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

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ABSTRACT

The Oak Ridge National Laboratory, Pacific Northwest National Laboratory, and the University of Minnesota have been conducting a three-year study of residential retrofit wall systems. The researchers have identified, tested, and verified the hygrothermal performance of 16 wall assemblies in retrofit applications. The approach to this study includes a comprehensive literature review, the involvement of an advisory group 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 presentation summarizes the findings of this research project and is intended to guide architects and designers on how to retrofit existing wall assemblies without creating durability issues.

SPEAKER

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André Desjarlais is the program manager for the Residential Buildings Integration Program at the Oak Ridge National Laboratory and has been involved in building enclosure research for 48 years. His areas of expertise include building enclosure energy efficiency, moisture control, and durability. Desjarlais has been a member of ASTM International since 1987, is the past chair of ASTM Committee C16, and was awarded the title of ASTM Fellow in 2011. He has been a member of ASHRAE since 1991 and is past chair of ASHRAE Technical Committee 4.4 on Thermal Insulation and Building Systems. Desjarlais is also a founding director of the RCI-IIBEC Foundation.

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

In the United States, 39% of total energy is consumed by the building sector, and 20% of that total is attributed to residential buildings.[1] Newly constructed houses built to meet modern energy codes incorporate a combination of tight, well-insulated building enclosure components, high-performing windows, controlled mechanical ventilation, and other efficient components that deliver comfort, adequate airflow, and moisture control in addition to significantly lower energy consumption than ever before.

Older houses (those built before 1992 when the U.S. Department of Energy [DOE] Building Energy Codes Program was established) represent approximately 68% of the U.S. residential building stock,[2,3] and these structures often have significant air leakage and inadequate insulation. In residences with little to no air sealing or insulation, heating and cooling losses can represent a substantial portion of utility bills.

The residential remodeling market continues to grow, amounting to $424 billion in 2017 (up 50% from 2010). In 2017, approximately 50% of home improvement projects included upgrades to mechanical and enclosure systems in aging housing stock (made up of approximately 93% wood-framed walls, 5% masonry, and 2% steel framing).[4] These upgrades include replacement of windows and doors; siding and roofing; heating, ventilation, and air-conditioning (HVAC) systems; and insulation. Approximately one in five homeowners have invested in energy efficiency retrofits.[4] Even so, the number of existing residential buildings with little to no insulation is staggering. An estimated 34.5 million houses with wood studs have no wall insulation,[5] representing approximately 38% of existing single-family detached houses in the United States. Similarly, 71% of existing houses have air leakage rates of 10 or more air changes per hour at 1.04 lb/ft^2 (50 Pa) of pressure, indicating a significant amount of air leakage through the building enclosure.[4]

There is a significant need for cost-effective methods of increasing wall insulation and reducing air infiltration for existing houses. In current practice, wall retrofits seldom include the air, moisture, and vapor controls that are considered best practices for high-performance new home construction, and the lack of such controls could potentially create problems that put the building materials or occupants at risk. Well-tested and documented retrofit wall systems can help save substantial amounts of energy 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 building's thermal enclosure, help manage indoor environmental pollutants, improve the building's aesthetics, and increase homeowner comfort.

> Done correctly, deep energy retrofits can significantly improve the energy and air-barrier performance of a building's thermal enclosure, help manage indoor environmental pollutants, improve the building's aesthetics, and increase homeowner comfort.

This paper describes a three-year DOE-funded project to identify high-performing wall retrofit systems and provide a real-world context for their thermal, moisture, and economic performance that can aid decision makers in balancing various goals for DERs.

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 April 19, 2019, in Arlington, Va., with 33 experts in attendance. A report summarizing this meeting was published.[6]

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

The literature review[7] was conducted and published in June 2019. It 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 houses, focusing on retrofit applications to the exterior side of a wall assembly. Given that the vast majority of

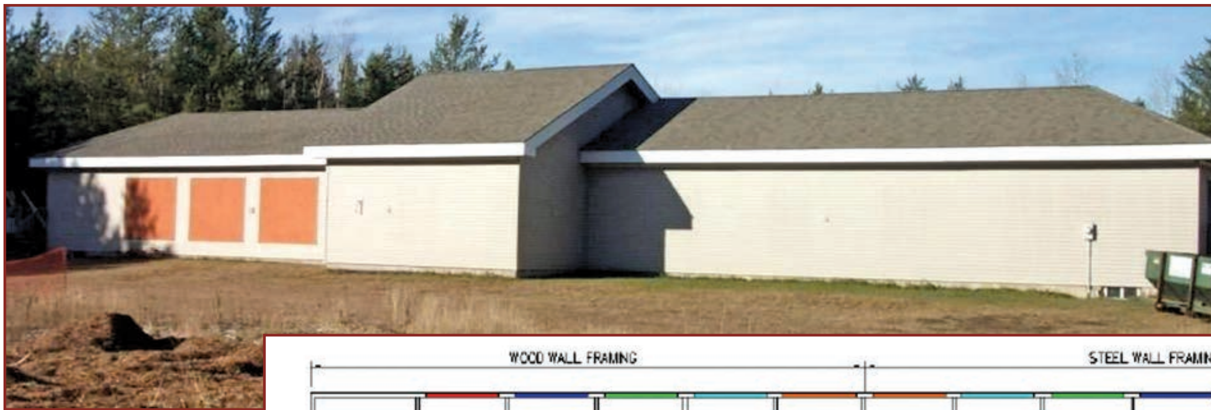


Figure 1. Cloquet Residential Research Facility was used for the in situ testing of retrofit wall assemblies.

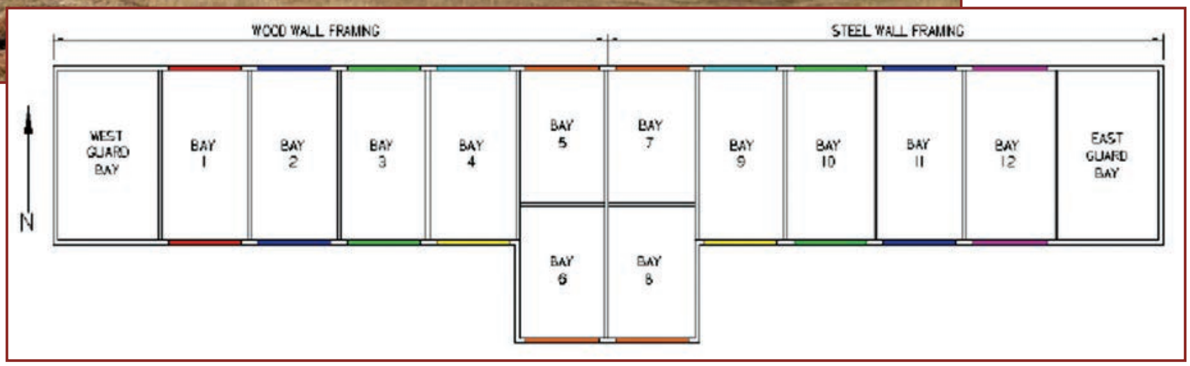


Figure 2. Floor plan of the Cloquet Residential Research Facility.

residential wall systems in the U.S. are wood framing, the report focused on this construction practice.

In addition to investigating wall assemblies, the literature review explores various innovative insulation materials and provides background for a techno-economic analysis, and the use of such analyses in building construction. A review of literature on the modeling and simulation of hygrothermal wall assembly performance is also presented, and references and links for a variety of sources of relevant information are included.

FIELD TESTING

Test Facility and Test Panels

The experimental portion of this project was carried out by the University of Minnesota at the Cloquet Residential Research Facility (CRRF), which is located on the Cloquet Forestry Center near Cloquet, Minn., approximately 20 miles (32 km) west of Duluth and in DOE Climate Zone 7. The CRRF building (**Fig. 1** and **2**) is elongated along an east-west axis to maximize the northern and southern exposures. It sits on a full basement with 12 independent above-grade test bays protected by two end-guard bays. The eight test bays that have both north and south exposures (Bays 1 to 4 and 9 to 12) were selected to conduct in situ testing for this project.

Baseline Test Panels

Two series of in situ experiments were conducted during this three-year project. The first series of test walls (Phase 1), which 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 evaluated for two winter periods. After studying the results of these first tests, the research team proposed a second series of wall assemblies (Phase 2) 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-facing and a south-facing wall opening. These openings are approximately 8 ft (2.4 m) wide and 7 ft (2.1 m) high, and for this project, they were divided in half to support two different test panels. Each test panel was mirrored on both the north and south orientations so eight pairs of wall assemblies were studied during each phase.

The test panels are approximately 4 ft (1.2 m) wide by 7 ft (2.1 m) high. Each test panel was divided into three wall cavities at approximately 16 in. (0.4 m) on center (oc) to represent older wood-frame construction. The center cavity of each test panel was a true 16 in. (0.4 m) 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.

To assess the impact of wall retrofits, a baseline wall assembly was designed and used as the starting point for each wall assembly and 16 identical test walls were constructed for each phase. The baseline test walls were constructed of 2 × 4 in. (51 × 102 mm) spruce, pine, or fir wood studs with 1 × 6 in. (25 × 152 mm) pine board exterior sheathing. The pine sheathing was loosely fit to reflect older construction. The sheathing was covered with a heavy no. 30 building paper lapped and stapled to the sheathing followed by 8 in. (203 mm) cedar lap siding finished with an oil-based primer, vapor-retarder primer, and 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 ⅝-in.-thick (16-mm-thick) gypsum board with a vapor-retarder primer was added. The interior finish was selected to represent an older house with heavy drywall or plaster and several coats of paint. The south-facing baseline walls from Phase 2 are shown in **Fig. 3**. Team members familiar with construction practices in the local climates indicated that vapor retarders were not historically included in construction practices for the time period that was being considered for initial constructions. Since the majority of retrofits were to be performed on the exterior side of the wall assembly, access to the interior side of the cavity was unavailable and therefore vapor retarders were not included in most of the retrofits.

Figure 3. Exterior view of baseline walls depicting cedar siding before wall retrofits.

Instrumentation

Depending on the specific construction, each test cavity had between 15 and 20 sensors installed. Sensors for 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, temperature sensors were installed on the interior and exterior surfaces of the drywall, the interior and exterior surfaces of the sheathing, and the exterior surface of the siding. Relative humidity sensors were placed on the cavity-side surface of the drywall and 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. **Figure 4** presents a schematic of a typical instrumentation array.

The data acquisition system for this experiment was based on the Campbell Scientific CR-1000X data logger. The centrally located logger collected data from modules located in each test bay. The data acquisition system 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 data 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 exposures. Data were continuously collected throughout the winter periods. These data were used to validate both thermal and hygrothermal models as described in the following.

Wall Retrofits

Over the course of the three-year project, 16 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.

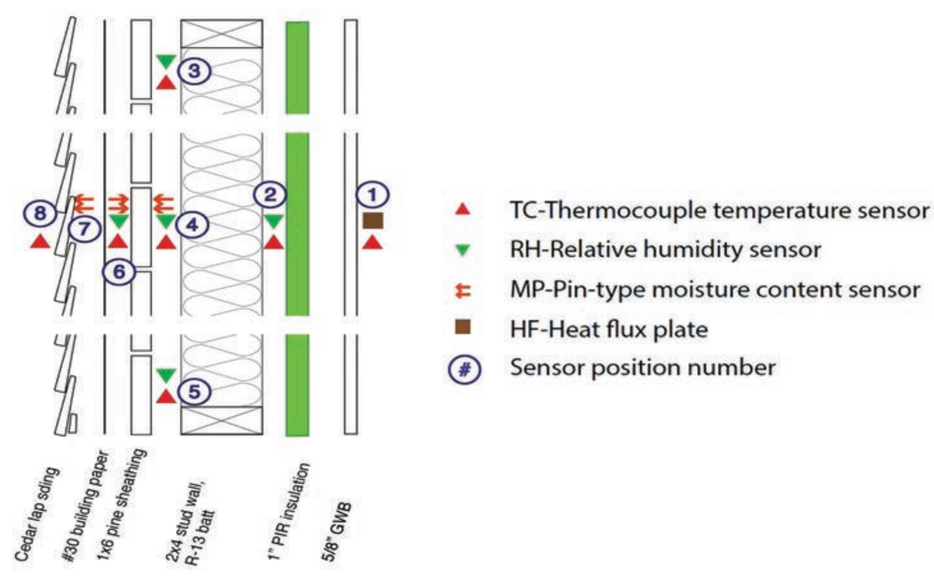


Figure 4. Typical layout of instrumentation in test panels.

Wall A: Base Case Wall #1

Wall A is the baseline wall without any retrofit treatment.

Wall B: Drill and Fill (Cellulose)

For Wall B, the siding was removed in two locations just below the midpoint 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 lb/ft^3 (56 to 64 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. The foam manufacturer's representatives managed all formulation and installation techniques, including the injection of the proprietary closed-cell polyurethane liquid foam through very small holes in the drywall. Infrared imaging was used to ensure the cavities were completely filled, and the holes in the drywall were sealed with the spray foam.

Wall D: Exterior Expanded Polystyrene Foam Panel (Siding Remains)

This wall treatment used a commercially available expanded polystyrene (EPS) insulation product that includes built-in drainage capabilities and an embedded structural ladder for attachment. A low-density fiberglass board was installed over the existing siding to remove the air channels that would be created between the existing lapped siding and the rigid EPS panel. 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-in.-thick [51- and 64-mm-thick]) 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 and Fill (Cellulose) with Exterior Extruded Polystyrene (Siding Removed)

For Wall E, dense-pack cellulose was installed as described for 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. Also, 2 in. (51 mm) of extruded polystyrene foam (XPS) were held in place, and 1 × 4 in. (25 ×102 mm) furring strips were fastened to the framing through the insulation layer with washer head screws. A ¾-in.-thick (19-mm-thick) XPS layer was placed between the furring strips to support the vinyl siding cladding that was attached to the furring strips.

Wall F: Drill and Fill (Cellulose) with Exterior Vacuum Insulation Panel/Vinyl Siding (Siding Removed)

For Wall F, dense-pack cellulose was installed as described for 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 vacuum insulation panel/vinyl siding composite panel was installed to the exterior sheathing.

Wall G: Exterior Mineral Fiberboard (Siding Remains)

For Wall G, a vapor-permeable liquid-applied membrane was applied over the existing lapped siding to provide a more robust water-control layer. A 2-in.-thick (51-mm-thick) mineral wool panel was held in place, while a second 2-in-thick mineral wool layer was installed with staggered joints. Also, 1 × 4 in. (25 × 102 mm) furring strips were installed with washer head screws. A semirigid fiberglass board was installed between the furring strips to act as an insect screen that allows drainage and drying, and fiber-cement siding was fastened to the furring strips.

Wall H: Exterior Structural Graphite-Impregnated EPS Panel (Siding Remains)

For Wall H, 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 in. (38 mm) structural oriented strand board (OSB) sheet was fastened with screws to the wall framing and covered with a fully adhered peel-and-stick membrane. Two layers of 2⅛-in.-thick (54-mm-thick) graphite-impregnated EPS were installed using a limited number of cap nails, and 1 × 4 in. (25 ×102 mm) furring strips were installed with washer head screws. A semirigid fiberglass board was installed between the furring strips to act as an insect screen that allows drainage and drying, and both fiber-cement siding and a metal panel siding were fastened to the furring strips. This wall treatment was envisioned to be an off-site fabricated panel, but for this study, it was installed in layers onto the existing wall.

Wall I: Base Case Wall #2

Wall I is a baseline wall without any retrofit treatment, identical to Wall A.

Wall J: Drill-and-Fill (Fiberglass)

For Wall J, the siding was removed in one location just below the midpoint and near the middle of the cavities, and holes were drilled through the building paper and sheathing. The fiberglass was installed by a certified contractor with a target density of 1.5 lb/ft^3 (24 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 with Fiberglass Batt

For Wall K, the drywall was removed and an unfaced fiberglass batt with an *R*-value of 13 (RSI 2.3) was carefully installed in the existing cavity. A 1-in.-thick (25-mm-thick) foil-faced polyisocyanurate foam board was installed over the studs. The drywall was reinstalled, and a sealant was used to ensure airtightness.

Wall L: Drill and Fill (Fiberglass) with Exterior Polyiso Insulation (Siding Removed)

For this wall, fiberglass was installed as described for 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-in.-thick (25-mm-thick) foil-faced polyisocyanurate foam board was installed with 1 × 4 in. (25 × 102 mm) furring strips fastened to the framing with washer head screws. A prefinished lap wood composite siding was fastened to the furring strips.

Wall M: Exterior Insulation and Finish System Panel (siding removed)

This treatment used a 6-in.-thick (152-mm-thick) piece of EPS foam finished on all six sides with a stucco material and was 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 exterior insulation and finish system (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 Polyurethane Blocks

For this prefabricated wall treatment, a housewrap was installed over the existing siding to serve as a new air- and backup 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 polyurethane foam block, which was mechanically attached. Subsequent blocks engage the block below with a large tongue-and-groove shape in the foam extrusion.

Wall O: Drill and Fill (Fiberglass) with Exterior Fiberglass Board Insulation

This wall treatment uses fiberglass installed as described for Wall J. The siding was repaired, but touch-up was not required, and a sheet of housewrap was draped from the top of the panel. Two-inch-thick (51-mm-thick) semirigid fiberglass boards were installed and held in place with 1 × 4 in. (25 × 102 mm) 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)

For Wall P, the existing siding, building paper, and sheathing were removed and an unfaced fiberglass batt with an *R*-value of 13 (RSI 2.3) was installed in the existing cavity, followed by a 1-in.-thick (25-mm-thick) XPS board installed over the studs. A ¾-in.-thick (19-mm-thick) OSB sheet was installed over the XPS and fastened securely to the studs with 4-in.-long (102-mm-long) screws. A housewrap was installed, followed by a typical installation of vinyl siding.

ENERGY MODELING

Energy modeling have been used in many studies to evaluate enclosure performance.[8] Laboratory and field evaluations of building enclosure performance are expensive. In the past decade, modeling software programs for building energy and enclosure performance have become more robust, and the value of findings from these programs is 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 houses after the 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 involving indoor space, outdoor environment conditions, HVAC, lighting, service water heating, other appliances and equipment, and occupancy behavior. In such analyses, the energy flow through enclosure elements such as the walls, roof, and windows is treated as one dimensional, 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 research and development 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 DOE's Building Energy Codes Program has used residential prototype buildings to evaluate the energy and economic performance of residential energy codes, and to develop proposed code changes.[9] However, the prototypes represent the new construction stock and minimal compliance with the residential prescriptive and mandatory requirements of the 2018 *International Energy Conservation Code* (IECC).[10] Thus, these prototype models were modified to represent the existing building stock, and the inputs for these modifications were taken from the National Renewable Energy Laboratory's ResStock database (a large-scale housing stock database developed by combining public and private data sources, statistical sampling, and detailed building simulations).[11,12]

The baseline house was created for this study with modifications using the ResStock data to better represent the existing building stock. Based on US Census Bureau data,[3] the baseline house is a single-family, two-story house with a gross floor area of 2400 ft^2 (223 m^2) with a slab-on-grade foundation type and either an electric resistance or gas-furnace heating system type. Details about the model can be found in the technical support document by Mendon, Lucas, and Goel.[13]

Based on ResStock data, a baseline energy model was constructed with the following assumptions:

1. The uninsulated walls were framed with wood 2 × 4s at 16 in. (0.4 m) oc, and the insulated, vented ceilings had *R*-value 30 (RSI-5.3) insulation
2. Natural gas heating system with an efficiency of 80% annual fuel utilization efficiency, and a cooling system with an efficiency of seasonal energy efficiency ratio of 10
3. Ducting inside of the conditioned space, eliminating the need for duct leakage modeling
4. Standard electric water heater 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 (6.92 W/m^2•K) and a solar heat gain coefficient (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 house infiltration rates of 15 air changes per hour at 1.04 lb/ft^2 (50 Pa) of pressure for the baseline house

The baseline house was modified to create a set of models representing each of the climate zones as defined by the IECC. Each baseline model was then simulated with all 14 wall retrofit options using EnergyPlus

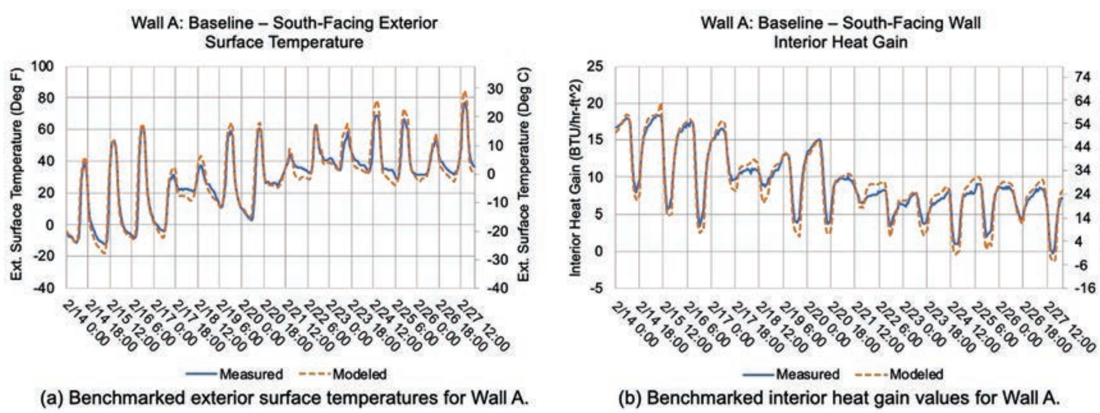


Figure 5. Energy modeling outputs compared with measured experimental data for Wall A.

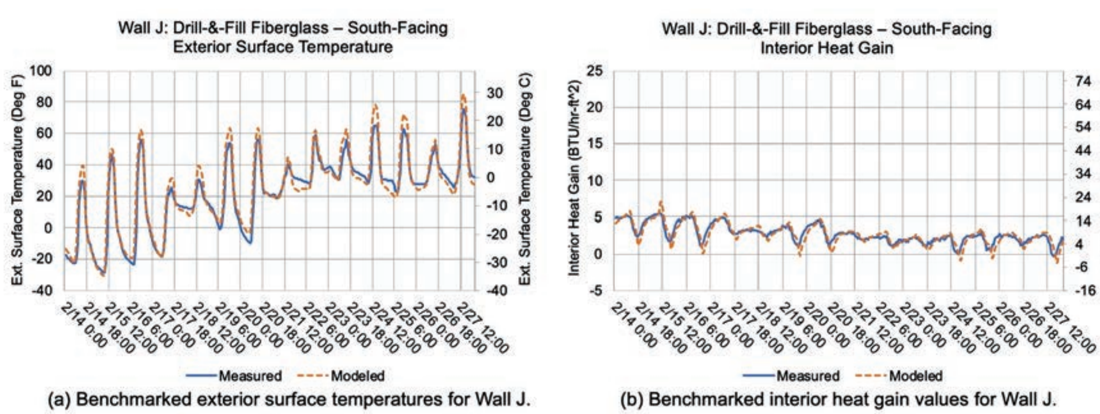
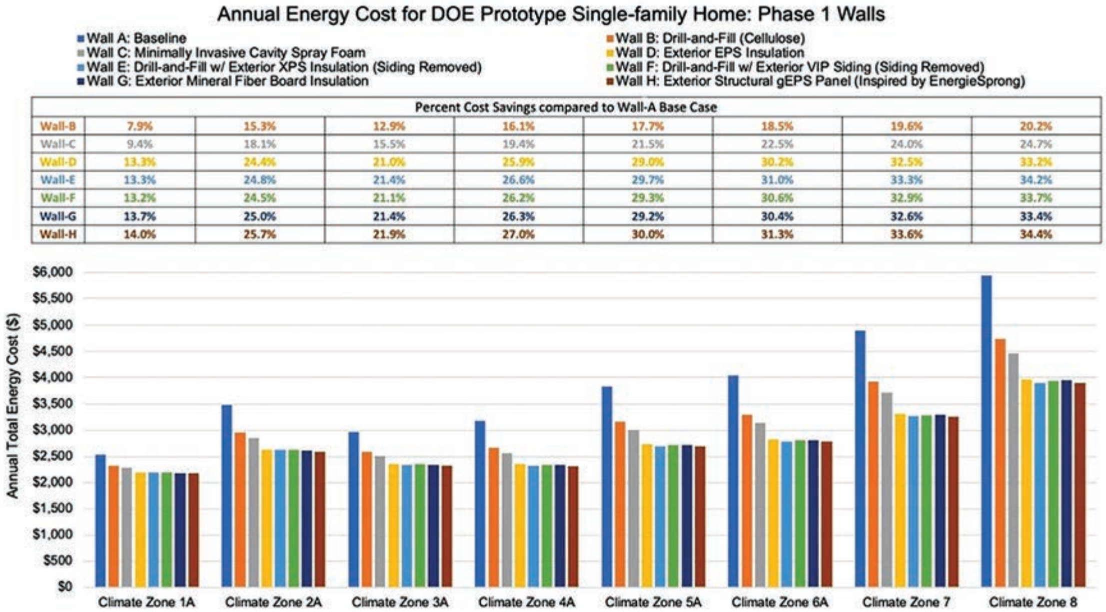
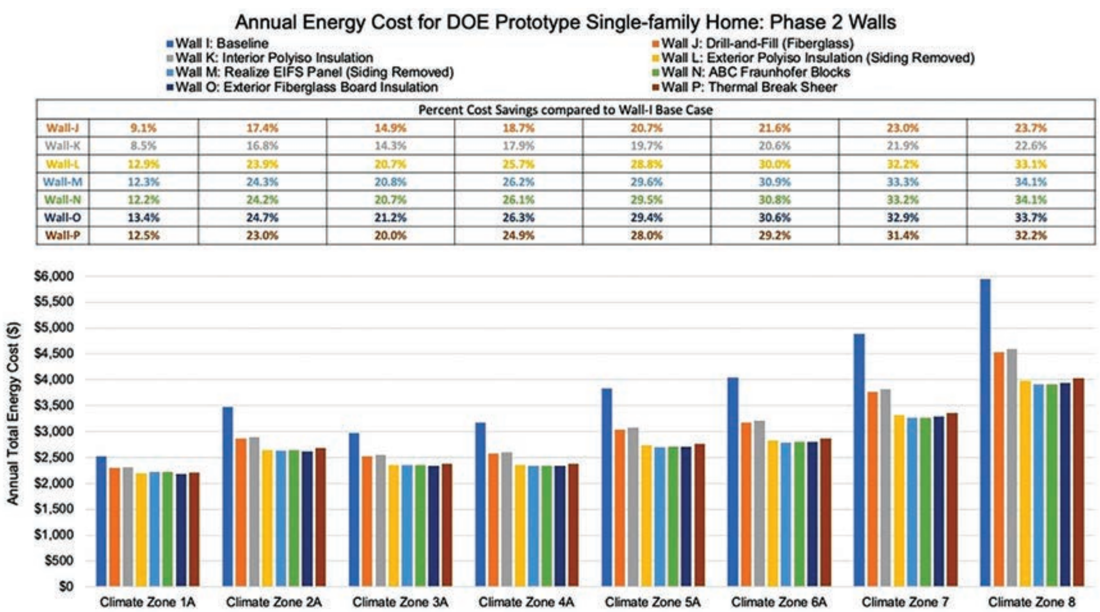


Figure 6. Energy modeling outputs compared with measured experimental data for Wall J.



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 retrofitted 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 retrofitted assemblies.

Version 8.6. However, because EnergyPlus uses a simplified one-dimensional calculation approach for conduction heat transfer through the building enclosure, the research team applied THERM,[14] a two-dimensional conduction heat-transfer analysis program developed by Lawrence Berkeley National Laboratory, to capture the multidimensional effects of thermal bridging. A THERM model was developed for each wall section using the as-built layout and thermal properties of the wall assemblies, and overall section U-values were obtained from THERM and applied to the respective EnergyPlus models.

To use 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' enclosure calculations, multiple energy models were constructed, each representing a residential building containing the candidate retrofit wall assemblies. These energy models were run using 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.

Figures 5 and 6 present benchmarking plot examples. In Fig. 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 data set, the root mean square error values are 4.7°F (2.6°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 are depicted in Fig. 6 for Wall J, the dense-packed fiberglass drill-and-fill wall.

Although 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 for the climate in which the experiment was conducted. Therefore, to improve understanding of the energy-saving potential of these candidate retrofit assemblies, researchers also performed simulations on the assemblies for the following cities selected from the IECC 2015 climate zones to represent a diverse set of climates: Miami, Fla. (Climate Zone 1); Houston, Tex. (Climate Zone 2); Memphis, Tenn. (Climate Zone 3); Baltimore, Md. (Climate Zone 4); Chicago, Ill. (Climate Zone 5); Burlington, Vt. (Climate Zone 6); Duluth, Minn. (Climate Zone 7); and Fairbanks, Alaska (Climate Zone 8). National energy prices were also assumed for this analysis. Energy cost values of $0.1013/kWh and $1.00/Therm were applied nationally for electricity and heating fuel, respectively.

Figures 7 and 8 depict the annual energy costs for the simulated prototype house 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 for 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 enclosure retrofits are those that are heating dominated (Climate Zones 5 through 8).

HYGROTHERMAL MODELING

Hygrothermal modeling is used to evaluate the condensation potential, moisture content, and drying capacity of the assembly, as well as the potential for mold growth and freezing-and-thawing damage. During the last two decades, several computer simulation tools have been developed to predict thermal and moisture conditions in buildings and the building enclosure. 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 modeling is a commonly used research tool in the building industry.[15-18] WUFI is an acronym for the German phrase *Wärme Und Feuchte Instationär*, which 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.

Hygrothermal modeling is used 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 enclosures are designed to naturally shed liquid water and attempt to minimize its entry into the building structure. Building enclosures should also be constructed to facilitate vapor transport so that moisture does not accumulate within the building enclosure 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 modeling were undertaken for this project. First, the model outputs were compared with 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, it was employed to generalize the findings for other climate zones.

In instances where certain materials used in the wall assembly constructions were not available in the model's material property database, the thermal conductivity and water vapor permeance were measured in accordance with, respectively, ASTM C518, *Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus*,[19] and ASTM E96, *Standard Test Methods for Water Vapor Transmission of Materials*.[20] 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 two months during the winter period. Data included weather data (temperature, relative humidity, wind speed and direction, rainfall, and solar loads). From the test panels, temperature, relative humidity, moisture content, and heat flux were measured. The data were used to validate the model for that test period. Simulations were compared to the measured values from the test panels, including both south and north orientations. **Figure 9** shows the simulation results compared with the measured values for temperature and relative humidity for wall assembly A (Phase 1). Comparisons are made in locations where both temperature and relative humidity were measured.

After the validation study was completed, hygrothermal simulations of all wall assemblies were carried out in the eight DOE climate

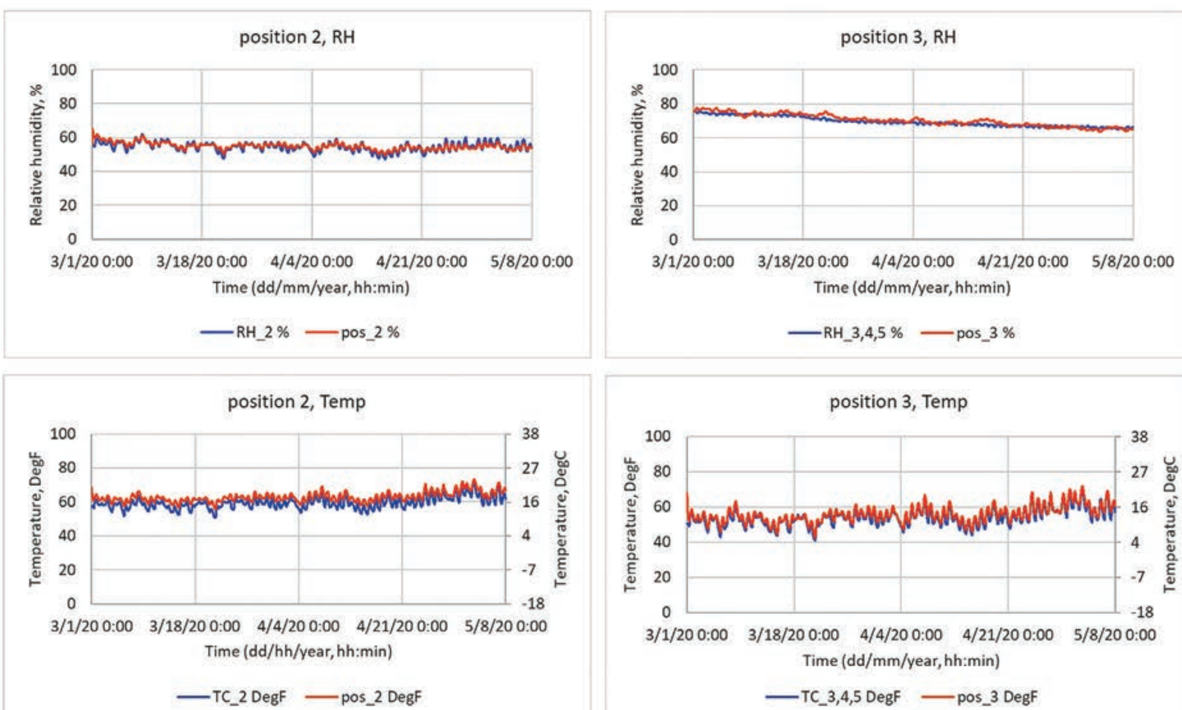


Figure 9. Comparison of measured relative humidity and temperature with calculated values using WUFI Pro (version 6.4) for Wall A (Phase 1). The simulated results are represented by pos_#, where # represents the probe position for temperature and relative humidity in the wall assembly. The measured temperature and relative humidity are represented by TC_# and RH_#, respectively, where # represents the probe position in the wall assembly.

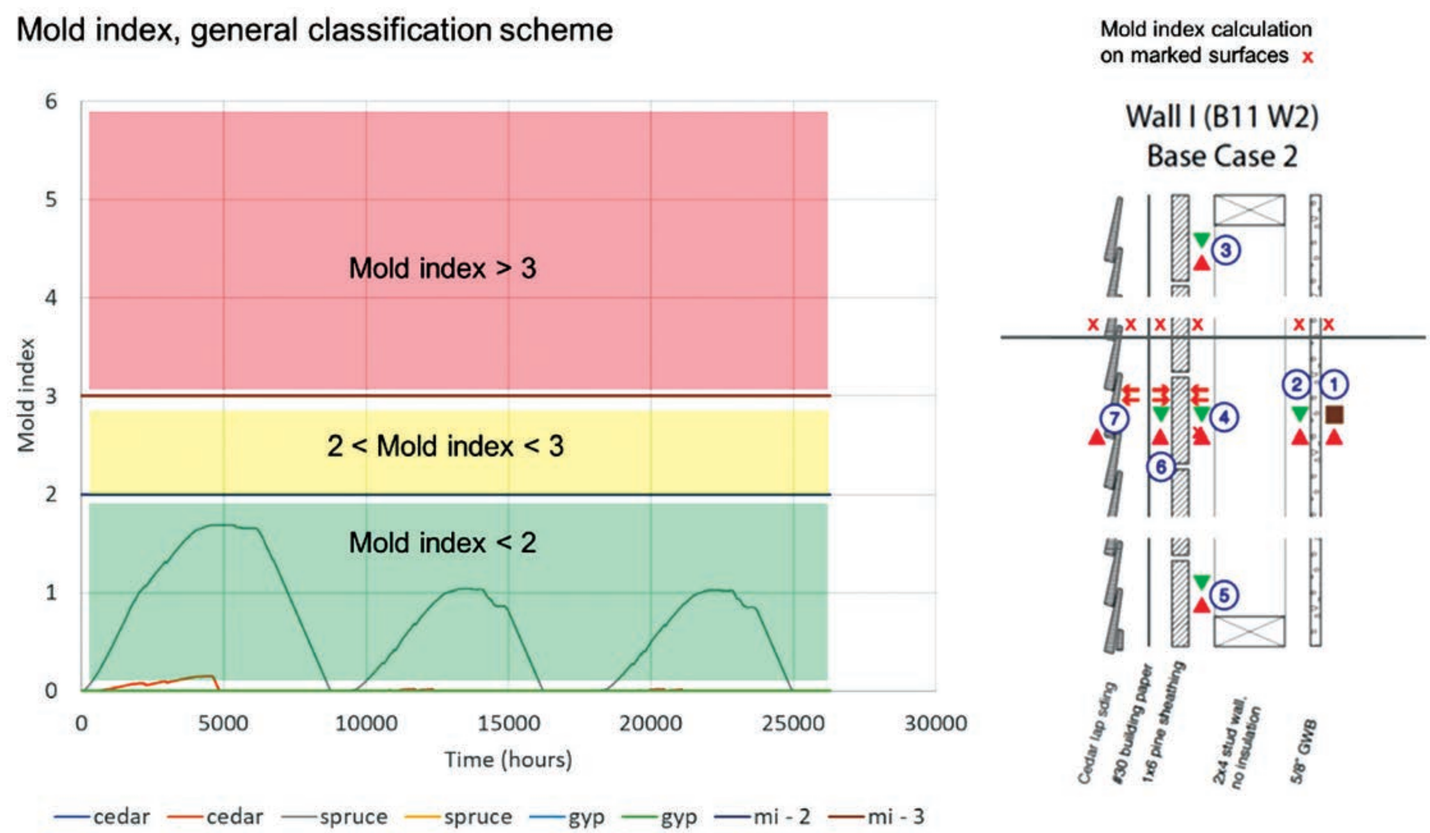


Figure 10. Classification scheme for the mold index values (left), and a wall assembly schematic showing locations where the mold index calculations were carried out (right).

zones to understand the impact of the retrofit systems on moisture performance/durability. The selected cities are Fairbanks, Alaska (subarctic); International Falls, Minn. (very cold); Boston, Mass. (cold); Charleston, S.C. (mixed humid); Amarillo, Tex. (mixed dry); Miami, Fla. (hot humid); Tucson, Ariz. (hot dry); and Seattle, Wash. (marine).

Simulations were carried out for northern exposures in accordance with ANSI/ASRHAE 160-2016, *Criteria for Moisture-Control Design Analysis in Buildings.*[21] The northern exposure was used because it represents the most severe hygrothermal conditions. 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% 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 Viitanen and Ojanen of VTT Technical Research Centre of Finland[22] to calculate a mold index for materials that make up the building enclosure. The calculation is based on experimental studies of typical building materials. According to ASHRAE 160, "to minimize problems associated with mold growth on the surfaces of components of building enclosure 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 presented in **Fig. 10**. The mold index takes on a value between 1 and 6. In this classification scheme, colors are assigned to the assmebly by index range: green for a mold index value less than 2; yellow for a value greater than 2 but less than 3; and red for any value greater than 3.

In the wall in Fig. 10, a line runs through the "x's" that mark the locations 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. **Figures 11** and **12** are the matrixes for all Phase 1 walls and all Phase 2 walls, respectively.

In most cases, all walls have building components where the mold index is less than 3; exceptions are Walls B and J, the walls that contain insulation in the wall cavity with no exterior or continuous exterior insulation. In the absence of any form of interior vapor control, the addition of exterior insulation, especially with moisture-tolerant materials, is expected to improve the hygrothermal performance of the wall assembly by pushing the point of condensation to the exterior side of the sheathing.

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 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 modeling and engineering design with economic evaluation for a quantitative and qualitative understanding of the financial viability of an investment.[23] In the 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.

Measures of 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 nonprofit organization that provides construction cost estimation in Portland, Ore. This organization was chosen for this activity because of its deep ties to the local residential building industry, which includes workforce training and building certification programs. These activities put the organization's team members 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 subdividing each wall system into individual material layers and operations whose costs could be determined separately. Material and labor costs were kept separate. For each wall system, estimates for material and labor were collected from three different contractors. 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 data from the *RS Means Residential Cost Databook*,[24] 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 estimates were then averaged, and the costs for 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 estimates for labor and materials were averaged and summed to produce an estimated total cost.

For the experimental wall systems, we reached out directly to manufacturers to help

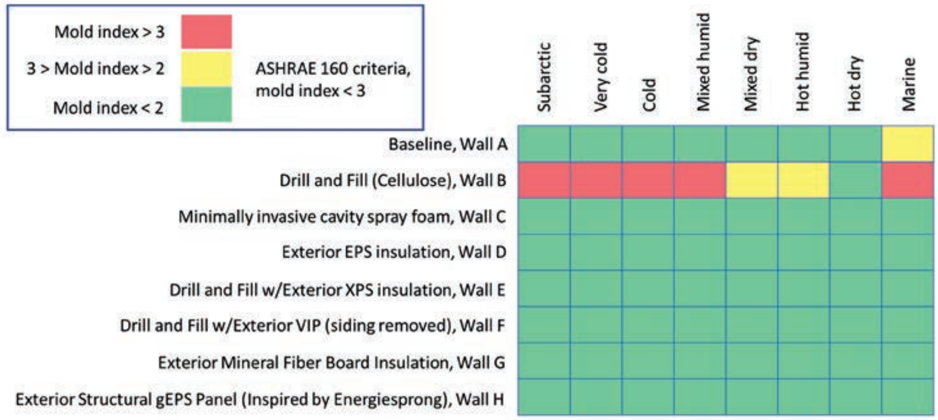


Figure 11. Mold index measures for Phase 1 walls in all eight U.S. Department of Energy climate zones.

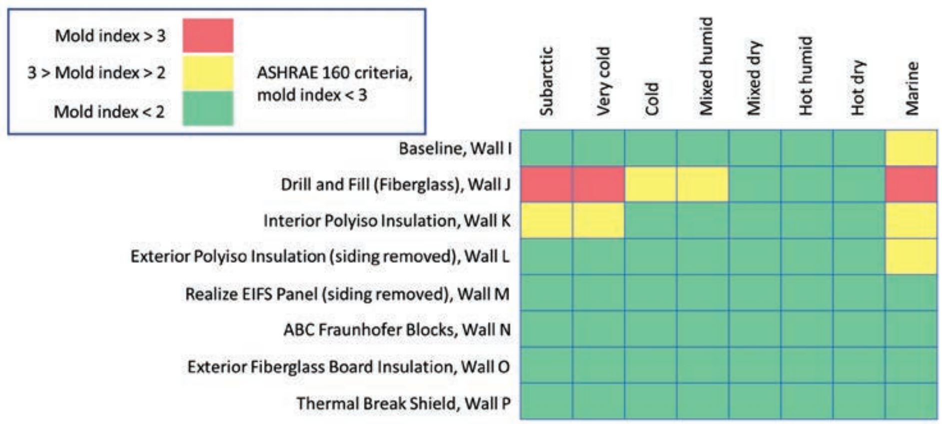


Figure 12. Mold index measures for Phase 2 walls in all eight U.S. Department of Energy climate zones.

with cost estimates. Some wall systems are highly experimental in nature, and manufacturers have not yet done detailed cost analyses. 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 databook was used to cross reference data gathered from the cost estimator. The RS Means regional indices were used to translate costs from Portland, Ore., to other regions throughout the United States.

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 that did not require additional siding. There were instances where the siding was integrated with the insulation in a panelized approach to the 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 vary dramatically and are 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 cost variations, the cost analysis assumed vinyl siding for all wall systems that factored siding as a separate layer to the construction process (that is, the walls that are not cavity-fill-only or panelized systems with integrated insulation/siding). This assumption limits the cost difference to the wall structure and control layers.

Material, labor, and energy costs are presented here in absolute dollar values for two cities, which were matched to the energy modeling analysis. The project focused on the cold climates, and the cities presented here are Salem, Ore. (Climate Zone 4C), Chicago,

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 1. Material, labor, and total costs per square foot for each wall studied for Salem, Ore., Chicago, Ill., and Burlington, Vt.

Ill. (Climate Zone 5A), and Burlington, Vt. (Climate Zone 6A). In addition to labor, materials, and energy costs, simple payback and internal rate of return (IRR) were calculated to assess the viability of the initial investment.

Table 1 presents the costs per square foot for labor and materials in the two selected climate zones. Table 2 presents the IRR and simple payback for each wall system in Salem, Chicago, and Burlington. The IRR is the annual rate of growth that an investment is expected to generate. Payback is presented in years, and IRR is presented as percentages. 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 of time, considering energy savings.

CONCLUSION

This paper provides an overview of a three-year, multipart study of the viability of multiple retrofit approaches for residential wall systems.. The study focused on the thermal, moisture, and economic performance of 14 wall assemblies (cavity-fill, interior, and exterior approaches with and 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 CRRF for physical testing. Data compiled during the in situ testing were 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 U.S. climate zones. It was found that the climate zones with the highest potential for retrofit savings are those that are heating dominated (Climate Zones 5–8). In these climate zones, the whole house energy savings associated with space conditioning for the simulated retrofit wall assemblies were in the range of 18% to 34%.

It was also observed that increasingly high *R*-value insulation improvements had a diminishing effect on wall conduction performance improvements. The highest potential for energy savings can be realized by going from

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

Table 2. Internal rate of return (IRR) and payback period for every wall system in Salem, Ore., Chicago, Ill., and Burlington, Vt.

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 whether the walls are moisture durable, WUFI Pro (version 6.4) was used to carry out hygrothermal simulations for northern exposures. The mold index measured in accordance with ASHRAE 160 was used as an indicator of moisture durability.

In all retrofit walls except Walls B and Wall J, the mold indices are less than 3. In the absence of any form of interior vapor control, 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.

For Chicago, total costs for labor and materials to retrofit a 2400 ft^2 house ranged from \$1.85/ft^2 for Wall B (drill-and-fill cellulose) to \$45.45/ft^2 for Wall M (EIFS panel with the siding removed). From a materials-only perspective, the costs ranged from \$0.40/ft^2 for Wall B to \$22.50/ft^2 for Wall M. With respect to labor costs, Wall B was the least expensive at \$1.45/ft^2 whereas Wall M was most expensive at \$22.50/ft^2. Wall J (fill-and-drill fiberglass) showed the highest IRR at 25% and the shortest payback at two years. Wall M showed the lowest IRR at –5% and the longest payback at 67 years.

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