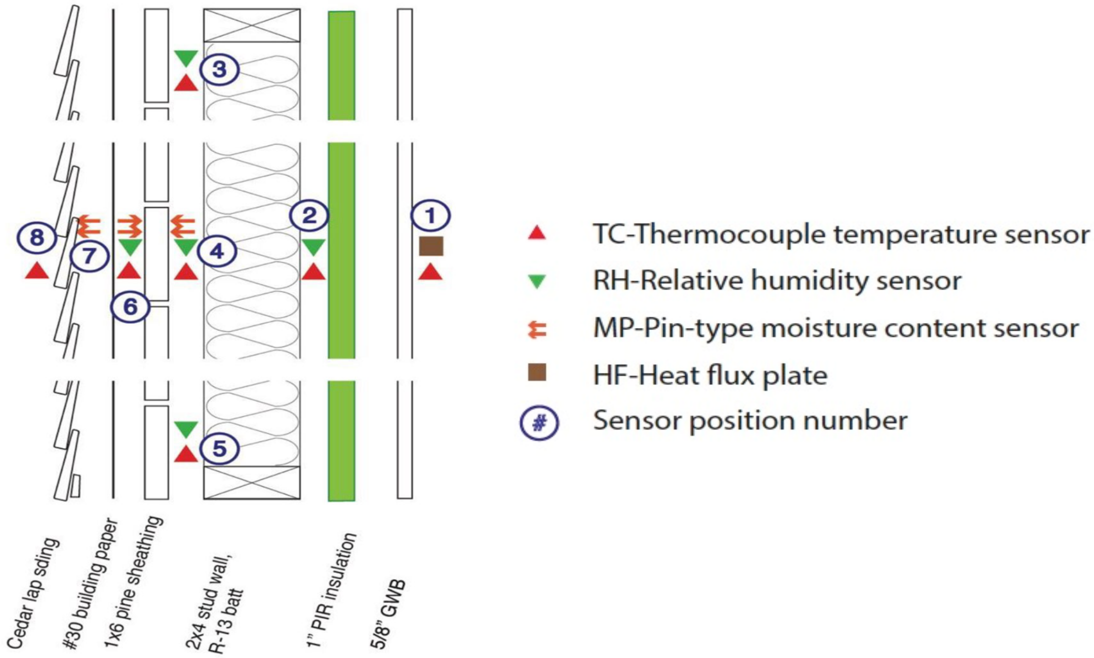


Figure 4: Typical layout of instrumentation in test panels.

The data acquisition system for this experiment was based on the Campbell Scientific CR-1000X datalogger. The centrally located logger collected data from modules located in each test bay. The DAS was also set up to collect interior and exterior boundary conditions. The interior temperature and relative humidity were measured in each test bay. In Phase 1, the exterior temperature, humidity, wind, and precipitation were gathered from local weather stations. For Phase 2, a local weather station was added to the CRRF with temperature, relative humidity, wind speed and direction, rain gauge and horizontal solar radiation instruments. Additional pyranometers were used to measure the solar radiation of the vertical wall surface on both the north and south exposure. Data was continuously collected throughout the winter periods. These data were used to validate both thermal and hygrothermal models as described below.

Wall Retrofits

Over the course of the three-year project, sixteen baseline/retrofit strategies were evaluated. Walls "A" through "H" were instrumented and installed in the CRRF in December 2019 and Walls "I" through "P" were set up in December 2020. Data collection on each wall has been ongoing continuously since their installation. A brief description of each retrofit follows.

Wall A: Base Case Wall #1
Baseline wall without any retrofit treatment.

Wall B: Drill & Fill (Cellulose)
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 by a certified contractor with a target density between 3.5 to 4.0 pcf (56.0 to 64.1 kg/m^3). The holes in the sheathing were sealed with spray foam, tape was used to repair the building paper, and the siding was replaced.

Wall C: Minimally Invasive Cavity Spray Foam
This treatment is a foam installed from the interior. They managed all formulation and installation techniques. The proprietary closed-cell polyurethane liquid foam was injected through very small holes in the drywall by the manufacturer's representatives. Infrared imaging was used to ensure the cavities were completely filled. The holes in the drywall were sealed by the with spray foam.

Wall D: Exterior Expanded Polystyrene Foam (EPS) (siding remains)
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 board 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 housewrap was stretched over the fiberglass board to provide a new air and water control layer. Two layers of EPS (2 and 2.5-inches, or 5.08 and 6.35 cm) were installed to the existing wall with screws using the integral fastening ladder. Vinyl siding was installed with screws to the integral fastening ladder in the second panel.

Wall E: Drill & Fill (Cellulose) w/ Exterior XPS (siding removed)
Dense-pack cellulose was installed as described in Wall B. In this case, the cedar lap siding and building paper were removed and housewrap was installed as a new air and water control layer. 2 inches (5.08 cm) of extruded polystyrene foam (XPS) was held in place and 1-x 4-inch (2.54 cm x 10.2 cm) furring strips were screwed through insulation layer and fastened to framing. A ¾-inch (1.91 cm) XPS layer was placed between the furring strips to support the vinyl siding cladding that was attached to the furring strips.

Wall F: Drill & Fill (Cellulose) w/ Exterior Vacuum Insulation Panel (VIP)/Vinyl Siding (siding removed)
Dense-pack cellulose installed as described in Wall B. The cedar lap siding and building paper were removed and a housewrap was installed as a new air and water control layer. A VIP/vinyl siding composite panel was installed to the exterior sheathing.

Wall G: Exterior Mineral Fiber Board (siding remains)
A vapor permeable liquid applied membrane was applied over the existing lapped siding to provide a more robust water control layer. A 2-inch mineral wool panel was held in place and a second layer of 2-inch (5.08 cm) mineral wool layer is installed with staggered joints. 1-inch x 4-inch (2.54 cm x 10.2 cm) furring strips are installed. A semi-rigid fiberglass board was installed between the furring strips acting as an insect screen that will allow drainage and drying and fiber-cement siding was fastened to the furring strips.

Wall H: Exterior Structural graphite impregnated EPS (gEPS) Panel (siding remains)
A low-density fiberglass board was installed over existing siding to fill potential air voids between the existing lapped siding and the retrofit panel. A 1.5-inch (3.81 cm) structural OSB sheet was fastened with screws to the wall framing and covered with a fully adhered peel and stick membrane. Two layers of 2-1/8-inch (5.40 cm) graphite impregnated EPS were installed using a limited amount of cap nails. 1-inch x 4-inch (2.54 cm x 10.2 cm) furring strips are installed. A semi-rigid fiberglass board was installed between the furring strips acting as an insect screen that will allow drainage and drying and fiber-cement siding was fastened to the furring strips and a metal panel siding was fastened to the furring strips. This wall treatment was envisioned to be an off-site fabricated panel but was installed in layers onto the existing wall.

Wall I: Base Case Wall #2
Baseline wall without any retrofit treatment identical to Wall A.

Wall J: Drill-and-Fill (Fiberglass)
The siding was removed in one location just below mid-point and near the middle of the cavities and a hole were drilled through the building paper and sheathing. The fiberglass was installed by a certified contractor with a target density between 1.5 pcf (24.0 kg/m^3). The holes in the sheathing were sealed with spray foam, a piece of building paper was used to repair the water control layer, and the siding was replaced.

Wall K: Interior Polyiso Insulation w/ Fiberglass Batt
The drywall was removed and an unfaced R-13 (RSI-2.29) fiberglass batt was carefully installed in the existing cavity. A 1-inch (2.54 cm) foil-faced polyisocyanurate foam board was installed over the studs. The drywall was reinstalled, and a sealant was used to ensure air tightness.

Wall L: Drill & Fill (Fiberglass) w/ Exterior Polyiso Insulation (siding removed)
For this wall fiberglass was installed as described in Wall J. In this instance, the cedar lap siding and building paper were removed and the holes were filled with spray foam. A housewrap was applied and a 1-inch foil-faced polyisocyanurate foam board was installed with 1- x 4-inch (2.54 cm x 10.2 cm) furring strips fastened to the studs with long screws. A prefinished lap wood composite siding was fastened to the furring strips.

Wall M: EIFS Panel (siding removed)
The treatment utilized a six-inch piece of EPS foam finished on all six sides with a stucco material and is intended to be prefabricated. The existing siding and building paper were removed and a coat of liquid-applied membrane was applied. All gaps and nail holes in the sheathing were filled with a proprietary caulk and a second coat of membrane was applied. The prefinished EIFS panels were fixed in place using a gun-grade adhesive and a temporary shelf at the bottom edge of the test panel supported the weight as the adhesive cured. The shelf supports were removed approximately 24 hours later.

Wall N: Prefabricated EPS Blocks
For this prefabricated wall treatment, a housewrap was installed over the existing siding to serve as a new air and back-up water control layer. A base plate was installed to receive the custom trim pieces at the top and both sides of the assembly. The custom metal starter strip was installed to receive the first EPS foam block that was mechanically attached. Subsequent blocks engage the block below with a large tongue-and-groove shape in the foam extrusion.

Wall O: Drill & fill (Fiberglass) w/ Exterior Fiberglass Board Insulation
This wall treatment uses fiberglass installed as described in Wall J. The siding was replaced, but touch up was not required, and sheet of housewrap was draped from the top of the panel. 2-inch (5.08 cm) semi-rigid fiberglass boards were installed and held in place with 1-x 4-inch (2.54 cm x 10.2 cm) furring strips, fastened to the framing with washer-head screws. A fiber cement siding was installed on the furring strips.

Wall P: Thermal Break Shear Wall (siding and sheathing removed)
The existing siding, building paper, and sheathing were removed and an unfaced R-13 (RSI-2.29) fiberglass batt was installed in the existing cavity followed by a 1-inch (2.54 cm) XPS board installed over the studs. A ¾-inch (1.91 cm) OSB sheet is installed over the XPS and

fastened securely to the studs 4-inch (10.2 cm) screws. A housewrap was installed followed by a typical installation of vinyl siding.

Energy Modeling

Energy and modeling have been used by many studies for envelope performance evaluations (Dentz and Podorson 2014). Laboratory and field evaluations of building envelope performance are expensive. In the past decade, modeling software programs for building energy and envelope performance have become more robust and are recognized by the research community and industry. Most building modeling tools are based on solving physics-based energy and mass equations; they can provide detailed outputs on many aspects of building performance.

To capture annual energy cost savings for homes after the Deep Energy Retrofits or DERs, whole-building energy modeling (BEM) tools were used. They simulate whole building energy consumption using hourly modeling of thermal loads and HVAC systems. BEM tools account for all the energy interactions between indoor space, outdoor environment conditions, HVAC, lighting, service water heating, other appliances and equipment, and occupancy behavior. In such analyses, the energy flow through envelope elements such as the walls, roof, and windows, is treated as one-dimensional (1-D) and mass flow of moisture and air and phase changes of moisture are not well captured. Among these tools, the DOE-sponsored EnergyPlus is a popular model because of its continuous R&D supported by DOE and the modeling community.

A reference set of residential building models representative of the existing national residential building stock was created to quantify the energy performance of the proposed walls. The residential prototype building models have been extensively used by the U.S. Department of Energy's Building Energy Codes Program to evaluate the energy and economic performance of residential energy codes, as well as in developing proposed code changes (Xie et al. 2018). However, the prototypes represent the new construction stock and minimal compliance with the residential prescriptive and mandatory requirements of the International Energy Conservation Code. Thus, these prototype models were modified to represent the existing building stock and the inputs for these modifications were taken from the ResStock database published by NREL (Wilson et al. 2017). ResStock is a large-scale housing stock database developed by combining public and private data sources, statistical sampling, and detailed building simulations.

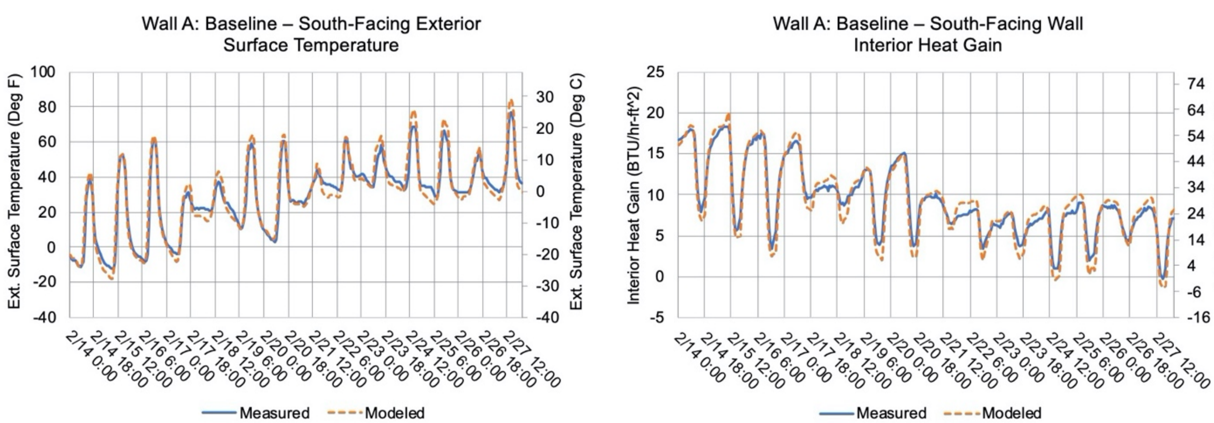
The baseline home was created for this study with modifications using the ResStock data to better represent the existing building stock. The baseline home is a single-family two-story 2,400 ft^2 (223.0 m^2) gross floor area house (US Census Bureau, 2017) with slab-on-grade foundation type and either electric resistance or gas-furnace heating system type. Details about the model can be found in (Mendon, Lucas, and Goel, 2012). Based upon ResStock data, a baseline energy model was constructed with the following assumptions:

1. 2x4 (38 mm x 89 mm lumber) 16-in (40.6 cm) on-center wood-framed, uninsulated walls and insulated, vented ceilings with R-30 (RSI-5.28) insulation.
2. Natural gas heating system with an efficiency of 80% AFUE and a cooling system with an efficiency of SEER 10.
3. Ducting inside of the conditioned space, eliminating the need for duct leakage modeling.
4. Standard electric water for Climate Zone 1 and Climate Zone 2 and gas water heaters for all other climate zones.

5. Clear, single-pane windows with a U-factor of 1.22 Btu/h-ft^2-F (6.93 W/m^2-K) and SHGC of 0.39 for Climate Zones 1-3 and clear, double pane windows with a U-factor of 0.62 Btu/h-ft^2-F (3.52 W/m^2-K) and SHGC of 0.39 for Climate Zones 4-8.
6. Whole-home infiltration rates of 15 ACH50 for the baseline home.

The baseline home was modified to create a set of models representing each of the climate zones as defined by the International Energy Conservation Code (IECC). Each baseline model was then simulated with all 14 wall retrofit options using EnergyPlus Version 8.6. EnergyPlus, however, uses a simplified 1-D dimensional calculation approach for conduction heat transfer through the building envelope. To account for the multi-dimensionality of thermal bridging, THERM, a 2-D conduction heat-transfer analysis program developed by Lawrence Berkeley National Laboratory was applied to capture the effects of thermal bridging (LBNL, 2019). A THERM model was developed for each wall section utilizing the as-built layout and thermal properties of the wall assemblies, and overall section U-value were obtained from THERM and applied to the respective EnergyPlus models.

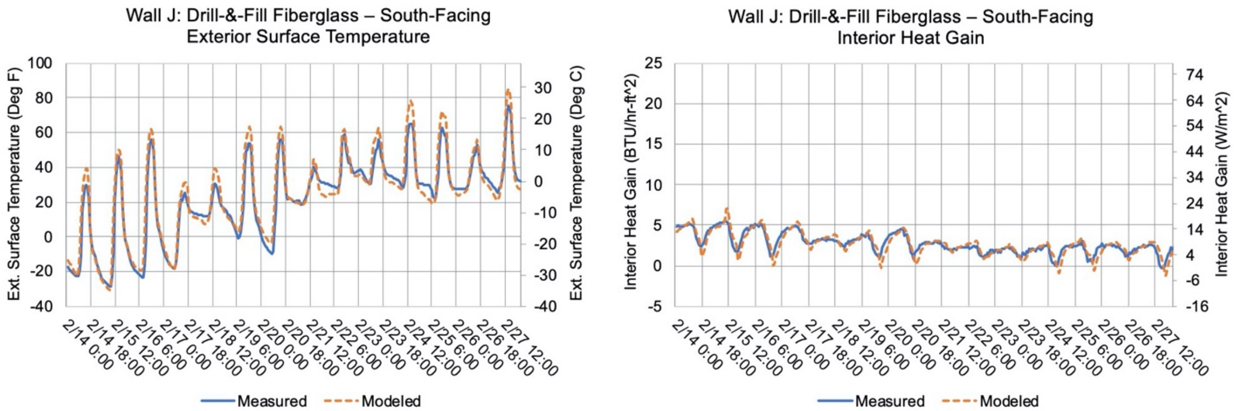
To utilize energy modeling to analyze wall performance on a national scale, it is first necessary to benchmark model results against measured data. Within this project, all 14 candidate wall retrofit assemblies were constructed and instrumented with sensors at the CRRF. To validate the energy models envelope calculations, energy models were constructed each representing a residential building containing the candidate retrofit wall assemblies. These energy models were run utilizing the site-measured weather data and the results of each of these models were compared against measured temperature and heat flux measurements. Interior-facing wall surface temperatures, exterior-facing wall surface temperatures, and interior-facing heat fluxes were compared between the measured and modeled assemblies to validate model performance. Sample benchmarking plots are displayed below in Figures 5 and 6.



(a) Benchmarked exterior surface temperatures for Wall A.
(b) Benchmarked interior heat gain values for Wall A.

Figure 5: Energy modeling outputs compared to measured experimental data for Wall A.

In Figure 5, the exterior surface temperature and interior surface heat flux values for Wall A, the baseline wall, are displayed and the measured and modeled data can be compared. For the displayed dataset, the root mean square error (RMSE) values are 4.70°F (2.63°C) and 1.10 BTU/hr-ft^2 (3.47 W/m^2) for exterior surface temperature and interior heat flux comparisons, respectively. Similar data is depicted in Figure 6 for Wall J, the dense-packed fiberglass drill-and-fill wall.

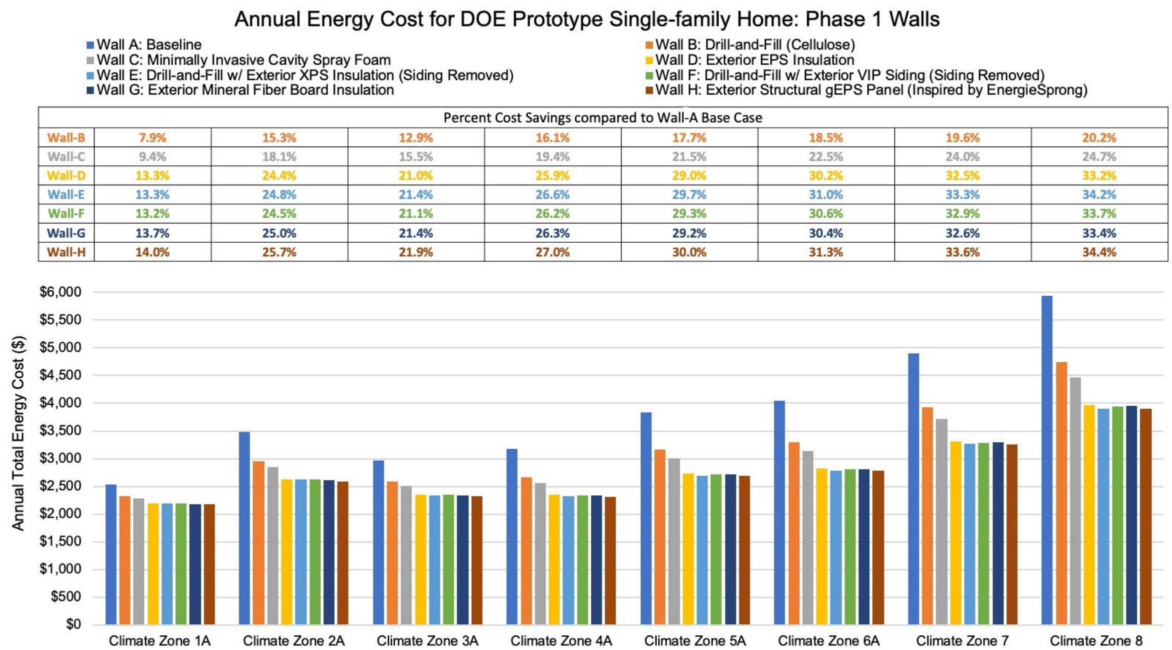


(a) Benchmarked exterior surface temperatures for Wall J.

(b) Benchmarked interior heat gain values for Wall J.

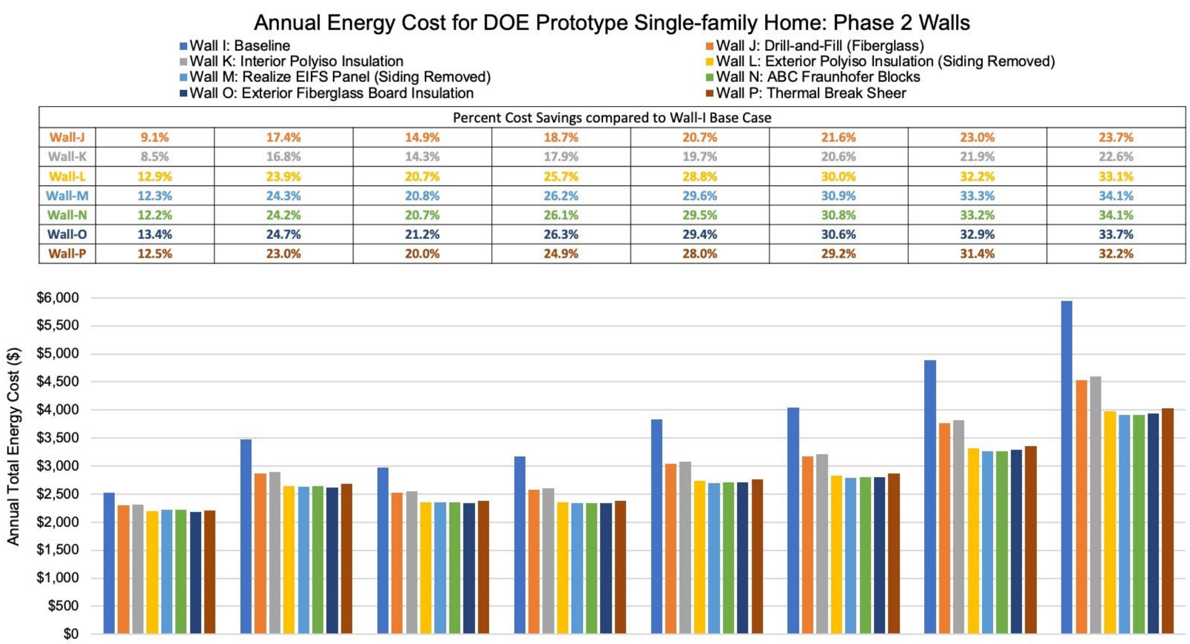
Figure 6: Energy modeling outputs compared to measured experimental data for Wall J.

While the test assemblies at the CRRF give insight into the real-world moisture and energy performance of the proposed retrofit assemblies, physical experiments only provide context to the climate in which the experiment was conducted. To further explore the energy-saving potential of these assemblies, candidate assemblies, simulations were performed to explore the energy performance of the retrofit assemblies across a diverse set of climates. To represent specific climates, representative cities were selected from the IECC 2015 climate zone. The representative cities simulated within this study were Miami, FL; Houston, TX; Memphis, TN; Baltimore, MD; Chicago, IL; Burlington, VT; Duluth, MN; and Fairbanks, AK. National energy prices were also assumed for this analysis. Energy cost values of $0.1013/kWh and $1.00 per Therm were applied nationally for electricity and heating fuel, respectively.



Percent Cost Savings compared to Wall-A Base Case								
Wall-B	7.9%	15.3%	12.9%	16.1%	17.7%	18.5%	19.6%	20.2%
Wall-C	9.4%	18.1%	15.5%	19.4%	21.5%	22.5%	24.0%	24.7%
Wall-D	13.3%	24.4%	21.0%	25.9%	29.0%	30.2%	32.5%	33.2%
Wall-E	13.3%	24.8%	21.4%	26.6%	29.7%	31.0%	33.3%	34.2%
Wall-F	13.2%	24.5%	21.1%	26.2%	29.3%	30.6%	32.9%	33.7%
Wall-G	13.7%	25.0%	21.4%	26.3%	29.2%	30.4%	32.6%	33.4%
Wall-H	14.0%	25.7%	21.9%	27.0%	30.0%	31.3%	33.6%	34.4%

Figure 7: The annual energy costs for the modeled residential prototype building with the Phase 1 wall retrofit assemblies.



Percent Cost Savings compared to Wall-I Base Case								
Wall-J	9.1%	17.4%	14.9%	18.7%	20.7%	21.6%	23.0%	23.7%
Wall-K	8.5%	16.8%	14.3%	17.9%	19.7%	20.6%	21.9%	22.6%
Wall-L	12.9%	23.9%	20.7%	25.7%	28.8%	30.0%	32.2%	33.1%
Wall-M	12.3%	24.3%	20.8%	26.2%	29.6%	30.9%	33.3%	34.1%
Wall-N	12.2%	24.2%	20.7%	26.1%	29.5%	30.8%	33.2%	34.1%
Wall-O	13.4%	24.7%	21.2%	26.3%	29.4%	30.6%	32.9%	33.7%
Wall-P	12.5%	23.0%	20.0%	24.9%	28.0%	29.2%	31.4%	32.2%

Figure 8: The annual energy costs for the modeled residential prototype building with Phase 2 wall retrofit assemblies.

Figures 7 and 8 depict the annual energy costs for the simulated prototype home for Phase 1 and Phase 2 walls, respectively. Broad conclusions related to the potential savings and cost-effectiveness of climate zones can be drawn. For Climate Zone 1, the average savings for all simulated retrofit options is 12%. Wall performance of this climate zone is led by Wall H, which is also the assembly with the highest effective R-value. Average cost savings continue to increase from Climate Zones 1 to 8, with Climate Zone 8 having an average savings of 31%. From a national scale, these results suggest that the most influential climates for envelope retrofits are those which are heating-dominated, i.e., Climate Zones 5 and above.

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. During the last two decades, several computer simulation tools have been developed to predict thermal and moisture conditions in buildings and the building envelope. In addition to their use as forensic tools in the investigation of building failures, these computer models are increasingly used to make recommendations for building design in various climates.

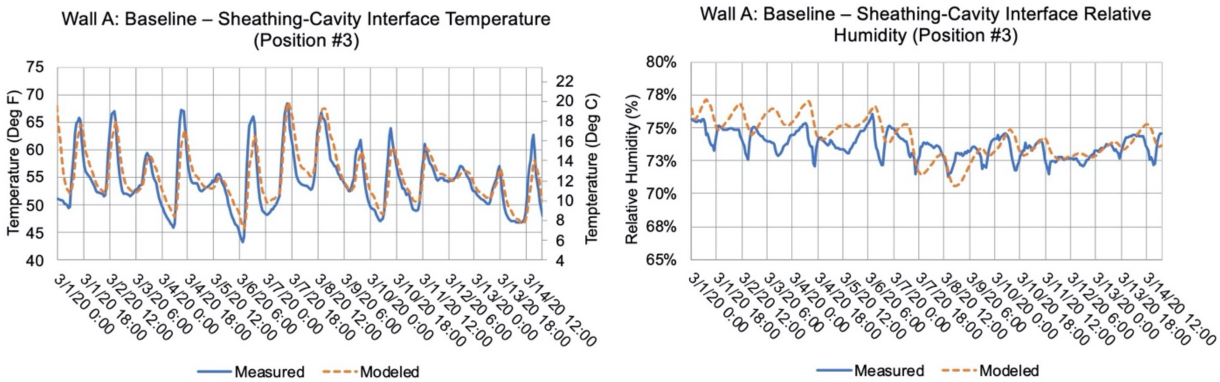
WUFI® is one of the commonly used researchers in the building industry (Antretter et al. 2011; Arena & Mantha 2013; Lepage & Lstiburek 2013; Lepage et al. 2013). WUFI® is an acronym for Wärme Und Feuchte Instationär which, translated, means heat and moisture transiency. The WUFI model is based on a state-of-the-art 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 purpose of performing the hygrothermal modeling is to verify that the proposed energy-efficiency retrofit measures do not create a durability issue. 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 are designed to naturally shed liquid water and attempt to minimize its entry. Building envelopes should also be constructed to facilitate vapor transport so that moisture doesn't accumulate within the building envelope and lead to moisture accumulation and its subsequent failure mechanisms.

Hygrothermal simulations were carried out using WUFI Pro (Version 6.4). Two types of hygrothermal modelling were undertaken for this project. First, the model outputs were compared to the field measurements to verify that the models were correctly capturing all the transport phenomena occurring in the field experiments. Once the model was validated, the model was employed to generalize the findings for other climate zones.

There were instances when certain materials used in the wall assembly constructions were not available in the model's material property database. In those instances, the thermal conductivity and water vapor permeance were measured. 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) and the vapor transmission rate was measured in accordance with ASTM E96, Standard Test Methods for Water Vapor Transmission of Materials (ASTM 2016). The material properties were compared to those in the model's materials database and modifications were made accordingly. In some cases, there were no material properties, so a new material property entry was created.

Field data from the test panels were collected over a two-month period during the winter period. Data included weather data (temperature, relative humidity, wind speed and direction, rain, and solar loads). From the test panels, temperature, relative humidity, moisture content and heat flux were measured. The data was used to validate the model for that test period. Simulations were compared to the measured values from the test panels, including south and north orientations. Figure 9 shows the simulation results compared to the measured values, temperature, and relative humidity, for wall assembly A (Phase 1). Comparisons are made where both temperature and relative humidity was measured. The simulated results are represented by probe position number, where position numbers correlate to the interface between materials in the assembly.



(a) Benchmarked material interface temperatures for Wall A.

(b) Benchmarked material interface relative humidity values for Wall A.

Figure 9: Comparison of measured relative humidity and temperature to calculated values using WUFI Pro (Version 6.4) for wall assembly A (Phase 1).

After completing the validation study, hygrothermal simulations of all wall assemblies were carried out in the eight DOE climate zones to understand the impact of the retrofit systems on moisture performance/durability. The selected cities are Fairbanks, Alaska (subarctic); International Falls Minnesota (very cold); Boston, Massachusetts (cold); Charleston, South Carolina (mixed humid); Amarillo, Texas (mixed dry); Miami, Florida (hot humid); Tucson, Arizona (hot dry); Seattle, Washington (marine).

Simulations were carried out for southern exposures in accordance with standard ANSI/ASRHAE 160-2016, Criteria for Moisture-Control Design Analysis in Buildings (ASHRAE, 2106). The initial moisture content for the assemblies was established by using the moisture content of the base case wall. Simulation of the base case was run for three years and the moisture content in the base case wall after the three-year simulation was used as the initial moisture content for the same elements in the retrofit construction. The equilibrium moisture content at 80 percent relative humidity was used for the new retrofit elements.

The mold index calculated in accordance with ASHRAE 160 was used as an indicator of moisture durability. ASHRAE 160 uses the model developed by Vitanen and Ojanen of VTT Technical Research Centre of Finland (Vitanen, 2007) to calculate a mold index for materials that make up the building envelope. The calculation is based on experimental studies of typical building materials. According to ASHRAE 160: “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).” The calculation was carried out for all the wall assemblies in all climate zones and a matrix was developed using the classification developed and illustrated in Figure 6. The mold index takes on a value between 1 and 6. In this classification scheme colors are assigned to different ranges. If the mold index is 2 or less, the assembly is given a value of green. If the value is less than 3 or greater than 2, the assembly is assigned the color yellow. Any value greater than 3 is assigned the color red.

The wall in Figure 10 shows a line running through it where the “x” marks the location where mold index calculations were carried out. The mold index is calculated on all surfaces except for weather resistive barriers. Using the VTT model in WUFI (which is the model used in ASHRAE 160), the mold index is calculated for all surfaces. The surface with the highest value is then used as the representative value for the wall assembly and a color is assigned accordingly. To compare assemblies in all climate zones a matrix is developed where the columns are assigned the climate zones and the rows represent the wall assemblies. Figure 11 is the matrix for all Phase 1 walls and Phase 2 walls are shown in Figure 12.

In most cases, all walls have building components where the mold index is less than 3 apart from the wall that contains cellulose insulation in the wall cavity with no exterior or continuous exterior insulation, wall B, Phase 1 (Figure 7). The reason for such a high mold index for this wall assembly is associated with the level of sensitivity. In this case, the cellulose insulation was treated as or assigned a classification of very sensitive. As a result, the mold index calculation was high. Cellulose insulation used today is treated with fire retardants and biocides. By raising or changing the classification from sensitive to resistant, the mold index would shift from a value greater than 3 to less than 3.

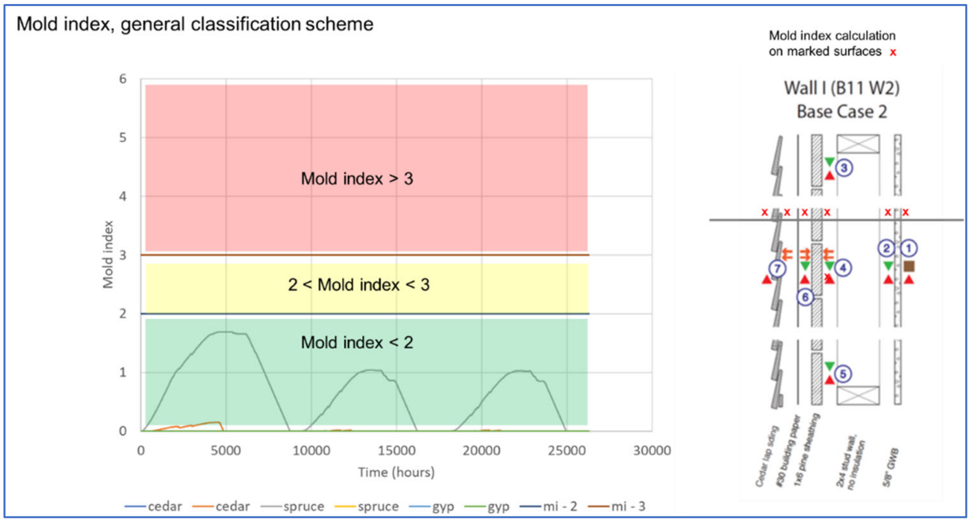


Figure 10. Classification scheme for the mold index values and the schematic of wall assembly that shows locations where the mold index calculations were carried out.

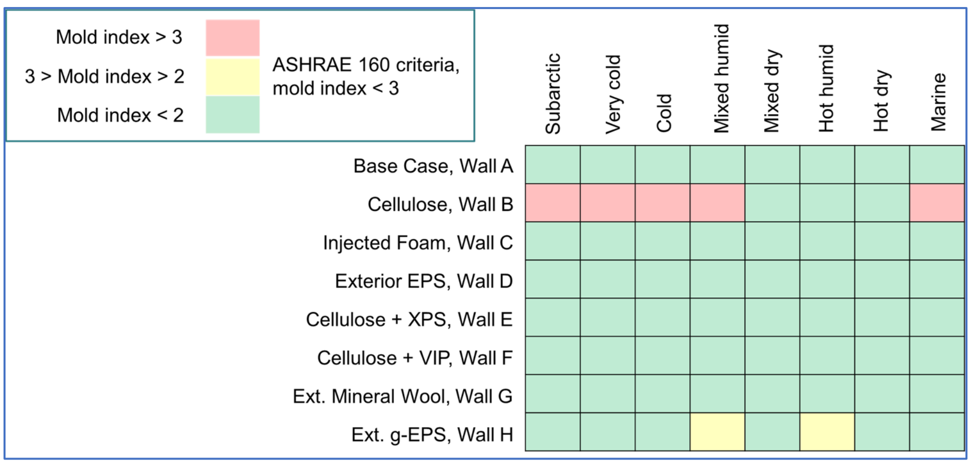


Figure 11. Mold Index measures for Phase 1 walls in all 8 DOE climate zones.

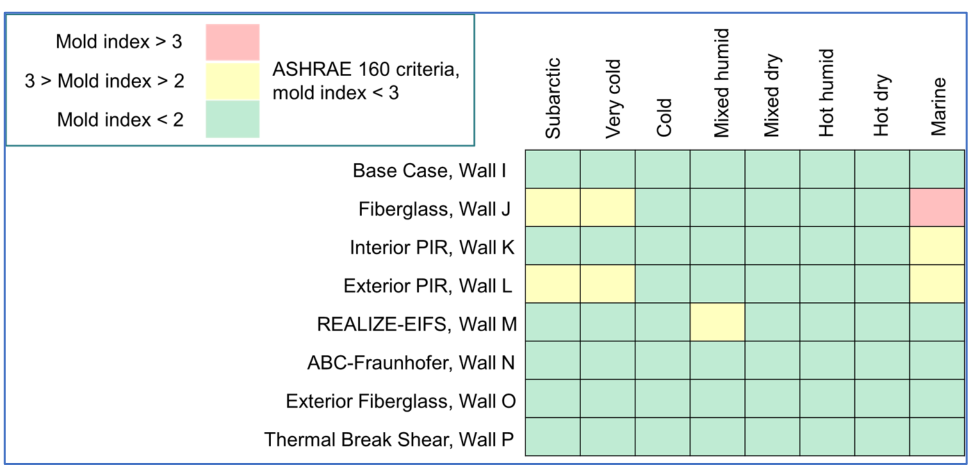


Figure 12. Mold index measures for Phase 2 walls in all 8 DOE climate zones.

Techno-Economic Assessment

A techno-economic study refers to the analysis of a technology from both a technical and economic perspective to understand the viability of new technologies and/or approaches in emerging markets. Many industries use such analyses, but depending on the application, the analysis method can vary significantly. In general, a techno-economic analysis combines process modelling and engineering design with economic evaluation for a quantitative and qualitative understanding of the financial viability of an investment (Draycott, Szadkowska, Silva, & Ingram, 2018). In the case of this current investigation, the framework for the techno-economic analysis combines the thermal/moisture modeling results, experimental results, and economic data to investigate the opportunity for a variety of residential wall retrofit approaches in the market. For this study, the techno-economic analysis is a synthesis exercise, designed to communicate overall research findings related to wall performance, cost and installation.

The economic performance of each wall included material, labor and energy costs for all materials and activities associated with the wall retrofits. Cost data were derived from a local non-profit organization that provides construction cost estimation in Portland, OR. They were chosen for this activity because of their deep ties to the local residential building industry which include workforce training and building certification programs. These activities put them regularly in the field, giving them access to many local contractors familiar with advanced building science approaches and principles. This connection was imperative to determine fair market costs associated with experimental approaches and installation techniques for materials not commonly used for exterior wall retrofits.

The method for gathering costs included breaking each wall system out into individual material layers that could be costed separately. Material and labor costs were kept separate. For each wall system, estimates for material and labor were collected from three different contractors. The three estimates were then averaged, and the wall layers were added to derive a total estimated cost. When demolition was necessary, the contractors provided an estimate which was appended to the material list. The three estimates for labor and materials were averaged and summed to produce an estimated total cost.

With experimental wall systems, we reached out directly to manufacturers to help with cost estimates. Some wall systems are highly experimental in nature and manufacturers have not yet done detailed analyses into costs. We asked the cost estimator to gather labor costs from contractors for installing these experimental materials. The labor costs for these walls represent a high-level estimate, based solely on the information provided to the contractors. It is reasonable to assume these costs will not represent a market value once the products and installation approaches are commercialized. In addition to gaining labor and material costs using a cost estimator, the RS Means Residential Cost Databook (RS Means, 2020) was used to cross-reference data gathered from the cost estimator. The RS Means regional indices were used to translate costs from Portland, Oregon to other regions throughout the country.

For each wall, a siding material was identified as the final layer of the wall system. In some cases, the treatment was a cavity-only application which did not require additional siding. There were instances where the siding was integrated with the insulation in a panelized approach to retrofits. In the cases where a new siding material was needed, the research team specified many different claddings including vinyl, fiber cement, stucco, and metal. The choice and associated cost of cladding 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 variations, the cost analysis assumed 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.

Material, labor, and energy costs are presented here in absolute dollar values for three cities, which were matched to the energy modeling analysis. The project focused on the cold climates and the cities presented here include Salem, OR (CZ 4C), Chicago, IL (CZ 5A) and Burlington, VT (CZ 6A). In addition to labor, materials and energy costs, simple payback and internal rate of return were calculated to assess the viability of the initial investment.

Total costs for labor and materials in the three selected climate zones are presented in Table 1. Note the location quotient for Salem, OR and Chicago, IL are the same per RS Means, so only the energy savings cost data varies in these areas. Table 2 presents the internal rate of return (IRR) and simple payback for each wall system in Salem, OR, Chicago, IL and Burlington, VT. The internal rate of return is the annual rate of growth that an investment is expected to generate. Payback is presented in years, and IRR is presented in percentage. Walls with high payback and negative IRR are not cost-effective. Walls perform similarly in each ranking exercise, with the lowest-cost walls paying back in the shortest amount to time, considering energy savings.

Table 1. Material, labor, and total costs for each wall studied for Salem OR, Chicago IL, and Burlington VT.

Title	Wall Description	Salem, OR & Chicago IL (USD)			Burlington, VT (USD)			Rank (least to most expensive)
		Material Cost	Labor Cost	Total Cost	Material Cost	Labor Cost	Total Cost	
Wall B	Drill-and-Fill (Cellulose)	867	1,423	2,289	875	1,437	2,312	1
Wall C	Minimally Invasive Cavity Spray Foam	9,000	2,134	11,134	9,090	2,155	11,245	4
Wall D	Exterior Expanded Polystyrene Foam, siding remains	16,780	35,772	52,552	16,948	36,130	53,078	11
Wall E	Drill-and-Fill (Cellulose), Exterior XPS, siding removed	8,814	27,878	36,692	8,902	28,156	37,059	9
Wall F	Drill-and-Fill (Cellulose), Exterior VIP/Vinyl Siding, siding removed	6,492	17,116	23,608	6,557	17,287	23,844	5
Wall G	Exterior mineral fiber board, siding remains	15,027	34,629	49,657	15,178	34,976	50,153	10
Wall H	Exterior Structural graphite impregnated EPS (gEPS) Panel (siding remains)	16,758	44,931	61,690	16,926	45,381	62,306	12
Wall J	Drill and Fill (Fiberglass)	867	5,110	5,976	875	5,161	6,036	3
Wall K	Interior Polyiso Insulation w/ Fiberglass Batt	1,729	3,619	5,349	1,747	3,655	5,402	2
Wall L	Drill & Fill (Fiberglass) w/ Exterior Polyiso Insulation (siding removed)	5,043	22,446	27,489	5,093	22,671	27,764	6
Wall M	EIFS Panel (siding removed)	110,000	46,678	156,678	111,100	47,144	158,244	14
Wall N	Prefabricated EPS Blocks	49,082	21,270	70,352	49,573	21,483	71,055	13
Wall O	Drill & Fill (Fiberglass) w/ Exterior Fiberglass Board Insulation	10,080	24,064	34,143	10,180	24,304	34,485	7
Wall P	Thermal Break Shear Wall (siding and sheathing removed)	7,337	27,512	34,849	7,410	27,787	35,198	8

Table 2. Internal rate of return (IRR) and payback period for every wall system in Salem, OR, Chicago, IL, and Burlington, VT.

Title	Wall Description	Salem, OR		Chicago, IL		Burlington, VT		Rank (lowest payback to highest)
		IRR	Payback (years)	IRR	Payback (years)	IRR	Payback (years)	
Wall B	Drill-and-Fill (Cellulose)	29%	3	92%	1	80%	1	1
Wall C	Minimally Invasive Cavity Spray Foam	5%	15	5%	15	18%	6	4
Wall D	Exterior Expanded Polystyrene Foam, siding remains	-3%	50	2%	22	2%	22	11
Wall E	Drill-and-Fill (Cellulose), Exterior XPS, siding removed	-1%	35	5%	15	5%	15	7
Wall F	Drill-and-Fill (Cellulose), Exterior VIP/Vinyl Siding, siding removed	2%	22	10%	10	10%	10	5
Wall G	Exterior mineral fiber board, siding remains	-3%	47	3%	20	3%	21	10
Wall H	Exterior Structural graphite impregnated EPS (gEPS) Panel (siding remains)	-4%	57	-2%	42	-1%	33	12
Wall J	Drill and Fill (Fiberglass)	12%	6	17%	6	22%	5	3
Wall K	Interior Polyiso Insulation w/ Fiberglass Batt	13%	7	18%	6	23%	4	2
Wall L	Drill & Fill (Fiberglass) w/ Exterior Polyiso Insulation (siding removed)	1%	27	3%	19	5%	15	6
Wall M	EIFS Panel (siding removed)	-8%	107	-7%	107	-6%	84	14
Wall N	Prefabricated EPS Blocks	-5%	67	-3%	48	-1%	38	13
Wall O	Drill & Fill (Fiberglass) w/ Exterior Fiberglass Board Insulation	-1%	32	2%	24	3%	18	8
Wall P	Thermal Break Shear Wall (siding and sheathing removed)	-1%	35	1%	25	3%	20	9

Conclusions

This paper provides an overview of a three-year, multipart study into the viability of multiple retrofit approaches for residential wall systems, conducted in partnership by the Oak Ridge National Laboratory, the Pacific NW National Laboratory, and the University of Minnesota. The study focused on the thermal, moisture and economic performance of fourteen wall assemblies (cavity fill, interior and exterior approaches with/without removing existing siding) that included traditional and experimental approaches, using a typical uninsulated residential wall as a baseline.

A prototype of each wall retrofit was instrumented and installed on a test facility at the University of Minnesota's Cloquet Residential Research Facility for physical testing. Data compiled during the *in-situ* testing was then compared to energy and moisture modeling. Once validated, the hygrothermal models were employed to generalize the findings to multiple climate zones. Along with the physical performance of each wall, researchers worked with a local cost estimator to gather material and cost data to assess the techno-economic viability of the wall systems.

Wall retrofits have the potential to affect energy savings of variable magnitude across the many different climate zones of the United States. The energy savings of the different retrofit wall assemblies were explored via a prototype single-family home energy model benchmarked with the experimental data. It was found that the climate zones with the highest potential for retrofit savings are those which are heating-dominated, i.e., Climate Zones 5 and above. In these climate zones, whole-home energy savings associated to space conditioning ranging from 18% to 34% were realized for the simulated retrofit wall assemblies.

It was also observed that increasingly high-R insulation improvements had a diminishing effect on wall conduction performance improvements. The highest potential for energy savings can be realized by going from an uninsulated wall to a wall with cavity or continuous insulation, as opposed to a cavity insulated wall being retrofitted to have both cavity and continuous insulation.

To determine if the walls are moisture durable, hygrothermal simulations were carried out using WUFI Pro (Version 6.4). These simulations of all of the retrofit wall assemblies were carried out in the eight DOE climate zones to understand the impact of the retrofit systems on moisture performance/durability. Simulations were carried out for southern exposures. The mold index measured in accordance with ASHRAE 160 was used as an indicator of moisture durability.

All retrofit walls have mold indices less except Wall B (Drill & Fill Cellulose). The reason for a high mold index for this retrofit wall assembly is associated with the level of mold sensitivity. is case, the cellulose insulation was treated as or assigned a mold classification of very sensitive. As a result, the mold index calculation was high. Cellulose insulation used today is typically treated with fire retardants and biocides which could impact its mold sensitivity. By raising or changing the mold classification from sensitive to resistant, the mold index for Wall B would be less than 3. In general, the addition of exterior continuous insulation, especially with moisture tolerant materials, is expected to improve the hygrothermal performance of the wall assembly by pushing the point of condensation or dew point to the exterior side of the exterior sheathing. As a result, in the absence of leaks behind the insulation layer or between the insulation layer and sheathing, the hygrothermal performance of the wall is very good, or there is little or no risk of moisture durability problems.

For Chicago IL, total costs for labor and materials to retrofit a 2,500 square foot home ranged from $2,289 for Wall B (Drill & Fill Cellulose) to $156,678 for Wall M (EIFS Panel with the siding removed). From a material only perspective, the costs ranged from $867 (Wall B, Drill & Fill Cellulose) to $110,000 (Wall M, EIFS Panel with the siding removed). With respect to the labor costs, Wall B (Drill & Fill Cellulose) was the least expensive at $1423 while Wall M (EIFS Panel with the siding removed) topped the labor costs at $46,678. Not surprisingly, Wall B (Drill & Fill Cellulose) showed the highest internal rate of return at 92% and the shortest payback at 1 year. Wall M (EIFS Panel with the siding removed) showed the lowest internal rate of return at -7% and the shortest payback at 107 years.

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