# Exploring High-Performance Envelope Retrofits

## The next step in single-family building weatherization

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**Prepared for: Minnesota Department of Commerce, Division of Energy Resources**

**Prepared by: Center for Energy and the Environment**

**Prepared by (Author Details Style + Bold):**
Josh Quinnell
Lindsay Genty

**Center for Energy and Environment**
212 3rd Ave N Suite #560
Minneapolis, MN 55401
Website: http://www.mncee.org
Project Contact: Josh Quinnell
Phone: 612-244-2437



Contract Number: 158619

**Prepared for Minnesota Department of Commerce, Division of Energy Resources:**
Grace Arnold, Commissioner, Department of Commerce
Aditya Ranade, Deputy Commissioner, Department of Commerce, Division of Energy Resources

Laura Silver, Project Manager, Department of Commerce, Division of Energy Resources
Phone: (651) 297-4523
Email: laura.silver@state.mn.us

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# Executive Summary

Despite utilities consistently meeting their savings targets, energy use and emissions from natural gas in the building sector continue to increase[1] and pose significant challenges for future energy and emissions goals. Lowering space heating loads through building envelope improvements is the greatest building energy efficiency opportunity in Minnesota, more so than all other residential efficiency measures combined. In fact, dramatic improvements in the energy efficiency of existing home building envelopes is likely necessary to meet current state energy savings and emissions goals.

The walls, windows, roof, and foundation comprise the building envelope, and their efficiency, or resistance to heat loss, determines space-heating energy requirements. Retrofit measures that seal air leaks, add insulation, and potentially treat or replace windows reduce energy loss though these components and improve building envelope efficiency. These improvements are typically known as weatherization measures, and they have long proved successful and cost-effective. Conventional weatherization measures are usually limited to less than 20% savings per home and ultimately focus on bringing existing buildings to a basic minimum standard rather than achieving high performance. On the other hand, significantly larger improvements in envelope efficiency are possible. For example, a concept called the deep energy retrofit, an idea nearly as old as weatherization, is a whole-home efficiency approach that is usually anchored by improvements in envelope efficiency of greater than 50%. In practice, such dramatic envelope improvements would cut heating loads by 400–500+ therms on average in existing Minnesota homes and enable downsizing heating system capacity by half.

This project focuses on high-performance envelopes, discussed here as a collection of efficiency measures that doubles the efficiency of existing residential buildings. It examines these measures as potential ways to achieve Minnesota Conservation Improvement Program (CIP) energy savings goals. They include traditional weatherization steps such as attic insulation, wall insulation, rim joist insulation, and air sealing, as well as continuous exterior insulation and new windows. Ideally, high-performance envelopes require special treatment of roofs, walls, windows, ventilation systems, the foundation, and the interfaces between these components. Many of the necessary improvements are highly invasive, time consuming, and are difficult if not impossible to carry out on occupied building stock using current construction practices. This project focuses on a subset of measures that are most like regular building projects, namely continuous exterior insulation applied at the time of siding replacement (re-siding projects) and window replacement. Recognizing that dramatic space heating savings are not only possible but potentially required across over a million homes in Minnesota, this project seeks to understand the barriers and opportunities for pursuing high-performance envelope projects according to stakeholders involved in their implementation. A model was developed to study the requirements for achieving 50% space heating savings from existing building stock and to analyze the costs and benefits as a function of underlying building characteristics and envelope measure packages.

[1] Minnesota Department of Commerce. 2020. *Energy Policy and Conservation Quadrennial Report.* Last modified March 1, 2021. https://mn.gov/commerce-stat/pdfs/20210301_quad_report.pdf.

# Existing Barriers

Direct outreach during this project and ongoing conversations about similar ideas at local and national venues revealed three consistent barriers to implementation. Collectively, they offer a comprehensive explanation as to why there is still little interest in high levels of envelope efficiency.

## Market Awareness and Interest

Energy efficiency is not appropriately valued in residential real estate transactions. In general, lenders, underwriters, appraisers, realtors, and consumers lack the knowledge, training, and time necessary to evaluate the costs and benefits of energy efficiency or high-performance buildings. Stakeholders in this space lack enthusiasm for capturing the value of energy efficiency and reduced energy costs over time, focusing instead on the additional work and costs, lack of data, and insufficient demand. As a result, there is little market pressure for higher energy efficiency performance from the existing residential building stock. That said, there is evidence that energy efficiency framed in terms of comfort and performance or when designated as such via certifications can command premiums commensurate with its value during real estate transactions.[2] This barrier suggests that insufficient resources are devoted to education and outreach efforts, especially in light of the fact that there are no strong technical limitations to achieving high performance standards with existing measures.

## Workforce Awareness and Interest

The workforce directly responsible for constructing building envelopes are unaware of or uninterested in high-performance envelopes and energy projects. There is a large amount of existing building science research, measure development, pilot programs, case studies, meta-analyses, and extensive interest in the subject among dedicated experts, but none of this appears to be accessible or appreciated by the professionals who complete and sell this work. Even contractors who implement existing weatherization measures are often unaware of the next steps for envelope efficiency. Ultimately, this workforce is already inundated with existing work, is not compelled by interest from partners and clients, and has little incentive to adopt (new-to-them) practices and job skills to appease a relatively small and demanding client base. On the other hand, architects and contractors often have high-trust relationships with their clients and from that position exert immense influence on project decisions that incorporate energy and comfort.

A small group of market participants specializes in supplying architectural, engineering, and contracting services that incorporate high performance envelopes in retrofit projects, generally for highly motivated consumers. Further, those most knowledgeable about the subject tend to be involved, passionate, and supportive of the ideas and possess a sophisticated understanding of the current barriers.

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[2]Elevate Energy. 2020. “Realizing the Value: An Appraiser-Led Analysis of the High-Performing Home Premium in Leading Midwest Markets. https://www.elevatenp.org/wp-content/uploads/2020-EE-realizing-the-value-paper-v9.pdf.

This barrier suggests that market demand is essential to driving workforce interest or the workforce must be otherwise incentivized to bring these ideas to market.

## Cost

Upfront costs and perceived cost-effectiveness loom heavy over all conversations on deep-energy retrofits and high-performance envelopes, but existing research demonstrates no clear trends in cost-effectiveness. Projects do have large upfront costs; as with electric vehicles and solar photovoltaics, energy investments are at the front end and typically require favorable financing, a full accounting of costs and benefits, and forecasting paybacks over a long and uncertain future. The sophistication of the required analyses and uncertainties in future outcomes, paired with an underappreciation of the value of energy efficiency in the marketplace, represent extensive cost-related barriers for these projects.

## Opportunities

Many other barriers disclosed by practitioners suggest project opportunities. For example, continuous exterior insulation requires the removal of siding, which is expensive, but if paired with existing maintenance projects it provides an opportunity to substantially lower incremental costs of energy efficiency work. Practitioners often highlight the lack of showmanship involved with energy efficiency projects. There is nothing for a consumer to broadcast their decision or investment to others as there is with competing energy investments like electric vehicles or rooftop solar. Coupling a high-performance envelope with a renewed building exterior provides that visual display. Further, new exterior siding and windows provide relatively good value-to-cost ratios compared to other home improvements, which enables a potential project cost discount upwards of 60% to 75%. High-performance envelope measures added to these projects have equivalent or higher return on investment than non-energy saving improvements via lower energy bills and improvements to occupant comfort. Given that home exterior work is currently undertaken at a rate approximately ten times that of weatherization, there are immediate opportunities to test and pilot high-performance envelope measure packages.

# Results

To understand the scope of existing projects, a model was developed to identify costs and benefits of upgrading cold climate building envelopes as an extension of weatherization work and on top of existing exterior re-siding projects. The model was built using audit and research data on existing buildings over the last decade. Building characteristics and envelope performance data were statistically sampled from these data sets to construct a representative data model of the existing building stock. The data were paired with an energy model to understand annual and design space heating loads of different building envelope components, their contribution to net load, and their variation across the building stock. Weatherization program data on project costs and project outcomes were also included in the model. High-performance envelope measures including continuous exterior insulation and windows were constructed using data from RS Means 2020 new and retrofit construction guides, retail cost data, and existing project bids to estimate project costs as they vary due building stock differences.

The data confirm many existing impressions.

- Pre-1990 homes in Minnesota have space heating loads that average about 900 to 1000 therms.
- Full weatherization of existing building stock to current standards using air sealing, attic insulation, rim joist insulation, and wall insulation measures where necessary yields 19% space heating savings on average.
- Walls, air leakage, and windows are the most important envelope components to target for further envelope efficiency on fully weatherized building stock.

Several types of continuous exterior insulation measures and window upgrades were paired with three baseline re-siding projects including basic vinyl siding, premium fiber cement siding, and synthetic stucco to determine the requirements for achieving 50% improvement in envelope efficiency across the building stock and the incremental energy costs to do so.

- There are many ways to achieve a high-performance envelope and the commensurate savings including different insulation types, siding accommodations, and window measures that suit variations present in the existing building stock.
- Saving targets of 50% natural gas reduction for space heating are difficult to achieve from weatherization, continuous exterior insulation, and window measures.
    - Achieving 50% median space heating savings from the existing building stock requires triple pane windows and R-18 continuous insulation.
    - R-9 continuous exterior insulation, replacement windows, and energy recovery ventilation produce 50% median space heating savings.
    - It is possible to obtain 40% space heating savings with lower cost replacement windows and R-6 continuous exterior insulation.
- For natural gas heated homes, no high-performance envelope projects studied — including complete weatherization packages — are cost-effective for participants or society on average across the building stock under the current cost benefits model.
    - Participant cost benefit ratios approach 1 for all high-performance envelope packages, and weatherization exceeds 1.4 when excluding the 20% least cost-effective projects.
    - Participant cost benefit ratios exceed one for all high-performance envelope packages, and weatherization exceeds 1.6 when excluding the 50% least cost-effective projects.
    - Participant cost benefit ratios approach 2 for many high-performance envelope packages for the 20% most cost-effective projects.
    - Just under 10% of the existing building stock appears repeatedly in the most cost-effective opportunities. These buildings tend to be smaller (1600 square feet versus 2200 square feet) and have about 10% higher window area but about 30% higher space heating per conditioned area than average.

# Conclusions

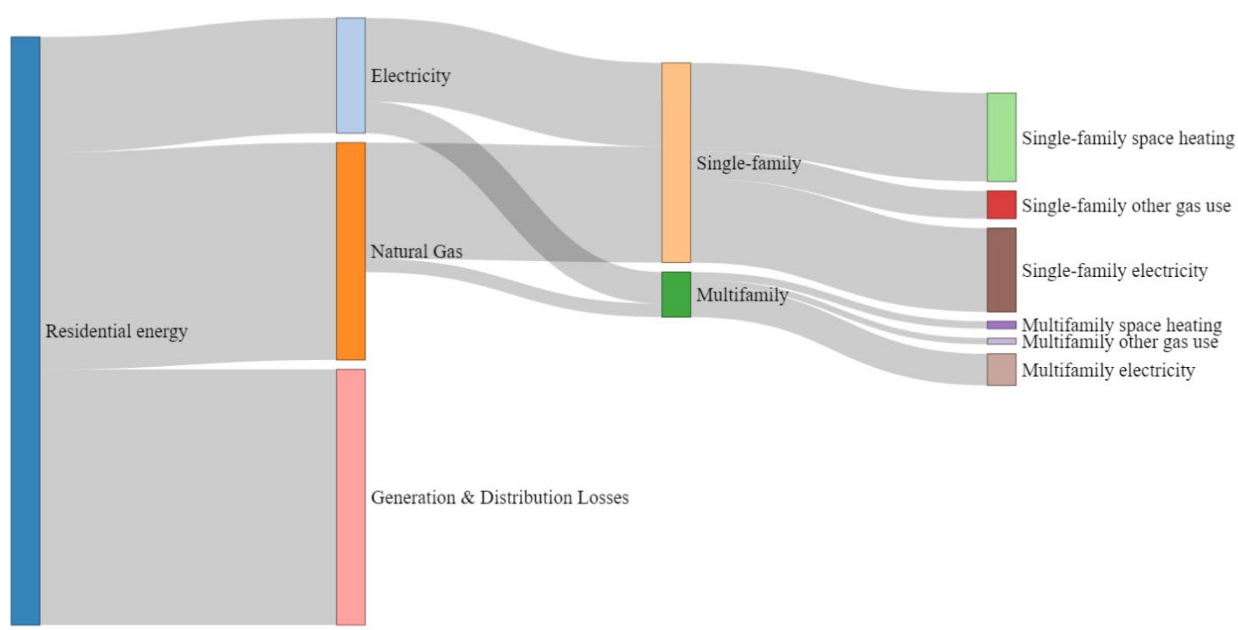
This project sought to examine the role high-performance envelopes may play within the CIP energy savings framework by soliciting stakeholder perspectives and attempting to model the costs and energy savings of a variety of high-performance envelope measures and packages using a data-based model to represent realistic variations across Minnesota's existing single family building stock.

This work is by no means conclusive, but it does demonstrate that there are substantial cost-effective opportunities not just to more aggressively pursue cost-effective weatherization efforts, but to expand them to include continuous exterior insulation and, in some cases, window replacements. It highlights that while upfront costs are barriers, large sections (up to 20%) of existing building envelopes can be cost-effectively transformed into a high-performance cold climate buildings. The project suggests there are excellent opportunities across a hundreds of thousands of existing Minnesota single-family homes upon which these ideas can be tested, practiced, and improved. At the very least, high-performance envelopes warrant significantly more attention in cold climate efficiency programming than they have received to date and that they are among the few viable pathways to significantly reducing natural gas consumption to levels necessary for meeting state climate goals.

# Introduction

Due to the cold climate, space heating is by far the largest building energy end use in Minnesota. Natural gas is the most popular fuel used to meet this load. Together these entail the largest natural gas efficiency opportunity in Minnesota: the reduction of space heating loads on existing single-family homes as shown in **Figure 1**, where the relative area of natural gas energy consumption for space heating is compared to that of other end use categories. The ability to lower this energy use via device efficiency is limited due to exceptional progress already made over the preceding decades. The average furnace is already about 85% efficient, leaving about 10% savings left from furnace efficiency across the existing single-family building stock. The only efficiency option for reducing natural gas consumption to levels required for state climate goals is to increase the efficiency of the building envelope itself. Natural gas use for space heating in single-family homes already produces over 20% of the State's overall 2050 GHG emission targets according to Minnesota climate goals[3], which is disproportionate considering the rest of the economy including all electrical generation, commercial buildings, transportation, industry, agriculture, and future growth have to fit within the remaining budget. When adding the energy use of other fuels such as propane and electricity used for space heating, the potential energy savings from increasing the building envelope efficiency in single-family homes likely exceeds all other residential energy efficiency measures combined.

**Figure 1: Site energy use in Minnesota residential energy sector**




[3] Partridge, Audrey and Rabi Vandergon, December 7, 2020. "It all adds up: Emissions from Minnesota's natural gas consumption," Center for Energy and Environment. (https://www.mncee.org/it-all-adds-emissions-minnesotas-natural-gas-consumption)

The building envelope is the collection of exterior surfaces through which energy is lost; it drives space heating demand. The building envelope is primarily composed of the walls, windows, roof, and foundation of a home. Building retrofits designed to reduce heat loss (which improve envelope efficiency) involve sealing air leaks, adding insulation, and improving windows. Collectively these improvements are known as weatherization measures and there is a long and successful history of applying these measures cost-effectively in Minnesota and nationally. However, conventional weatherization measures are also limited to about 15% to 20% savings potential on average. Even when coupled with remaining furnace efficiency gains this may be insufficient to reach climate goals. On the other hand, dramatic improvements in envelope efficiency are possible. For example, Passive House standards (for both new and retrofit applications) can lead to around 90% to 95% reduction in space heating. Somewhat more common is a concept called the deep energy retrofit. Deep energy retrofits are an efficiency approach for the entire home, where all systems are targeted for savings, but they are typically anchored, especially in cold climates, by high levels of envelope efficiency. The deep energy retrofit idea is as old as weatherization, but they often emphasize comfort and indoor air quality in addition to energy savings. They often target a 50% improvement in envelope efficiency, two to three times the savings targeted by weatherization.

# Background

The building envelope, sometimes called the building shell, is the assembly of surfaces that make up the exterior of the building including the slab, foundation, walls, windows, and ceilings/roofs. Energy passing through these surfaces drives the heating and cooling loads for the building. In Minnesota, heat loss through the building envelope during the winter is the largest load for detached single-family homes.

There is an extensive literature on high-performance envelopes and deep energy retrofits going back decades. Previous studies highlight the necessity of higher performance envelopes, explore the building science, examine specific measures, and document and evaluate complete projects. There are pilot programs, voluntary programs, and certifications as well as discussions about scaling projects, marketing projects, and selling projects. There are also considerations about developing a workforce that can accomplish these activities.

Weatherization measures typically target the worst performing building envelopes, often older construction that predates modern energy and building codes. These efforts comprise minimally invasive and cost-effective procedures within the framework of the existing construction. However, these measures typically stop short of the time, budget, and interventions necessary for aggressive (more than 30%) energy savings. Many have recognized the opportunity for savings beyond weatherization efforts that are possible by converting existing building stock into high performance building stock [1-18]. These activities are commonly referred to as deep energy retrofits. Historically, deep energy retrofits are invasive, highly customized projects that are often coordinated with other extensive non-energy efficiency work like additions and major remodels. Their goals, developed through detailed engineering analysis, aim to drastically reduce energy consumption inside buildings by selectively targeting the major loads and end uses. These projects are motivated by energy and comfort, and cost is usually a secondary concern. While individual goals are dictated on a per project basis, it is common to target whole building savings of 30% to 70% with 50% being the most common goal. These projects usually hit savings targets by treating all building systems including the building envelope, HVAC systems, domestic hot water, and lighting measures. Contributions of individual measures vary, but in most climates building envelope improvements yield the greatest portion energy savings.

For the purposes of this project, we defined enhanced envelope efficiency upgrades or high-performance envelopes as retrofits that encompass measures that seal air leaks and increase overall insulation levels of the building envelope. While in some cases, these efforts may overlap with conventional weatherization techniques, they should generally be understood to go further than established weatherization efforts, entailing additional time and expense. These envelope treatments will specifically exclude HVAC equipment updates, lighting, plug loads, and domestic hot water that are often included in a whole-home deep energy retrofit.

The emphasis of this project on the building envelope more closely resembles a concept called retrofit-over-time in which elements of a deep energy retrofit are staged over time to decrease the impact of cost and disruption, while better aligning with home repair and maintenance schedules [12]. In the case of a staged approach, initially focusing on envelope elements may reduce costs and dictate different, lower cost improvements or alternative options for later stages (e.g., HVAC and technology investments). This may be even more true if electrification gains momentum as a decarbonization and efficiency pathway.

To establish the scope of this project, **Table 1** lists definitions for deep energy retrofits that were extracted from prior work.

**Table 1: Deep energy retrofit definitions**

| Definition summary | Citation |
| --- | --- |
| Whole building retrofits for achieving significant reductions in energy intensity (annual energy consumption per unit of floor area) | Jermyn 2016 |
| Reduce annual energy use by 50% | Leinartas 2015 |
| Market-relevant strategies to achieve 40% reductions in existing home energy use | Less 2015 |
| Aggressive and comprehensive whole-house renovations that target energy savings beyond those typically achieved in weatherization or utility retrofit programs | Less 2014a |
| A 50% savings target represents a reasonable, achievable definition of the minimum requirements, though greater savings levels are desirable | Less 2014b |
| Aim to save more than 50% of the energy used in the home | Cluett 2014 |
| Save at least 30% on a whole-house basis | Blanchard 2012 |

| Definition summary | Citation |
| --- | --- |
| Reduce energy consumption by 30% to 50% or more on a whole-house basis | Chandra et al. 2012 |
| A deep retrofit aims to achieve 30% to 50% energy savings | Wolfe 2012 |
| Definitions of DERs range from 30% to 75% of annual energy use compared with a pre-retrofit baseline; the most appropriate DER definition should be on the high end of this scale at the 70% level | Walker 2012 |
| Reduce an existing home's energy use by 50% or more | Keesee 2012 |
| Cost effective savings of 30% to 50% | Bianchi 2011 |
| 40% to 70% reductions of annual heating and cooling energy | Chitwood 2011 |
| The optimal savings are above 50%, about twice what the leading retrofit programs are achieving today | Neem 2011 |
| Characterized by a substantially higher level of insulation and air tightness than would normally be found in a new home | Wigington 2010 |
| All three projects shared the same overall prescriptive goals: R-10 basement floor; R-20 basement walls; R-40 above-grade walls; R-60 roof, 0.2 windows; air leakage of roughly 1 ACH50; and ventilation meeting ASHRAE 62.2 | Eldenkamp 2010 |
| New technologies and systems must increase whole-house energy savings by an additional 40% relative to those that can be currently provided by best available residential components and systems | Anderson 2008 |
| Deep retrofit: costs US$50,000/home, saves 7,000 kWh and 600 therms annually | Henderson 2007 |

There are common themes among the definitions. Very broadly, all the definitions:

1. Require measures beyond those common in weatherization programs.
2. Target whole-house energy savings of 30% to 70% with 50% being the most frequent goal.
3. Target all energy use but generally recognize that envelope components are the most impactful, expensive, invasive, and necessary to achieve savings targets.
4. Have aspirational savings targets[4].

There is remarkable consistency in savings goals among prior work, despite the lack of a rigorous justification for these targets. While there are a few studies that offer definitions specific to the building

[4] The targets are seldom tied to actual energy consumption, rarely climate adjusted, and not quantitatively justified by specific emissions, decarbonization, or energy efficiency targets.

envelope [6, 11], these loads are generally lumped into total site (household) energy. Given the restricted scope of the present work, establishing a definition consistent with prior work entails added uncertainty.

Nonetheless, initial targets will be chosen for consistency with previous deep energy retrofit efforts. In cold climates, heating loads typically comprise between 60% and 80% of total site energy for detached single-family homes. For this range of heating load fraction, targeting 30% to 70% reduction in heating load through the building envelope yields site energy savings ranging from 18% to 56%. This target matches the aggressive standards of past work while enabling some flexibility to deal with variations among the existing building stock and the suitability of future higher efficiency HVAC systems. For example, a reduction of 30% in space heating energy may be appropriate for homes that have had prior weatherization work completed, whereas 70% reduction targets may be appropriate for homes that have neglected energy efficiency updates.

In practice, the savings targets outlined here must be tempered by logistical and cost realities identified in the project since cost-effective savings is still the primary goal. In this way, a working definition of an enhanced envelope upgrade is "a combination of envelope measures targeting 30% to 70% reduction in heating loads (equivalent to 18% to 56% reduction in site energy), which can be completed up to the cost-effective limit."

# Justification

There are several additional justifications for considering single-family envelope efficiency the preeminent energy efficiency opportunity in Minnesota.

- Not only do building envelopes represent the largest energy efficiency opportunity, but they must be addressed to maintain progress towards state energy efficiency goals in the face of diminishing returns from past successes in furnace, lighting, appliance, and behavioral efficiency.
- As the largest energy load in single-family homes, space heating also represents the highest building energy cost. Unfortunately, high energy costs also give rise to high energy burdens as older homes and homes less likely to have energy efficiency work are disproportionately occupied by low-income households, which are also disproportionately represented by historically disadvantaged groups.
- High-performance envelopes will increase comfort in a variety of ways including 1) lowering drafts from infiltration, 2) decreasing temperature gradients and improving temperature uniformity throughout the home, 3) increasing mean radiant temperature and thus comfort at the same thermostat setpoint temperature, 4) reducing the need for winter humidification and reduce summer dehumidification, and 5) improving indoor air quality via lowered infiltration and increased efficacy of balanced, filtered mechanical ventilation systems.
- High-performance envelopes will yield additional cost savings via future HVAC equipment downsizing.
- Improved ability to heat homes with air source heat pump systems. Heat pump systems typically have lower capacity than the fuel-burning systems they displace and more variables to consider

in their sizing and performance. A large majority of existing homes have prohibitively large space heating loads at winter design temperatures, exceeding the capacity of currently available heat pump systems.

- Decarbonization by way of electrification will place additional stress on the electrical grid. Transitioning space heating loads to the electrical system will not only increase peak load but will also drastically change the demand curve such that peak loads and demand charges will shift from cooling season peaks to heating season peaks. Envelope upgrades will reduce these peaks and strongly impact utility resource plans.

## Research Objectives

This project was initially focused on identifying market opportunities for high levels of single-family building envelope efficiency. The work pivoted based on early outcomes to estimate the scope of the efficiency benefits, current barriers to adoption, and preliminary costs and energy benefits of the currently available options for achieving 30% to 70% energy savings targets for existing single-family building envelopes. The project comprises two components:

1) outreach with stakeholders in this market (real estate community, contractors, architects, and energy professionals) and
2) modeling the costs and benefits of currently available measures for high-performance envelopes.

# Methodology

The first component of the project attempts to understand high-performance envelopes and the barriers and opportunities they present to existing stakeholders' perspectives. The second component aims to quantify potential high-performance envelope packages and how their potential savings and costs vary across the existing building stock.

## Outreach

One goal of this project was to understand existing stakeholder and industry perspectives on high-performance single-family building envelopes. To that end, authors attended a variety of workshops and conferences and sought to interview stakeholders across a range of disciplines with a role in residential retrofit projects. Interviews were conducted to understand baseline knowledge and assess the extent of stakeholders' interest in building envelope efficiency and barriers and opportunities associated with high-performance envelopes. These stakeholders include individuals from the following groups:

**General contractors:** Those involved in renovation, exterior siding, windows, and roofing for single-family homes.

**Energy contractors:** Those who have existing experience upgrading insulation and air tightness on single-family homes (e.g., those who implement existing weatherization programs).

**Architects:** Those who work on renovation projects for single-family homes.

**Advocacy Organizations:** Those who advocate on behalf of building occupants in housing policy or who practice general environmental advocacy with respect to buildings.

**Realtors:** Those who possess knowledge of the existing single-family real estate market.

**Appraisers:** Those who appraise and value existing single-family homes as part of real estate transactions.

**Energy Engineers:** Those who work on renovation projects for single-family homes.

**Distributors/Suppliers:** Those who are knowledgeable of the existing market channels for building products and materials for retrofit and renovation projects.

**Trade Associations:** Organizations directly involved in supply chains and manufacturing for contractors and distributors.

The interviews followed a similar template with sections varying according to discipline and level of knowledge. The first half of the interview was designed to gauge general knowledge of high-performance envelope retrofits and related ideas and was given to all participants. The second half of the interview was designed to gain knowledge about their clients regarding energy efficiency and the relationship between their work and high-performance envelopes. This portion was given to participants who demonstrated knowledge of a deep energy retrofits, passive house retrofits, or general high-performance envelope concepts. Unsuccessful attempts to reach participants prompted research staff to adjust the approach several times, generally toward more informal conversations. Low response rates also motivated research staff to engage participants regarding the outreach approach itself. The solution proposed by potential participants was to offer compensation, which was outside the project scope. Finally, this outreach began during the early COVID lockdown period making participant contact difficult for a variety of reasons; alternative in-person methods for collecting feedback were not possible.

# Cost and Benefits Modeling

The goal was to relate building characteristics and estimated project outcomes to understand variations in envelope performance and costs of envelope measures across the Minnesota building stock and develop a strategy to prioritize future envelope work. This project attempted to duplicate NREL's ResStock methodology [19] that they developed to analyze the technical and economic potential of energy efficiency upgrades in the national building stock. In this process, multiple data sources for building characteristics are combined into a single data model where relationships between building characteristics are preserved. The data model is then statistically sampled to obtain a representative model population of single-family buildings. The overall approach is summarized graphically in **Figure 2**.

In the present project, data were pulled from over 11,000 records of home energy audits that were conducted in the Twin Cities Metro Area, past research projects, and a recent statewide homeowner survey conducted during the 2018 Minnesota Potential Study. These data were statistically sampled to estimate the baseline representation of existing building stock. Specific parameters used in this study are given in **Table 2**; they emphasize key geometry and envelope performance parameters available from these datasets.

**Figure 2: High level graphical overview of the model developed for this project**

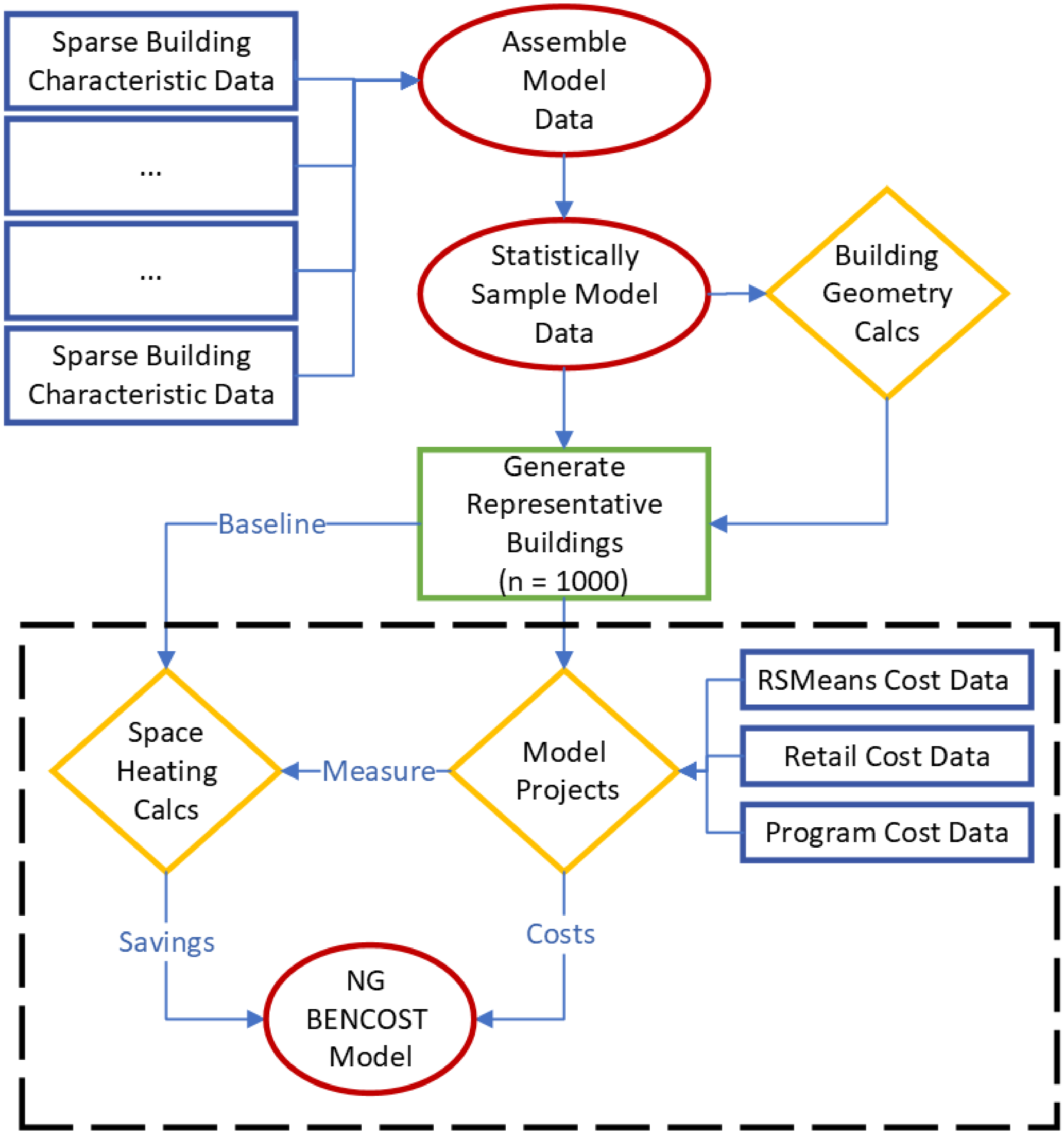


**Table 2: Input data for this study**

| Variable | Description |
|---|---|
| **Building age** | Age data by decade <1920 – 1989 |
| **Building size** | Total size ~600 – 6000 sf |
| **Building type** | 1 story, 1.5 story, 1.75 story, 2 story, 2.5 story, 3+ story, split-level |
| **Siding type** | Vinyl, wood, stucco, steel aluminum, asbestos, masonry |
| **Window area** | Ratio of window to wall area |
| **Attic geometry** | Slants, knee walls, flat area estimates |
| **Attic insulation R-value** | ~ 0 – 60 $ft^2$·°F·hr/BTU |
| **Wall insulation R-value** | ~ 0 – 40 $ft^2$·°F·hr/BTU |
| **Rim joist insulation R-value** | ~ 0 – 20 $ft^2$·°F·hr/BTU |
| **Foundation insulation R-value** | ~ 0 – 20 $ft^2$·°F·hr/BTU |
| **Air leakage** | 200 – 4,000 CFM |
| **Header insulation** | Y/N |
| **Wall geometry** | Wall area estimates |
| **Window type/details** | # panes, glazing spec, storms |

The above data were consolidated into a single dataset. Generally, this entailed recoding categorical data for consistency, differentiating unknown data from zero values, and removing incomplete data. In some cases, data were omitted from certain sources due to conflicts or insufficient detail.

A pair-wise correlation matrix was produced to determine the correlation between each set of two parameters to yield the relationships between the data. Each variable was then represented as an empirical probability distribution function representing underlying data. These distributions and their correlation data were sampled using a Latin Hyper Cube (LHS) approach to produce a representative dataset with fewer samples and less outliers. It took about 1000 samples for the distributions obtained from the data model to accurately represent the data.

A simple energy model was built to estimate overall heat transfer coefficients from the building samples including their geometry, insulation values, and typical residential construction practices and materials. This model takes a q = UAdT approach for heat loss, which is generally sufficient for heating calculations [20]. Notably, solar gains, internal gains, scheduling, and temperature setbacks are neglected. This model estimates heat loss through (1) walls, (2) windows, (3) roof/attic, (4) above- and (5) below-grade foundation, (6) rim joists, and (7) overall air leakage by developing thermal resistance models from parameters in **Table 2** and typical stick-frame construction details.

Envelope project costs were estimated by building up project estimates using RS Means 2019 Retrofit and RS Means 2019 New Construction cost guides & methodology. These data were also supplemented with retail data, bids on previous projects, and consultation with practitioners. In general, we used RS Means guides for capital and labor requirements of construction tasks with adjustments for geography. These cost estimates are typically related to underlying geometry, such as surface area, window count, lineal foot of perimeter, etc. In this manner, we established several project types and then applied them to the building model to estimate the differences in cost and energy savings across the building stock.

Project cost and energy savings results were then used with the 2020 Minnesota BENCOST Model for Gas CIPs to compute cost benefit ratios for each unique combination of project and building sample.

# Results

## Stakeholder Perspectives

The objective of the outreach process was to understand stakeholder knowledge of high-performance envelopes and their perspectives about the opportunities and barriers associated with high-performance envelopes in the market. General trends observed through direct stakeholder interviews were broadly consistent with findings discussed by researchers and practitioners at workshops and seminars attended by project staff.

Research staff reached out to 303 organizations and netted 33 participant interviews, a response rate of just under 11%. In total, six different stakeholder groups are represented: four general contractors, 14 energy contractors, eight architects, three housing advocates, two realtors, and two suppliers. Contractors exhibited the largest participation gap between staff projections and actual participation. Participants, potential participants, other researchers identified the COVID lockdown, historically high workload, no compensation for interview subjects, and general disinterest in research participation as reasons for this outcome. Due to the low number of results and the variations across interviews, the authors do not represent these responses as statistically representative for any stakeholder cohort. The results are organized around reoccurring themes expressed in the interviews.

The team asked participants about barriers and opportunities associated with including extensive energy efficiency work in existing projects to find these trends. Fifty nine percent of participants identified the addition of extensive energy efficiency work as an opportunity, 14% identified additional energy efficiency work as a barrier, and 27% identified it as both. Energy contractors were most likely to describe extensive energy efficiency work as an opportunity. Though 59% of stakeholders believed that adding extensive energy efficiency work onto existing projects was an opportunity, only 5% exclusively described opportunities associated with these projects. Regardless of their response to the question, most participants went into more detail about the barriers.

Those who described adding extensive energy efficiency work to existing projects as both an opportunity and a barrier tended to emphasize the barriers. For example, some said:

- “We do not do energy projects with renovation because it is too invasive. Most of the time it is not done well, either, because general contractors are not knowledgeable about building envelopes or enthusiastic to learn.”
- “It is not an opportunity in general.”
- “In today’s market, the opportunity is small.”

The results are presented around the main barriers identified in this process because they constituted a theme in many conversations. The major barriers are categorized in the following themes.

- Lack of knowledge, education, or awareness
- Lack of interest among key stakeholders
- Concerns about cost-effectiveness

## Level of Familiarity

Many participants were unaware of concepts like deep energy retrofits, passive house, and high-performance envelopes. Participants that showed familiarity with these topics often described this lack of knowledge or education among other key stakeholders (e.g., contractors) as a key barrier.

To begin our interview, we asked the question, “Are you familiar with a deep energy retrofit, passive house retrofit, or other high-performance envelope retrofit?” 68% of participants reported being familiar with the concepts, and two individuals agreed they had some familiarity once prompted with more description. The stakeholder’s knowledge on these topics varied with their background. For example, contractors and housing advocates were the most knowledgeable about what a deep energy retrofit was (nine contractors and two housing advocates defined the term), while architects were the most knowledgeable about passive house retrofits (three architects defined this term). Thus far, the only group unable to define any of these terms or who were unfamiliar with the concepts were realtors and general contractors.

Some participants believed they had a vast knowledge of the topics discussed but were unable to demonstrate that knowledge in follow-up questions. Some participants were knowledgeable about green buildings, energy efficiency, and the market, but they were unfamiliar with the terms deep energy retrofits, passive house, and high-performance envelopes. Lastly, several participants demonstrated little knowledge of envelope work in general.

Seventeen stakeholders attempted to provide descriptions of these concepts, but only six accurately described deep energy retrofits, four described passive house retrofits, and seven provided generic or partial descriptions of high-performance envelope retrofits. Examples of generic descriptions included:

- “High energy efficiency.”
- “Air stays in when it is supposed to stay in.”
- “It’s energy; home is properly insulated.”
- “Getting blower door numbers down and reducing air leakage.”

While 68% of participants claimed familiarity, only 58% of those interviewed demonstrated it in spirit and 52% could offer substantive details. In other words, about half the participants were unfamiliar with the ideas presented. Of the remainder, 18% percent admitted no knowledge of the ideas, 12% did not answer, and 3% did not reach this stage of the interview.

Much of the response ambiguity is consistent with literature findings. For example, deep energy retrofit is inherently imprecise and ambiguously references larger scale energy efficiency projects. The definition offered as interviews progress is that deep energy retrofit is “at least a 50% overall target reduction of building energy.” In this project, we specifically emphasize the building envelope components such that improvements to the thermal envelope reduce heating and cooling loads by at least 50%. A few of the responses describing large residential efficiency projects were given as follows:

- “There are varying degrees of deep energy retrofits, but I think that they fall into two main categories: non-invasive and invasive. Non-invasive approach refers to installing more energy efficient lightbulbs, HVAC systems, etc. Invasive projects are when they are added onto existing envelopes through insulation injections and other forms of retrofitting."

- "That is hard to define because it is extremely technical, but I guess if I had to describe it, I would say it's pulling out all the guts of the house, filling it with good insulation, adding better HVAC systems to the house, and making the building overall more airtight and energy efficient."

Participants who demonstrated knowledge of these retrofit ideas were questioned about the source of their knowledge. Fifteen participants stated they learned it either by being around projects that include this type of work or from a mentor. 73% of these participants were energy contractors, 20% were architects, and one was a housing advocate. The others were self-motivated to learn about these concepts through reading and online research.

Participants were also asked about their clients' general knowledge of energy efficiency. Of the 24 responses, 30% disclosed that their clients understood energy efficiency, 30% disclosed that their clients did not understand energy efficiency, and 42% described some clients as more knowledgeable than others.

In general, we would classify about 30% of participants as completely unfamiliar with high-performance envelope concepts, 30% as aware or partially aware of popular terms and ideas, and less than 30% as deeply familiar with the ideas such that they could freely describe measure details such as air sealing, insulation, and related design concepts.

## Level of Interest

Eight participants stated that builders and contractors are a major barrier for expansive energy efficiency work; attitudes toward this cohort are broadly described as frustrated. They were described as unwilling to learn or apply new methods, unwilling to learn about energy efficiency, or lacking in expertise to incorporate energy efficiency work in new projects. Participants mentioned that builders and contractors tend to not want to participate in any innovative projects or anything that may require more effort than required by code. Those who have been involved in expansive energy projects were forward about their frustrations when engaging with builders and contractors. Unfortunately, the contractor/builder cohort described here was not represented in this outreach (participation rate of less than 1%) and this lack of participation is consistent with these responses.

The most frequently mentioned complaint with builders is their unwillingness adapt to changing codes and technologies. In total, nine stakeholders expressed dissatisfaction with contractors and energy efficiency work and of these nine, six cited contractors' unwillingness to engage new methods. Notably, responses to this question were inexplicably tied to builders and new construction despite the emphasis on retrofits (and a consistent focus on retrofits for other questions). A few examples of their comments were:

- "Most contractors are not excited about new housing standards or codes. They don't want to learn new ways of doing things. An incentive program that gets contractors involved in a positive way would overcome this barrier."

- “The work is too hard for most contractors, and they don’t want to do it.”
- “… Also, home builders’ opposition [is a barrier]. Labor groups have more nuance with some willingness to take on new technology.”

## Cost-Effective

The most frequently cited barrier across all interviewed participants (55%) is the cost of high-performance energy efficiency work. This barrier encompasses concerns about initial capital costs, long-term cost-effectiveness, split incentives, and managing financing logistics across many subcontractors. This barrier was discussed across stakeholder cohorts. Five architects, five energy contractors, and two housing advocates discussed in detail the reality of these projects’ cost barriers. Many of the stakeholders have low-income clients for whom cost barriers are especially large.

Some participant responses are included below.

- “Cost. The cost of materials and construction is so high right now that the market does not allow for this type of work at all.”
- “Within my customer base, residents are open to energy efficiency improvements. The people typically working on these projects are people who have financial security that allows them to invest into projects of this scale”
- “You know this kind of work is not financially feasible for most people. We work with low-income rental properties. The property owners don’t see much benefit in energy upgrades because they aren’t the ones paying the electric bill. Of course, tenants can see the benefit, but in their mind why would they care what someone does to a property that they will be out of in 6 months?”
- “Money. In about 20% of the homes we do business with weatherization is the main energy [efficiency] work they do because it can show people savings in the short term. Most people we encounter do not know what their utility bill is, but when they do, they believe that the payback period is too long to even begin to consider a deep energy retrofit.”

Conversations about cost-effectiveness were followed by questions regarding rebates and incentives. Of the 20 participants completing this stage of interview, 95% responded that rebates and technical assistance programs in general are excellent incentives to help promote this type of work. Seven architects, nine energy contractors, and three advocates all shared positive opinions of rebate programs. However, participants often expanded in detail about stipulations for technical assistance and incentives.

Eleven individuals expanded their comments to describe alterations needed to improve rebate programs. A common suggestion was the need for rebate programs to include more flexibility on materials. Energy contractors, for example, described rebate programs as too narrow in the materials allowed in projects and occasionally in conflict with green certifications. The following are a few examples of comments given during the interview.

- “Rebates are nice for building owners. The issues involved with retrofits are typically due to the initial cost of materials. With rebates, you get back that initial cost so you can start getting the life-cycle costs back faster, which is appealing to most clients.”
- “Rebate incentives would be motivating if the outlets used to obtain them remained in their respective categories. Technical assistance would be a great incentive if they did not dwindle into the financial side of the programs and remained purely technical. The technical assistance programs put price tags on different blower door readings, and I feel that the work scope needs to be narrowed for a rebate program to sound appealing. There is more to retrofitting than just payback periods and free cash. It is also air quality, environmental importance, and many reasons other than just money, but the utilities companies are making it only about money. The utilities companies and government-funded programs need to remain product neutral in their programs because many of the products that are required for such projects should not be monopolized. However, in my experience, there is a growing monopoly among specific products because these rebate programs require only certain makes/models/etc. of retrofitting materials such as cellulose insulation. Rebate programs alienate small business owners and create a monopoly within government-funded programs.”
- “Rebates are pretty perceptive. We look at things differently as insulators and we’re focused on cellulose. I guess rebates do help people do the right thing because there is an incentive. Most of the time, though, customers don’t make their money back because the people distributing rebates are stuck on R-values, and most the time it is more money for the materials to achieve those R-values than you get for the payback. They tend to be too restrictive on materials and they hardly ever go with spray foam anyway.”

Many of the participants described less-than-ideal experiences with rebate and technical assistance programs. Nevertheless, these comments should be considered in revising rebate programs when more than half (55%) of stakeholders believe that rebate revisions hold the key for market acceptance of high-performance envelope work.

# Existing Building Stock

One of the challenges of retrofits is the countless differences in residential construction over decades (even centuries). The materials, workforce, tools, techniques, and codes all change over time. Furthermore, even homes that ostensibly share all those features deviate over time as various owners, renovations, updates, additions, remediation, and energy projects impact homes in different ways. The consequences of these vast differences are also often not immediately apparent even to very experienced practitioners who work directly in this space day after day. In other words, the wide variation among retrofits leads to uncertainty on work scope, requirements, and outcomes and these risks need to be managed. The following results are a preliminary attempt to characterize these differences and their consequences based on available data.

## Building Characteristics

Data representing the existing (pre-1990) building characteristics including age, siding type, home type, size, and window ratio are given in **Figure 3** Generally, they show most existing building stock is extremely old, with both the average and median age of pre-1990 construction between 70 and 80 years.

Siding types impact options and costs for retrofitting high-performance envelopes. Siding types are generalized into three groups: conventional, stucco, and masonry.

- Conventional siding (typically boards, sheets, planks of wood, vinyl, steel, or aluminum) that is fastened to the sheathing and make up 69% of homes. This consists of about one third of existing homes that are clad in wood and slightly less than a quarter (24%) that are clad each in vinyl and wood siding. Aluminum and steel, presumably lapped siding, make up about 12%.
- Stucco siding is found on 24% of homes.
- Masonry clad buildings make up just under 5% of existing homes.

Approximately 2% of buildings remain sided with asbestos. No engineered siding products including fiber cement or engineered wood show up in this dataset.

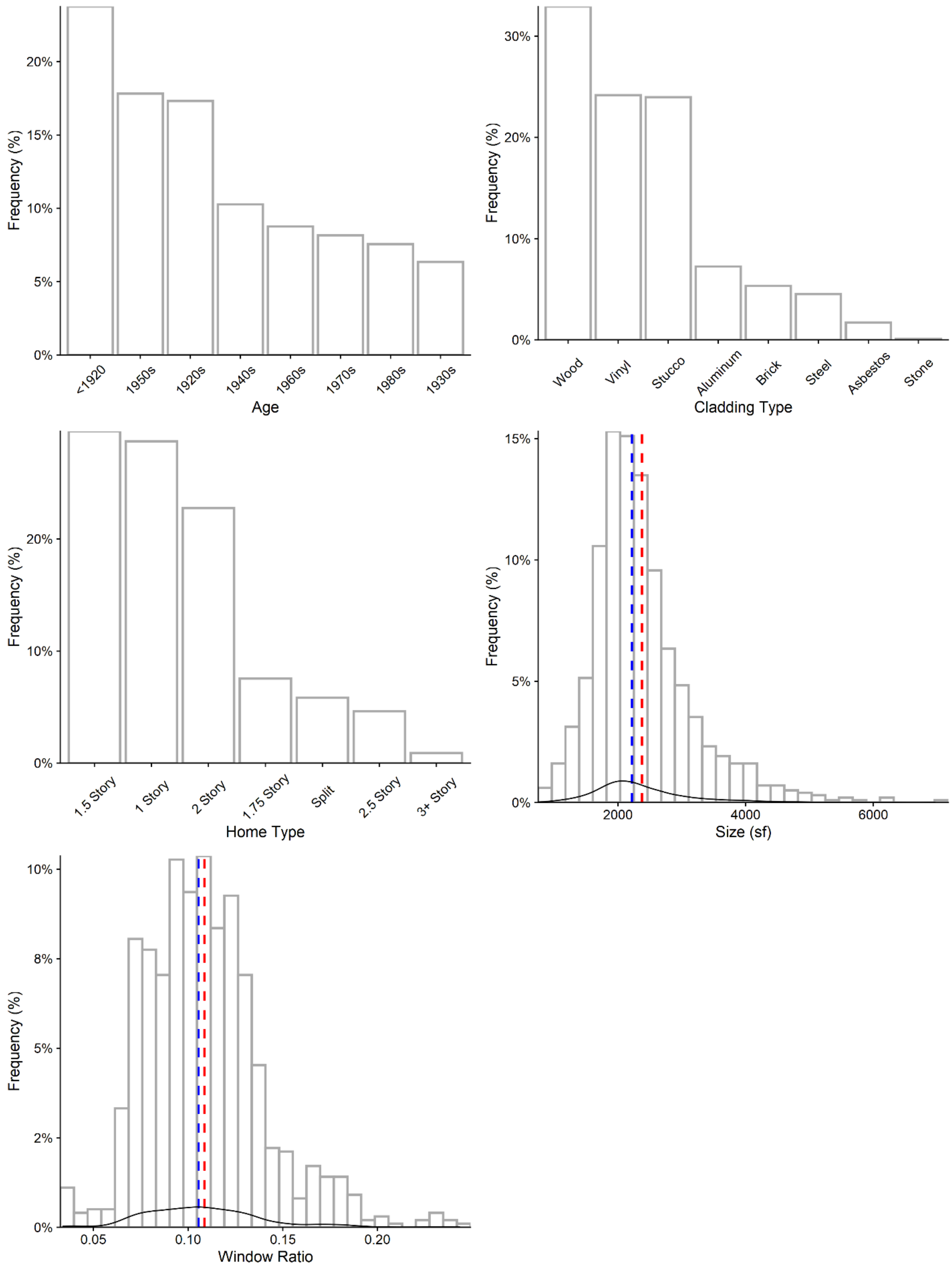
House types also vary. About 73% of the housing stock is less than two full stories and 27% is two full stories or greater. About 38% of the building stock includes partial second stories, which bring more complicated attic insulation planes and lower attic insulation potential.

Building sizes are characterized by a skewed normal distribution, biased toward larger homes as evidenced by the large deviation of the mean (2,380 sq ft) and median (2,200 sq ft). About 16% of homes are larger than 3,000 sf. One third of homes are less than 2,000 sf. Only 1% of homes are less than 1,000 sf.

Window ratios are somewhat narrowly distributed across a small range with some skew due to buildings with very high window ratios. The average window to floor ratio is 11%, representing about 260 sq ft of window area, excluding doors, and a median window area of 234 sq ft. This window area is about equal to approximately 20 typical size windows.

Later when we model energy savings and project costs, we define a median home as a 2,100 sq ft, one and a half story home with 21 windows.

**Figure 3: Baseline building characteristics; red is the average value and blue is the median value. Continuous distributions have skew due to a small population of unique homes**



# Baseline Envelopes

Envelope performance data are significant because they ultimately reveal where the building envelope loses energy, and subsequently where to focus efforts to improve envelope performance. The baseline data are given in **Figure 4**. Wall insulation remains around R-10 to R-11 $ft^2 \cdot °F \cdot hr/BTU$, which is consistent with 2x4 cavity fill or batts. A significant portion of homes (~50%) have less than this value. These are older buildings that have not had wall insulation work. Attic and rim joist values vary over a large range and are more independent of other housing characteristics, likely because improving these measures has been a focus of past energy efficiency work. Baseline leakage values show average leakage rates of about 2,500 cfm. When normalized by building square feet this leakage ratio is 1.065, supporting prior findings and anecdotal accounts that Minnesota homes are of tighter construction than national averages.

Foundation insulation and insulated headers are extremely rare and apparently only appear on homes constructed in the 1980s or later. Most windows are double pane (either via the addition of storm windows or retrofit/replacement windows). However, glazing treatments are somewhat rare, indicating mostly older, lower performance double pane windows or single pane plus storm window combinations.

In **Figure 5** and **Figure 6** the baseline portion of the total space heating loads associated with the major envelope components are shown for HDD65 = 8000. The boxplots show the distribution of heat loss through the envelope components across the single-family building stock. Each component is ranked by its proportion to the overall space heating load. Walls comprise the largest portion of heat loss on these homes (31% / 292 therms), followed by infiltration (23% / 220 therms), windows (16% / 155 therms), the roof/attic (9% / 85 therms), the foundation components, and the rim joists. Overall, the absolute heat loss and the percentage of heat loss through each component vary substantially, reflecting the large variations in the building stock.

These data reflect the success of past weatherization efforts. Attic insulation, rim joist insulation, and the near elimination of single pane windows have especially reduced the proportion of heat loss through these assemblies on many buildings. However, many baseline buildings still lack basic weatherization measures and a similar number of buildings have seen only partial weatherization to older, lower performance standards. Walls remain the most significant component of the remaining load in older single-family construction. From a weatherization perspective, this makes sense; retrofitting walls is a more involved and expensive retrofit.

**Figure 4: Baseline envelope thermal properties; red is the average value and blue is the median value. Most data distributions are somewhat skewed by a small population of large or efficient homes**

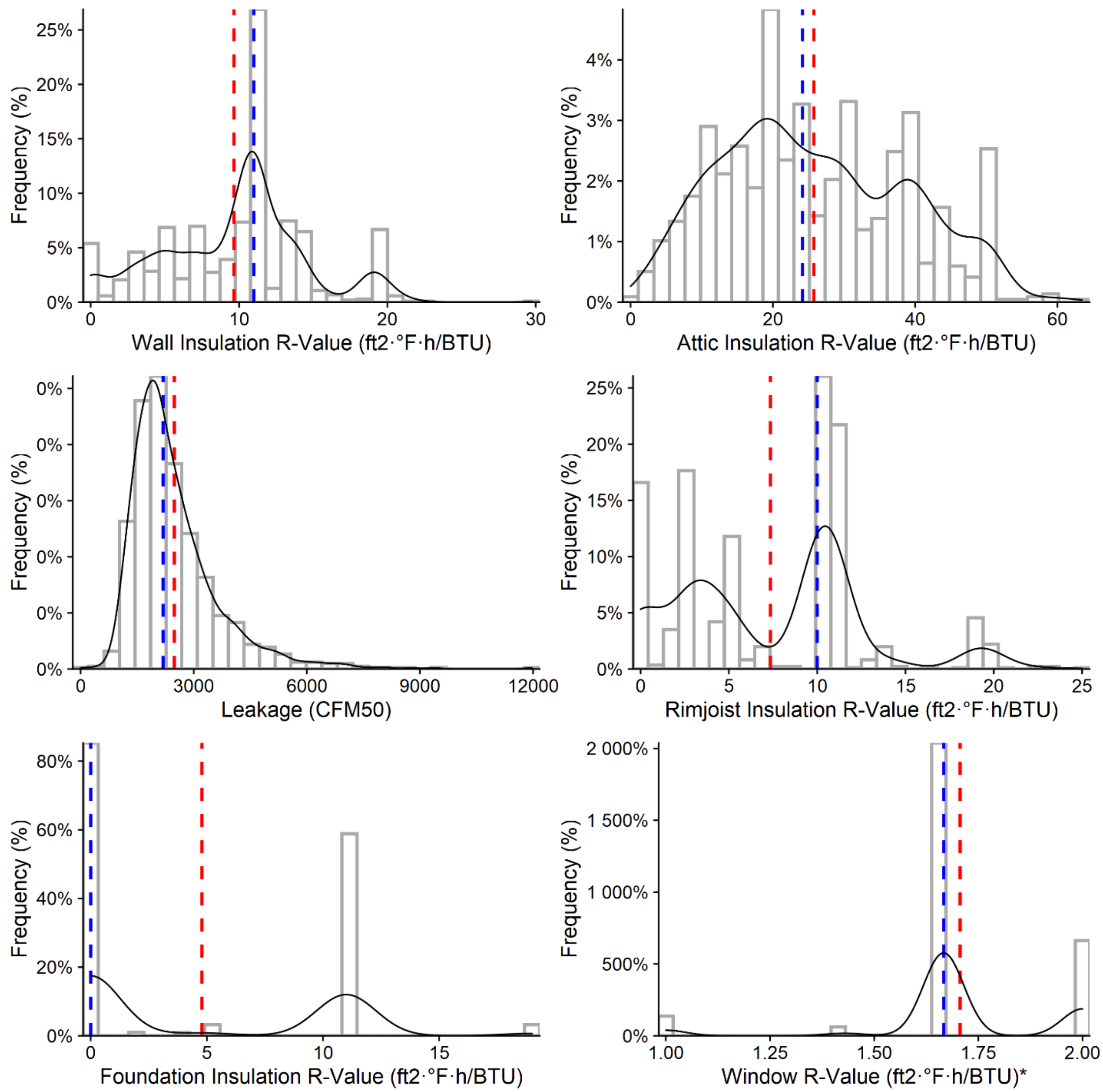


**Figure 5: Space heating loads of major envelope components in therms for HDD65 = 8000**

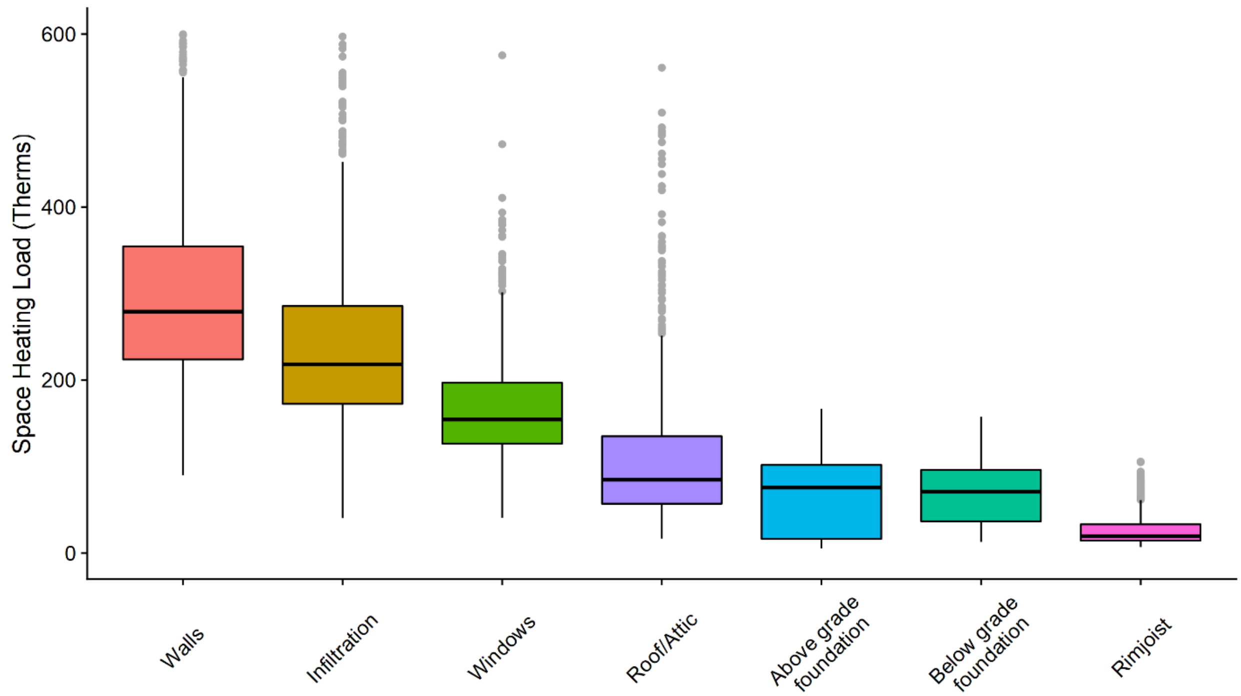
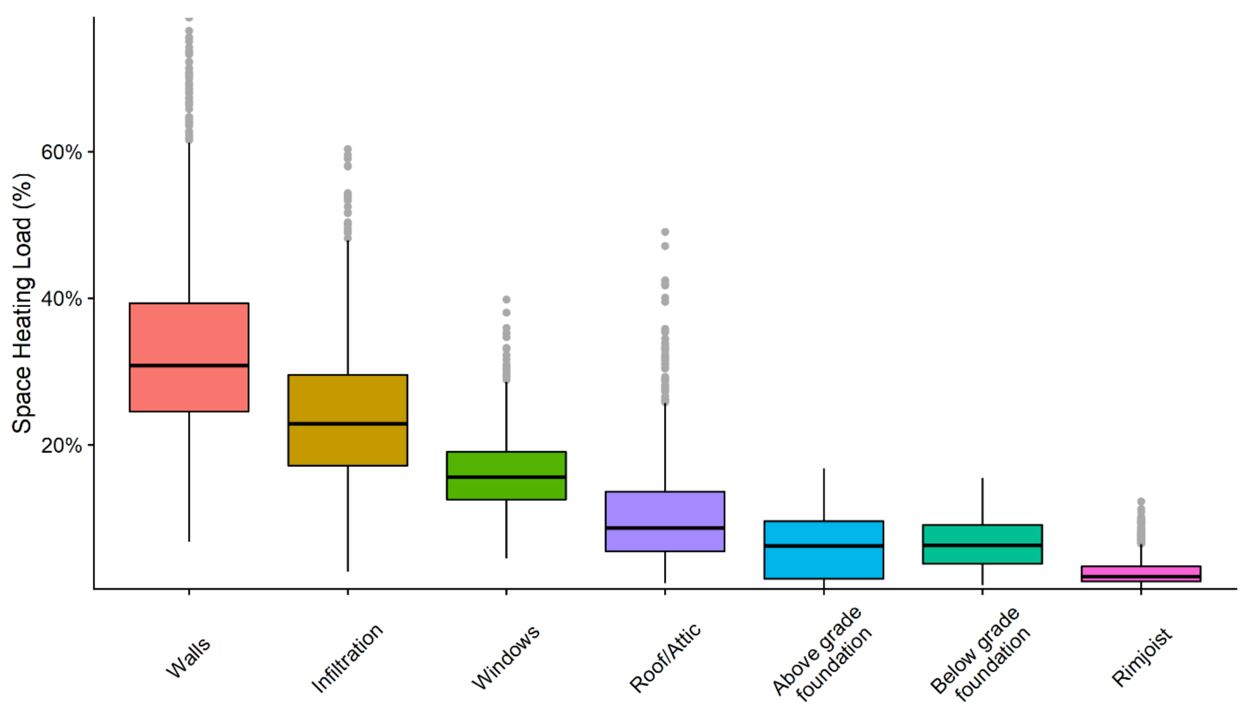



**Figure 6: Space heating loads of major envelope components in percentage of total space heating load**



# Weatherization

Data on the number of buildings that have been weatherized or have had other envelope efficiency updates are not available, but there is substantial evidence of past weatherization efforts in the dataset from reported insulation values in older buildings. Nonetheless, the data suggest most buildings have not completed all weatherization measures to current standards. Since weatherization measures, including air sealing, wall insulation, attic insulation, and rim joist insulation, are generally cost-effective on a program basis, they are assumed to be prerequisites for high performance envelopes. These completed weatherization measures may impact the costs (and cost-effectiveness) of additional envelope work, but those interactions are left for future work.

The model weatherizes existing building stock according to the criteria listed in **Table 3**. Air sealing work is performed on buildings with leakage rates exceeding 1.08 CFM50/sf and assumed to reduce overall infiltration by 15%. Dense pack insulation is added to wall cavities with existing wall insulation R-values less than R-8 $ft^2$·°F·hr/BTU to bring them up to R-11 and assumed to reduce infiltration by 10%. Attic insulation is added for buildings with average attic R-value less than 21.2 or 50 $ft^2$·°F·hr/BTU, depending on the insulation plane, to bring values up to the criteria value. Buildings with half or three-quarter stories factor in attic peak insulation, knee wall insulation, and slant insulation and are weatherized for average R-values less than 21.2 ft2·°F·hr/BTU, whereas buildings insulated in the attic floor are insulated to an R-value of 50 $ft^2$·°F·hr/BTU. Both have infiltration leakage reductions of 10%. Rim joist insulation of less than R-4 $ft^2$·°F·hr/BTU is insulated up to level of R-10 and infiltration is reduced by 5%. Weatherization often leads to relatively tight envelopes requiring mechanical ventilation. Continuous mechanical exhaust is added when infiltration supplies less than 50% of the IECC2012 ventilation requirements, which yields a similar result as suggested by the ASHRAE home tightness standard.

**Table 3: Criteria to determine if building qualifies for each weatherization measure**

| Measure | Criteria | Post-weatherization |
|---|---|---|
| **Air Sealing** | > 1.08 CFM50/sf | 0.85 CFM50/sf |
| **Wall Insulation** | < R-8 | R-11 / 0.9 CFM50/sf |
| **Attic Insulation** | < R-21.2* / R-50** | R-21.2* / R-50 and 0.9 CFM50/sf |
| **Rim Joist Insulation** | R < 4 | R-10 / 0.95 CFM50 |
| **Continuous Exhaust Ventilation** | < 50% code ventilation served by infiltration | NA |

*R-21 is an estimated overall value (including bridging, knee walls, slants, peak, and open roof areas) for 1.5 and 1.75 style homes

** Open attic floors

Summaries of the weatherization measure needs across existing building stock are shown in **Figure 7** and **Figure 8** Overall, about 98% of the existing homes built before 1990 need at least one weatherization measure, 41% of existing homes need two weatherization measures, 35% need three measures, 10% need four measures, and less than 1% of building stock need all five measures. The most needed weatherization measure is attic insulation at 80%. However, about half these buildings have already had existing attic insulation added to R-30 or higher. The second most needed measure is mechanical ventilation at 58%. Ventilation is often needed after performing attic insulation, wall insulation, or air sealing. Rim joist insulation is needed in 36% of existing homes, wall insulation is needed in 35% of existing homes, and air sealing is needed in 34% of existing homes.

**Figure 7: Weatherization measures needed in older building stock according to criteria in Table 3**

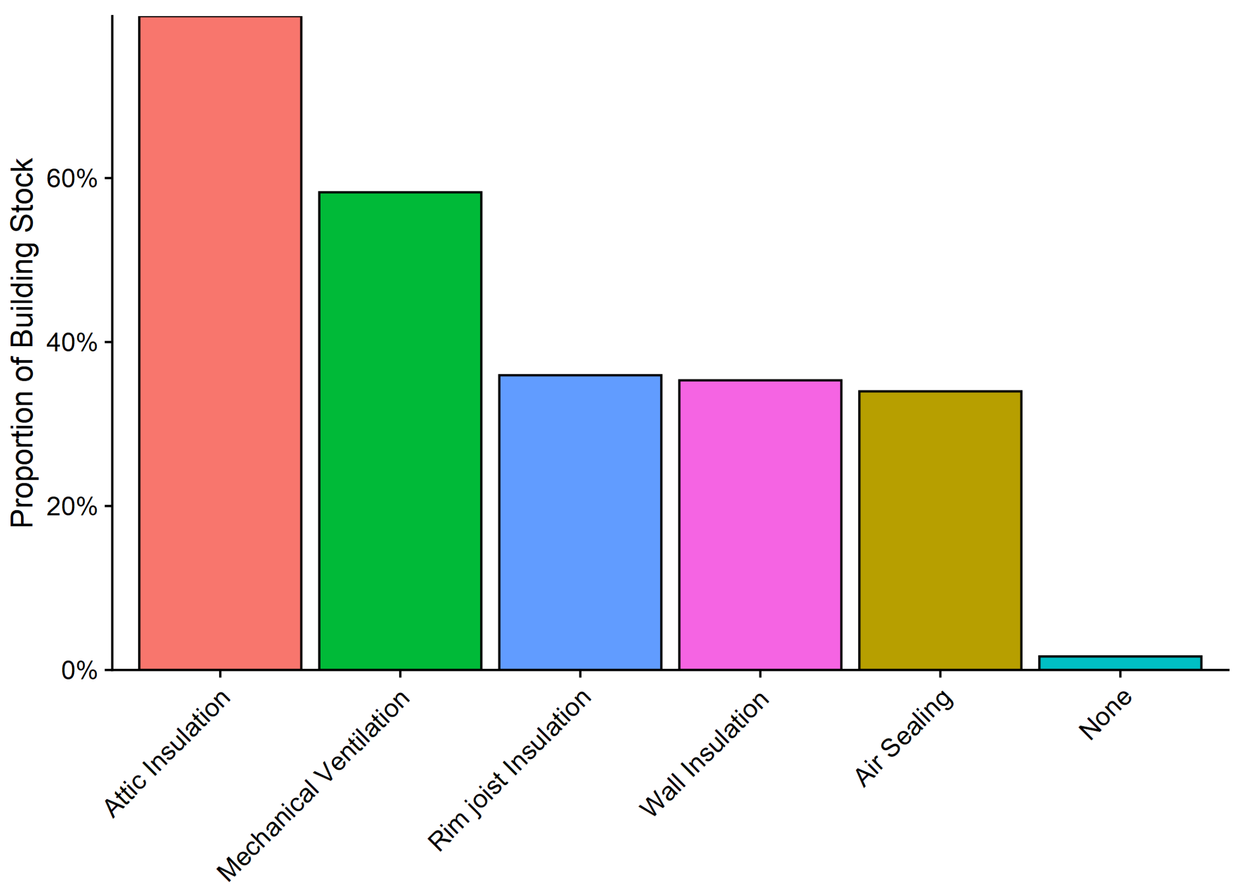
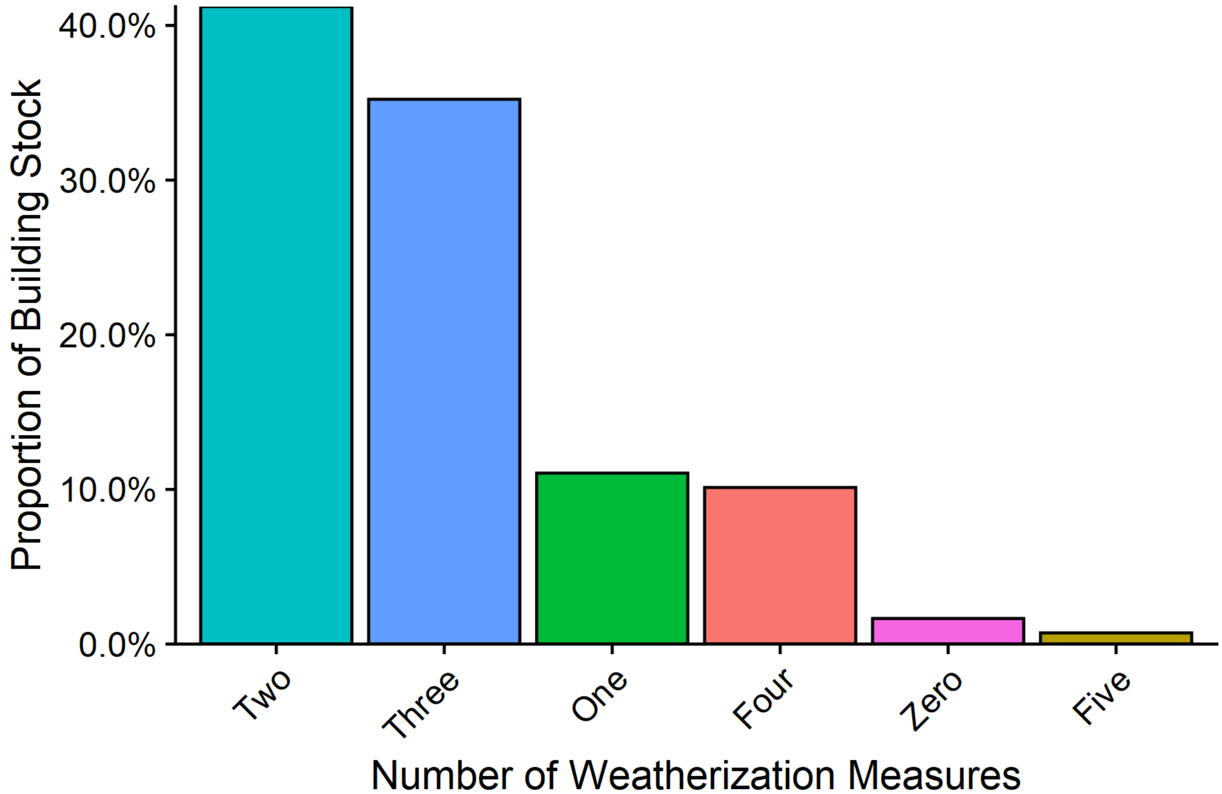
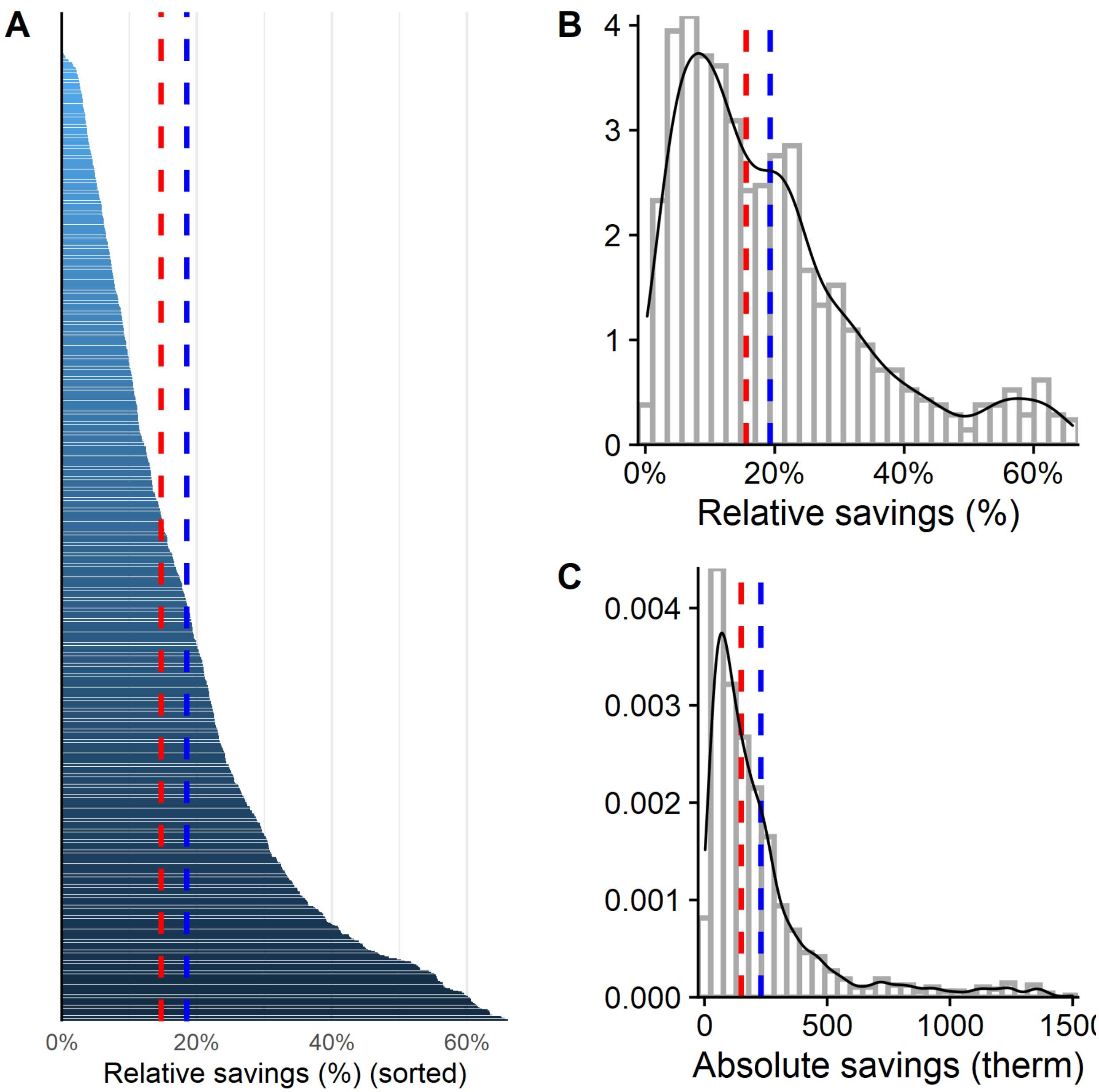


**Figure 8: Number of weatherization measures needed in older building stock according to criteria in Table 3**



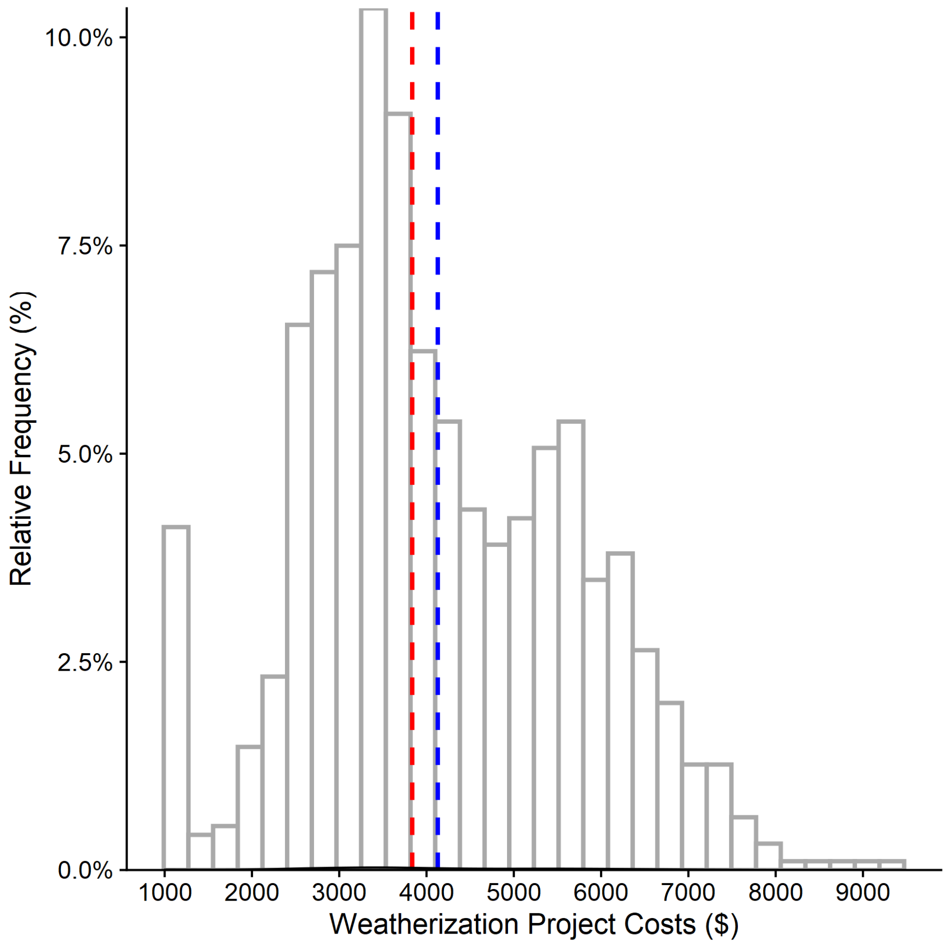

Weatherization energy savings results are summarized in **Figure 9**. Both the absolute space heating savings (therms) and the percentage savings are shown. While savings of 40% to 60% are possible in some buildings, average savings are 19%, and median savings are 15%. At HDD65 = 8000, this can amount to values in excess of 1,000 therm savings for some homes. However, the average and median space heating savings are 221 therms and 141 therms, respectively.

**Figure 9: Space heating savings from performing weatherization measures on existing housing stock according to criteria in Table 3. (a) Ranked from least to most savings, (b) The distribution of relative savings (%), and (c) The distribution of absolute savings (therm). The blue dashed line is the average savings, and the red dashed line is the median savings.**




Weatherization project costs as modeled from real project bids are shown in **Figure 10**. Costs range between $500 and $9,500. The cost distribution is bifurcated with local project cost peaks around $3,500 and $5,500, respectively, due to the requirement of either one or both wall insulation and attic insulation, the two most costly measures. Average project costs are $4,130 and median project costs are $3,840 to complete the weatherization measures required according to criteria in **Table 3.**

**Figure 10: Project costs estimates for completing weatherization measures on existing building stock according to criteria in Table 3. The blue dashed line is the average savings, and the red dashed line is the median savings.**




In **Figure 11** and **Figure 12**, the major envelope components' space heating loads for the existing building stock after undergoing weatherization are shown for HDD65 = 8,000. As with the baseline, the boxplots show the distribution of heat loss through the envelope components across the weatherized single-family building stock and each component is ranked by its proportion to the overall space heating load. Walls still comprise the largest portion of heat loss on these homes (30% or 252 therms), followed by infiltration (24% or 129 therms). Windows are unchanged by weatherization and still have a median space heating loss of 155 therms, but now represent 19% of the loss through the envelope. The roof/attic has dropped to 50 therms from the previous 85 therms and now represents about 6% of the space heating loss (9% or 85 therms), which has placed its proportion to overall space heating load behind that of both the above-grade and below-grade foundation components. One effect of weatherization is to tighten both the distribution of load across the treated components and also the proportion of each component to the overall load. This is observable in the compressed box plots (smaller interquartile range) as well as the substantially lower maximum loads and fewer outliers across the building stock compared to the baseline existing building stock. This follows from the fact that these weatherization measures simply bring deficient envelopes up to a minimum standard. However, the distribution of space heating loads across components doesn't change much, despite weatherization treatments affecting nearly every building.

**Figure 11: Space heating loads of major envelope components in therms for HDD65 = 8000 for weatherized building stock**

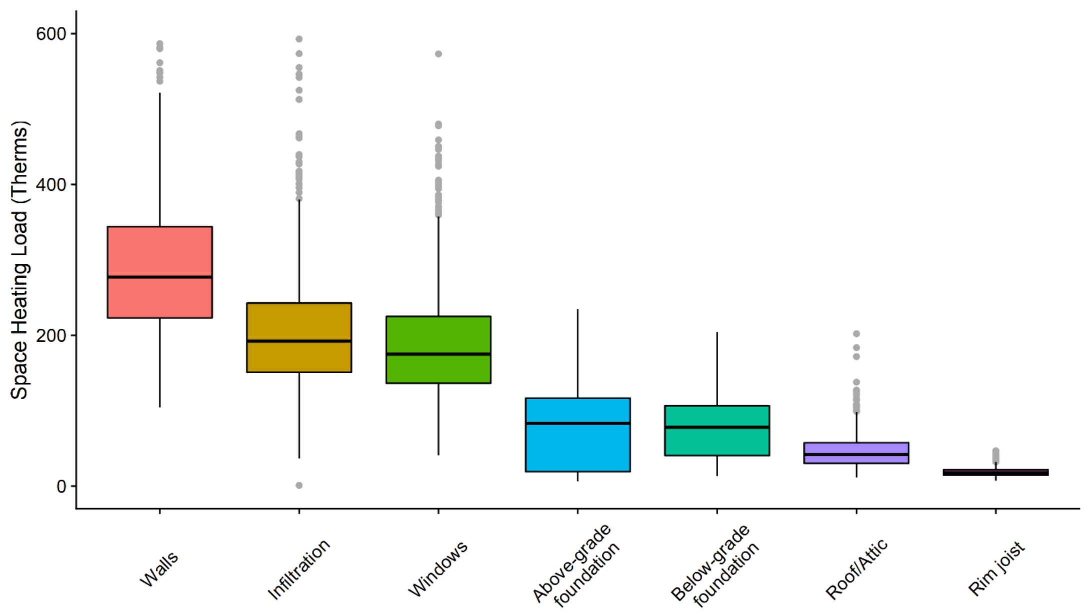
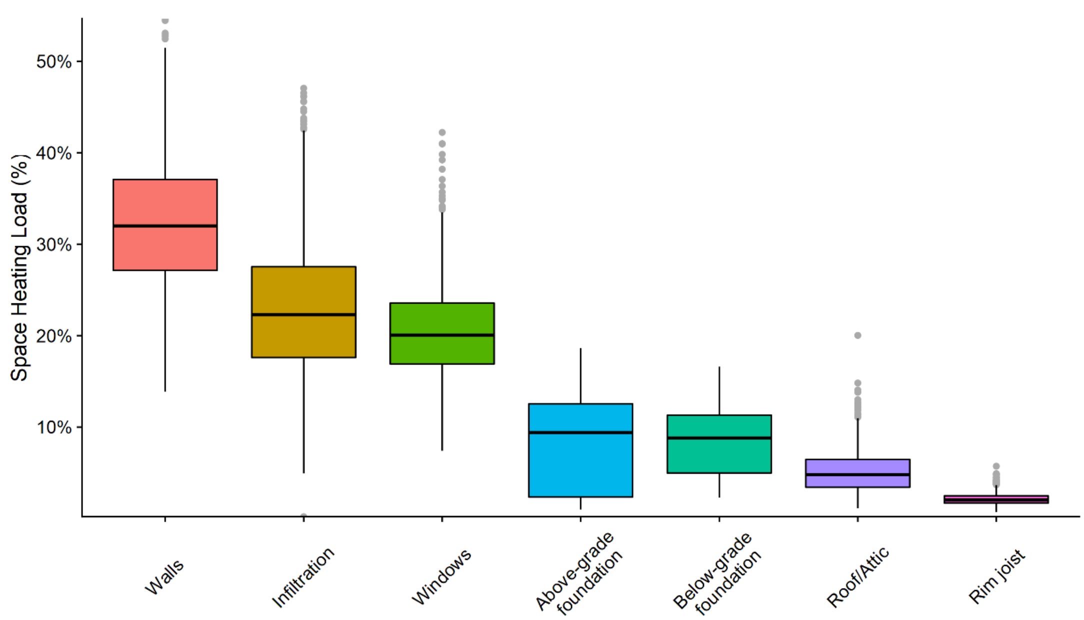



**Figure 12: Space heating loads of major envelope components in percentage of total space heating for weatherized building stock**



Of the weatherized single-family building stock, heat losses through walls, windows, and infiltration drive 74% of the space heating loads. However, 58% of the weatherized building stock needs mechanical ventilation to meet ventilation requirements such that additional improvements in air tightness are likely going to either compromise indoor air quality or require balanced ventilation with energy recovery. Since HVAC systems are neglected in this project, walls and window improvements become the focus of high-performance envelopes. Even so, it is likely that substantially more airtightness is achieved via additional wall and window improvements and the ventilation issue must be addressed.

# High-Performance Envelopes

## Baseline Measures

This study focuses exclusively on continuous insulation added to the exterior of buildings during re-siding or siding replacement projects. There's opportunity for these re-siding projects either at end-of-life replacement or early replacement, for example, as part of a larger renovation project. Re-siding is often necessary because most siding is typically not designed to be removed and reapplied, and the work process and most fixed costs of continuous exterior insulation coincide with re-siding. Furthermore, exterior retrofits such as new siding and windows have some of the highest value-to-cost ratios of home improvements, returning on average 55% to 75% of the cost of the project to equity for the past several years.[5] In these projects, existing siding is removed and insulation is added prior to the addition of new siding. In some cases, insulation and new siding are applied over the existing siding (the over-siding approach). However, since siding is long-lived and usually not meant to be reapplied, it is critical that continuous exterior insulation coincide and coordinate with re-siding work. Exterior fixtures and wall penetrations need to be reworked to accommodate the increased thickness of the wall assembly. Likewise, windowsills must be extended to the new wall plane. Alternatively, if this work is coordinated with window replacement, the window can be moved to the exterior, but in this case sill extensions are required.

This study models building envelope retrofit projects that consist of adding continuous exterior insulation and re-siding with three types of material.

### *Vinyl Lap Siding*

Vinyl siding remains the most common siding for re-siding projects on existing homes because it is low cost and low maintenance. While some insulated vinyl siding products are available, these products are neglected here. In most cases existing siding is removed, and a weather barrier and new vinyl siding is applied. In some cases, vinyl siding may be removed and reapplied, but these cases are ignored here. For existing stucco buildings, the over-siding approach is also considered due to the high demolition costs of existing stucco siding. This project considers triple-3 vinyl lap siding, but several other formats offer potential aesthetic variability at similar cost.

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[5] Remodeling Magazine, Annual Cost vs. Value Study, https://www.remodeling.hw.net/cost-vs-value/

## *Fiber Cement Lap Siding*

Fiber cement is a combination of cellulose fiber and cement. While not very common in retrofit projects, it is very popular in new construction. In most cases existing siding is removed, and a weather barrier and new fiber cement siding is applied. For existing stucco buildings, the over-siding approach is also considered due to the high demolition costs for existing stucco siding. Fiber cement serves as the premium siding baseline. This project considers eight-inch lap siding, but fiber cement is available in other styles, including different plank dimensions, shingle/shakes, board & batten, and vertical siding, to enable significantly more aesthetic variety than typical lap siding.

## *Synthetic Stucco*

Synthetic stucco, also called exterior insulation and finish system (EIFS), is a modern, lightweight version of traditional stucco. While aesthetically like stucco, its lighter weight reduces mechanical loading requirements. Typically, fiber mesh typically replaces the metal lathe found in traditional stucco. It serves as a baseline option for replacing original stucco siding while maintaining the original aesthetic. It is the only siding system that incorporates continuous exterior insulation by default. The baseline incorporates one inch of continuous XPS insulation, providing R-5 insulation value.

The applications of the above baseline siding projects with the existing siding types are summarized in **Table 4**. Vinyl siding and fiber cement siding are considered for all existing siding types except masonry and asbestos. Conventionally clad buildings include wood, vinyl, steel, and aluminum. While over siding is an option for brick and stone buildings,[6] they are neglected here due to their low incidence in the building stock (<5%). Buildings that are partially clad in brick (e.g., brick lowers or front facades) are also neglected due to this data's absence from the dataset. Asbestos clad buildings are ignored due to low incidence (<2%) and variable cost of abatement.

**Table 4: Re-siding measures considered as baseline projects for high performance envelopes**

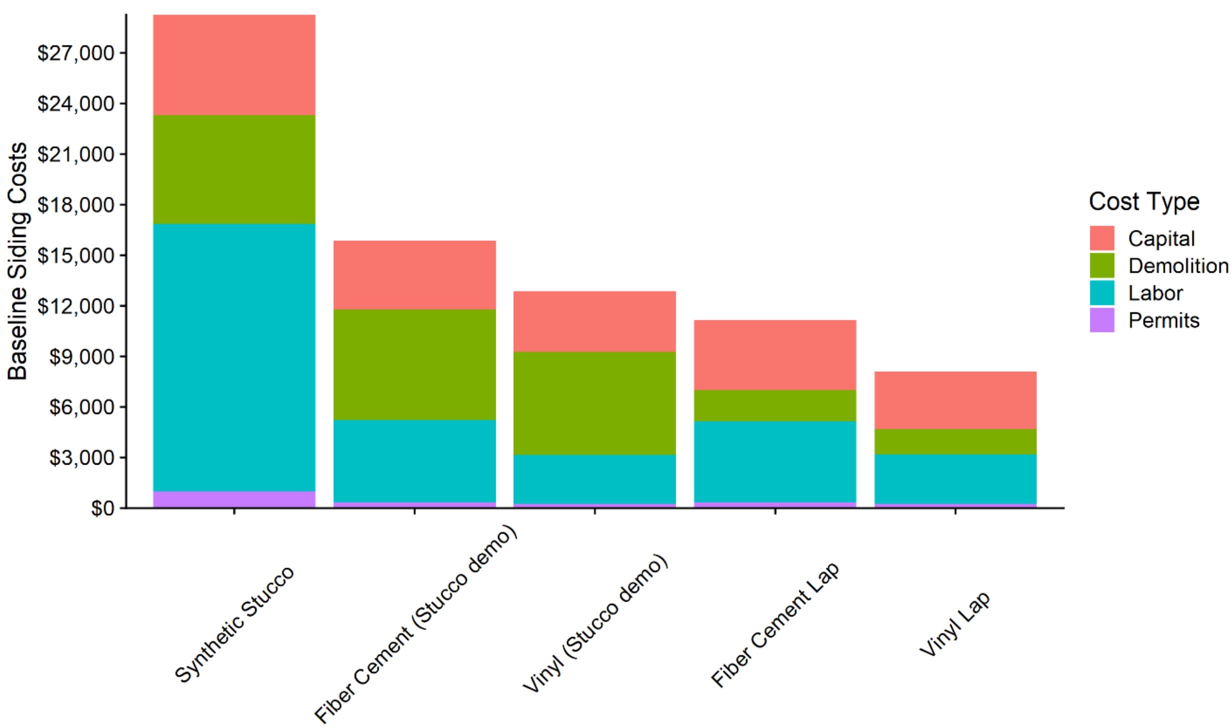
| **New Siding** | **Existing Siding** | | | | | | |
|---|---|---|---|---|---|---|---|
| **-** | Wood | Vinyl | Aluminum | Steel | Stucco | Masonry | Asbestos |
| **Vinyl** | X | X | X | X | X | - | - |
| **Fiber Cement** | X | X | X | X | X | - | - |
| **Synthetic Stucco** | - | - | - | - | X | - | - |

[6] Neuhauser, Ken, August 30, 2013. "BA-1311: Evaluation of Two CEDA Weatherization Pilot Implementations of an Exterior Insulation and Over-Clad Retrofit Strategy for Residential Masonry Buildings in Chicago," Building Science Corporation. (https://www.buildingscience.com/documents/bareports/ba-1311-evaluation-two-ceda-weatherization-pilot-implementations/view)

## *Baseline Siding Costs*

Re-siding costs for a median application are shown in **Figure 13**. Due to differences in material costs, labor costs, and their relationship to building geometry, the median application varies with the siding type. Siding projects on stucco buildings command very high premiums, about two to three times conventional siding projects. The labor costs to remove stucco even for replacement add about a 50% to the cost of conventional fiber cement and vinyl siding projects. Labor costs account for the most of all siding projects' costs: 54% for vinyl siding, 60% for fiber cement siding, and 76% for synthetic stucco. While lowering overall project costs substantially, the demolition of stucco to be replaced with vinyl or fiber cement also yields high labor costs, 70% and 72% respectively. Permit costs, as averaged across methodologies from several Minnesota jurisdictions, range from about 2.0% to 3.5% of total project cost.

**Figure 13: Baseline re-siding costs for the median home (median home characteristics depend on siding project)**




Costs for the baseline siding projects across the entire building stock are shown in **Figure 14** and **Table 5.** As with the median case, projects involving existing stucco are the most expensive across the entire building stock, owing to the demolition costs of existing stucco siding. Removing stucco siding and replacing with a synthetic stucco finish has a median cost of $29,137. Demolishing stucco is labor intensive, costing around $4,000 to $6,000 total, which doubles the cost of both vinyl and fiber cement applications at the low end compared to an over-siding approach. Median fiber cement siding costs are $11,197, which represents nearly a 40% premium over median vinyl siding costs of $8,057. Average siding costs are about 2% to 3% larger than median siding costs due to the influence of large and complex homes. Median siding costs vary from about 6% of assessed home value for vinyl, 8% for fiber cement, and 20% for synthetic stucco. Replacing stucco with vinyl and fiber cement cost about 9% and 11% of assessed home value, respectively.

**Figure 14: Re-siding costs for baseline siding projects**

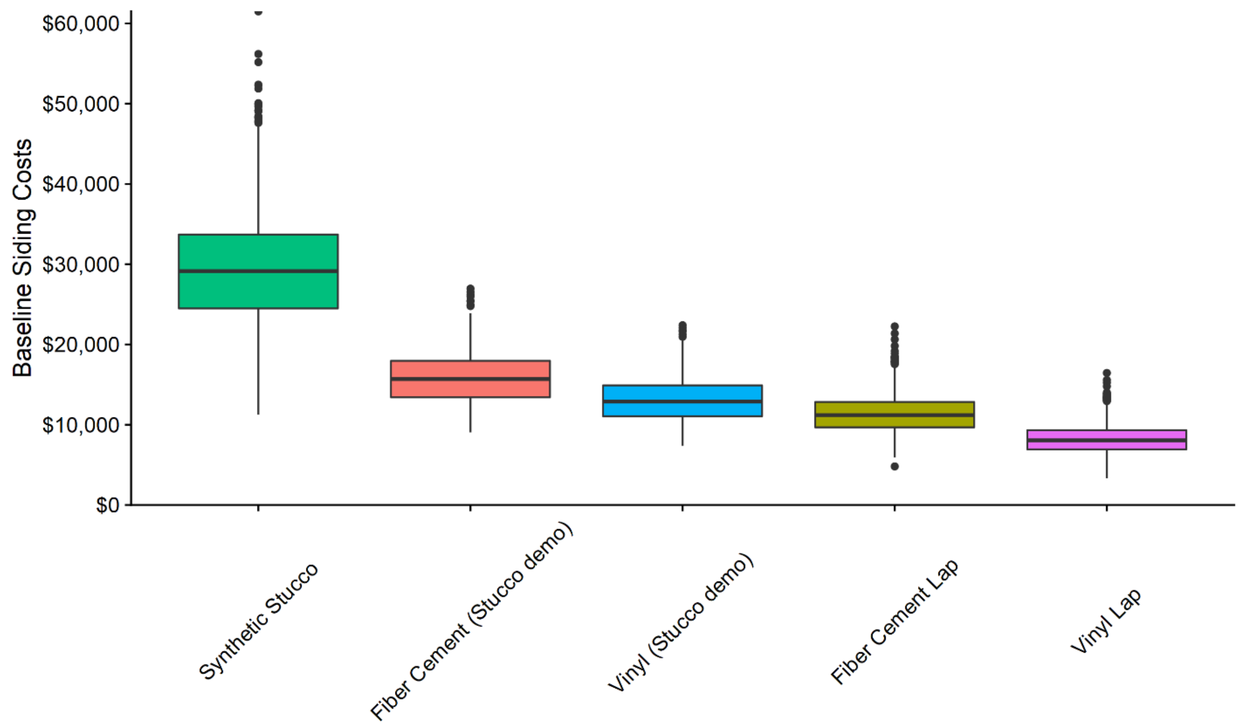



**Table 5: Re-siding costs for baseline siding projects**

| - | Synthetic Stucco | Fiber Cement | Vinyl | Fiber Cement (Stucco Demo) | Vinyl (Stucco Demo) |
|---|---|---|---|---|---|
| **Min** | $11,252 | $4,806 | $3,355 | $9,050 | $7,391 |
| **25th Percentile** | $24,491 | $9,681 | $6,922 | $13,417 | $11,047 |
| **Median** | $29,137 | $11,197 | $8,057 | $15,688 | $12,889 |
| **75th Percentile** | $33,699 | $12,829 | $9,308 | $17,962 | $14,896 |
| **Max** | $61,495 | $22,246 | $16,445 | $26,945 | $22,392 |
| **Average** | $29,710 | $11,445 | $8,266 | $16,058 | $13,249 |

## Window Measures

According to the modeled building stock, windows represent the third biggest opportunity for reducing envelope heat loss. While most of the existing building stock has upgraded to double-pane windows from original single panes, most of these upgrades are either via older double-pane technology or through the addition of storm windows to original single pane windows. These older retrofits likely have U-factors of 0.5 to 0.7 Btu/h·ft$^2$·F, whereas new builder spec windows have U-factors of 0.3 to 0.32 Btu/h·ft$^2$·F. In other words, the low end of current double-pane windows (builder-spec) offers an opportunity to reduce window losses 40% to 50% from existing building stock. This study considers three types of window projects shown in **Table 6**, a low-end retail vinyl replacement window, custom vinyl replacement windows, and high-performance fiberglass (new construction) triple pane windows. In all cases, cost data vary widely. For the purposes of this study, several window types and sizes were considered and consolidated to get average costs per square foot that are applied equally based on existing building window area. While window installation costs (especially with new-construction) are lower when coupled with other exterior work (e.g., re-siding and continuous insulation), these cost-saving synergies are not considered here.

We assume retail and custom replacement windows have the same performance, U value of 0.3 Btu/h·ft$^2$·F. The major difference is that retail windows are typically restricted by window type, color, and size. Custom replacement windows can be adapted to any size, aesthetic, or type. Notably, both replacement windows are designed to fit within the existing sash. Custom replacement windows have similar installation labor costs, but about 60% higher material costs than the retail type. The high-performance triple pane windows replace the entire existing window assembly (new-construction windows), but achieve an additional 50% improvement in U-factor (U = 0.2 Btu/h·ft$^2$·F). However, they do so at 20% higher capital cost of custom replacements and nearly double the installation cost. Additional performance features such as glazing treatments that affect solar gains and visibility are neglected here but will generally have a positive impact on both heating and cooling performance when incorporated into custom products.

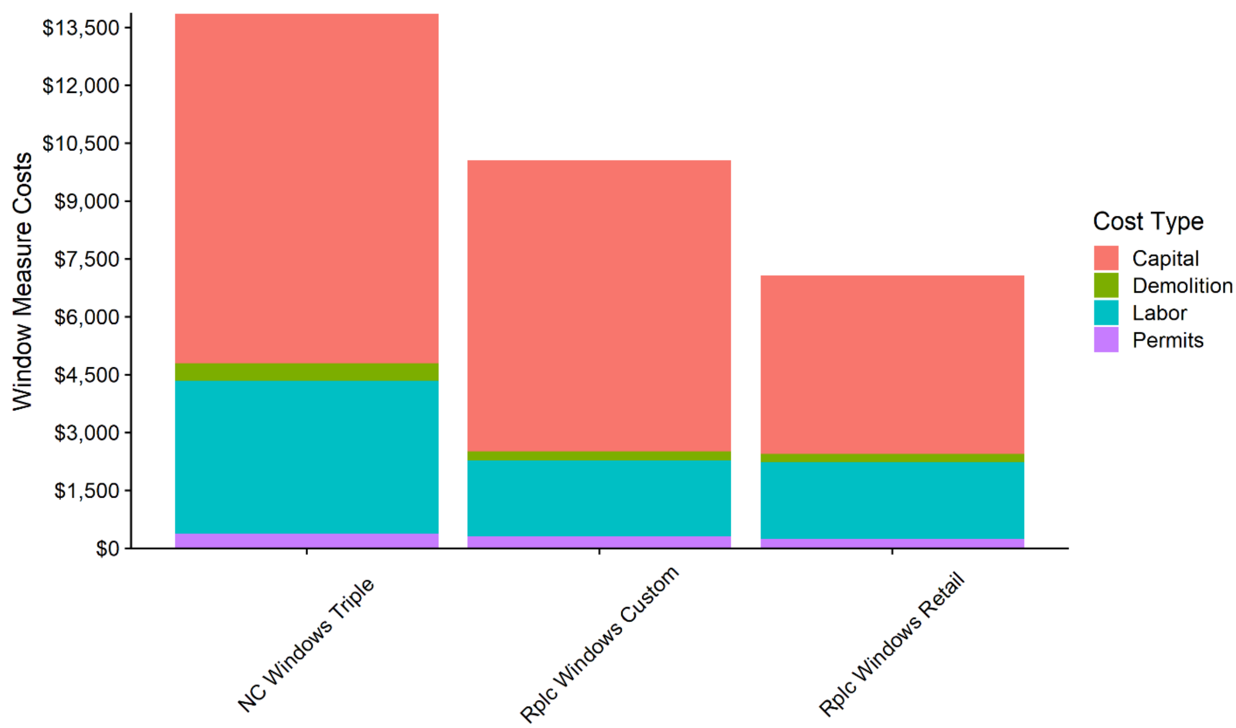
**Table 6: Window measures considered for high performance envelopes**

| Window Type | Advantages | Disadvantages |
|---|---|---|
| **Vinyl Replacements - Retail** | Low cost | Limited sizes, aesthetics |
| **Vinyl Replacements – Custom** | Custom sizes and aesthetics | Extra cost |
| **Fiberglass New Construction – Triple-pane** | Custom sizes and aesthetics, high performance | Very high cost |

## *Window Installation Costs*

Modeled window costs for a median application (2,100 sf, one and a half story home with 21 windows) are shown in **Figure 15**. Labor costs represent 31% of retail vinyl replacement window costs, 22% of custom vinyl replacement window costs, and 32% of high-performance triple pane window costs. The difference between retail and custom replacement windows are higher capital costs for custom window sizes and aesthetics. Permit costs range from 2.7% to 3.5% of total project cost in a median application, depending on measure type. Fully loaded window costs are $335, $476, and $656 per window for retail replacements, custom replacements, and high-performance new construction windows, respectively.

**Figure 15 Window measure costs for a median application (2,100 sq ft, one and a half story home with 21 windows)**




The cost of these window measures across the building stock are summarized in **Figure 16** and **Table 7**. Even under simplified cost assumptions, window measure costs vary by a factor of nearly 15 across the building stock due to variations in building size and window area ratio. Retail vinyl replacement windows range from $1,781 to $25,404 with median and average costs of $7,123 and $7,614, respectively. As shown previously, custom replacement windows have similar labor costs to retail replacements but higher capital costs, yielding install costs that range from $2,533 to $36,527 with median and average costs of $10,127 and $10,829, respectively. New construction high-performance triple pane windows have higher capital and installation costs ranging from $3,463 to $50,207 with median and average costs of $13,948 and $14,929, respectively. Average costs exceed median costs by about 7% due to the influence of large and high window ratio homes.

Figure 16. Window measure costs across existing building stock

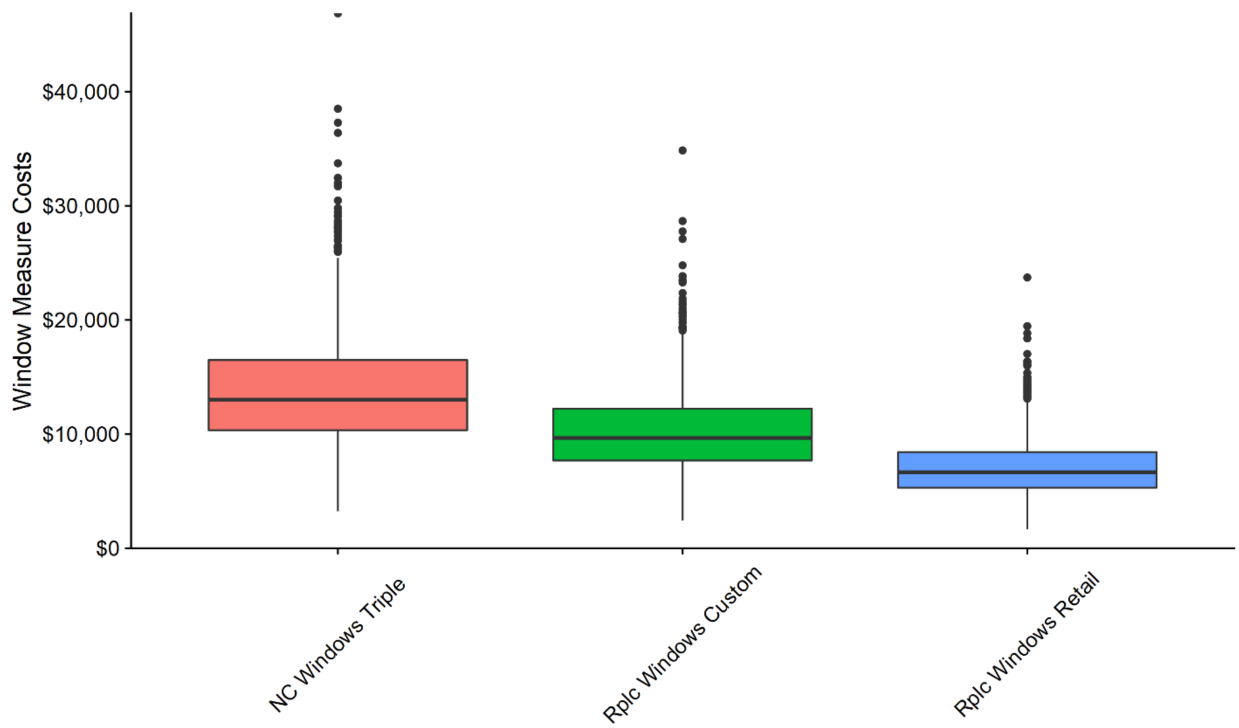



Table 7: Window measure costs

| - | Replacement – Retail | Replacement – Custom | New Construction – Triple Pane |
|---|---|---|---|
| **Min** | $1,781 | $2,533 | $3,463 |
| **25th Percentile** | $5,670 | $8,050 | $11,081 |
| **Median** | $7,124 | $10,128 | $13,948 |
| **75th Percentile** | $9,011 | $12,824 | $17,670 |
| **Max** | $25,404 | $36,527 | $50,207 |
| **Average** | $7,614 | $10,829 | $14,930 |

## *Window Measure Performance*

Annual energy savings at HDD65=8000 are shown in **Figure 17**and **Figure 18** for replacement windows and triple pane windows, respectively. Retail and custom replacement window measures are assumed to have the same performance. Median energy savings are 10% and 13% or 84 therms and 108 therms for replacement and high-performance windows, respectively. Median and average energy savings for replacement windows coupled with weatherization are 24% and 27% or 230 therms and 310 therms, respectively. Median and average energy savings for high-performance windows and weatherization are 27% and 30% or 257 therms and 336 therms, respectively.

**Figure 17. Annual energy savings (HDD65 = 8000) for replacement windows across the existing building stock. The red dashed line denotes median savings; the blue dashed line denotes average savings.**

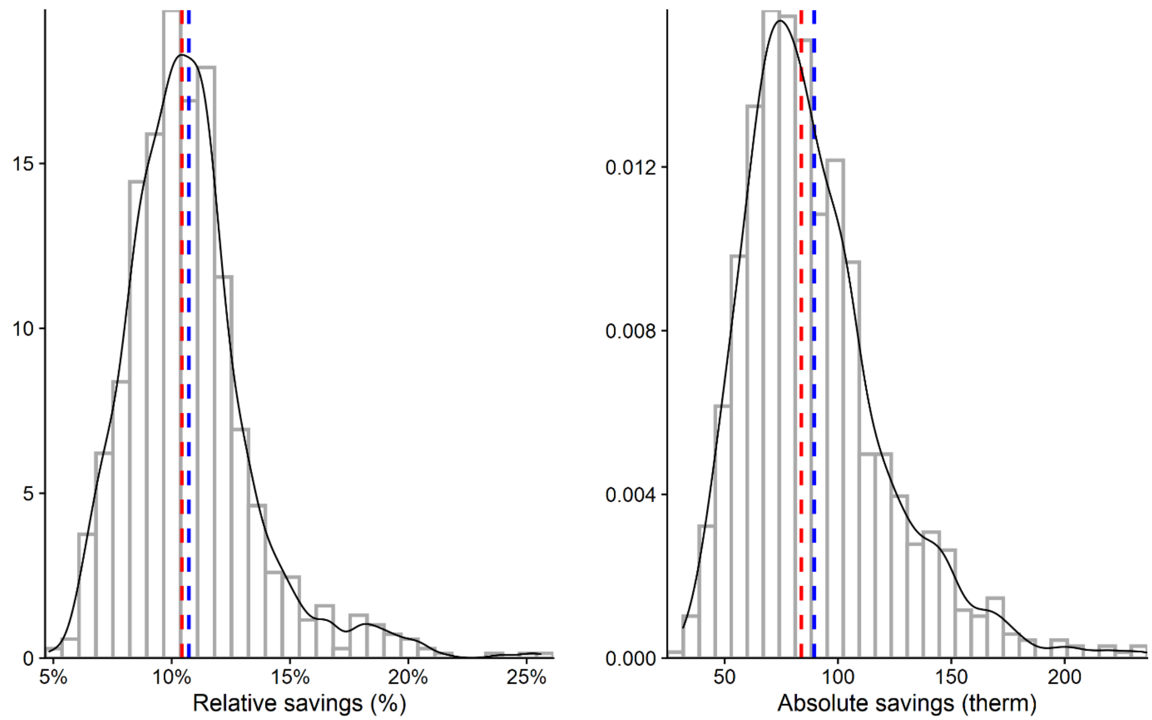
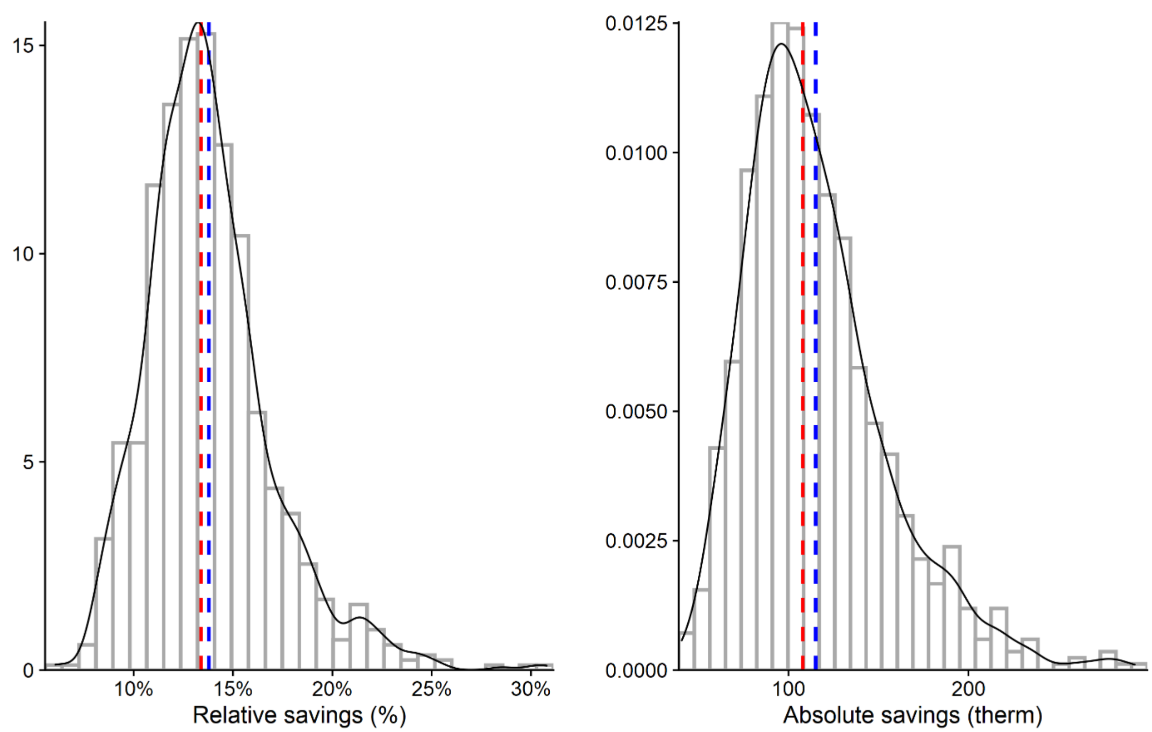



**Figure 18: Annual energy savings (HDD65 = 8000) for new construction triple pane windows across the existing building stock. The red dashed line denotes median savings; the blue dashed line denotes average savings.**



## Continuous Insulation Measures

The modeled building stock, even when weatherized with cavity-fill insulation, shows that exterior walls remain the largest opportunity for improving envelope performance. The continuous exterior insulation measures considered in this project to supplement existing wall insulation are outlined in **Table 8**. Eight types of insulation measures are considered:

- extruded polystyrene (EPS),
- expanded polystyrene (XPS),
- Synthetic stucco (EIFS) with expanded polystyrene XPS,
- polyisocyanurate (POLYISO),
- structural insulated panel (SIP) with EPS,
- closed cell spray foam (CCSF),
- mineral wool, and
- wood fiber insulation.

All eight insulation types can be added to both baseline vinyl and fiber cement siding projects. Synthetic stucco (EIFS) applications are assumed to only use XPS insulation. Excluding synthetic stucco, each insulation measure includes an air gap between the new wall assembly and the siding. Sometimes called a rainscreen application, the air gap helps dry the new insulation assembly and provides an additional level of forgiveness against installation mistakes. The gap is assumed to be 3/8 inches thick and requires vented flashing at the top and bottom of the assembly for airflow and to prevent insect infiltration. The gap is created using furring strips that are fastened to the studs by fasteners appropriate to the assembly's thickness. The baseline siding is then fastened to the furring strips according to regular specification. This step adds significant costs but provides a wall section that is capable of high thermal performance and better moisture management. It also potentially enables an additional flashing plane for windows.

Alternatively, insulation can be added to the inside of the existing wall assembly by building out a second stud wall and filling the wall cavity and interstitial space between the two walls with insulating material such as dense-pack cellulose.  The walls can be constructed an arbitrary distance away from the exterior wall, allowing for very high insulation values. However, wall fixtures and existing window jams must be moved or rebuilt to accommodate the new interior dimensions. This measure is neglected here due to its invasiveness; nonetheless, it remains a viable option for unoccupied larger homes that have interior space to spare and exterior aesthetics to maintain (e.g., historical preservation).

**Table 8: Continuous exterior insulation measures considered for high performance envelopes.**

| Type | R-value per inch | Thickness (in.) |
|---|---|---|
| **EPS** | 4 | 1.5, 2, 3, 4, 6 |
| **XPS** | 5 | 1, 1.5, 2, 3, 4 |
| **EIFS - XPS** | 5 | 1.5, 2, 3, 4 |
| **POLYISO** | 6 | 1, 1.5, 2, 3 |
| **SIP - EPS** | 4 | 3.5, 5.5 |
| **Closed Cell Spray foam (CC)** | 7 | 1, 1.5, 2, 3 |
| **Mineral wool (MWOOL)** | 4 | 1.5, 2, 3, 4 |
| **Wood fiber (WFIBER)** | 4 | 1.5, 2, 3, 4 |

## *Incremental Costs of Continuous Exterior Insulation*

The incremental costs of continuous exterior insulation are shown by project for a median application in **Figure 19**. Labor costs vary between about 34% and 44% of project cost. SIP projects have the lowest labor costs (26%), and low R-value projects (<R-10) tend to have higher relative labor costs from 45% to 52%. Permit costs range from 1.5% to 4.4%.

The distribution of incremental costs by project across the existing building stock are summarized in **Figure 20** and **Table 9**. These costs are normalized by the added R-value of the project in **Figure 21** and **Table 10**. Overall, there are large cost variations across the project type and the building stock (up to a 25-fold difference). Even within specific measure types costs vary 4- to 6-fold. Measures with low insulation values (<R-7) have incremental costs that vary from about $3,000 to $10,000 or about $500 to $2,500 per R-value. Measures with high insulation values (>R-20) have incremental costs that vary from about $4,400 to $36,000 or about $300 to $1,500 per R-value. For most types of insulation measures, capital (materials) costs are the largest component.

**Figure 19. Incremental costs of continuous exterior insulation for a median application by project type**

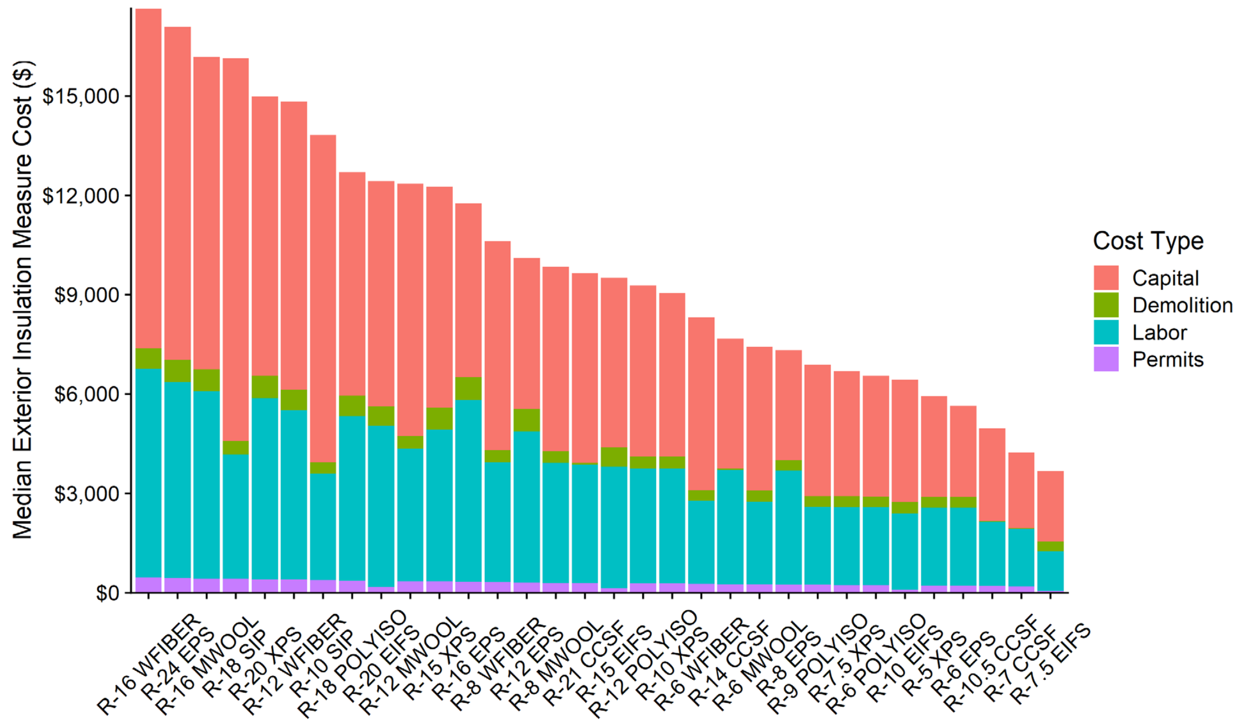



**Figure 20. Incremental costs of continuous insulation measures across existing building stock**

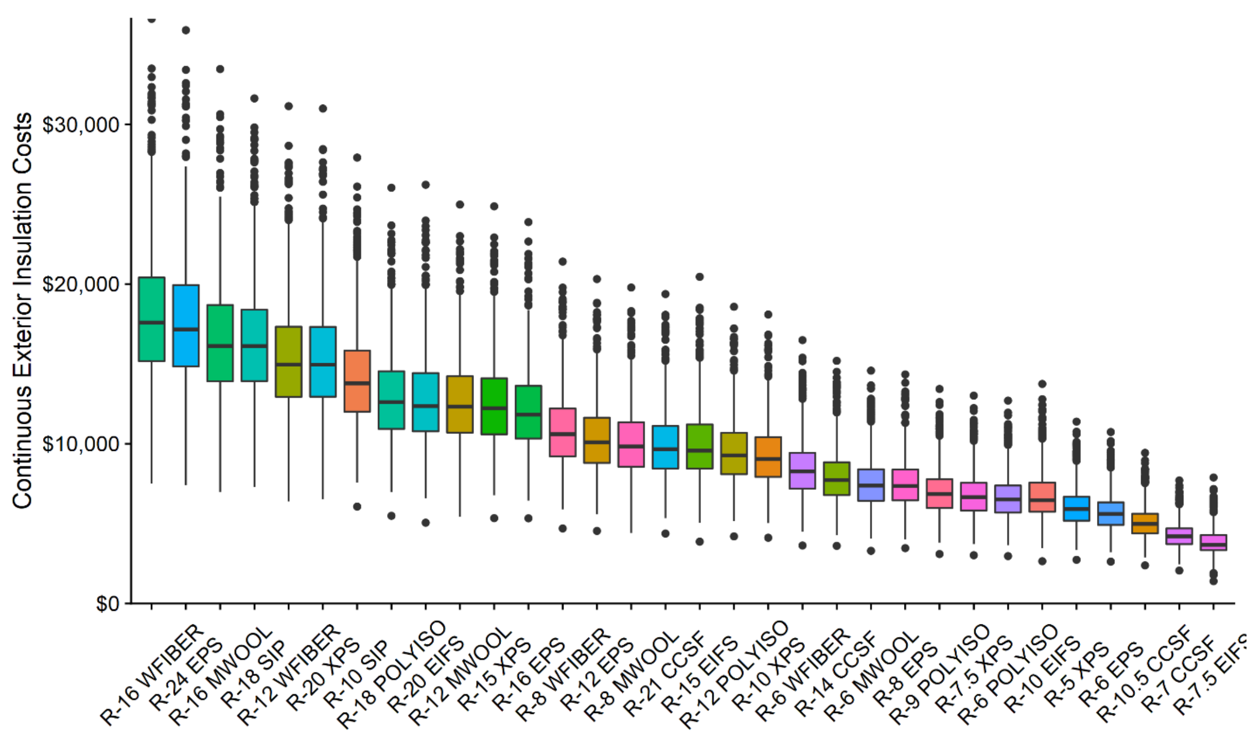


**Figure 21. Incremental costs of continuous insulation measures across existing building stock per R-value of added insulation**

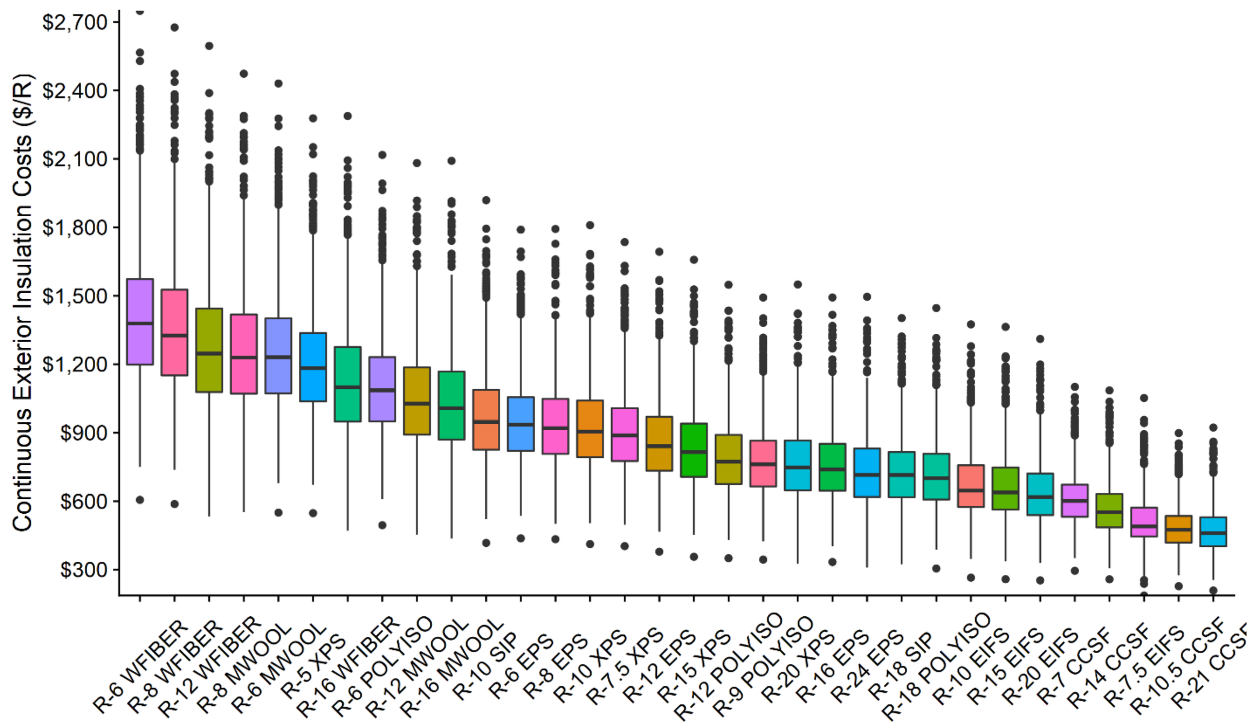



**Table 9: Incremental costs of continuous insulation measures across existing building stock**

| Project | Min. | 25th percentile | Median | 75th percentile | Max. | Average |
|---|---|---|---|---|---|---|
| **R-5 XPS** | $2,738 | $5,187 | $5,915 | $6,685 | $11,389 | $6,062 |
| **R-6 EPS** | $2,624 | $4,922 | $5,611 | $6,336 | $10,739 | $5,753 |
| **R-6 MWOOL** | $3,299 | $6,431 | $7,386 | $8,406 | $14,583 | $7,580 |
| **R-6 POLYISO** | $2,969 | $5,697 | $6,516 | $7,389 | $12,704 | $6,687 |
| **R-6 WFIBER** | $3,634 | $7,191 | $8,275 | $9,440 | $16,492 | $8,488 |
| **R-7 CCSF** | $2,065 | $3,721 | $4,209 | $4,708 | $7,708 | $4,300 |
| **R-7.5 EIFS** | $1,400 | $3,340 | $3,671 | $4,289 | $7,891 | $3,820 |
| **R-7.5 XPS** | $3,024 | $5,819 | $6,661 | $7,557 | $13,016 | $6,835 |
| **R-8 EPS** | $3,467 | $6,458 | $7,361 | $8,387 | $14,343 | $7,543 |

| Project | Min. | 25th percentile | Median | 75th percentile | Max. | Average |
|---|---|---|---|---|---|---|
| **R-8 MWOOL** | $4,416 | $8,568 | $9,836 | $11,346 | $19,787 | $10,134 |
| **R-8 WFIBER** | $4,701 | $9,210 | $10,605 | $12,214 | $21,408 | $10,905 |
| **R-9 POLYISO** | $3,097 | $5,980 | $6,855 | $7,783 | $13,433 | $7,034 |
| **R-10 EIFS** | $2,648 | $5,748 | $6,466 | $7,575 | $13,749 | $6,738 |
| **R-10 SIP** | $6,069 | $12,012 | $13,785 | $15,835 | $27,922 | $14,227 |
| **R-10 XPS** | $4,119 | $7,929 | $9,049 | $10,412 | $18,096 | $9,330 |
| **R-10.5 CCSF** | $2,388 | $4,395 | $4,985 | $5,620 | $9,433 | $5,120 |
| **R-12 EPS** | $4,545 | $8,802 | $10,093 | $11,638 | $20,315 | $10,407 |
| **R-12 MWOOL** | $5,435 | $10,700 | $12,329 | $14,234 | $24,981 | $12,677 |
| **R-12 POLYISO** | $4,204 | $8,099 | $9,276 | $10,686 | $18,580 | $9,560 |
| **R-12 WFIBER** | $6,393 | $12,940 | $14,963 | $17,332 | $31,142 | $15,415 |
| **R-14 CCSF** | $3,610 | $6,791 | $7,727 | $8,841 | $15,197 | $7,952 |
| **R-15 EIFS** | $3,874 | $8,452 | $9,574 | $11,213 | $20,457 | $9,987 |
| **R-15 XPS** | $5,345 | $10,599 | $12,226 | $14,102 | $24,870 | $12,572 |
| **R-16 EPS** | $5,336 | $10,331 | $11,825 | $13,628 | $23,884 | $12,170 |
| **R-16 MWOOL** | $6,983 | $13,921 | $16,123 | $18,690 | $33,462 | $16,604 |
| **R-16 WFIBER** | $7,523 | $15,179 | $17,589 | $20,410 | $36,607 | $18,107 |
| **R-18 POLYISO** | $5,491 | $10,931 | $12,615 | $14,541 | $26,034 | $12,969 |
| **R-18 SIP** | $7,300 | $13,929 | $16,119 | $18,397 | $31,628 | $16,557 |
| **R-20 EIFS** | $5,061 | $10,780 | $12,362 | $14,427 | $26,221 | $12,821 |
| **R-20 XPS** | $6,532 | $12,950 | $14,957 | $17,323 | $30,994 | $15,410 |
| **R-21 CCSF** | $4,380 | $8,455 | $9,661 | $11,121 | $19,378 | $9,961 |
| **R-24 EPS** | $7,420 | $14,845 | $17,161 | $19,937 | $35,899 | $17,668 |

**Table 10: Incremental costs of continuous insulation measures across existing building stock per R-value of added insulation**

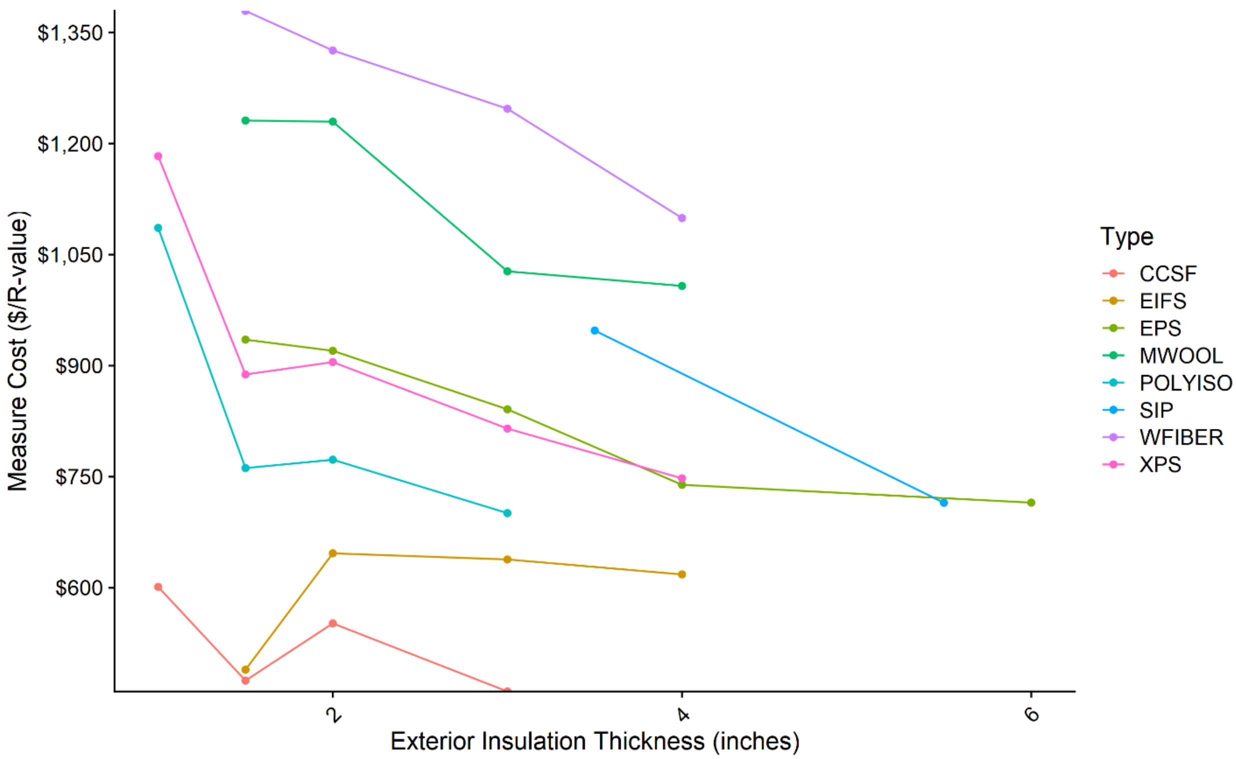
| Project | Min. | 25th percentile | Median | 75th percentile | Max. | Average |
|---|---|---|---|---|---|---|
| **R-5 XPS** | $548 | $1,037 | $1,183 | $1,337 | $2,278 | $1,212 |
| **R-6 EPS** | $437 | $820 | $935 | $1,056 | $1,790 | $959 |
| **R-6 MWOOL** | $550 | $1,072 | $1,231 | $1,401 | $2,430 | $1,263 |
| **R-6 POLYISO** | $495 | $949 | $1,086 | $1,231 | $2,117 | $1,115 |
| **R-6 WFIBER** | $606 | $1,199 | $1,379 | $1,573 | $2,749 | $1,415 |
| **R-7 CCSF** | $295 | $532 | $601 | $673 | $1,101 | $614 |
| **R-7.5 EIFS** | $187 | $445 | $489 | $572 | $1,052 | $509 |
| **R-7.5 XPS** | $403 | $776 | $888 | $1,008 | $1,735 | $911 |
| **R-8 EPS** | $433 | $807 | $920 | $1,048 | $1,793 | $943 |
| **R-8 MWOOL** | $552 | $1,071 | $1,230 | $1,418 | $2,473 | $1,267 |
| **R-8 WFIBER** | $588 | $1,151 | $1,326 | $1,527 | $2,676 | $1,363 |
| **R-9 POLYISO** | $344 | $664 | $762 | $865 | $1,493 | $782 |
| **R-10 EIFS** | $265 | $575 | $647 | $757 | $1,375 | $674 |
| **R-10 SIP** | $417 | $826 | $947 | $1,088 | $1,919 | $978 |
| **R-10 XPS** | $412 | $793 | $905 | $1,041 | $1,810 | $933 |
| **R-10.5 CCSF** | $227 | $419 | $475 | $535 | $898 | $488 |
| **R-12 EPS** | $379 | $733 | $841 | $970 | $1,693 | $867 |
| **R-12 MWOOL** | $453 | $892 | $1,027 | $1,186 | $2,082 | $1,056 |
| **R-12 POLYISO** | $350 | $675 | $773 | $890 | $1,548 | $797 |
| **R-12 WFIBER** | $533 | $1,078 | $1,247 | $1,444 | $2,595 | $1,285 |
| **R-14 CCSF** | $258 | $485 | $552 | $631 | $1,085 | $568 |
| **R-15 EIFS** | $258 | $563 | $638 | $748 | $1,364 | $666 |

| Project | Min. | 25th percentile | Median | 75th percentile | Max. | Average |
|---|---|---|---|---|---|---|
| **R-15 XPS** | $356 | $707 | $815 | $940 | $1,658 | $838 |
| **R-16 EPS** | $334 | $646 | $739 | $852 | $1,493 | $761 |
| **R-16 MWOOL** | $436 | $870 | $1,008 | $1,168 | $2,091 | $1,038 |
| **R-16 WFIBER** | $470 | $949 | $1,099 | $1,276 | $2,288 | $1,132 |
| **R-18 POLYISO** | $305 | $607 | $701 | $808 | $1,446 | $720 |
| **R-18 SIP** | $324 | $618 | $715 | $816 | $1,403 | $734 |
| **R-20 EIFS** | $253 | $539 | $618 | $721 | $1,311 | $641 |
| **R-20 XPS** | $327 | $647 | $748 | $866 | $1,550 | $771 |
| **R-21 CCSF** | $209 | $403 | $460 | $530 | $923 | $474 |
| **R-24 EPS** | $309 | $619 | $715 | $831 | $1,496 | $736 |

Median measure cost of continuous exterior insulation per R-value as a function of insulation thickness are shown in **Figure 22**

The incremental cost per added R-value is shown as a function of insulation thickness in **Figure 23**. The cost per R-value typically decreases with increasing insulation thickness. The labor efficiencies and capital cost reductions typically exceed the added costs associated with thicker wall assemblies. For example, the labor costs are about the same to install a thicker piece of rigid foam and rigid foam is cheaper per R-value for increasing thickness. These savings are greater than the added costs of additional window detailing and flashing and framing out non-insulated portions of exterior walls. The two exceptions are EIFS and closed cell spray foam, which also have the lowest cost per R-value. The incremental costs of EIFS are very low because the material inherently includes continuous insulation. However, overall project costs for EIFS remain high because re-siding projects cost two to three times that of other siding types. Closed cell spray foam costs also do not show a clear trend with increasing thickness and however, they are also relatively low per R-value. Despite their different R-values, XPS and EPS have similar installed costs per R-value across a range of insulation thicknesses. POLYISO insulation yields lower costs due to high R-value relative to the other two rigid boards. Mineral wool and wood fiber insulation have the highest costs per R-value of the measures considered here.

**Figure 22. Median measure cost of continuous exterior insulation per R-value as a function of insulation thickness**




## *Annual Space Heating Energy Savings of Continuous Exterior Insulation Measures*

The average annual space heating energy savings of the continuous insulation measure compared to the weatherized existing building stock are summarized in **Figure 23**, **Figure 24**, and **Table 11**. Continuous insulation measures provide an additional 151 to 260 therms or 18% to 32% savings on top of weatherization energy savings. When weatherization energy savings are included, the total median savings from continuous exterior insulation and weatherization is 290 to 410 therms or 30% to 42% savings compared to the baseline existing building stock.

**Figure 23. Annual incremental space heating energy savings from continuous insulation measures across the weatherized existing building stock**

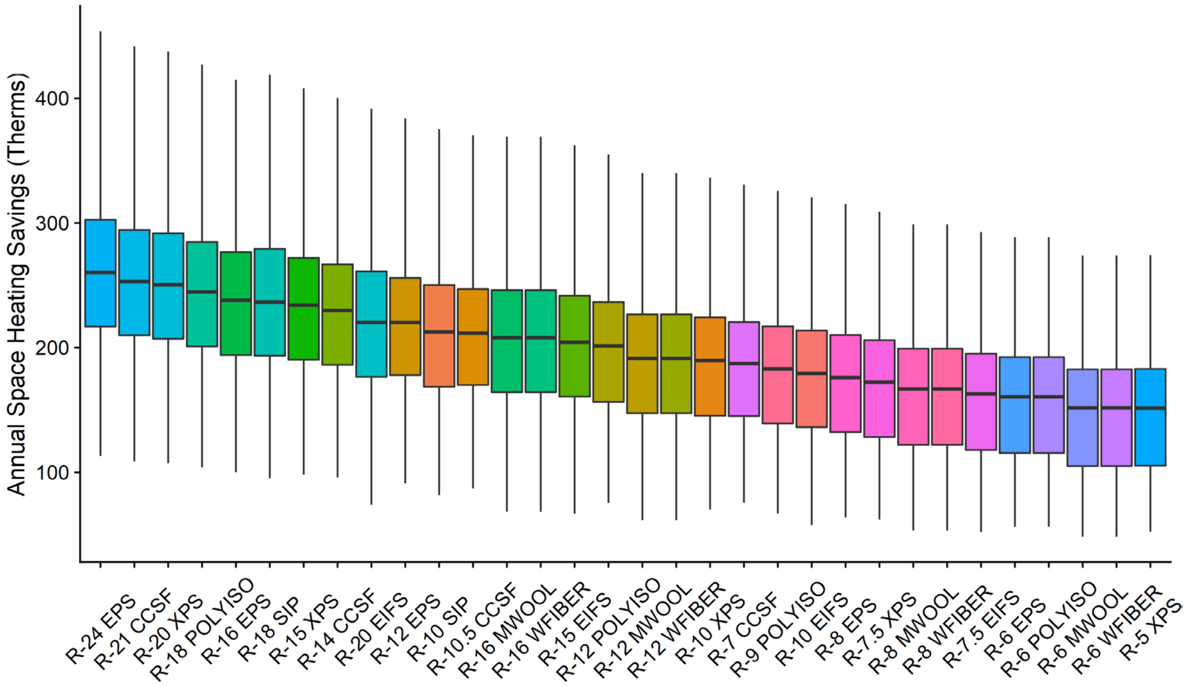



**Figure 24. Annual incremental space heating energy savings from continuous insulation measures across the weatherized existing building stock**

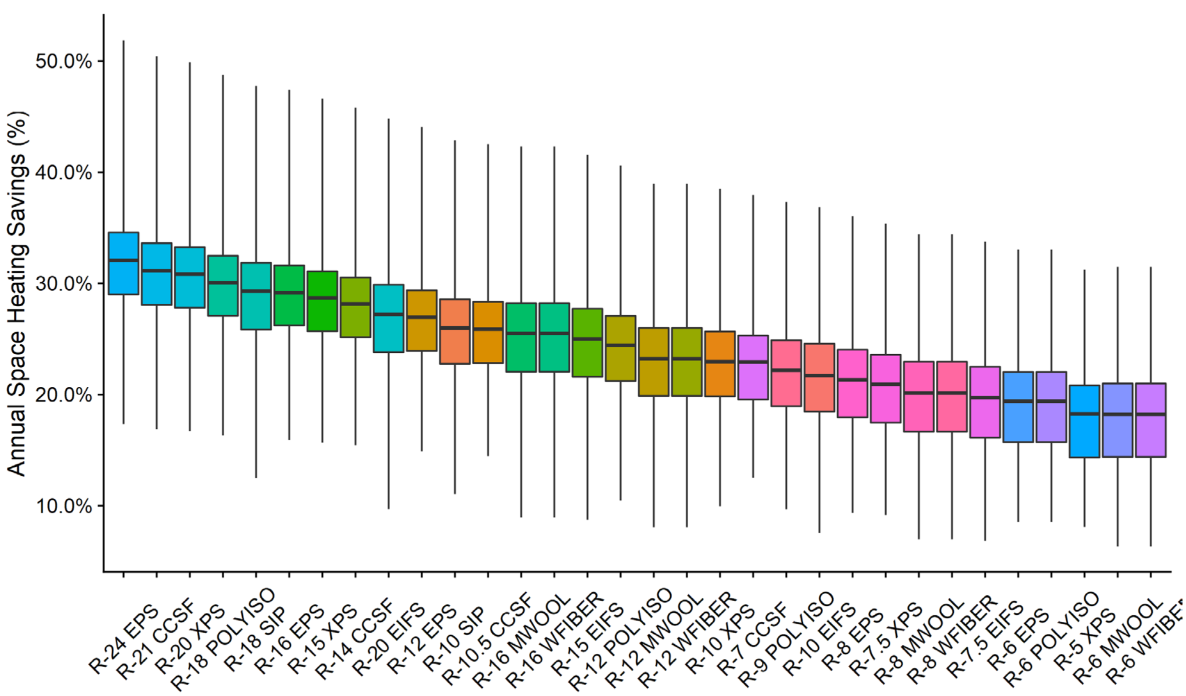


**Table 11: Annual incremental space heating energy savings from continuous insulation measures across the weatherized existing building stock**

| Project | Min. | 25th percentile | Median | 75th percentile | Max. | Average |
|---|---|---|---|---|---|---|
| R-5 XPS | 52 | 105 | 151 | 183 | 274 | 147 |
| R-6 EPS | 57 | 116 | 161 | 192 | 289 | 157 |
| R-6 MWOOL | 48 | 105 | 152 | 183 | 274 | 146 |
| R-6 POLYISO | 57 | 116 | 161 | 192 | 289 | 157 |
| R-6 WFIBER | 48 | 105 | 152 | 183 | 274 | 146 |
| R-7 CCSF | 76 | 145 | 187 | 221 | 331 | 186 |
| R-7.5 EIFS | 52 | 118 | 163 | 195 | 293 | 159 |
| R-7.5 XPS | 62 | 128 | 172 | 206 | 309 | 170 |
| R-8 EPS | 64 | 132 | 176 | 210 | 315 | 173 |
| R-8 MWOOL | 53 | 122 | 167 | 199 | 299 | 163 |
| R-8 WFIBER | 53 | 122 | 167 | 199 | 299 | 163 |
| R-9 POLYISO | 67 | 139 | 183 | 217 | 326 | 181 |
| R-10 EIFS | 58 | 136 | 179 | 214 | 321 | 177 |
| R-10 SIP | 82 | 169 | 213 | 250 | 375 | 211 |
| R-10 XPS | 70 | 145 | 190 | 224 | 337 | 187 |
| R-10.5 CCSF | 87 | 170 | 212 | 247 | 371 | 211 |
| R-12 EPS | 91 | 178 | 220 | 256 | 384 | 219 |
| R-12 MWOOL | 62 | 147 | 191 | 227 | 340 | 189 |
| R-12 POLYISO | 76 | 157 | 202 | 237 | 355 | 199 |
| R-12 WFIBER | 62 | 147 | 191 | 227 | 340 | 189 |
| R-14 CCSF | 96 | 186 | 230 | 267 | 400 | 229 |
| R-15 EIFS | 67 | 161 | 204 | 242 | 363 | 203 |

| Project | Min. | 25th percentile | Median | 75th percentile | Max. | Average |
|---|---|---|---|---|---|---|
| **R-15 XPS** | 98 | 190 | 234 | 272 | 408 | 233 |
| **R-16 EPS** | 100 | 194 | 238 | 277 | 415 | 237 |
| **R-16 MWOOL** | 68 | 164 | 208 | 246 | 369 | 207 |
| **R-16 WFIBER** | 68 | 164 | 208 | 246 | 369 | 207 |
| **R-18 POLYISO** | 104 | 201 | 245 | 285 | 427 | 245 |
| **R-18 SIP** | 95 | 194 | 237 | 279 | 419 | 237 |
| **R-20 EIFS** | 74 | 177 | 220 | 261 | 392 | 220 |
| **R-20 XPS** | 107 | 207 | 251 | 292 | 438 | 251 |
| **R-21 CCSF** | 109 | 210 | 253 | 294 | 442 | 254 |
| **R-24 EPS** | 113 | 217 | 260 | 303 | 454 | 261 |

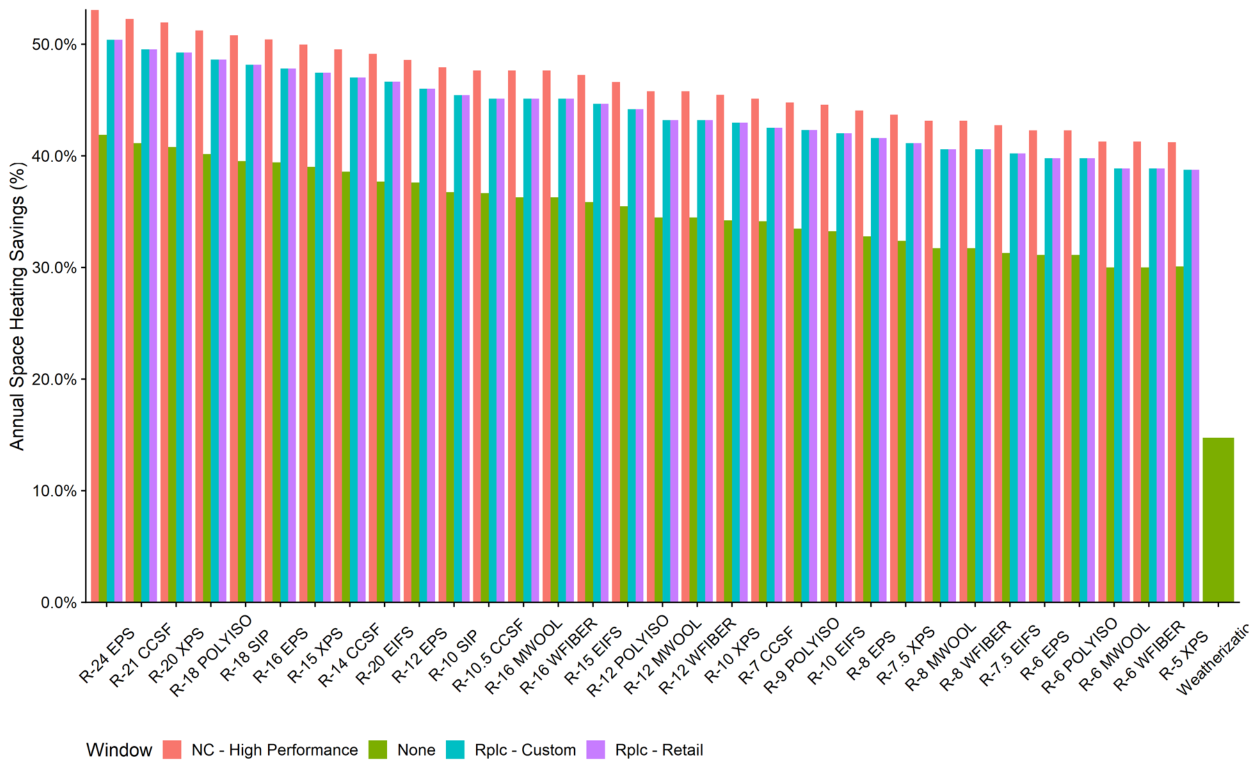
## Complete Envelope Packages

Weatherization and each type of window measure, including no window measures, are combined with each of the continuous exterior insulation measures where appropriate and one of the five appropriate baselines regarding siding projects to determine the total costs and savings potential for a variety of high-performance envelope packages.

Total annual space heating savings as a percent of the existing space heating load are shown in **Figure 25**. Eight high performance envelope packages that include triple pane windows manage to exceed the 50% target space heating savings, while just one high performance envelope package achieves 50% savings with replacement windows. On the other hand, all high-performance envelope packages including windows and continuous exterior insulation with R>6 exceed 40% annual space heating savings. While mechanical ventilation is outside the scope of this project it is worth considering that if the continuous exhaust ventilation added during weatherization measures is replaced by energy recovery with 50% effectiveness, all high-performance envelope packages that include high-performance windows exceed 50% median annual space heating savings across the building stock. All high-performance envelope packages with continuous exterior insulation R≥9 exceed 50% median annual space heating savings with replacement windows. However, all high-performance envelope packages that exclude windows remain below 50% median annual space heating savings. Greater effectiveness is likely in practice from energy recovery ventilation and these targets are conservative.

These results suggest that there is ample flexibility in achieving the target 50% savings goal from high-performance envelope packages, but that ventilation energy recovery is essential in most cases.

**Figure 25. Total median annual space heating savings of high-performance envelope packages including different window measures**




Total project costs including weatherization, the baseline re-siding project, continuous exterior insulation, and window measures are shown in **Figure 26**. The incremental energy costs and the fraction of incremental energy costs to total project costs, assuming a 65% value-to-cost ratio for window measures, are shown in **Figure 27** and **Figure 28** respectively. Median project costs without window measures range from about $20,000 to $45,000. Window measures increase median project costs from about $30,000 to nearly $60,000. Synthetic Stucco (EIFS) has the lowest incremental energy costs, typically 20% to 35% of total project cost. Other siding types have higher incremental costs due to the lower cost baseline re-siding project. Incremental energy costs range from 45% to 70% for most projects. Incremental costs for vinyl siding are about 5% higher and incremental costs for fiber cement siding are about 5% lower than these figures, respectively. All weatherization costs are considered energy costs.

**Figure 26. Total median project costs for re-siding and high-performance envelope measures including weatherization including different window measures**

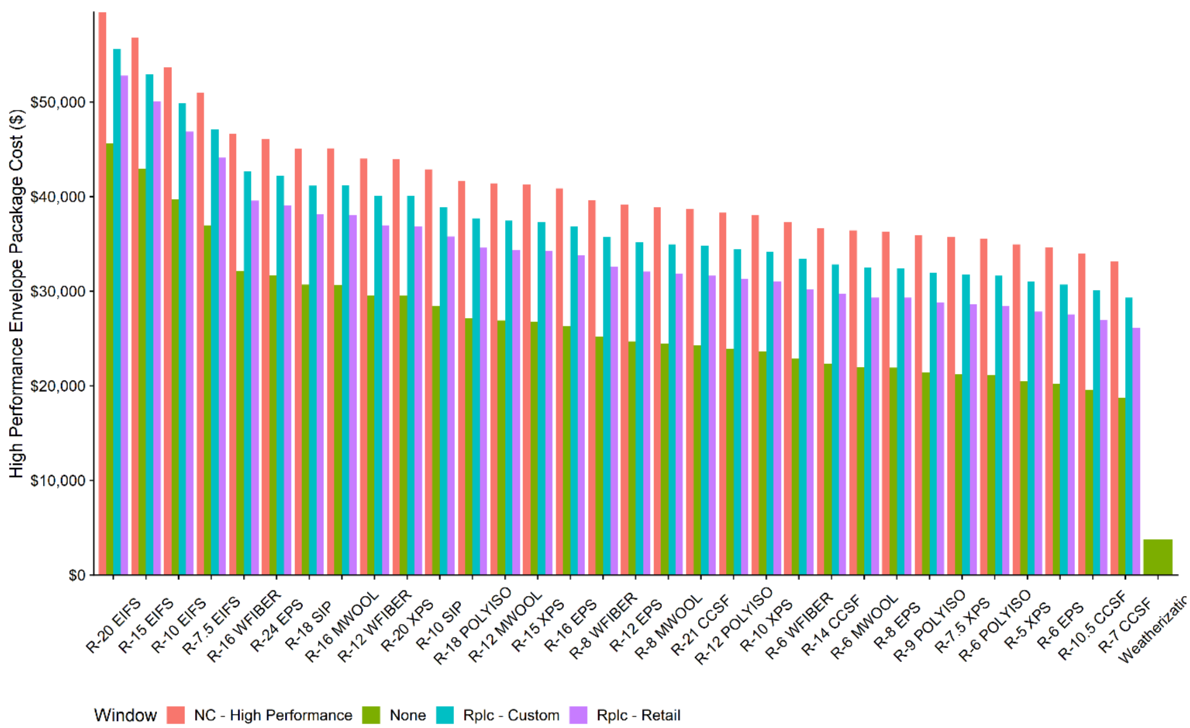



**Figure 27. Median incremental project costs for energy related components, including value-to-cost ratio of 65% for window measures**

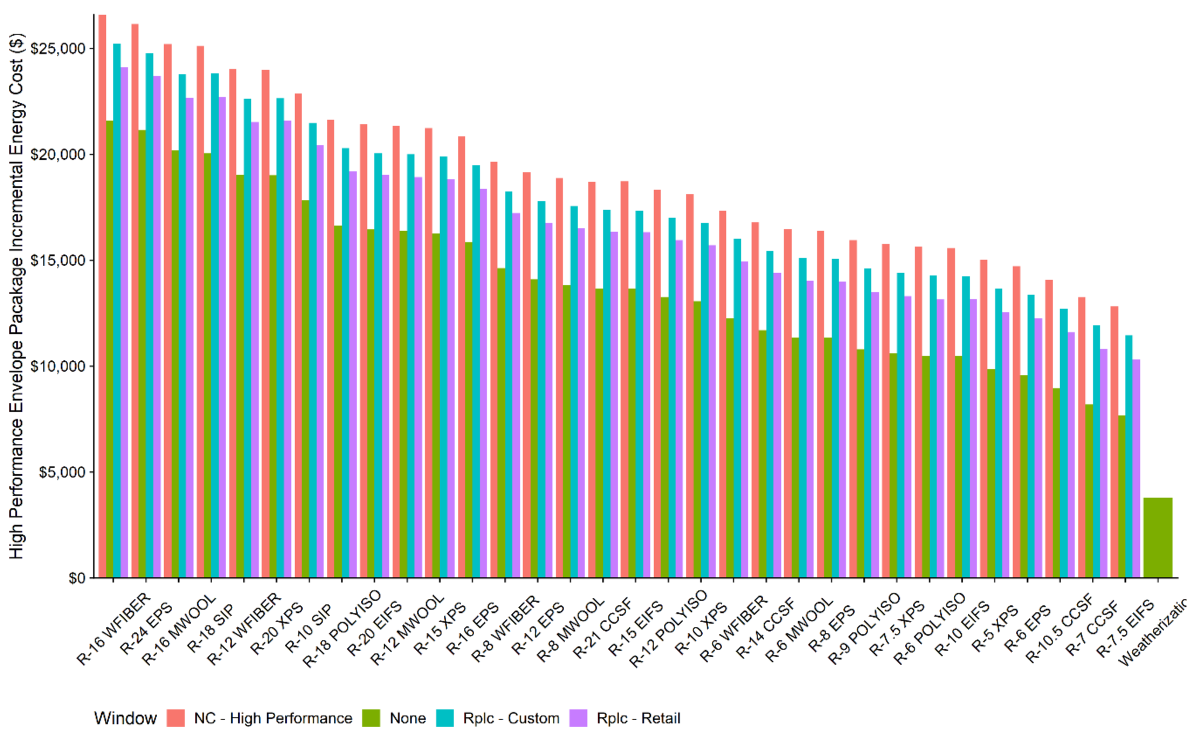
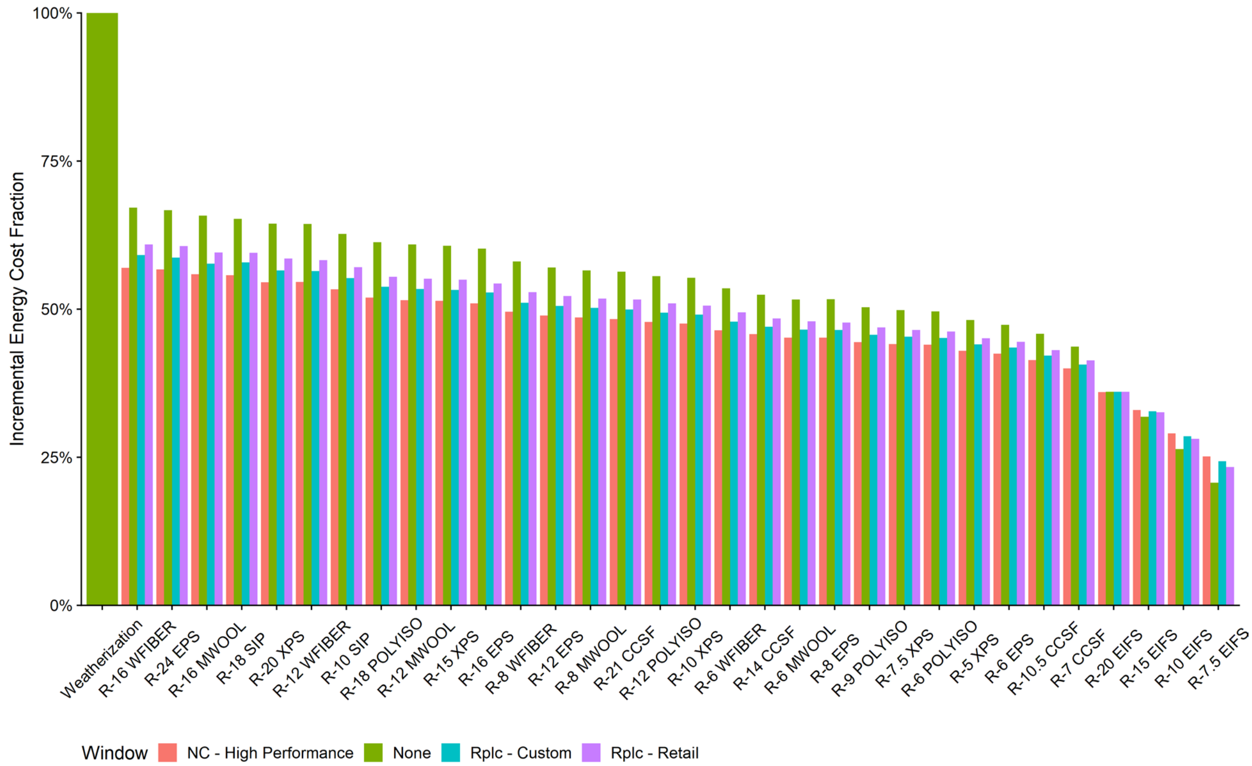
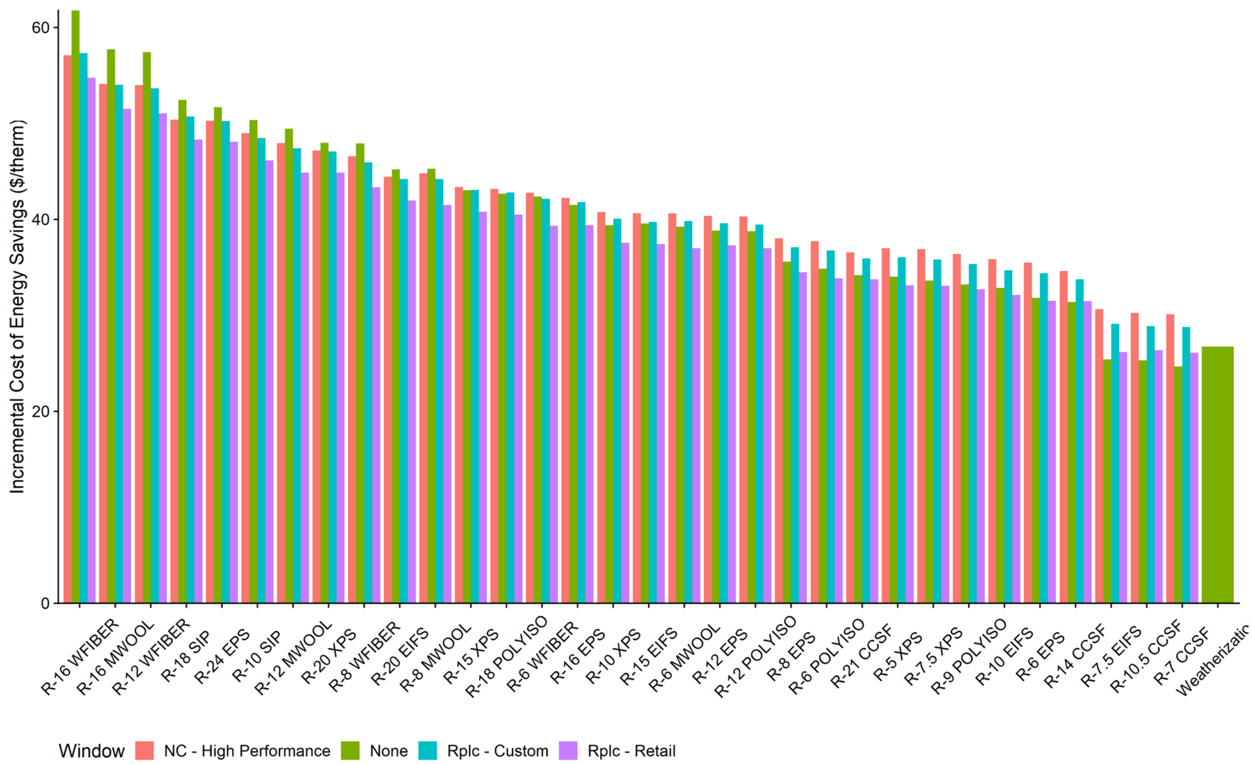


**Figure 28. The fraction of incremental energy costs to total project costs assuming value-to-cost ratio on window measures of 65%**




The costs of incremental energy savings ($/therm) are shown in **Figure 29**. Weatherization sets a benchmark at just under $28/therm. Interestingly, several high-performance envelope packages that include closed cell spray foam at one-inch or 1.5-inch thicknesses come in at slightly lower cost, ranging from $24.5/therm without windows and $26.5/therm with retail windows. Most of the rigid board insulation measures at one-inch to two-inch thickness and R-6 to R-15 range from about $30/therm to $40/therm. The most expensive measures, including the more expensive mineral wool and wood fiber insulation exceed $50/therm or about half the cost-efficiency of weatherization.

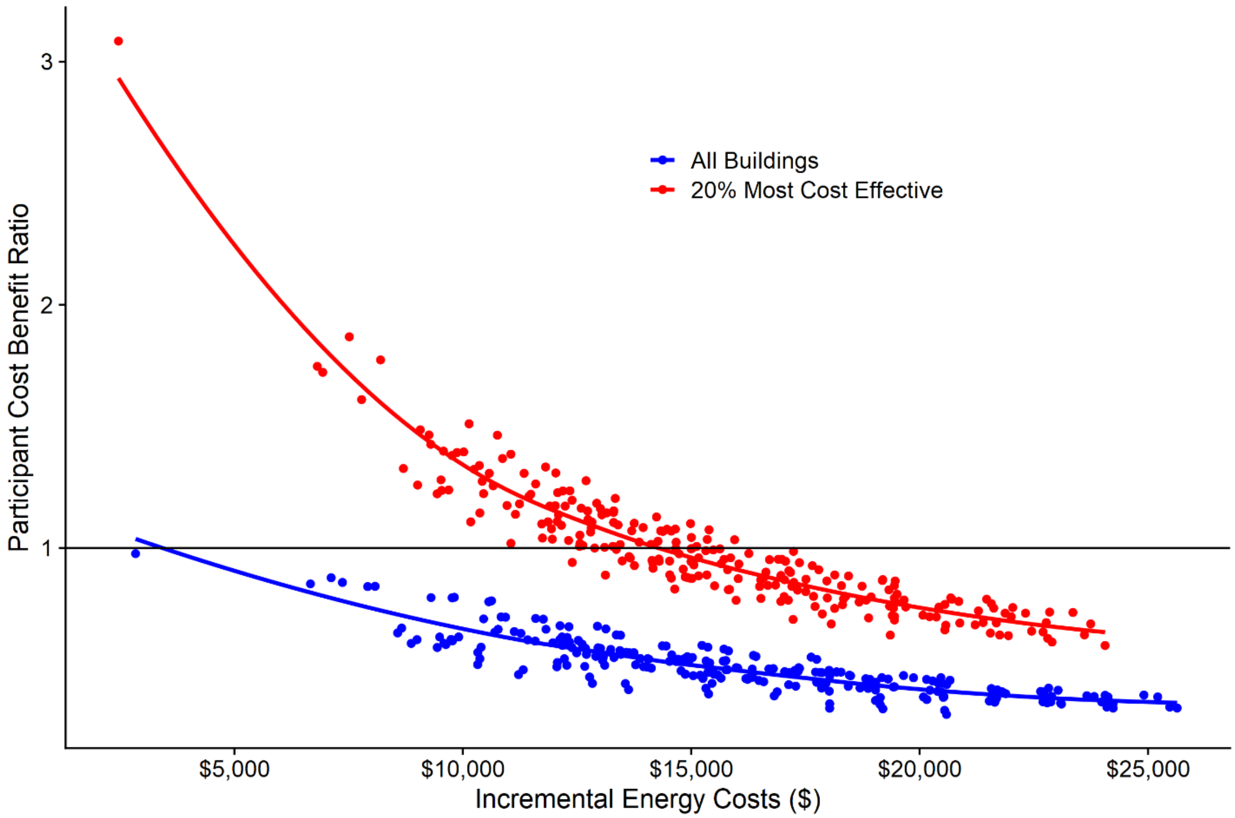
**Figure 29. Incremental cost of energy savings for high-performance envelope packages**




## Cost-effectiveness

The BENCOST natural gas model was used to estimate the participant cost-benefit ratios for the incremental costs of high-performance envelope energy efficiency work. All input values were taken from the approved inputs approved inputs for the 2021-2023 triennial planning unless otherwise noted. The focus here is on participant cost-effectiveness. Median participant cost benefit ratios for the building stock subjected to each one of the types of projects, including 32 continuous envelop improvement measures, 4 window measures, 5 siding baselines, and weatherization, representing approximately 465 unique project types are each plotted in **Figure 30**

**Figure 30. Median participant cost effectiveness ratio for all combinations of weatherization, continuous exterior insulation, and window measures**

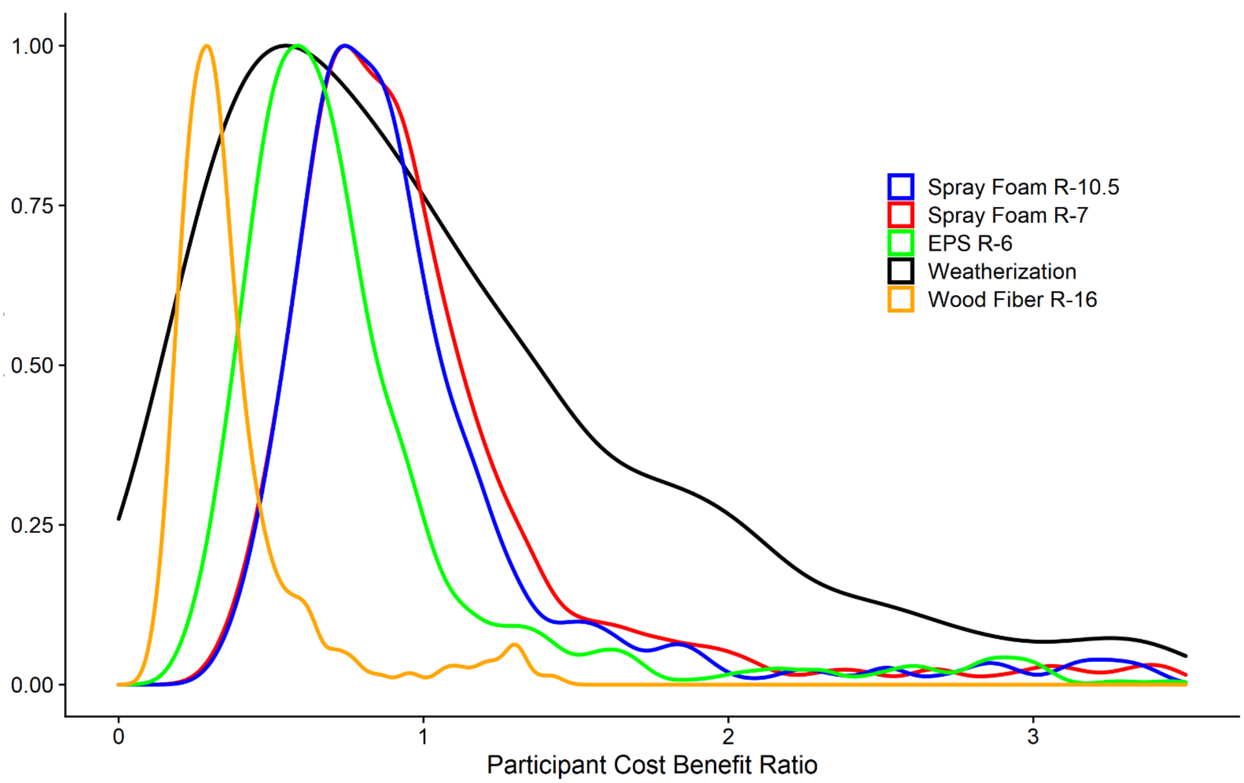



As shown in the figure, weatherization, with incremental energy costs of just under $4,000 have a participant cost effectiveness ratio that is 0.97. Recalling savings results, the median savings from these weatherization projects was 15% and average savings were 19%. All high-performance envelope retrofit projects (which include weatherization measures) have cost effectiveness less than weatherization by itself. In general, the median participant cost effectiveness decreases monotonically with increasing incremental energy costs. However, analyzing the subset of the 20% most cost-effective outcomes per project, as shown in red, yields substantially different results. In this case, the 20% most cost-effective project that only receive the basic weatherization measures in **Table 3**, yield a median participant cost effectiveness ratio that exceeds 3. In fact, most modeled continuous envelope insulation projects with incremental energy costs less than $16,000, show median participant cost effectiveness ratios that exceed one. In other words, many types of high-performance envelope projects are cost effective against natural gas heating costs for upwards of 20% of the building stock. The result suggests that not only is weatherization nearly-cost effective state-wide on all homes built before 1990, but that there are hundreds of thousands of opportunities to cost-effectively pursue high performance envelope retrofits as well.

Each of the points in **Figure 30** represents a distribution of outcomes across the approximately 250 - 1000 qualifying modeled buildings for a specific high performance envelope project. Several of these distributions are highlighted in **Figure 30** to show variations in cost effectiveness for specific continuous exterior insulation (CEI) with weatherization measures. Weatherization is shown in black, and it has a much wider distribution in cost effectiveness than high performance envelope measures, reflecting large differences in baseline building stock. In fact, it is the long tail of very cost-effective weatherization projects that causes weatherization to be nearly cost effective overall.

The continuous exterior insulation measures supplement a more-uniform building stock that has been treated with weatherization measures. Consequently, the range of cost-effectiveness outcomes for different continuous envelope insulation projects is narrower, which is reflected by the distributions shown in **Figure 31**. Exterior applied spray foams are the most cost-effective exterior insulation measure identified in this study. Their distributions, red and blue in the figure, demonstrate only a very minor difference in cost effectiveness between 1” and 1.5” thick applications, (R-7 and R-10, respectively). The distribution of cost effectiveness is also shown for 1.5” of EPS (R-6) and 4” of wood fiber insulation (R-16). In both these cases, the distributions show that application of these insulation types to weatherized buildings have participant cost effectiveness ratios less than one for most buildings.

**Figure 31. Participant cost effectiveness ratios for weatherization and several different continuous exterior insulation measures**




Identifying building characteristics that correspond to cost-effective high-performance envelope project opportunities requires focusing on those buildings that appear across multiple project types. These buildings tend to be smaller (1,600 sq ft versus 2,200 sq ft), have about 10% higher window area, but otherwise are generally geometrically simpler buildings that have not been updated with bump-outs, dormers, additions, or finished basements. These features seem to be disproportionally present in homes built in the 1950s. While the distributions of other building characteristics differ from the overall stock, we observed no clear trends. In terms of existing energy performance, these homes have little-to-no wall insulation and are slightly leakier than the overall existing building stock. However, due to their size, their space heating loads, and air leakage values are about 30% higher per conditioned area than the overall building stock. The buildings have no significant differences in attic, rim joist, or foundation insulation values, which suggests these homes have already been partially weatherized at rates comparable to the overall building stock.

On the other hand, about 22% of the existing building stock cannot achieve cost-effectiveness for any projects, including weatherization. An additional 6% of the building stock is only modeled to achieve basic weatherization measures cost-effectively. Significantly, these homes have had some type of existing energy efficiency work, such that the incremental cost of savings to reach the given criteria are much higher than the buildings without some or all of these measures.

# Conclusions and Recommendations

This project attempted to examine the role that high-performance building envelopes may play within the Minnesota Conservation Improvement Program energy savings framework by soliciting stakeholder perspectives and modeling the costs and energy savings of different high-performance envelope measures and packages. The model uses data to represent realistic variations across Minnesota's existing single-family building stock. While the results presented are inconclusive, they demonstrate that high-performance building envelope upgrades and weatherization are an extremely fruitful if not necessary component of future natural gas savings potential. Additionally, the project has demonstrated that aggressive weatherization is likely cost-effective on a much broader scale than currently realized and that dozens of different types of high-performance envelope retrofits are likely cost effective for hundreds of thousands of buildings statewide. This work should be viewed as one of many steps necessary to more strongly include envelope efficiency retrofits in residential energy efficiency programs in Minnesota. Among the first of these steps should be piloting aggressive weatherization and continuous exterior insulation across building types with cost-effective characteristics.

## Outreach

Over the course of this project, we reviewed existing literature, attended training workshops, webinars, and conferences, and conducted interviews to learn various stakeholders' perspectives on high-performance envelope opportunities.

- There is a large amount of existing building science research, pilot programs, meta-analyses, and interest in the subject among dedicated experts, but virtually none of this work is known or appreciated by professionals who are likely to complete and sell this work. Even contractors who implement existing weatherization measures are largely unaware of the next steps for envelope efficiency.
- While there are ongoing efforts to change this, the real estate community (lenders, underwriters, appraisers, realtors, and consumers) are unequipped to and generally uninterested in appropriately valuing energy efficiency and its impact on comfort, the environment, and the total cost of home ownership.
- Contractors and their trade organizations lack interest and/or knowledge or are otherwise dismissive of high-performance envelopes and incorporating high levels of envelope efficiency into their existing projects. Even those who view the ideas favorably tend to focus on barriers rather than the opportunities.
- Those knowledgeable about the subject tended to passionately support the ideas (typically on environmental and performance grounds), but also possessed a sophisticated understanding of the current barriers (interest, knowledge, cost-effectiveness, market opportunities, etc.), likely because they're constantly encountering these barriers.
- Despite these issues, there has been a steady and dedicated, though small, interest among architects, contractors, and highly motivated homeowners supply a continuous stream of successful projects over the past several decades. They are strongly motivated by comfort and

environment and are simultaneously engaging in other activities to reduce their footprint (e.g., solar, EVs, and behavioral changes). Ultimately, they still have cost sensitivities that drive project choices.

- Of those knowledgeable about high-performance envelopes, the majority reported they gained this knowledge through direct participation in these types of projects or from colleagues and mentors.
- The consensus among those knowledgeable on the subject is that cost is the main barrier to these projects. However, interpretations as to what is a cost barrier vary widely and include upfront costs; overall payback; emphasis on smaller, cost-effective measures; split incentives; and constraints of low-income households.

## Energy Savings Results

- Weatherization remains an essential prerequisite to high-performance envelope projects by virtue of its relatively strong savings profile across the existing building stock (15% median and 19% average savings), fewer requirements, lower upfront costs, and higher cost-effectiveness.
- Reducing space heating loads by 50% across the entire existing building stock with a combination of weatherization, continuous exterior insulation, and windows is difficult and requires high-cost measures such as triple pane windows and continuous exterior insulation with R-18 ft2·°F·hr/BTU or higher or more invasive or complete retrofits than studied here.
- However, 50% savings become feasible if energy recovery ventilation is considered.
    - Continuous exterior insulation with R-6 ft2·°F·hr/BTU or higher, paired with triple pane windows, provides 50% median energy savings across the building stock when coupled with energy recovery ventilation.
    - Continuous exterior insulation with R-9 ft2·°F·hr/BTU or higher, paired with code-minimum double pane windows, provides 50% median energy savings across the building stock when coupled with energy recovery ventilation.
- Without windows, continuous exterior insulation with as little as R-6 ft2·°F·hr/BTU paired with weatherization is limited to 40% to 50% median energy savings depending on the level of existing insulation.

## Cost-Effectiveness

- With a median participant cost effectiveness ratio of 0.97; this modeling shows that aggressive weatherization is nearly cost effective overall on over 1 million Minnesota single family homes built before 1990.
- Although median participant cost-effectiveness ratios are less than one for all high performance retrofit projects, the modeling shows that most projects with incremental energy costs less than $16,000 are cost effective on approximately 20% of the building stock, which equates to hundreds of thousands of homes in Minnesota.

## Building Criteria for Cost-Effective Projects

- Both the high-performance envelope package type and the underlying building characteristics play an important role in cost-effective energy savings.
- Minnesota homes that are most likely to have cost-effective opportunities for high performance envelope retrofits:
  - Are smaller than the overall building stock (1,600 sq ft versus 2,200 sq ft).
  - Have about 10% higher window area but are otherwise generally as geometrically simpler buildings that have not been updated with bump-outs, dormers, additions, or finished basements, features that are disproportionally present in homes built in the 1950s.
  - Have little-to-no wall insulation and are slightly leakier than the overall existing building stock. Due to their size, their space heating loads and leakage rate values are about 30% higher per conditioned area than the overall building stock.
  - Have no significant differences in attic, rim joist, or foundation insulation values, which suggests these homes have already been partially weatherized at rates similar to the overall building stock.
- About 22% of the existing building stock cannot achieve cost-effectiveness for any high-performance envelope package including weatherization by itself. An additional 6% of the building stock is only cost-effective under weatherization. Significantly, most of these homes have had some type of existing energy efficiency work, leading to a much higher cost of incremental energy savings for ostensibly similar projects.

## Future Work

By their connection to building aesthetics and as drivers of energy costs, building envelopes and large-scale potential projects are deeply intertwined with many major issues that society is currently facing, including climate change, inequity in housing, workforce development, and technology disruption. Coupled by the finding that hundreds of thousands, if not a million or more, existing single-family homes will likely need this work in the next 20 to 30 years to affect the required change, high performance envelope retrofits present an opportunity to simultaneously make progress on multiple interrelated issues, but more research and development is required to realize this potential.

### Technical

- Researchers need to investigate the necessity of rainscreen siding applications. There may be a balance between the rainscreen applications' added resilience and their added cost (+10% to +15%) that will warrant abandoning them to improve cost-effectiveness.

- Researchers need to investigate the role of existing interfaces and untreated thermal bridging on savings and costs, particularly for complex roof geometries, roof-wall interfaces, and wall-foundation interfaces.

- This project focused on methods to achieve high-performance envelopes with the most established and traditional methods available, but there is significant recent and ongoing R&D focused on developing new methods and materials that will impact the savings and cost-effectiveness metrics. These methods and materials include:
    - New products that lower labor requirements for continuous exterior insulation (e.g., specialized flashing materials; prefabricated sill extensions and pre-treated, cut, or sized insulation assemblies).
    - Strategically incorporating exotic high R-value and low-thickness materials into these projects (e.g., vacuum or aerogel-based insulations).
    - Advanced measurement and on-site fabrication techniques that minimize error and improve on-site efficiency (e.g., augmented reality, 3D scanning and measuring, computer-aided construction tools, etc.)).
    - Off-site fabrication methods (e.g., factory-built, site assembled measures).
    - Additional cost synergies across existing and new projects (e.g., simultaneous weatherization, continuous exterior insulation, window measures, updated HVAC incorporation, roof assembly updates, solar photovoltaics, etc.)
- Just as the practical implementation of weatherization has required installation of continuous exhaust ventilation in air-sealed homes, additional airtightness from these new envelope measures may justify balanced ventilation with energy recovery, which is anticipated to produce median savings of at least 10%.

## Outreach

- A major gap in this project is key stakeholder cohort feedback from contractors involved in relevant residential work, including siding, windows, and general remodeling projects. Both their feedback on the opportunities and barriers and their acceptance is required for completing this work in practice. Furthermore, they may have important input into planning, cost, and labor assumptions implicit in the present work.

## Modeling Improvements

- This work was a brute-force calculation across a selection of high-performance packages across all representative building types. Applying optimization methods could identify high-performance envelope and weatherization measures based on underlying building characteristics and measures that maximize cost-effectiveness or performance. Such an approach might also elucidate how high-performance envelope measures could be combined in different ways (e.g., by multiple types of insulation).
- The existing model could be significantly expanded with additional data (e.g., assessor data, newer energy audit data, utility billing data, and additional real project costs), which in order to improve the fidelity and utility of this approach in predicting energy savings, costs, and variances across the building stock.

## Cost-effectiveness

- While this project used approved inputs to the BENCOST model for investor-owned natural gas utilities for the 2021-2023 CIP triennium, the validity of several assumptions with respect to high-performance envelopes are open to debate. The current project life assumed in the BENCOST model is limited to 20 years for several reasons included below.
    a) Increasing uncertainty of events in outlying years
    b) Diminishing measure savings over time
    c) Disconnect between current ratepayers-as-funders and future beneficiaries
    d) More cost-effective alternatives that should be pursued if measures cannot payback within 20 years

On the other hand,

a) Insulation lifetimes exceed 20 years and artificially assigning short lifetimes to these long-lived measures distorts their true cost-effectiveness.
b) Insulation savings are likely to dissipate at a rate below many other types of savings.
c) Increasing the weight of emissions and environmental impacts within the cost effectiveness analysis may justify more long-term thinking.
d) No other measures (cost-effective or not) may be capable of providing the magnitude of savings necessary for future climate goals.

- Additionally, there is no recognized mechanism to value the non-energy benefits of improved thermal comfort or improved indoor air quality, despite recognized economic impact [20], yet prior work has shown these benefits as strong motivators of deep energy retrofits.
- Upfront costs remain a high barrier regardless of overall cost-effectiveness. New financing models (e.g., on-bill financing, streamlined home equity or mortgage financing, and pay-for-performance models) may enable additional project opportunities and are being developed and are starting to be adopted in some jurisdictions.
- Over a quarter of existing homes in Minnesota are heated by propane and electricity. Cost-effectiveness ratios for these heating fuels are likely much higher.
- Likewise, this analysis neglects cooling electric savings and electric savings from furnace blowers and portable space heaters. Incorporating these details will positively impact project cost-effectiveness.
- Regulators and municipalities can influence cost effectiveness; permit fees, and sales tax and may represent 6% to 10% of project costs. Furthermore, property tax relief may be a tool to incentivize high performance envelope retrofits and reduce the lifetime impact of project costs.

## Program Development and Logistics

- Project logistics need to be simplified and standardized for feasible implementation. Aspects of logistics include: managing multiple trade workers and utility interests, occupant needs, aesthetic flexibility and other non-energy construction work, financing, and the single-point contact/management of projects.

- High-performance envelope packages (e.g., window types, insulation types, siding types) need to be optimized for specific program goals and balance other important considerations (e.g., embodied energy, global warming potential, source efficiency).
- The following workforce issues need to be addressed: shortage of required trades, competition with new construction, and training.
- Lack of interest and knowledge among the existing workforce remain large barriers. Policy makers and stakeholders should consider initiatives to incentivize participation via pay-for-performance and building codes or regulations that tie energy improvements to exterior maintenance work.
- Program administrators need to explore implementation strategies that can identify and leverage the most cost-effective opportunities first while building expertise to improve cost-effectiveness for more challenging projects.
- Program implementors need to increase the scale of existing activities in high performance envelope projects. While a small amount of the building stock has been undergoing these projects, broader climate goals will only be served by much larger rates of participation over the next 20 to 30 years.

## Raising Awareness

There is a long history of successful high performance envelope projects, albeit in limited number. Program administrators and others need to raise awareness and better market the ideas' benefits.

- Home improvement shows are extremely popular and inexpensive to produce, but rarely incorporate or feature energy efficiency work. Creating relationships between high performance envelopes, thermal comfort, quality of life, and updated visual appeal has untapped potential that could be explored through this marketing channel.
- Energy disclosures as part of Truth in Sale of Housing (TISH) reports can help emphasize the energy, comfort, and value of high-performance envelopes.
- Program administrators need to educate consumers about the benefits of thermal comfort. Ultimately, many modest projects would have amortized costs in the range of tens of dollars per month, which is a reasonable value proposition based on improved comfort alone.
- Elevate the efficiency potential of the space heating load in Minnesota to a level commensurate with its importance and impact. Overall, it has a similar or greater level of impact as electric vehicles and solar photovoltaics, at similar if not lower incremental cost.
- Address building envelopes from an infrastructure perspective and address the opportunity to invest in the built environment versus an indefinite reliance on imported fuels. Provide individuals and society the opportunity to leave a legacy of a building stock commensurate with future needs.

## Energy Burden and Social Equity

- Policy makers and stakeholders need to examine the role high-performance envelope efficiency can play to lower energy burdens, providing jobs, and enabling participation in climate solutions for populations that have been historically disadvantaged by prior housing policies and trends.
- Policy makers and stakeholders need to allow for and leverage alternative funding and financing mechanisms for some projects that can address efficiency and other socio-economic issues simultaneously.
- Stakeholders should recognize that improving and modernizing building exteriors and aesthetics can have broader impacts on neighborhood and community development as well as long-term property valuations.
- Policy makers and stakeholders need to examine the split incentives that often occur between renters that pay for utilities and the public and private landlords that need to pay for building envelope and exterior maintenance.

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