PNNL-28690

Wall Upgrades for Residential Deep Energy Retrofits: A Literature Review

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U.S. DEPARTMENT OF ENERGY

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Pacific Northwest National Laboratory
Richland, Washington 99352

Abstract

In the United States, 39% of total energy is consumed by the building sector, 20% of the total is attributed to residential buildings (U.S. Energy Information Administration, 2018). New, high-performance homes incorporate a combination of tight building envelopes, mechanical ventilation, and efficient components to ensure comfort, adequate airflow, and moisture control. These systems work together to create energy efficient homes that use measures to manage moisture, comfort, energy efficiency, and the indoor environment. Older homes, built before 1992 when the U.S. Department of Energy's Building Energy Codes Program was established represent approximately 68% of residential building stock in the country and often have significant air leakage and inadequate insulation. Homes with little to no air sealing or insulation have heating and cooling losses that can represent a substantial portion of utility bills. Done correctly, deep energy retrofits can significantly improve the energy performance of a home's thermal envelope, and increase homeowner comfort and health. This literature review summarizes current practices for exterior wall retrofits for existing homes, provides an overview of techno-economic approaches to investigating residential wall systems, and discusses thermal and hygrothermal modeling strategies. This literature review is part of a larger effort to identify state-of-the-art technologies for energy efficient wall retrofit systems that are suitable for cold and very cold climate zones. Retrofit wall systems that can be applied over existing siding offer a possible approach to reducing installation costs.

Summary

The Pacific Northwest National Laboratory, Oak Ridge National Laboratory, and the University of Minnesota are conducting a 3-year, multipart study of residential retrofit wall assemblies. The project is funded by the U.S. Department of Energy Building Technologies Office. Researchers will identify, test, and verify the hygrothermal performance of wall assemblies in retrofit applications. The approach to this study includes

- a comprehensive literature review and involvement of an expert advisory group made up of thermal enclosure experts, which will inform wall selection.
- energy and thermal simulation of selected wall assemblies using EnergyPlus and THERM, and hygrothermal simulation using WUFI, to model both the thermal and moisture performance of candidate wall assemblies to select upgrade strategies for physical experiments.
- experimental testing of eight wall assemblies in an in situ laboratory environment at the University of Minnesota, with a typical residential wall used as a baseline. The in situ experiment will measure the physical hygrothermal performance of each assembly.

Simulation and experimental results will be combined with an economic analysis to produce a techno-economic study of residential wall systems for deep energy retrofits. The process for the techno-economic study is presented in the flowchart below.

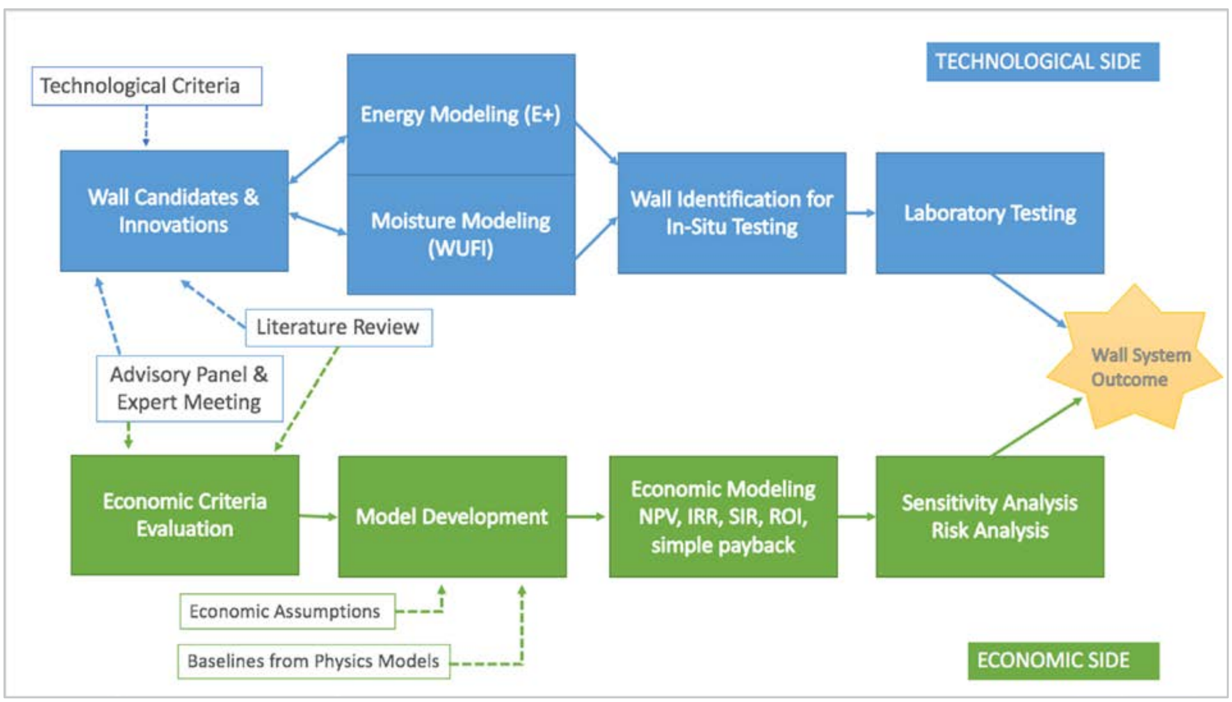

Figure ES.1. Techno-economic study flowchart.

Older homes, built before 1992 when DOE's Building Energy Codes Program was established represent approximately 68% of the residential building stock in the country (Livingston et al. 2014; U.S. Census Bureau 2017), and often have significant air leakage and inadequate insulation. Homes with little to no air sealing or insulation have heating and cooling losses that can represent a substantial portion of utility bills. Furthermore, 43% of these homes have little to

no insulation in the walls (National Renewable Energy Laboratory 2019). There is a significant need for cost-effective methods of improving wall insulation and reducing infiltration for existing homes. In current practice, wall retrofits seldom include the air, moisture, and vapor controls that are considered best practices for high-performance new home construction. Well-tested and documented retrofit wall systems can help to achieve substantial energy savings and improve home durability, comfort, health, and resilience.

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

Done correctly, deep energy retrofits (DERs) can significantly improve the energy performance of a home’s thermal envelope, help manage indoor environmental pollutants and increase homeowner comfort. Significant savings in residential building energy consumption through retrofit projects cannot be achieved without creating high-performance enclosures. This literature review provides an overview of the thermal and moisture performance of wall assemblies, identifies relevant research, and summarizes current practices for exterior wall retrofits for existing homes, focusing on retrofit applications to the exterior side of a wall assembly. Ventilated facades or rainscreen wall construction details are included in most applications for moisture management. The following wall systems are discussed:

- exterior insulated sheathing, exterior super-insulation
- thermal break shear wall assembly
- spray foam outer shell retrofits
- retrofit insulated panels
- insulated vinyl siding systems
- exterior insulation and finish systems (EIFSs)
- masonry wall retrofit applications
- EnergieSprong (REALIZE Initiative) prefabricated panels.

In addition to investigating wall assemblies, this literature review explores various innovative insulation materials, and provides background for a techno-economic analysis, and the use of such analyses in building construction. Finally, a review of literature on the modeling and simulation of hygrothermal wall assembly performance is presented. This literature review is part of a larger effort to identify state-of-the-art technologies for energy efficient wall retrofit systems that are suitable for cold and very cold climate zones. Retrofit wall systems that can be applied over existing siding offer a possible approach to reducing installation costs and are of particular interest in this study.

Acknowledgments

The Pacific Northwest National Laboratory is partnering with Oak Ridge National Laboratory and the University of Minnesota to conduct a 3-year, multipart study of residential retrofit wall assemblies. The authors acknowledge Andre Desjarlais and Florian Antretter at the Oak Ridge National Laboratory for support with experimental design and WUFI modeling, and Patrick Huelman and Garret Mosiman at the University of Minnesota for experimental design and physical experimentation of wall assemblies at the Cloquet Residential Research Facility. The project team gratefully acknowledges and thanks the DOE Building Technologies Office for funding this project, and Eric Werling, manager of the U.S. Department of Energy's Building America Program, for his managerial and technical guidance.

This project will involve the formation of an expert advisory committee. Thirty five people registered, and 33 people attended an expert meeting to help identify and characterize candidate wall systems. We thank all of the participants in the expert meeting and advisory committee for their time and acumen in building science and wall design, deployment, and performance. We thank Kohta Ueno of the Building Science Corporation for his review and input to this literature review, and Iain Walker at the Lawrence Berkeley National Laboratory for additional resources on DER's, mold and moisture.

Acronyms and Abbreviations

ASHRAE	American Society of Heating Refrigerating and Air-Conditioning Engineers
BEM	building energy modeling
BEopt	Building Energy Optimization Tool
BSC	Building Science Corporation
BTO	U.S. Department of Energy Building Technologies Office
CFD	computational fluid dynamics
CLT	cross-laminated timber
DER	deep energy retrofit
DOE	U.S. Department of Energy
EIA	Energy Information Administration
EIFS	exterior insulated finish systems
EPS	expanded polystyrene
ET	(U.S. Department of Energy) Emerging Technologies (program)
EU	European Union
EUI	energy use intensity
GDP	gross domestic product
GSHP	ground-source heat pump
HAM	heat, air, and moisture
HOMER	Hybrid Optimization Model for Electric Renewable
HVAC	heating, ventilation and air-conditioning
IAQ	indoor air quality
ICF	insulated concrete form
IMP	insulated metal panel
ISO	polyisocyanurate (rigid foam insulation)
LBNL	Lawrence Berkeley National Laboratory
MEEFS	Multifunctional Energy Efficient Façade System for Building Retrofitting
NREL	National Renewable Energy Laboratory
NSIP	natural fiber structural insulated panel
NYSERDA	New York State Energy Research and Development Authority
OECD	Organisation for Economic Cooperation and Development (EU)
ORNL	Oak Ridge National Laboratory
OSB	oriented strand board
PCM	phase change material
PERR	Prefabricated Exterior Energy Retrofit
PNNL	Pacific Northwest National Laboratory

PV	photovoltaic
R&D	research and development
RECS	Residential Energy Consumption Survey
RH	relative humidity
RIP	retrofit insulated panel
SIP	structural insulated panel
TBS	thermal break shear wall system
VIP	vacuum insulation panels
WRB	weather-resistant barrier
XPS	extruded polystyrene

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1.0 Introduction

In the United States, 39% of total energy is consumed by the building sector, and 20% of that total by residential buildings (EIA 2018). New, high-performance homes incorporate a combination of tight building envelopes, mechanical ventilation, and efficient components to ensure comfort, adequate airflow, and moisture control. These systems work together to create energy efficient homes that use measures to manage moisture and indoor pollutants. Older homes, built before energy code integration, represent approximately 68% of the residential building stock in the country (USCB 2017), and often have significant air leakage and inadequate insulation. Homes with little to no air sealing or insulation have heating and cooling losses that can represent a substantial portion of utility bills. Done correctly, deep energy retrofits (DERs) can significantly improve the energy performance of a home's thermal envelope, decrease indoor pollutants, and increase homeowner comfort.

The U.S. Department of Energy's Building Technology Office collaborates with stakeholders in the building industry to improve energy efficiency in new and existing buildings. The Residential Buildings Integration program sponsors this research as part of a larger research portfolio aimed at reducing energy use intensity in residential buildings. This literature review summarizes current practices for exterior wall retrofits for existing homes, provides an overview of techno-economic approaches to investigate residential wall systems, and discusses thermal and hygrothermal modeling strategies. Accompanying this literature review is a larger effort to identify state-of-the-art technologies for existing wall energy efficiency retrofit systems that can be applied over existing siding and are suitable for the cold and very cold climates. The project team includes the Pacific Northwest National Laboratory, Oak Ridge National Laboratory and the University of Minnesota.

The ensuing sections of this report describe the results of a review of literature related to four topics. Section 2.0 summarizes the current practices for exterior wall retrofits for existing homes, discusses deep energy retrofits and residential retrofit market characterization. Section 3.0 describes high-performance wall research and development (R&D) conducted by DOE. Section 4.0 describes the techno-economic study of high-performance residential buildings, and Section 5.0 provides a review of literature on the modeling and simulation of hygrothermal wall assembly performance and hygrothermal modeling strategies. Conclusions are provided in Section 6.0.

2.0 Background on Wall Construction, Deep Energy Retrofits and Market Characterization

This section provides background information on wall construction for thermal and moisture durability, approaches to deep energy retrofits, and residential market characterization.

2.1 Wall Construction for Thermal Performance

Residential wall systems consist of individual components that are assembled to deliver thermal and moisture performance of the wall. The materials that compose the building envelope, the integrity of their assembly, and their resulting collective properties of thermal resistance, airtightness, and moisture control determine the thermal and hygrothermal performance of the wall system (Al-Homoud 2005; Karagiozis & Salonvaara 2001; Lstiburek 2007). The physical properties of wall materials, combined with the physics of air, water, and vapor movement are complex and require special attention in order to avoid failure of the wall assembly. The cold or warm conditions at both the interior and exterior surfaces of the wall structure can allow moisture to condense, which can result in moisture problems if the wall structure is assembled incorrectly E 2017). Thus, thermal and moisture performance are essentially one and the same. Control layers for heat, air, and moisture are incorporated into walls using different approaches, depending on climate, to ensure the wall system is hygrothermally sound (Lstiburek 2002, 2007). Figure 1 illustrates a wall system with control layers in place to ensure proper thermal and moisture performance in residential buildings.

In addition to thermal performance, wall construction details include structural elements that resist and distribute live and dead loads, ensuring the integrity of the structure. Complementary methods protect the structure from disasters, such as high winds, flooding, and wildfire. While important, these specific topics are outside the scope of this review.

As illustrated in Figure 1, a typical high-performance residential wall assembly consists of interior and exterior components. The interior surface includes gypsum board and latex paint or textured wall finishes. The wall cavity includes framing (most commonly wood stud in residential buildings) and insulation (batts, blown cellulose, spray foam). The wall cavity is covered with a sheathing of plywood, oriented strand board (OSB), or exterior gypsum board, then covered with a weather barrier, such as housewrap, that protects the wall cavity. The OSB (or other material) on the exterior side of the wall cavity is intended to provide shear strength for the building structure. Exterior, continuous rigid insulation may then be applied, and a drainage cavity, or gap, is left between the exterior insulation and the cladding (often furring strips are used for this purpose). Common cladding materials for existing residential buildings include fiber cement or wood lap siding, stucco, masonry, or vinyl, although more advanced materials exist. Wall assemblies may position these materials in different locations within the wall assembly, may design the assembly so that some materials have multiple functions, or may use different materials, altogether.

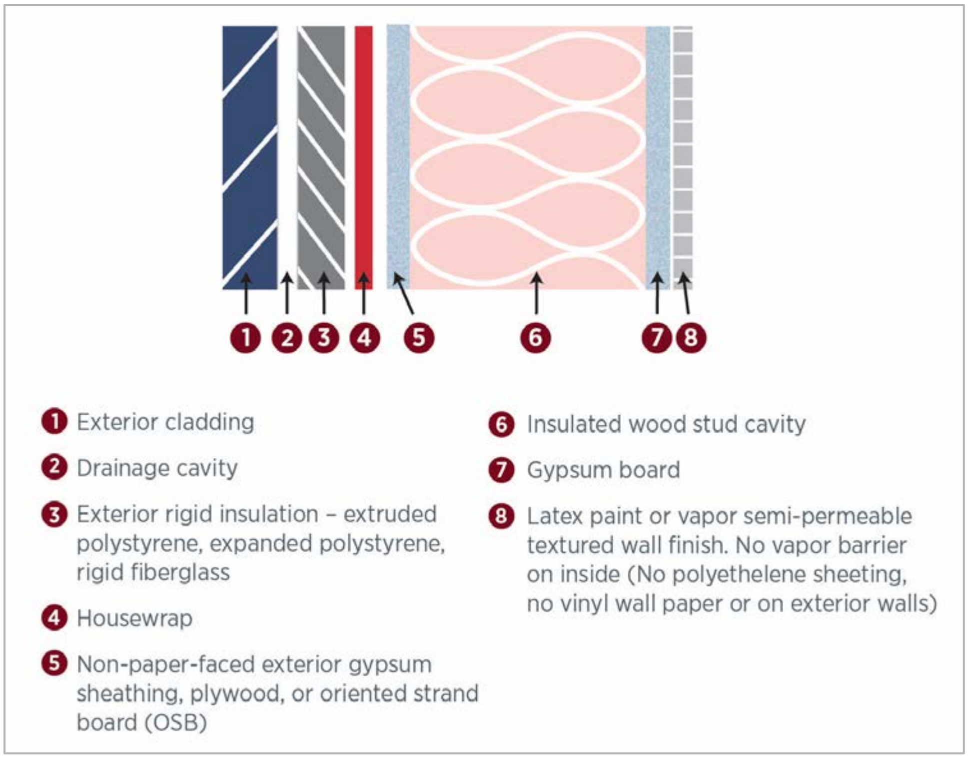

Figure 1. Examples of basic components of a high-performance residential wall assembly with exterior rigid insulation.

In addition to the construction of the wall assembly itself, many interior and exterior environmental factors impact the movement of heat, air, and moisture within a wall assembly. These include ambient temperature and humidity levels, indoor temperature and humidity, solar radiation, exterior condensation, wind-driven rain, construction moisture, ground- and surface water, and air pressure differentials (ASHRAE 2017). Thus, wall assemblies must be constructed in a way that can mitigate the negative effects of environmental conditions.

Wood is the typical framing material used in the United States, although steel and concrete are also available. Steel framing is more common in commercial and multifamily construction, and is rarely used in residential construction due to the low cost of lumber. Modular panels, such as structural insulated panels, incorporate framing and insulation materials in one panelized unit, typically with either a polystyrene or polyurethane core. Insulated concrete forms (ICFs) are concrete cores cast in place between or around rigid insulation. Both panelized construction and ICFs are growing in popularity in residential construction. Tables 1 and 2 below present common framing and insulation materials for residential construction.

Table 1. Examples of common residential framing materials.

Residential Framing Materials
Framing Lumber/Dimensional Lumber
Light Structural Lumber
Heavy Timber
Finger-Jointed Lumber
Engineered Roof Trusses

Residential Framing Materials	
	Open Web Roof Trusses
Engineered Wood	
	Cross-Laminated Timber (CLT)
	Glulam
	Oriented Strand Board (OSB)
	Plywood
	I-Joists
	Open Web Joists
	Structural Composite Lumber
Panelized Wall Systems (Frameless)	
	Structural Insulated Panels (SIPs)
	Insulated Concrete Forms (ICFs)
	Welded Wire Panels
	Insulated Precast Concrete Panels
Steel Framing	
	Stick-Built
	Prefabricated Systems
Concrete Block Framing	

Table 2. Common residential insulation materials (adapted from Baechler et. al 2012).

Insulation Type	Product Form	R-Value/in.	Advantages	Disadvantages	Relative Cost
Cellulose Insulation					
Recycled newsprint, finely shredded and chemically treated to resist fire, corrosion, fungal growth, and vermin. Loose-fill is most suitable for existing homes.	Blown-in, loose-fill Blown-in, dense-pack Sprayed-on	R-2.9 to R-3.4 R-3 to R-3.4 R-3.6 to R-3.8	Inexpensive. Contains at least 70% recycled paper. Commonly used for energy upgrades in existing homes.	Requires chemical treatment with fire retardant. Cellulose must be kept away from chimneys and metal flues. Address mold issues before installing cellulose. Accidental wetting and high humidity can cause cellulose to absorb large quantities of water, reducing thermal resistance, draining fire retardant, and creating risk of mold and moisture damage to building components.	$ $ $
Cementitious Insulation					
Magnesium oxide from sea water.	Sprayed-on foam	R-3.9	Excellent air barrier. High fire and mold resistance. Nontoxic. Does not off-gas any volatile	Expensive. Must be applied by a trained installer. Few installers trained in this specialty. Expands as it sets and can crack walls if installed incorrectly. Can	$$$

Insulation Type	Product Form	R-Value/in.	Advantages	Disadvantages	Relative Cost
			chemicals. Does not shrink or settle.	be fragile or brittle if exposed to frequent vibration, reducing its performance.	
Cotton Insulation					
Low-grade, recycled, or waste cotton. Borate treated for pest and fire resistance.	Batts	R-3.4	Nontoxic.	Limited availability. Batts may not be sized for standard stud cavity widths. Difficult to cut. Absorbs moisture, does not insulate when wet. Water can carry away pest and fire retardant.	$$$
Fiberglass Insulation					
Glass spun into long fibers and woven. May contain 30% or more post-consumer recycled glass. Batts come with or without vapor-retarder facings such as kraft paper, foil-kraft paper, or vinyl.	Batts	Standard density: R-2.9 to R-3.8 High density: R-3.7 to R-4.3	Batts are inexpensive. Excellent fire and moisture resistance. Resistant to mold and pests. R-value depends on density.	Installation requires protective measures to prevent skin and eye contact. Gaps between batts may allow air infiltration or condensation, reducing effectiveness. Batts are not an air barrier. Available with kraft paper, foil-kraft paper, or vinyl facings to act as a vapor retarder. Kraft paper facing is flammable. Some brands contain formaldehyde, a toxic gas.	$
Glass spun into long fibers and woven. May contain 30 percent or more post-consumer recycled glass.	Blown-in, loose-fill Blown-in, dense-pack	R-2.2 to R-2.7 R-3.6 to R-4.4	Produces little dust during installation. Non-flammable.	Blown fiberglass: Many blowing machines over-fluff fiberglass in attics, reducing density and R-value. Blown-in fiberglass requires careful protective measures to prevent breathing of fibers and skin and eye contact. Must be fully enclosed to prevent entry of glass particles into living spaces.	$ $
	Rigid board	R-2.2 to R-4.3	Excellent for soil contact.	Rigid board can be expensive	$$
Mineral wool					
Slag (a non-metallic by-product of steel-making) or rock,	Batts Loose-fill Sprayed-on	R-3.7 R-3.7 R-3.7	Non-combustible. Excellent sound insulation.	Absorbs water. Vapor permeable. For batts: Improper installation reduces effectiveness; loses R-value when	$$

Insulation Type	Product Form	R-Value/in.	Advantages	Disadvantages	Relative Cost
melted and spun into fibers.				compressed. May not be readily available.	
Polyisocyanurate					
A petroleum product. Can be partially soy-based.	Rigid foam board	R-5.6 to R-8; R-7.1 to R-8.7 with foil facing	Highest R-value per inch, which is valuable when space is limited. When faced with aluminum foil, foil facing protects surface, retains R-value, and serves as vapor retarder.	Expensive. Requires a fire barrier. Should not be used in contact with soil. Its closed cells contain low-conductivity gas. Over time, R-value decreases as some of the gas escapes and is replaced by air. Foil and plastic facings can help stabilize the R-value.	$$$
Polystyrene – Expanded (EPS)					
A petroleum product. Also known as bead board.	Rigid foam board	R-3 to R-4	The least expensive foam board. Comes in many densities and grades.	Absorbs some water. Not a vapor retarder. Requires a fire barrier. Melts at 200°F.	$$$
	Exterior and interior rigid foam block systems	R-10 to R-26	When replacing siding, provides high R-value for walls without drilling or removing interior dry wall. Can be covered by any type of siding.		
Polystyrene – Extruded (XPS)					
A petroleum product.	Rigid foam board	R-5.0	High R-value per inch. Excellent moisture resistance. Good vapor retarder. Preferred material for soil contact or as rain shield.	Requires a fire barrier. Melts at 300°F. Requires a capillary break between soil and insulation. Hydrochlorofluorocarbon, a potent greenhouse gas, is used in its production.	$$$
Polyurethane					
Petroleum or soy or castor-based product	Rigid foam board	R-7 to R-9		Requires a fire barrier.	$$$
	Spray foam: closed-cell, medium-density	R-7 to R-9	Very resistant to moisture. Excellent air barrier; can eliminate the need for separate airtightness detailing. Great adhesion. Closed-cell foam strengthens a structure. Closed-	Expensive. Installation difficult. Requires a fire barrier.	$$$$

Insulation Type	Product Form	R-Value/in.	Advantages	Disadvantages	Relative Cost
			cell foam is a vapor retarder.		
	Spray foam: Open-cell, low-density	R-3.5 to R-3.8	Not a vapor retarder. Is an air barrier.	Expensive. Installation is difficult.	$$$$
	Spray foam with castor or soy oil	R-values comparable to 100% poly-urethane foam	Available in both open- and closed-cell types.	Expensive. Installation difficult. Requires a fire barrier.	$$$$
Sheep's wool					
Sheep’s wool and borate	Batts Loose-fill	R-3.5	Borate-treated for pest, mold, and fire resistance. Maintains insulation effectiveness when moist.	Repeated wetting and drying can carry away the pest and fire retardant.	$$$
Radiant barrier					
Aluminum foil with backing		NA	Reduces attic temperatures. Cost-effective in hot climates.	Not recommended and not cost-effective for cold climates. May create moisture problems. Not for use in unvented attics.	

Along with the typical insulation methods listed in Table 2, emerging materials, not readily available to typical contractors and builders, may become commonly available to insulate new or existing walls. These insulation materials do not yet constitute common practice or come as part of an integrated system, but could be used in combination with other materials to retrofit existing walls. These materials are described in the following sections.

2.1.1 Aerogel Thermal Insulation

Aerogels are gel products that have their liquid component replaced by air. Aerogel blankets have high R values, approximately R-10/in. Aerogel insulation materials are fire resistant, lightweight, nontoxic, and water repellent. Aerogel insulation has been evaluated for use in existing buildings, because of its thin profile and lightweight nature (Berge & Hagentoft 2013; Shukla et al. 2012). However, aerogels are still not cost competitive in the market, resulting in higher installation costs. Simulations using aerogels have shown a wall thickness reduction of 60% and the same thermal conductivity as conventional insulation (Berge & Hagentoft 2013), due to the thin nature of the material. One study estimated the cost of an exterior wall retrofit using aerogel insulation, once it has reached economies of scale, could be as much as 18–23% less expensive than other exterior wall insulation methods because less material is required (Shukla et al. 2012), even though aerogel insulation is currently considered more expensive than typical insulation materials. Traditional drying techniques, known as supercritical drying, for aerogels have been considered a drawback for large-scale material production. Supercritical drying involves a high-pressure, high-temperature process performed in stainless steel drums.

Recent advancements in the drying process, using ambient drying techniques showed superior hygrothermal performance of aerogel blankets, and may drive down the costs associated with the drying process (Nocentini et al. 2018).

2.1.2 Phase Change Materials

A growing body of literature is investigating the use of phase change materials (PCMs) to help decrease building energy consumption by absorbing and releasing heat within the thermal enclosure (Diaconu & Cruceru 2010; Fang et al. 2009; Kosny et al. 2012; Lee et al. 2015; Tyagi et al. 2011). In one study, PCMs consisting of small polymer pouches wrapped in layers of aluminum foil and sandwiched between rigid foam board insulation were installed in the south-facing wall of a residential test building; the material absorbed solar heat then slowly released it to reduce peak heat flux through the wall by 51% (Lee et al. 2015). PCMs are thin and can provide an ample increase in effective R-value without the need to construct an overly thick wall through one of four primary methods: (1) direct incorporation, (2) immersion, (3) macroencapsulation, or (4) microencapsulation. Sun et al. (2018) have proposed a pipe-encapsulated method to reduce the potential for moisture issues.

2.1.3 Vacuum Insulation Panels

Vacuum panel insulation (VIP) is a composite insulation product made of an air-filled core material that is wrapped in layered polymer film. The panels are lightweight and highly insulating but delicate, and if punctured they will lose their thermal properties, which is a significant drawback of the technology. The thermal performance of VIPs has been shown to be greater than traditional insulation materials, but care must be taken to account for thermal bridges caused by studs and fasteners and at panel edges (Mandilaras et al. 2014). One analysis in a multifamily building found decreased moisture content in a VIP retrofit compared to the reference wall (Johansson 2012).

2.2 Wall Construction for Moisture Durability

Hygrothermal building physics refers to the movement of both heat and moisture through building walls, influenced by material characteristics, material placement, climate, and ambient conditions. While the moisture issues and thermal performance of wall assemblies are essentially integrated, the focus of residential construction for decades has been on the thermal performance of building envelopes. Ignoring moisture issues has led to envelope failures in highly insulated homes (Figure 3), primarily caused by faulty construction or a lack of understanding of building science.

Figure 2. Moisture intrusion problems in the building envelope (Source: DOE Emerging Technologies Roadmap, 2019).

Fundamentally, heat and moisture movement are realized through different transport mechanisms but are not easily separated because they act in unison—moisture carries heat with it, and differences in temperature affect the way moisture moves. Thermal conduction, thermal convection, and thermal radiation are modes of heat transfer. Moisture transport occurs through bulk water movement, convection, or diffusion in a gaseous state, or by capillary transport in a liquid state. Traditional building construction allows moisture movement because natural materials such as stone and wood are permeable and porous. Energy efficient construction, which tightens envelopes using combinations of permeable and non-permeable air and vapor materials, may introduce moisture issues by limiting pathways for moisture transport. Less heat is lost through modern enclosures, which improves energy performance but may introduce moisture risks (Lstiburek 2008). Wall assembly failures almost always involve moisture (Little et al. 2015). Further, the presence of moisture increases the risk of deteriorating indoor air quality (IAQ) associated with increased humidity, which can lead to mold growth (Moon et al. 2014; Simonsonet al. 2002; Sundell et al. 2003).

The traditional path to energy efficient envelope construction has been to increase the overall R-value of the wall and tighten the envelope to limit air movement. However, many have noted that this approach could introduce moisture and IAQ concerns (Straube & Smegal 2009; Tsongas 1993; Ueno 2015b). IAQ and moisture issues related to wall systems become a problem when wood framing is exposed to high moisture conditions, leading to fungal growth and potential decay. Mold and dampness in homes has been determined to increase the risks of respiratory illness, especially in children and other sensitive populations (WHO 2009). Mold growth is complicated and depends on both moisture content and temperature. Research has indicated that wood moisture content under 20%, regardless of temperature, will inhibit mold growth (Carll & Highley 1999). Moisture content of around 20–30% with temperatures ranging from 21–32°C is optimal for most decay fungal growth (Carll & Highley 1999). A study in the Pacific Northwest in the 1980s showed that although there was high moisture content and wetting in wood-framed residential wall assemblies, the winter temperatures were low enough to prohibit fungal growth (Tsongas 1985). (American Society of Heating Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 160 aims to control moisture content in building design, sets a standard to minimize mold growth on building materials by “30-day running average surface RH < 80% when the 30-day running average surface temperature is between 5°C (41°F) and 40°C (104°F)” (ASHRAE 2009). Studies have analyzed wall systems using ASHRAE 160 criteria, and found that simulated walls fail, even though physical monitoring indicated low risk (Arena et al. 2013a; Ueno 2015a), indicating ASHRAE 160 may be overly conservative.

To mitigate moisture issues wall assemblies must be constructed in a manner that allows pathways for moisture transport out of the assembly, allowing the wall to dry to the interior and/or exterior when it gets wet. In terms of moisture performance, exterior drainage cavities and wall ventilation details should be considered in the overall assembly structure (Forest & Walker 1990; Straube et al. 2004; Ueno 2010b). Sometimes this construction detail is called a rainscreen, which refers to the combination of the siding, drainage plane, and moisture/air barrier. The location of ventilation openings and cladding materials both affect the hygrothermal performance of the wall system. One study found that closing the upper ventilation opening in a wall assembly with siding (rather than masonry) reduces the ventilation rate by 30–36%; and brick-veneer claddings reduce ventilation rates by up to two orders of magnitude (Langmans et al. 2015). Drainage cavities and wall ventilation details will minimize moisture risk with all cladding types by preventing wetting and providing ventilation to speed drying.

2.3 Deep Energy Retrofits

Deep Energy Retrofits (DERs) are defined as housing renovations that include comprehensive upgrades to the envelope and mechanical systems, achieving energy savings beyond typical weatherization programs, by as much as 30–50 percent on a whole-house basis. Historically, state-level weatherization programs have achieved an average annual energy reduction of 23 percent (Schweitzer 2005). One goal used to describe DERs is to reduce energy consumption by 30 to 50 percent on a whole-house basis (Widder & Baechler 2011). The variability in existing homes makes the path to achieving a DER difficult, as different home configurations and existing components, combined with economic considerations may optimize different sets of packages in order to achieve efficiency goals (Walker & Less 2013). Furthermore, it has been noted that while typical DERs achieve greater airtightness improvements compared to conventional retrofits, ventilation systems are often not installed consistently, raising concerns for impacts on IAQ (Less & Walker 2014). Additionally, simulated versus actual performance after DER's has been questioned, particularly due to differences between simulated and actual occupant behavior (Blanchard et al. 2012). Regardless, in order to achieve energy efficiency goals throughout the United States, comprehensive approaches to retrofitting older housing stock is imperative.

The thermal performance of building envelopes varies by climate zone, and thus requires different retrofit approaches to achieve optimal levels of energy efficiency reductions, compared to cost. For example, compared to cold climates, existing homes in mild climates may be able to achieve DER-level retrofits without extremely high levels of insulation or airtightness. One study in California demonstrated that DERs with code-level insulation upgrades (IECC 2012) achieved on-average 65% net-site energy reductions when coupled with heating, ventilation, and air-conditioning (HVAC) and other end use reductions (Less & Walker 2015 2013). In contrast, another study in Toronto, Canada, determined DER-level retrofits to be optimized for both thermal and economic performance with a combination of highly insulated exterior wall and slab foundations (Jermyn & Richman 2016). Methods for determining optimal retrofit packages have been investigated, using a modified BEopt™ (Building Energy Optimization Tool) model for a 1960s single-family house in eight different U.S. cities, as an example use case (Polly et al. 2011). Less & Walker (2015) outline approaches and packages for DERs in each climate zone. Blanchard et al. (2012) identify approaches to true models based on whole-house energy consumption and utility bills as a way to avoid over-estimating energy savings from DERs.

2.4 Residential Retrofit Market Characterization

According to the latest census data, there are approximately 135 million total housing units in the United States, and single-family detached housing represents 62% (83.5 million) of the total (USCB 2017). Only 32% of the existing homes were built after the 1992 Energy Policy Act, which mandated more stringent building energy efficiency codes. Age profile data from the 2013–2017 American Community Survey shown in Table 3 tell a similar story—nearly 70% of the residential housing stock in the United States (over 92 million homes) is estimated to have been built before 1990.

Table 3. U.S. housing stock by region and year (Source: U.S. Census Bureau, American Community Survey 2013–2017).

Age of House	Northeast Region	Midwest Region	South Region	West Region	Total
	# of Homes	# of Homes	# of Homes	# of Homes	# of Homes
Pre 1949	8,420,173	7,396,551	4,783,916	3,754,540	24,355,180
Built 1950-1969	6,062,780	7,082,877	9,434,290	6,226,701	28,806,648
Built 1970-1989	5,253,461	7,460,513	16,955,096	9,650,399	39,319,469
Built 1990-2009	3,864,657	7,328,388	18,401,099	9,015,711	38,609,855
Post 2010	437,300	705,028	2,271,276	888,808	4,302,412
Total	**24,038,371**	**29,973,357**	**51,845,677**	**29,536,159**	**135,393,564**
Built before 1990	**19,736,414**	**21,939,941**	**31,173,302**	**19,631,640**	**92,481,297**
% built before 1990	**82%**	**73%**	**60%**	**66%**	**68%**

The most common types of wall cladding in the nation are wood siding and lap siding made of aluminum, vinyl, or steel (from 2015 U.S. Energy Information Administration [EIA] Residential Energy Consumption Survey [RECS]; see Table 4). These are also the siding types that experience the highest percentages of poor and no insulation. Much of the wood siding is also lapped.

Table 4. Major outside wall construction by Building America climate region based on RECS 2015 (millions of houses).

Climate Region	Total U.S.	Very Cold/Cold	Mixed-Humid	Mixed-Dry? Hot-Dry	Hot-Humid	Marine
Siding (aluminum, vinyl, or steel)	40.2	19.7	13.8	0.7	4.5	1.5
Brick	32.9	11.1	13.5	0.7	7.7	+
Wood	18.0	6.7	3.5	2.0	3.3	2.5
Stucco	15.3	1.8	0.7	8.4	2.5	1.8
Concrete or concrete block	6.7	1.1	0.8	0.7	3.6	0.4
Shingles (composition)	3.0	1.3	0.7	0.2	0.5	0.3
Stone	1.4	0.4	0.4	+	0.5	+
Some other material	0.7	0.3	+	+	+	+

+ Data withheld because either the Relative Standard Error was greater than 50% or fewer than 10 households were sampled.

The residential remodeling market continues to grow, amounting to $424 billion in 2017 (up 50% from 2010). In 2017, approximately 50% of home improvement projects included upgrades to systems in aging housing stock such as new windows and doors, siding, roofing, HVAC systems, and insulation, and an estimated one in five homeowners invested in energy efficiency retrofits (Joint Center for Housing Studies of Harvard University 2019). Of these replacements, almost 1 million projects included siding replacement, amounting to $4.9 billion dollars (Joint Center for Housing Studies of Harvard University, 2019). The number of siding projects already taking place around the country every year represents an opportunity to integrate advanced envelope insulation technologies.

Even considering the opportunity, the number of existing residential buildings with little to no insulation is staggering. An estimated 34.5 million homes have wood studs and no insulation (NREL 2019); this representing approximately 38% of single-family detached homes in the United States. Similarly, 71% of existing homes have air leakage rates of 10 or more air changes per hour at 50 pascals of pressure (ACH50), indicating a significant amount of air leakage through the building envelope. Figure 4 below presents ResStock national baseline housing characteristics for insulation and air leakage.

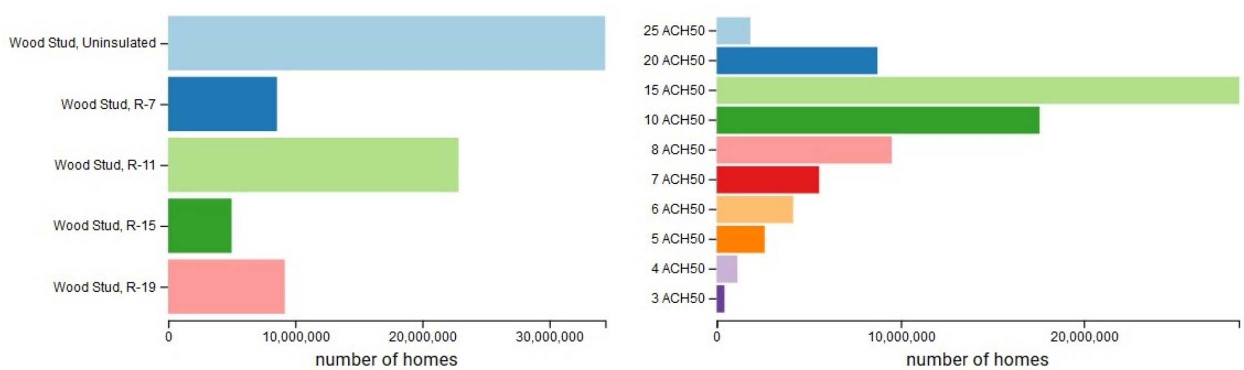

Figure 3. Existing housing stock wall insulation levels and air infiltration rates (Source: ResStock).

3.0 U.S. Department of Energy and European Union High-Performance Wall Research and Development

DOE's BTO oversees R&D in the building sector. The mission of the BTO is to "develop, demonstrate, and accelerate the adoption of technologies, techniques, tools, and services that are affordable, as well as to enable high-performing, energy-efficient residential and commercial buildings in both the new and existing buildings markets." (DOE 2016). BTO's goal is to reduce building energy use intensity (EUI) by 30% by 2030, and reduce energy use per square foot of all buildings by 50% compared to 2010 levels, by 2030 (DOE 2016). Specific program areas within BTO include Emerging Technologies, Residential Buildings Integration, Commercial Buildings Integration, Appliance and Equipment Standards Program, and the Energy Codes Program. Residential envelope research has been a focus of BTO's Residential Buildings Integration and Emerging Technologies (ET) program areas, both of which are discussed in this section.

In addition to DOE effort, this section also provides an overview of efforts funded by the European Union for residential envelope retrofits.

3.1 Building America Research

In the residential building sector, BTO's Building America program has invested in residential research funding since the mid-1990s. The Building America program partners with industry, national laboratories, and applied research organizations to collaborate on residential R&D, designed to bring energy efficient innovations to the marketplace. The program has invested in research in both new and existing residential construction, including enclosures, HVAC, IAQ, and equipment. Building America funding is distributed through competitive solicitations open to both the public and private sector. DOE also invests in state-of-the-art research facilities at the national laboratories.

The Building America program produces R&D Plans and Roadmaps, designed to focus program goals, and develop solutions to building science problems in the housing industry. One primary focus of Building America R&D is developing solutions to promote high-performance, moisture-managed envelopes in new and existing homes (DOE 2015). A synopsis of residential envelope research focused specifically on walls in existing homes in presented in Table 5.

Table 5. U.S. Department of Energy Building America wall assembly research in existing homes.

Building America Team Name	Project Name	Technology/ Application	Citation
Advanced Residential Integrated Energy Solutions Collaborative	Evaluating an Exterior Insulation and Finish System for Deep Energy Retrofits	Exterior Wall System	(Dentz & Podorson 2014)
Building Science Corporation	Cladding Attachment Over Thick Exterior Insulating Sheathing	Exterior Sheathing	(Baker & Lepage 2013)
Building Science Corporation	Analysis of Joist Masonry Moisture Content Monitoring	Moisture	(Ueno 2015b)

Building America Team Name	Project Name	Technology/ Application	Citation
Building Science Corporation	Mineral Fiber High-Performance Enclosure Retrofit	Exterior Sheathing	(Neuhauser 2015)
Building Science Corporation	External Insulation of Masonry and Wood-Frame Walls	Exterior Sheathing/ Masonry Walls	(Straube, et al. 2012)
Building Science Corporation	Hygric Redistribution in Insulated Assemblies: Retrofitting Residential Envelopes without Creating Moisture Issues	Exterior Sheathing	(Smegal & Lstiburek 2013)
Building Science Corporation	Evaluation of Two CEDA Weatherization Pilot Implementations of an Exterior Insulation and Over-Clad Retrofit Strategy for Residential Masonry Buildings in Chicago	Exterior Sheathing/ Masonry Walls	(Neuhauser 2013)
Building Science Corporation	Moisture Durability with Vapor-Permeable Insulating Sheathing	Exterior Sheathing	(Lepage & Lstiburek 2013)
Building Science Corporation	Deep Energy Enclosure Retrofit for Double-Stud Walls	Interior Wall Structure/Insulati on	(Loomis & Pettit 2015)
Building Science Corporation	Moisture Management for High R-Value Walls	Moisture	(Lepage et al. 2013)
Consortium for Advanced Residential Buildings	Moisture Research – Optimizing Wall Assemblies	Moisture	(Arena & Mantha 2013c)
Consortium for Advanced Residential Buildings	Installing Rigid Foam Insulation in the Interior of Existing Brick Walls	Masonry Walls	(Natarajan et al. 2012)
IBACOS	Spray Foam Exterior Insulation with Stand-Off Furring	Exterior Wall System	(Herk et al. 2014)
Florida Solar Energy Center	Investigating Solutions to Wind Washing Issues in 2-Story Florida Homes, Phase 1	Wind Washing	(Homes et al. 2009)
Partnership for Home Innovation	Using Retrofit Nail Base Panels to Expand the Market for Wall Upgrades	Modular Panels	(Bianco & Wiehagen 2016)
Partnership for Home Innovation	Extended Plate and Beam Wall System: Concept Investigation and Initial Evaluation	Modular Panels	(Wiehagen & Kochkin 2015)

CEDA = Community and Economic Development Association of Cook County, Incorporated

3.1.1 Hygric Redistribution in Insulated Assemblies

The Building Science Corporation (BSC) conducted research on the moisture performance of exterior wall retrofits over existing cladding. Specifically, BSC tested the moisture behavior of the drainage cavity to see how moisture moves and whether it affects the general durability of the assembly. Through laboratory and field tests, the study found that there were no moisture risks when retrofit wall construction included a drainage gap between the exterior insulation and sheathing (Smegal & Lstiburek 2013).

3.2 Emerging Technologies Research

BTO's ET program supports R&D for new technologies, systems, and software that can contribute to reducing building energy consumption. The ET program provides R&D support in five primary areas: solid-state lighting; heating, ventilation, air-conditioning, and refrigeration (including water heating and appliances); sensors and controls; windows and envelope; and modeling and tools. The primary ET focus is the development of new technologies, and ET-funded research is often experimental in nature.

Like Building America, ET develops R&D Plans and Roadmaps outlining program objectives and R&D focus areas. The latest roadmap (in press) describes objectives associated with high-performance wall assemblies. Table 6 describes current and recent ET research related to envelope systems in existing residential buildings.

Table 6. U.S. Department of Energy Emerging Technologies program residential envelope research.

Research Organization	Project Name	Technology	Link to Description
Industrial Science and Technology Network	A New Generation of Building Insulation by Foaming Polymer Blend Materials	Insulation	Project link
Poly-Cel, Inc.	Automated Process for the Fabrication of Highly Customized Thermally Insulated Cladding Systems	Insulation	Project link
Fraunhofer	Bio-Based, Noncorrosive, Nonflammable Phenolic Foam Insulation	Insulation	Project link
PPG Industries, Inc.	Fluorescent Pigments for High-Performance Cool Roofing and Facades	Cool Roof/Facades	Project link
Iowa State University	Novel Infiltration Diagnostics Based on Laser-line Scanning and Infrared Temperature Field Imaging	Envelope Diagnostics	Project link
Oak Ridge National Laboratory	Optimization of Very Low Thermal Conductivity Material	Insulation	Project link
Oak Ridge National Laboratory	Core Research Support for BTO Envelope Program	Insulation; Air Barriers	Project link
Oak Ridge National Laboratory	R25 Polyisocyanurate Composite Insulation Material	Insulation	Project link
Lawrence Berkeley National Laboratory; Oak Ridge National Laboratory	Robust Super Insulation at a Competitive Price	Insulation	Project link
Lawrence Berkeley National Laboratory; Oak Ridge National Laboratory	MOISTHERM: Integrated Heat/Moisture Transfer Envelope Modeling Tool	Envelope Modeling	Project link

3.3 European Union Research

The European Union (EU) has two primary directives driving energy efficient building retrofits in their member states, which are Directive 2010/31/EU Energy Performance of Buildings (2010), and Directive 2012/27/EU Energy Efficiency (2012). Efforts under these directives include not only technology development and retrofit project implementation, but also market characterization and typology efforts. One such effort is the EPISCOPE and TABULA[1] project, which developed energy savings potentials (using modeling methods) of 13 member countries of the EU which classifies groups of buildings that are typical in those regions (Mata et al. 2018). The project provides not only analyses of building typologies by region, but it also provides calculators for users to run scenario analyses for residential retrofits, which models future energy consumption. Researchers have noted that these programs have revealed gaps in technology development, particularly pertaining to insulation and HVAC systems for residential retrofits (Mata et al. 2018).

Envelope technology research underway in the EU includes a variety of explorations, methods and applications for exterior envelope retrofits. For example, pre-fabricated rigid foam panels for multi-family building investigate in Italy have shown potential to reduce building energy demand by as much as 82% (Pittau et al. 2017). The Multifunctional Energy Efficient Façade System for Building Retrofitting (MEEFS) was a program was an EU funded program from 2012-2016, with was a large collaboration between nine EU countries. The project was focused on development of a panelized modular retrofit system that combined advanced passive solar protection/energy absorption, and a passive solar collection/ventilation unit. The modules sit outside the existing façade of the building in an exterior application and connect to a building energy management system so they are fully integrated into the structure (European Commission 2019).

Currently funded projects under EU frameworks are presented in Table 7 below.

Table 7. European Union funded projects for advanced envelope retrofits.

Program Name	Program Description	Technology	Link to Description
BIM4EEB	Develop a BIM-based toolset for construction companies to carry out building retrofits	Tools	Project link
BIM-SPEED	Augment BIM4EEB for deep energy retrofits	Tools	Project link
4RinEU	Timber-based prefabricated multifunctional facade	Retrofit Panels	Project link
BRESAER	Prefabricated materials encased in a lightweight mesh	Facades and Roofs	Project link
E2VENT	Integrated cladding, modular heat, and thermal energy storage for retrofits	Integrated facades	Project link
Gelclad	Exterior cladding with aerogel insulation	Cladding/ Insulation	Project link

[1] http://episcope.eu/index.php?id=97

Program Name	Program Description	Technology	Link to Description
AptiWall	Lightweight concrete panel with thermal storage potential and integrated heat exchanger	Panels	Project link

4.0 Current Wall Systems for Residential Retrofits

Many factors affect material and technology selection for wall retrofits. Unlike new homes, existing structures have to be assessed based on the wall system that is currently in place. While similarities exist based on building age and location, there may be little consistency between structures, even on the same block. Additionally, the built or current state of the wall system is a large factor that will affect retrofit choices. In general, factors that affect wall system choices for existing homes include the following:

- physical built characteristics including framing type, amount/type of insulation, weather barrier, cladding type, fenestration, wall intersections, foundation type, interior wall materials, presence of hazardous materials such as lead and asbestos, structural integrity, and general repair of the existing wall structure;
- climate zone;
- cost;
- material availability; and
- expertise of contractor.

One common option for adding insulation to an existing wall is to blow in dense-pack fiberglass or cellulose insulation into the cavities between the framing (drill-and-fill). This is usually achieved by drilling small holes into the interior or exterior side of the wall, between the framing and blowing in a fiberglass or cellulose insulation. This approach is sometimes combined with exterior rigid insulation to improve existing homes that have little to no insulation. Drill-and-fill is generally considered cost effective because it can be applied with little disturbance to the wall assembly, and case studies have shown improvement in thermal performance (Puttagunta 2015). When not coupled with exterior rigid insulation, the drill-and-fill method does not address thermal bridging, which is a significant cause of heat loss through wall cavities (Straube & Smegal 2009; Theodosiou et al. 2015). The presence of irregular framing, other obstructions, and knob and tube wiring in the wall cavities in older homes hinders the dense-pack of cellulose or fiberglass insulation, leaves gaps in wall coverage, and reduces the R-value. For DER retrofits, a more comprehensive method of insulating uninsulated walls should be used.

Figure 4. Drill-and-fill exterior residential wall retrofit.

Kamel and Memari (2016) published a paper in the Third Residential Building Design & Construction Conference titled “Different Methods in Building Envelope Energy Retrofit” (Kamel & Memari 2016). The paper describes a number of other options, of which the most relevant ones are described in the individual sections below.

4.1 Ventilated Facades/Rainscreens

Ventilated facades (sometimes called a rainscreen or ventilation cavity) refer to exterior cladding systems that include a frame or other type of ventilation cavity to provide a gap between the cladding and weather barrier. They are not a wall assembly themselves, but are construction details that are recommended for managing moisture in high-performance enclosures, which is why they are discussed in detail here.

The gap can be created by installing some kind of spacer material on the wall over the weather barrier and under the cladding. The spacer material can consist of furring strips of wood, plastic, or metal that are installed vertically at even spaces of 16 to 24 inch Plastic mesh and corrugated or dimpled house wrap are also used as spacers. This type of construction detail should be considered for wall systems in high-rainfall climates to protect the assembly from moisture intrusion (BSC 2004; Straube 2012). The ventilation rate varies depending on the siding type and openings, which should be considered in the design-phase of the wall assembly (Langmans et al. 2016). In one alternative, the cladding can be placed with thin joints where individual pieces of the cladding abut one another to allow air to enter and leave the wall cavity, which is referred to as an open-joint ventilated façade and results in energy savings in hot climates (Sanjuan et al. 2011).

The many rainscreen products on the market range from prefabricated cladding systems with integrated rainscreens to site-built methods specified by the building designer, architect, contractor, or other professional. The market for rainscreens is undetermined; however, it is noted in the industry that rainscreens are not often used in residential buildings because of their associated increased cost.

4.2 Exterior Wall Insulation Retrofits

Exterior wall insulation retrofits include all methods by which the wall assembly is retrofitted from the exterior of the house, with minimal disruption to the interior and conditioned areas. Because the interior of the home is not generally affected by this approach, a primary benefit is that the homeowners can remain in the house during construction. Most of these approaches, however, require the removal/reinstallation of windows and/or doors, which can be expensive and burdensome. Other methods can be applied without removing windows by integrating air and water control layers with flashing details (Pettit et al. 2013). However, it has been noted that the benefits are most fully realized (i.e., cost effective) if the homeowner is already considering a cladding replacement (Ueno 2010a).

One benefit to retrofitting a wall from the exterior is that new, likely more robust and continuous, air, water, and vapor control layers can be established (Lstiburek 2007). These control layers can be placed on the interior or exterior of the insulation. Regardless of the exact order of the control layers in an exterior wall retrofit, the details around the roof, foundation, and building openings (windows and doors) are critical to a successful project (Baker 2013). This report also stresses the importance of choosing the correct fasteners and cladding to avoid any unwanted deflection of thick rigid insulation.

Exterior wall retrofits can be done either by installing a compressible layer (i.e., 1/4 inch or 3/8 inch “fan fold” foam, typically used as a siding retrofit substrate) over the cladding to help level the surface, or by removing the existing cladding to start with a more even surface. Specific methods are discussed below.

4.2.1 Exterior Insulated Sheathing, Exterior Super-Insulation

The use of exterior insulated sheathing or exterior super-insulation requires removal of the exterior cladding system and underlying materials down to the existing sheathing of the original wall. Wall cavities are insulated with batts, or blown-in insulation, and rigid foam boards are added to the underlying material (strand board, plywood, or dimensional lumber sheathing). A weather barrier (water control layer) may be applied over the sheathing, and integrated with flashings, followed by exterior rigid insulation. If installed in a continuous manner, the weather barrier can act as an air barrier as well. Window and door jambs, along with flashing and sills should be extended to match the new depth of the wall (Roberts & Stephenson 2012). Common continuous rigid insulation types include polyisocyanurate, extruded polystyrene (XPS), expanded polystyrene (EPS), rigid fiberglass board, and rigid mineral wool. Applying rigid foam board insulation to an existing wall improves thermal performance by adding insulation and the insulation layer is continuous across the studs, which reduces thermal bridging, but it also can reduce the ability of the wall to dry to the outside (Roberts & Stephenson 2012). Ueno (2010) describes a method of applying two layers of 2 in. foil-faced polyisocyanurate in a staggered pattern to avoid a straight path for air and water to penetrate the assembly. A rainscreen can be added over the rigid insulation, or a gap or ventilation cavity can be left between the rigid insulation and the cladding for drainage. The new siding is added last. The full assembly detail is presented in Figure 6.

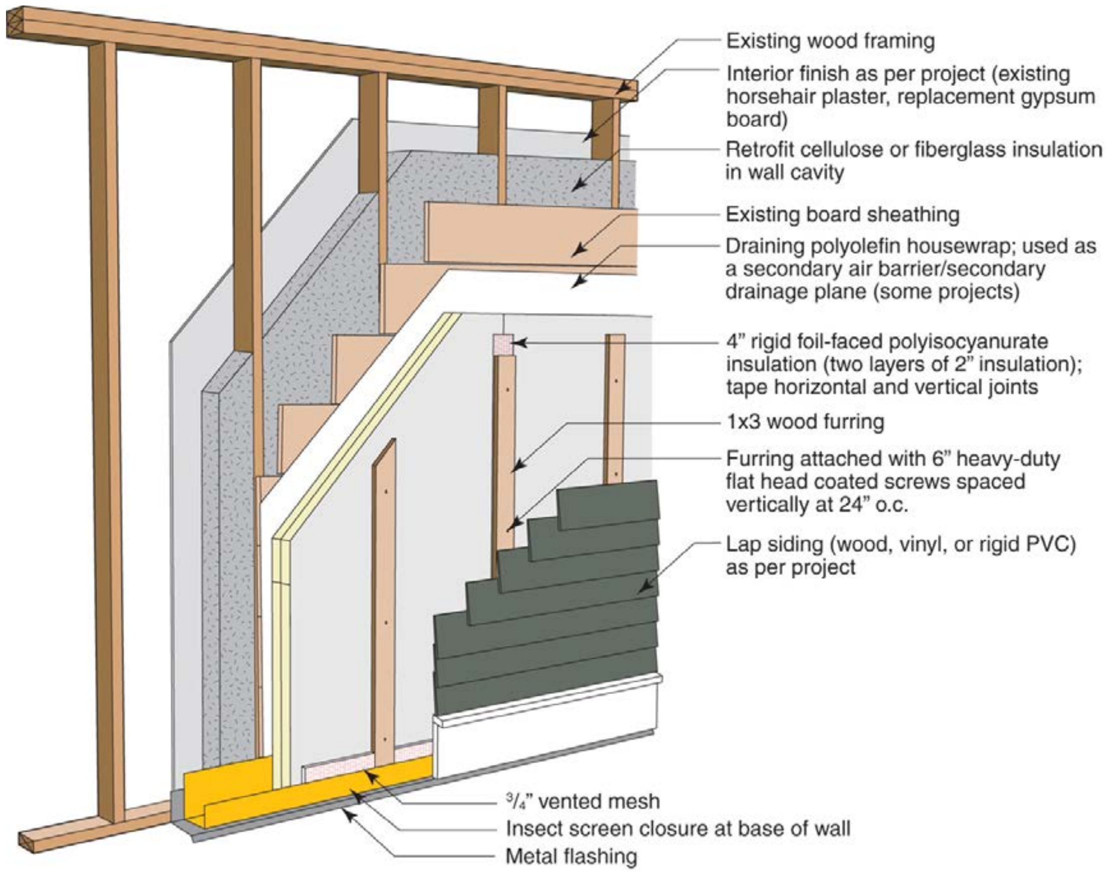

Figure 5. Exterior super-insulation retrofit assembly details (Ueno 2010).

4.2.2 Thermal Break Shear Wall Assembly

The application of a thermal break shear (TBS) wall was initially investigated in the Pacific Northwest as a method of providing thermal and seismic performance enhancements to residential buildings. A TBS wall assembly uses standard framing, but adds a 1.25 inch layer of rigid insulation directly on top of the framing, followed by a layer of sheathing using a staggered nailing pattern (see Figure 7). The continuous rigid insulation provides protection against thermal bridging, and the sheathing on top of the insulation provides seismic resistance. The Northwest Energy Efficiency Alliance analyzed the thermal performance and Oregon State University's Knudsen Wood Engineering Laboratory analyzed the seismic performance. Cyclic lateral load tests showed that compared to a traditional shear wall, which experienced catastrophic failure under a 5,600 pound load at 1-3/4 inch of deflection, the TBS wall could resist up to the test protocol maximum deflection at 5 inches (Miltner Construction Management LLC 2016). Thermal performance for the entire wall assembly was determined to have a nominal R-value (not accounting for the effects of thermal bridging) of 25.7 (2x6 TBS wall, 24 in. O.C., high-density batts, 1.25 in. polyisocyanurate [ISO] rigid insulation) or 30.6 (2x8 TBS wall, 24 inch O.C., high-density batts, 1.25 inch ISO rigid insulation).

Figure 6. Cross section of a TBS wall assembly for new construction, showing the framing, rigid insulation, and sheathing (Miltner Construction Management LLC 2016).

In a retrofit situation, the exterior cladding, weather barrier, and insulation layers are removed from the outside of the wall, exposing the framing. New batt or spray foam insulation is added between the studs, and a rigid foam board is applied over the studs, followed by the sheathing, weather-resistant barrier, rainscreen, and exterior cladding (Earth Advantage 2018a). A TBS wall retrofit provides both a thermal and seismic upgrade. Costs for a retrofit project in Portland, Oregon, were determined to be \$23.05/ft^2, compared to \$18.70/ft^2 for a traditional re-siding project that includes standard sheathing, cavity insulation, weather-resistant barrier, and siding (Earth Advantage 2018b).

4.2.3 Spray Foam Outer Shell Retrofit

Techniques for re-framing over existing cladding systems include using 2x4 framing lumber or 2x3 furring strips.

4.2.3.1 2x3 Furring Strips Over Existing Siding with Spray Foam

This method was developed as a method for DERs and is achieved by adding 2x3 furring strips to the exterior side of existing sheathing to hold a closed-cell spray foam using 8 inch heavy duty wood screws (Coldham 2009; Straube 2009[1]). The spray foam provides continuous insulation and an air barrier when correctly installed and sealed (i.e., extended over the top plate to seal with the ceiling drywall), and it is strong enough to stabilize the furring strips and carry the load of the cladding. Plywood boxes are attached to openings to provide a new surface for windows and doors. The foam acts as an air, vapor, and water barrier, so a rainscreen detail is not required (Coldham 2009).

[1] Straube J. 2009. What Would I do? Presented at Building Science Corporation. Unpublished.

4.2.3.2 2x4 Stud Framing over Existing Siding with Spray Foam

In an effort to provide a DER strategy for existing envelopes, BTO's Building America team IBACOS, the New York State Energy Research and Development Authority (NYSERDA), and GreenHomes America developed a method for re-siding over the existing cladding of a home. This method was used to provide a DER retrofit that encapsulated existing lead paint. 2x4 framing was installed directly over the existing siding, filled with spray foam, and covered with a thin profile 3/8 in. exterior sheathing and vinyl siding (Herk et al. 2014; IBACOS 2013a) (see Figure 8). Windows were also replaced. Insect guard and ventilation details were attached to the bottom of the wall, facing the foundation. In addition to installing the new wall structure, the team had to install three standard "L" brackets to the top and bottom of the new wall structure to secure it to the existing wall. This approach was chosen because of a lack of technical information about the structural strength of adhering spray foam to wood.

A blower door test was conducted before and after the project to test for airtightness. Total air leakage was reduced from 2,675 to 1,625 CFM (cubic feet per minute), which represented a 39% reduction. Herk et al. (2014) did not discuss moisture durability. Total costs were $19.26/ft^2 for the entire project (Herk et al. 2014).

Figure 7. Spray foam installed between studs in new framing built over existing siding (IBACOS 2013b).

4.3 Modular/Panelized Systems

Modular wall systems are prefabricated panels that are built in manufacturing facilities, then transported to the building site. Generally, paneled walls are studless, which decreases thermal bridging. Unlike framed (stick-built) walls that are built onsite with individual framing, insulation, air barrier, and cladding materials, modular construction incorporates many envelope layers into one panel system, the panels, or modules, are designed offsite, manufactured in a facility, then transported to the building site where they are placed on the foundation. Some examples of these systems include CENTIRA's insulated metal wall panels or customized panels (Pihelo et al. 2017).

4.3.1 Retrofit Insulated Panels

Retrofit insulated panels (RIPs) refer to prefabricated panels that include rigid foam insulation laminated to a single sheet of OSB structural sheathing (Figure 9). They are also referred to as nail base panels, or half-SIPs. The rigid insulation provides better thermal performance, and the OSB panel provides the rigid structure on which to apply the exterior siding or other cladding material. Panels are cut to fit onsite and attached over an existing wall. New underlayment and cladding are applied onsite. Panels come in different thicknesses, ranging from 2 in. to 11-¾ in, representing R-values between 7.9 - 43, respectively. Panels are generally available in sizes ranging from 4x8, 4x12, and 4x16 ft. The home's existing exterior siding, underlayment, and weather barrier should be removed before installing the new panels, and a new weather-resistant barrier should be added either between the existing sheathing and the retrofit panel or over the new retrofit panel. Existing windows should be removed (SIPA, Home Innovation Research Labs 2015). There are multiple manufacturers of retrofit panels.

One study found that residential wall construction using SIPs saved as much as two-thirds of the site framing costs over traditional framed methods (Mullens & Mohammed 2006).

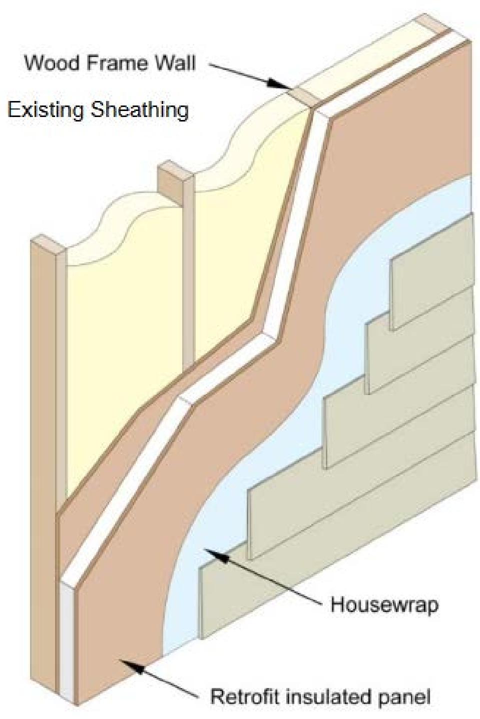

Figure 8. Retrofit insulated panel wall assembly (Bianco & Wiehagen 2016).

One Building America demonstration project reported costs of a DER with retrofit panels to be $8.94–$10.75/ft^2 for above-grade walls, resulting in R-values ranging from R-18 to R-30 (Bianco & Wiehagen 2016). Passive House in Canada has also developed what they call a "PEER

Panel Prototype" (PEER stands for Prefabricated Exterior Energy Retrofit). This system includes a 1/4 in. or 3/8 in. fan fold foam, typically used as a siding retrofit substrate (sometimes referred to as a "squishy" layer), which helps to absorb irregularities on the existing exterior (Natural Resources Canada 2018).

Another option for panel systems includes natural fiber-reinforced structural insulated panels (NSIPs), which are a panelized wall assembly that use a natural, fiber-reinforced composite laminate for skin material, replacing the OSB that is used commonly in SIP panels. Fiber options for NSIPs include glass-polypropylene, carbon-epoxy, glass epoxy, and natural fibers such as jute, sisal, cotton, coir, (coconut fiber), hemp, and kenaf (Uddin & Kalyankar 2011). Various products on the market use natural materials as alternatives to synthetics.

4.3.2 Solid Panel Perfect Wall

Typically used for new construction, using structural engineered panels, the Perfect Wall system aims to create a studless, continuous rigid shell using wood composite. The weather, vapor, air, and thermal barriers are then applied to the exterior surface, providing continuous thermal and hygrothermal barriers around the entire structure (University of Minnesota, Center for Sustainable Building Research, U.S. Department of Energy 2018). The aim of the Perfect Wall system is to create a wall construction method that a single contractor can complete in a short amount of time, with lower labor costs. The Perfect Wall system is currently being field tested; full thermal and hygrothermal results will be presented in 2019 or 2020.

4.4 Insulated Siding/Cladding Systems

Insulated siding and external wall insulation systems are applications of insulation materials that do not provide shear strength to the wall. Instead, they are integrated into siding materials in various manners to provide additional envelope insulation without needing to remove layers of the existing wall assembly. Specific applications are discussed below.

4.4.1 Insulated Vinyl Siding

Typical insulated vinyl siding systems include vinyl cladding with an installed layer of EPS on the inside of the siding system that is permanently adhered to the vinyl using adhesives. R-values of traditional insulated vinyl siding are low, ranging from R-2 to R-5. In a moisture performance experiment, Drumheller & Carll (2010) found that compared to other wall configurations, insulated vinyl siding had some of the lowest moisture content after a 22-month in situ experiment, possibly due to warmer within-wall temperatures.

Oak Ridge National Laboratory (ORNL) is developing a vinyl siding system that meets code requirements for continuous insulation (see Figure 10). The proposed vacuum-insulated vinyl siding represents a 4- to 5-fold thermal improvement over currently available insulated siding products. It has a sufficient R-value to significantly improve thermal performance and a much thinner profile that facilitates its application to existing homes without the need for expensive re-trimming of the architectural details. Full-scale laboratory testing has demonstrated that an R-12 is achievable (Desjarlais & Biswas 2019). Royal Building Products and NanoPore are manufacturing partners.

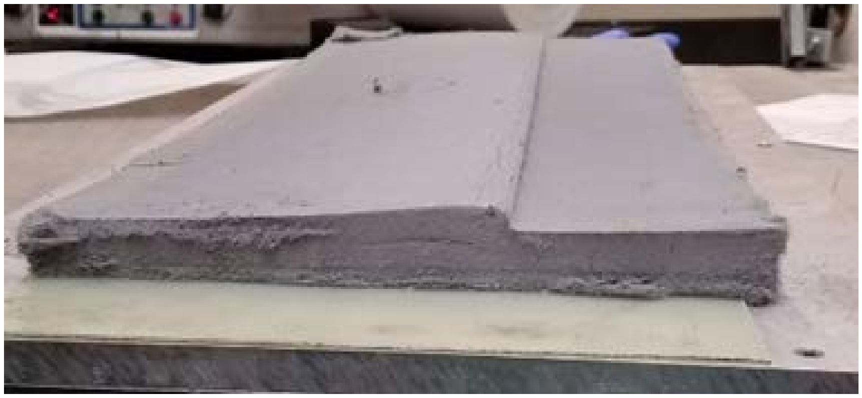

Figure 9. Insulation for an insulated vinyl siding panel (Source: ORNL 2019).

4.4.2 Exterior Insulation and Finish Systems

EIFSs, sometimes referred to as External Thermal Insulation Cladding Systems (ETICSs), integrate continuous insulation and an external finish (sometimes referred to as synthetic stucco), that can be installed over sheathing in wood-framed walls, or masonry walls. EIFSs were developed initially to insulate masonry walls, but have been adapted to be exterior systems for wood-framed residential walls. EIFSs are non-load bearing and do not provide shear strength to the wall. Typically, the EIFSs are installed with adhesive or mechanical fasteners over a continuous sheathing system. Historically, EIFS have had moisture issues caused by water intrusion when installed over wood sheathing (Auman & Egan 2016; Bronski & Ruggiero 2000; Brown et al. 1997), making the addition of a drainage plane essential. If installed correctly, with a drainage plane to protect the interior wall cavity, EFISs have shown strong hygrothermal performance (Beaulieu et al. 2002; Desjarlais & Johnston 2014).

4.5 Masonry Walls

According to RECS (EIA 2015), 11.1% of exterior cladding in the cold (or very cold) climate is made of brick masonry. These walls are not typically insulated because insulating from the inside would mean giving up valuable square footage, and insulating from the outside would take away the architectural feature of the exterior brick. Interior insulation of solid mass masonry walls should be approached with caution. Interior insulation will reduce heat flow through the assembly, thereby reducing drying and possibly increasing risks of freeze-thaw damage to the masonry. In addition, low-performance interior insulation assemblies (e.g., fiberglass and polyethylene) add risks due to potential wintertime air leakage condensation on the now-cold brick surface (Straube et al. 2012). Exterior insulation eliminates these problems, by keeping the mass masonry wall on the "warm and dry" side of the assembly. By providing exterior insulation and water control, the durability of the wall is significantly improved (see Figure 11). The amount of exterior insulation needed to safely insulate masonry walls depends on the climate zone in which they are installed.

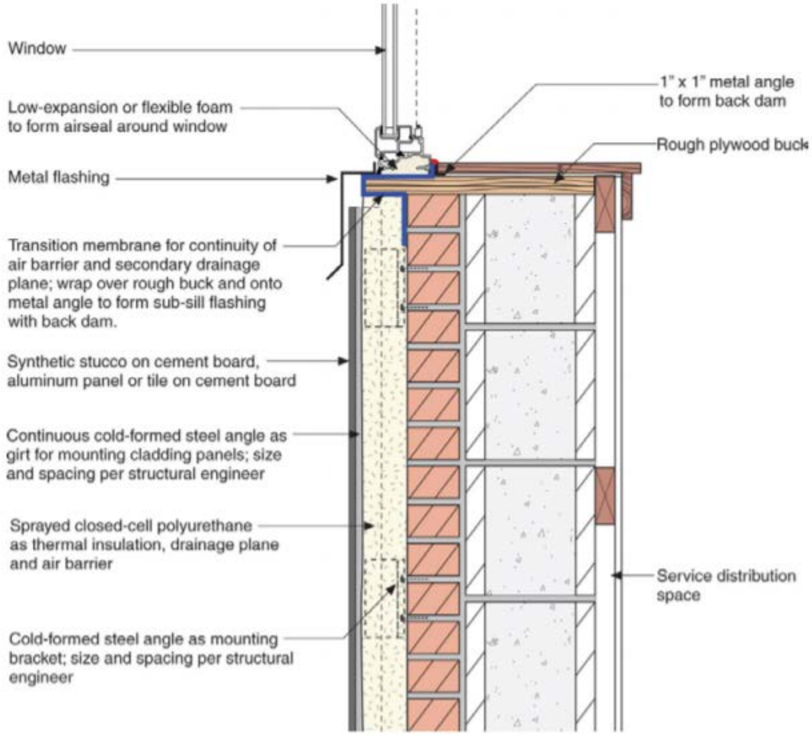

Figure 10. Typical exterior masonry wall retrofit (Straube et al. 2012).

A difference between exterior wall retrofits on wood-frame vs. masonry buildings is that masonry buildings are slightly less vulnerable to wetting of the original wall due to water control imperfections (i.e., rain leakage). Mass masonry walls can often survive this leakage (given that they were fully exposed to the elements before), while wood-frame walls can be at risk of failure. When adding insulation to the exterior of masonry buildings, one difference compared to wood-frame buildings is that an additional furring strip is needed to which to attach an exterior cladding (hidden from the profile seen in Figure 11, but visible in the profile seen in Figure 12).

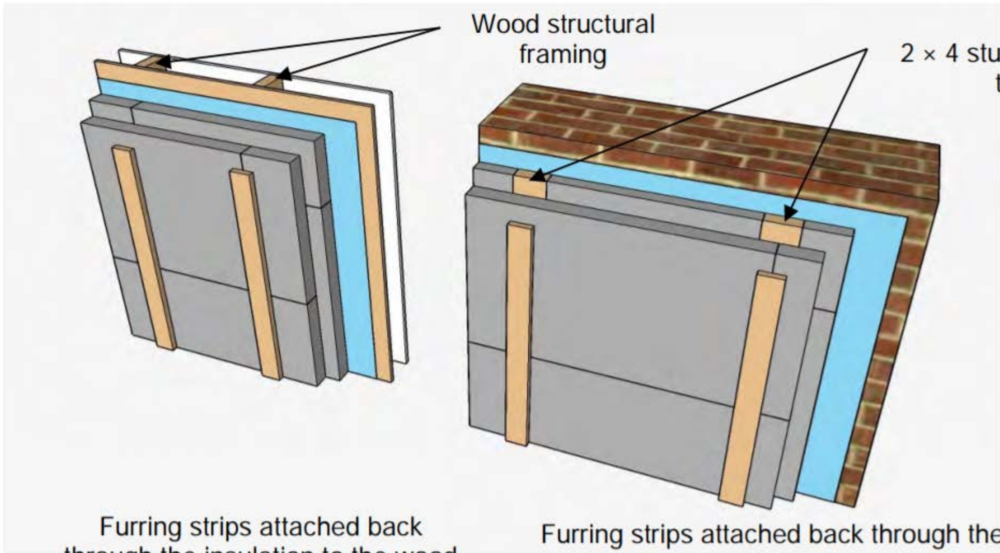

Figure 11. Additional step required for masonry buildings (Baker 2013).

Most approaches to exterior insulation retrofits can be done on any cladding, including masonry. In some cases, a masonry retrofit may be easier than a retrofit over an existing stucco or vinyl cladding because of its relatively flat surface and relatively stable exterior. Many case studies of masonry retrofits are multifamily buildings. In a project involving the Castle Square Apartments in Boston, Massachusetts (Neuhauser et al. 2012), a low-rise multifamily building was air sealed, had windows replaced, and was ventilated to try to help improve energy performance and IAQ. In this case, the window replacements accounted for about 15% of air leakage reduction, and the other air sealing measures accounted for about 40% of the air leakage reduction. This, along with HVAC replacements, led to an overall energy savings of 30% for the building. Air sealing for compartmentalization between residential units for odor, smoke, and sound control also was performed. Air sealing also occurred behind the brick during all window replacements. The cost of the air sealing portion of this project was $\$4.80/ft^2$ installed. See how this compares to the BEopt costs in 8.

Table 8. Reported cost vs BEopt cost for a masonry retrofit.

BEopt Measure	10 ACH50 (Existing)	6 ACH50
Description of wall Upgrade	NA	Air seal to 6 ACH50
Cost (BEopt)	$0.00	Material: $\$0.00/ft^2$ finished floor area Labor: $\$0.65/ft^2$ finished floor area Variable 1: $\$-0.21/[\text{Delta ACH50}*ft^2$ Finished Floor] Variable 2: $\$0.00/[\ln(\text{ACH50})*ft^2$ finished floor area]
Cost (Reported)	$0.00	$\$4.80/ft^2$

Another portion of this project was related to insulating the exterior of the walls in a high rise building on the property. After weighing the pros and cons of various strategies, the consultant—BSC—landed on a strategy that used insulated metal panels (IMPs) because of their relatively high R-value, durability, and fire rating (Neuhauser 2013b). In this case, and a fluid-applied air/water barrier was painted on top of the original brick cladding. This ensured that the building as a whole was air sealed, and also provided compartmentalization for each individual unit. Super-IMPs were placed on top of the air barrier using metal furring strips with mineral fiber insulation in between them. This is a relatively fool-proof way of retrofitting a masonry wall, but it comes at a premium cost, and requires careful details at the roof, window, and foundation interfaces. This case study resulted in 50% gas savings (which included heating and hot water). No specific cost data are available for this project.

Another project in Chicago (Neuhauser 2013a) used a similar exterior retrofit strategy, but it was funded through a weatherization program, so the cost was a much more important factor. In this project, another liquid-applied air and water control membrane was applied directly over the brick. 2x4 furring strips were placed on top of that (24 in. O.C. with 16 in. O.C. vertical), with 1.5 in. of polyisocyanurate rigid insulation in between, and 4 more inches of rigid insulation on top of that. 1x3 wood strapping was placed on top of that, and a fiber-cement cladding was attached all the way through to the 2x4 furring strips. After the installation was complete, the contractor provided an estimate for future projects like this of \$12.60/ft^2 for two and fewer stories, and about \$21/ft^2 for homes of more than two stories (Neuhauser 2013c). If a project is considering overcladding a masonry building, the added cost of adding proper control layers and insulation can increase the project cost from \$9–\$15/ft^2 depending on the complexity of the project. Using lapped siding, instead of large panels of fiber cement siding, would actually help decrease the cost of this project by \$0.55/ft^2 because the smaller/lighter siding strip would be easier to handle.

Table 9. Reported cost vs BEopt cost for masonry retrofit for a building that is two or fewer stories.

BEopt Measure	6 in. hollow CMU (Existing)	6 in. hollow CMU with 1.5 in. of XPS	6 in. hollow CMU with 2 additional in. (R-10) XPS	6 in. hollow CMU with 4 additional in. (R-20)
Description of wall Upgrade	NA	1.5 in. of XPS between 2x4 wood on flat at 24 in. O.C. and cladding	Previous system plus 2 in. of XPS and strapping to support cladding	Previous system plus 2nd layer of continuous 2 in. XPS layer
\$/ft^2 Insulation over Masonry Wall (BEopt)	\$0.00	NA	\$1.06 materials \$1.108 labor	NA
\$/ft^2 Insulation over Masonry Wall (Updated)	\$0.00	\$11.12	\$14.82	\$16.82

Table 10. Reported cost vs BEopt cost for masonry retrofit for a building that has more than two stories.

BEopt Measure	6 in. hollow CMU (Existing)	6 in. hollow CMU with 1.5 in. of XPS	6 in. hollow CMU with 2 additional in. of (R-10) XPS	6 in. hollow CMU with 4 additional in. of (R-20)
Description of wall Upgrade	NA	1.5 in. of XPS between 2x4 wood on flat at 24 in. O.C. and cladding	Previous system plus 2 in. of XPS and strapping to support cladding	Previous system plus 2nd layer of continuous 2 in. XPS layer
$/ft^2 Insulation over Masonry Wall (BEopt)	$0.00	NA	$1.06 materials $1.108 labor	NA
$/ft^2 Insulation over Masonry Wall (Updated)	$0.00	$15.96	$21.28	$23.28

4.6 EnergieSprong (REALIZE Initiative)

EnergieSprong (https://energiesprong.org/) is a method that provides net zero energy building retrofits on a large scale. The EnergieSprong concept, which originated in the Netherlands, aims to provide both a financial and an engineering solution to DERs for older buildings. The EnergieSprong model is being replicated into the U.S. market through the REALIZE Initiative which is being implemented by the Rocky Mountain Institute. The REALIZE project is under way and the Rocky Mountain Institute is working on getting all the partners in place to move past the prototype phase to push these innovative projects on a larger scale.

The EnergieSprong Company typically works with a local government to fund the initial project, which usually is a public housing project. The building retrofit ends up lowering the energy costs for the building occupants, while generating enough income from the solar panels to fund the next project. This model is repeated until, presumably, all government-funded buildings in a given community have been retrofitted. Due to the high cost of the EnergieSprong method, all projects to date have been older multifamily buildings in cold climates. These buildings have typically been masonry, but that is not a requirement.

The actual retrofit approach is one that involves a sophisticated scan of each building to determine dimensions, then a prefabricated wall and roof panel system is delivered to the site and installed in typically less than 1 week. The architectural design is typically improved compared to the existing building, and all control layers are located on the exterior surface of the old building.

Of course, this method comes with challenges, because any exterior obstacles need to be removed prior to installation. This may include nearby sidewalks, HVAC systems, awnings, utility connections, fences, mature landscaping, sheds, etc. (Amerongen 2018). Therefore, a cost-effective analysis must be done for each individual building attempting to use this method.

The typical panels comprise the following layers:

- original wall
- gap for tolerance

- 3/8 in. OSB
- horizontal 2x2 wood studs with R-10 Roxul in cavities
- vertical 2x4 wood studs with R-14 Roxul in cavities
- 7/16 in. OSB
- air-tight, vapor open weather-resistant barrier
- 3/8 in. rainscreen
- cladding.

5.0 Techno-Economic Study of High-Performance Residential Buildings

A techno-economic analysis involves the study of a technology from both an engineering and an economic perspective. Many industries use such analyses, but depending on the application, the analytic method can vary significantly. It combines process modeling and engineering design with economic evaluation for a quantitative and qualitative understanding of the financial viability of an investment (Draycott et al. 2018).

For a comprehensive perspective of techno-economic analyses, it is essential to start with the origin of the concept of innovation, its role in driving economic growth, and the observed complementarity that exists between conventional economic planning and technology-based planning that starts at the level of the firm and builds up to the level of the economy.

The first economist to attempt a formal analysis of the phenomenon of technological change was Joseph Schumpeter. According to Schumpeter, technology along with institutions and social organizations was “exogenous”, i.e., determined “outside of the domain of economic theory” (Schumpeter 1911). He distinguished between *innovation* and *invention*, referring to innovation as “the commercial introduction of a new product or a ‘new combination’” and invention as belonging to the realm of science and technology (Perez 2010). Placing the entrepreneur at the center of this model, Schumpeter was focused on trying to explain the role of innovation in driving economic growth and business cycle fluctuations. With profitability dictating the adoption of innovations and the adaptation of inventions, Schumpeter’s work laid the foundations for the modern day “techno-economic paradigm.”

The neo-Schumpeterians, in a bid to understand the relationship between technical change and organizational (institutional) change and between these and economic performance, took his work a step further and chose to look at technology, engineering, and business organizations through the lens of both the economist and the social scientist.

Since then, innovation has been recognized as a *systemic* phenomenon (Fagerberg 2003), because it is an outcome of the constant interaction between numerous actors, and the concept has evolved to mean, “the implementation of a new or significantly changed product (a good or service) or process (production or delivery, organization, or marketing processes)” (Gault 2016).

5.1 Micro and Macro Applications of Techno-Economic Analysis

Since Schumpeter, a lot of studies (at the level of the individual firm and the economy alike) have tried to empirically assess the role of innovation in driving economic growth.

Solow (1956) was the first economist to point out the existence of a long-term relationship between innovation and economic growth. Using the estimates of total factor productivity for the U.S. economy between 1909 and 1949, he concluded that technical change was the main driver of economic growth during this period. Following his seminal work, studies by Denison (1962), and Jorgenson and Griliches (1967), in this same growth accounting tradition, confirmed this phenomenon but accorded a lower contribution to technical change.

Ulku (2004), in a more comprehensive study spanning 20 OECD (Organisation for Economic Cooperation and Development) and 10 non-OECD countries for the period from 1981 to 1997, found a positive relationship between per capita gross domestic product (GDP) and innovation for both groups of countries. An associated interesting find, however, was that while innovation leads to an increase in output, the effects are not persistent, highlighting the non-stationary nature of the process. In a multi-country study for the Central and Eastern European countries (Poland, Czech Republic, and Hungary), Pece et al. (2015) found evidence of a positive relationship between innovation and economic growth. In a study spanning 19 European countries over a 25-year period, Maradana et al. (2017) found evidence of a long-term relationship between innovation and per capita economic growth, but the strength of the relationship varied relative to the choice of the indicator used.

That this relationship holds at the firm level too (irrespective of the type of the economy) has been confirmed in the literature. Dabla-Norris et al. (2010), using data for the 2005–2007 period for both developed and developing countries, concluded that innovation has a major impact on the financial performance of companies and this effect is mediated through financial markets.

Using data for 19 U.S. manufacturing industries over the period from 1975 to 2000, Minniti and Venturini (2014) find that while incentives to foster research activities result in an increase in the growth rate, the effects are transient.

Griliches and Mairesse (1981), using a sample of 133 large U.S. firms over the period from 1966 to 1997, found the presence of a strong relationship between firm productivity and the amount of investments in R&D. Cainelli et al. (2006), in an attempt to explore the bi-directional relationship between innovation and economic growth in services using a firm level data set, found that innovation is positively affected by past economic performance and it affects both growth and productivity. More interestingly, productivity and innovation reinforce each other to boost economic performance even further.

5.2 Energy Efficiency and Residential Applications of Techno-Economic Analyses

Economic growth and energy efficiency are related. The ongoing debate on the direction of causality between energy efficiency and economic growth notwithstanding, there is consensus about the positive effect of energy efficiency on economic growth. Multiple investigations have found that output and energy consumption are linked (Apergis & Payne 2010; Ozturk 2010). Rajbhandari and Zhang (2018), in a study to examine the causal relationship between energy efficiency and economic growth for 56 high- and middle-income countries over the period from 1978 to 2012, found evidence of a long-term relationship between economic growth to lower energy intensity for all countries. Interestingly, the causality is bi-directional for middle-income countries only. One reason for this is that as countries move from industrializing to post-industrialized nations, their markets shift from extraction-based to service-based economies.

Bataille and Melton (2017) used a highly customized general equilibrium model, to estimate the effect of energy efficiency improvements on the Canadian economy. They found, in general, that energy efficiency improvements increased GDP by 2%, and that the degree of energy efficiency practiced by firms and households affects economic activity, which in turn has effects on environmental quality and energy security.

Energy efficient technologies, by reducing the energy consumed per unit of output produced, will lower the demand for energy and, consequently, energy prices. The associated cost savings can then be spent (in the case of individuals) or re-invested (in the case of the firms), both of which lead to higher output levels. It comes as no surprise then that energy efficient industries and countries have been shown to possess a competitive cost advantage. However, there is also a behavioral phenomenon known as the “rebound effect” in relationship to technological innovation—energy efficiency gains are offset by the increased consumption to make up for the unit reduction of efficiency gains (Brännlund et al. 2007). In energy efficiency, this phenomenon is also referred to as Jevons’ Paradox, after the researcher who found that economical use of coal in engines actually increased overall coal consumption (Alcott 2005). While this phenomenon is difficult to measure, research has indicated that energy plays an important role in economic development, and that economy-wide rebound effects are larger than assumed (Sorrell 2009).

Techno-economic study has been employed in residential building research for a variety of energy efficient technologies, in many cases focusing on alternative electricity production. Table 11 provides a synopsis of techno-economic study in the literature, including information about both economic and simulation methods used.

Table 11. Review of techno-economic analyses in the Residential Building Sector.

Residential Sector Techno-Economic Analyses						
Paper	Economic Method	Simulation Method	Technology Analyzed	Location	Research Objective	Year
(Shaahid & Elhadidy 2008)	Life-cycle cost	Hybrid Optimization Model for Electric Renewable (HOMER)	Hybrid PV-diesel-battery power systems	Saudi Arabia	Optimize PV and battery size	2006
(Alanneet al. 2010)	Simple payback	IDA-ICE (Indoor Climate and Energy)	Micro-combined heat and power (micro-CHP)	Europe	Optimize system configurations and operational strategies; decrease in primary energy consumption	2010
(Napoli, et al. 2015)	Net present value	MatLab performance simulations	micro-CHP	Italy; Europe	Calculate decreases in primary energy consumption and cost	2015
(Blum, et al. 2011)	Capital cost; spatial regression	Ground-Source Heat Pump (GSHP) performance	GSHP	Germany	Assess design and performance of GSHPs	2011
(Bakos, et al. 2003)	RETScreen	RETScreen	Building-integrated photovoltaic systems	Greece	Optimize economic variables with system design	2002
(Guo, et al. 2012)	Initial investment; annual cost; present worth	System performance calculations; uncertainty analysis	GSHP and ground-coupled heat pump	China	Compare two GSHP systems in terms of investment	2012
(Liuet al. 2012)	Life-cycle cost	HOMER	Grid connected PV	Australia	Optimize system design with net present cost and carbon emissions	2012
(Linssenet al. 2017)	Battery-Photovoltaic-Simulation	Battery-Photovoltaic-Simulation	Photovoltaic (PV) battery systems	Germany	Present a cost-optimal PV battery system	2017

Residential Sector Techno-Economic Analyses						
Paper	Economic Method	Simulation Method	Technology Analyzed	Location	Research Objective	Year
(Gan, et al. 2013)	Simple payback	Physical test in university facility	Light-emitting diode (LED) Lighting	Malaysia	Case study analyzing LED replacement and performance, compared to operating cost savings	2013
(Esenet al. 2007)	Annual cost	System performance calculations; uncertainty analysis	GSHP and air-source heat pump (ASHP)	Turkey	Compare GSHP and ASHPs	2007

The techno-economic analysis parameters that will be used to analyze residential wall systems for DER are presented in Figure 13. The analysis is focused on the design, simulation, in situ testing, and economic evaluation of retrofit wall systems that will (1) develop moisture-durable, high-performance retrofit wall systems, and (2) identify and evaluate the economic performance and risk of chosen wall systems.

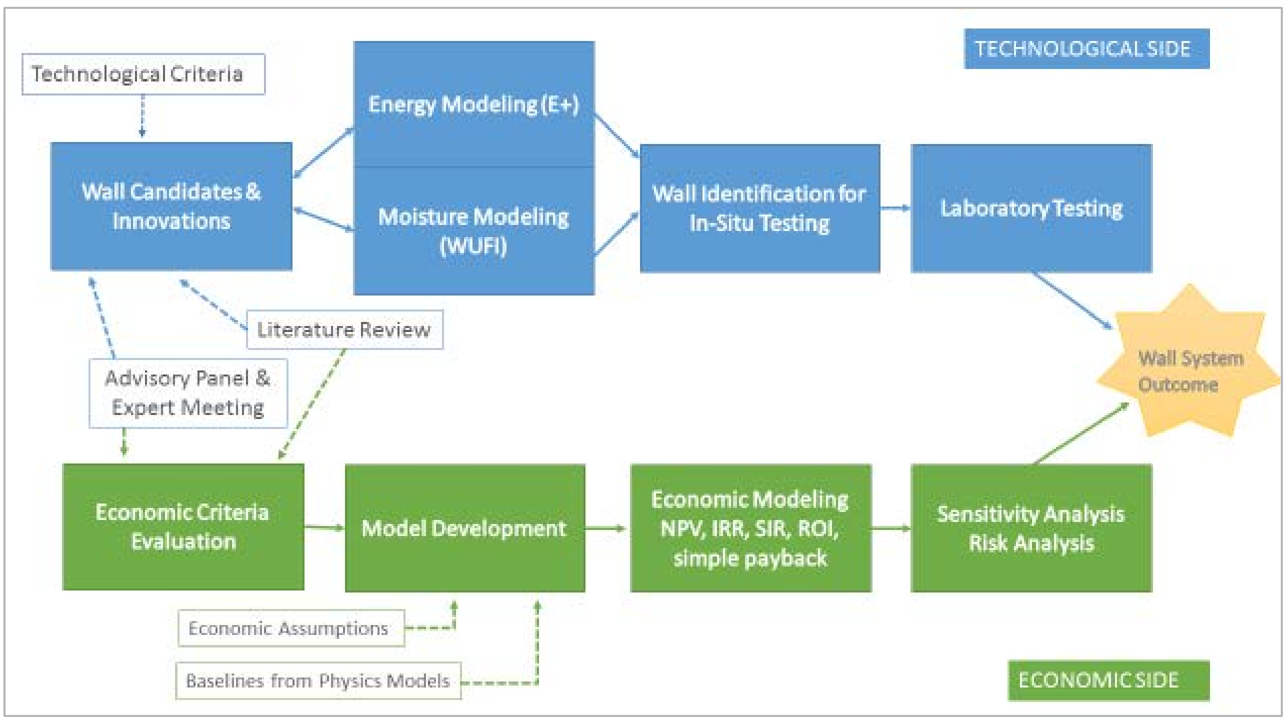

Figure 12. Techno-economic analysis flowchart.

6.0 Modeling and Simulation Review

Laboratory and field evaluations of building envelope performance are expensive and it is difficult to control environmental conditions, especially for multiple climates. Energy and hygrothermal modeling has been used by many studies for envelope performance evaluations (Dentz & Podorson 2014; Lepage & Lstiburek 2013). In the past decade, modeling software programs for building energy and envelope performance have become more robust and are recognized by the research community and industry. As such, industry standards on evaluating and applying the modeling tools are already established; they include ANSI/ASHRAE Standard 160-2016 Criteria for Moisture-Control Design Analysis in Buildings (ANSI/ASHRAE 2016) and ANSI/ASHRAE Standard 140-2017 Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs (AS HR AEASHRAE 2017).This section starts with the research questions to be answered by the modeling methods; describes the review of literature about modeling tools, modeling inputs and assumptions, and their limitations; and ends with a summary of a draft modeling plan.

6.1 Research Questions to Be Studied Using Modeling

Most building modeling tools are based on solving physics-based energy and mass equations; they can provide detailed outputs on many aspects of building performance. The research questions of the current study involve the annual energy cost savings and the envelope durability of the post-retrofit homes. The cost savings will be inputs to the techno-economic study to evaluate the cost effectiveness of the retrofits. The durability is as important as the cost effectiveness of successful retrofits. Therefore, the literature review of modeling is focused on identifying the proper modeling tools, modeling assumptions, limitations, and applications, especially for envelop retrofit studies.

To capture annual energy cost savings for homes after the DERs, whole building energy modeling (BEM) tools are used. They simulate whole building energy consumption using hourly modeling of thermal loads and HVAC systems. BEM tools account for all of the energy interactions between indoor space, outdoor environment conditions, HVAC, lighting, service water heating, other appliances and equipment, and occupancy behavior. In such analyses, the energy flow through envelope elements such as the walls, roof, and windows, is treated as one-dimensional (1-D) and mass flow of moisture and air and phase changes of moisture are not well captured.

Heat, air, and moisture (HAM) modeling, also referred to as hygrothermal modeling, is used to analyze wall durability, including the potential for mold growth and freeze-thaw damage, the mass transfer of air and moisture, and the phase changes of moisture.

It would be desirable to analyze both energy savings and building durability with a single modeling tool that includes both BEM and HAM. A few recent research efforts by Antretter and Pallin (2019) and Chen et al. (2015) to develop such tools show that the research is still in progress. Therefore, the current study will develop a modeling strategy to use BEM and HAM separately, but will allow modeling inputs and outputs to be shared by the two analyses. More details about sharing the inputs and outputs is discussed in later sections.

6.2 Building Energy Modeling

The review of BEM tools is focused on their capability and accuracy for modeling thermal insulation and reduced air leakage. DOE complied a comprehensive list of the BEM tools that can be found in Building Energy Software Tools Directory.[1] Although many tools in the list appear to have the required capabilities, some are platforms or user interfaces of a few major modeling engines, such as DOE-2, EnergyPlus, IES-VE, ESP-r, and TRNSYS. Among these engines, the DOE-sponsored EnergyPlus is a popular one because of its continuous R&D supported by DOE and the modeling community in the last decade.

The development of EnergyPlus was primarily focused on commercial buildings, in which space air-conditioning is primarily provided by mechanical air systems. A typical house with a single thermostat and a forced air furnace and air-conditioning system is usually treated as a single-zone HVAC system and the zone heat balance represents a “well stirred” model for a zone. In single-family homes, some detailed energy flow characteristics, such as infiltration through the wall cracks and three-dimensional (3-D) conductive and convective heat flow through walls, are not easily captured. Modeling reduced infiltration and improved wall insulation is important for the current project and are discussed in Section 6.2 below. To properly model other aspects of residential buildings, the National Renewable Energy Laboratory (NREL) developed and maintains Building America House Simulation Protocols Wilson, et al. 2014a) that provide some baseline modeling guidelines and default assumptions for both new and existing residential homes. To further assist researchers who do not need to dig into the modeling details, NREL used the Simulation Protocols and developed the BEopt software (Wilson et al. 2014b), which evaluates residential building designs and identifies cost-optimal efficiency packages for new and retrofit applications. Like several software programs on the BEM list, BEopt is based on EnergyPlus and incorporates several default modeling assumptions to simplify the user’s work in providing home inputs. Because of these defaults, the flexibility of modifying BEopt models is limited, so for the current research, we would like to use EnergyPlus directly.

6.2.1 DOE Residential Prototype Building Model

PNNL simulates energy savings associated with changes in energy codes and standards. DOE's Building Energy Codes Program uses the simulation results to evaluate published versions of the code and to develop proposed code changes. For residential buildings, PNNL uses two base prototypes: a single-family detached house and multifamily low-rise apartment building. Details of the models can be found in report by Mendon et al. (2015). PNNL’s simulation infrastructure uses EnergyPlus to perform annual whole building energy simulations across multiple climate zones and vintages. The simulation infrastructure and residential prototype models have been used in numerous large-scale energy savings and energy cost savings studies in the past (Mendon et al. 2015, 2012; Xie et al. 2018).A scorecard of the single-family prototype building is provided by.

6.2.1.1 Modifications to the Prototype Building Models to Represent Existing Home Stock

The residential prototypes represent the new construction stock and minimal compliance with the residential prescriptive and mandatory requirements in a few editions of the International

[1] https://www.energy.gov/eere/buildings/building-energy-modeling

Energy Conservation Code. Thus, to use the prototype models for the current study they need to be modified to represent the existing conditions. The inputs for these modifications are taken from the ResStock data published by NREL (Wilson et al. 2017), which is a large-scale housing stock database developed by combining public and private data sources, statistical sampling, and detailed building simulations. Further inputs are used from the Building America House Simulation Protocols (Wilson et al. 2014a) to make the prototype models representative of the existing building stock. The Simulation Protocol provides specifications to facilitate accurate and consistent analysis of existing single-family and multifamily buildings. It provides information about the design assumptions, default values for components of existing houses, and a set of standard operating conditions.

A preliminary review of the ResStock Analysis Tool was done through communication with the developers at NREL. More detailed information about the existing building stock will be available to help in making assumptions about baseline existing homes. The information on wall type, wall insulation level, and infiltration level will be used to modify the prototype model for baseline performance of existing homes at all representative U.S. climate locations. Other building stock information from ResStock regarding lighting, HVAC systems, and envelope components other than walls will also be used to modify the prototype model, but their inputs will remain the same in the post-retrofit models.

6.2.2 Modeling Thermal Bridging and Infiltration

EnergyPlus calculates the building thermal zone loads by developing a heat balance model using different surface heat-transfer algorithms for conduction, convection, and radiation transfers through surfaces, and zone air heat balance algorithms for evaluating outdoor air, zone air, and system air heat transfers over specified timesteps. However, the fundamental assumption of these heat balance models is that air in a thermal zone is distributed with a uniform temperature throughout. Although this does not reflect physical reality well, the only current alternative is computational fluid dynamics (CFD)—a complex and computationally intensive simulation of air movement (Crawley et al. 2001). Several studies have shown that the improvement in modeling accuracy from using CFD for building energy simulations is negligible compared to the increase in time and computational power required to run such models (Martinet al. 2017; Tan & Glicksman 2005; Tian et al. 2018; Zhai et al. 2002). CFD models look at the thermal zone at a discretized level by breaking it into large amounts of control volumes, which is not useful for running annual simulations of the whole building (Martin et al. 2017). This method becomes further challenging when the modeling approach involves performing multiple annual parametric runs to study the effect of certain input parameters on the simulation results.

Building envelope technologies have a complex internal structure that makes it necessary to consider all the possible heat and mass transfer effects in the energy simulations for an accurate representation of the reality. Several studies have shown that 2-D and 3-D heat-transfer effects are significant at the thermal bridges, which are created by highly conductive structural materials breaking the layers of insulating materials. Kośny & Kossecka (2002) illustrated the difference in the thermal resistance calculated using a simplified 1-D model of heat transfer and a more complicated 3-D model capturing the effects of thermal bridging. The study concluded that the latter method resulted in errors of up to 44% and 27% in the R-value calculations of metal and concrete framing materials, respectively. Another study (Ge & Baba 2015) showed that including the effects of thermal bridging using a 3-D dynamic model resulted in an increase in the annual heating load of 18% and a reduction in the annual cooling load of 24% compared to the case without thermal bridging.

EnergyPlus, however, uses a simplified 1-D, parallel-path approach for conduction heat-transfer calculations through the building envelope that ignores the effects of thermal bridging. Thus, this study proposes the use of THERM, a 2-D conduction heat-transfer analysis program based on finite-element method developed by Lawrence Berkeley National Laboratory (LBNL; THERM Simulation Manual). A THERM model is developed for the wall section selected for simulation and the overall U-value obtained from THERM is used as the equivalent U-value in EnergyPlus by adjusting the modeled insulation inputs. The equivalent U-value thus helps account for the significant thermal bridging effects occurring at the structural components of the wall, which are otherwise neglected in EnergyPlus. Ge and Baba (2015) used a similar approach to compare the energy performance of a low-rise residential building and concluded that this approach helps improve the accuracy of heating and cooling load predictions. (Real et al. (2016) used this approach to study the effects of structural lightweight aggregate concrete on the reduction of thermal bridging effects in residential buildings.

Airtightness is another significant parameter for evaluating building envelope technologies and has a significant impact on building energy performance and IAQ. Envelope airtightness is accounted for in EnergyPlus by modeling the air infiltration rates (Crawley et al. 2001). In EnergyPlus, the air mass balance module deals with various mass streams, such as ventilation air, exhaust air, and infiltration. This module is linked to COMIS Huang et al. (1999), a state-of-the-art airflow model, which helps improve multi-zone airflow, infiltration, and ventilation calculations. Gu (2007) validated EnergyPlus' airflow network model against measured data from both ORNL and the Florida Solar Energy Center and found good agreement between simulation results and measured data.

EnergyPlus includes several different algorithms for modeling infiltration. The residential prototype models use the "Effective Leakage Area" model, which is based on Sherman and Grimsrud (1980) and is considered appropriate for low-rise residential buildings. In this model, the infiltration is specified by an effective leakage area at a 4 Pa pressure differential, wind and stack coefficients, and is a function of wind speed and temperature difference between the zone and the outside air. In addition to getting the infiltration model right, it is necessary to get the effective leakage area right to represent the conditions in the existing residential stock. These data are available in a tool developed by LBNL called Residential Diagnostics Database, which includes building envelope air leakage data from 147,000 U.S. single-family and multifamily houses (Chan et al. 2013).

6.3 Hygrothermal Modeling

Hygrothermal modeling is used to evaluate the condensation potential, moisture content, drying capacity of the assembly, potential for mold growth, and freeze-thaw damage. During the last two decades, a number of computer simulation tools have been developed to predict thermal and moisture conditions in buildings and the building envelope. In addition to their use as forensic tools in the investigation of building failures, these computer models are increasingly used to make recommendations for building design in various climates.

WUFI is one of the most popular models that is widely used by hygrothermal modeling researchers (Antretter et al. 2011; Arena & Mantha 2013a; Lepage & Lstiburek 2013; Lepage et al. 2013). According to American Society for Testing and Materials ASTM (2001), although WUFI is a highly validated model for hygrothermal applications, it has several limitations, including the following:

- Because WUFI deals only with 1-D processes, it cannot adequately model multidimensional thermal and moisture bridges.
- Airflows in the component, uptake of groundwater, and gravity effects have been neglected.
- Some materials like wood and concrete can change their material properties as a function of their present and past moisture content and, as a result, do not lend themselves to simplified transport equations.

Figure 14 shows how moisture hygrothermal analysis can be performed to assist the design of the wall. It is applicable to the current retrofit analysis as well.

As shown in Figure 14, hygrothermal modeling needs indoor and outdoor boundary conditions. When dynamic information about the indoor environment conditions is not available, ASHRAE Standard 160-2016 provides some guidelines about default assumptions. For the current project, because we plan to use the modified DOE residential prototype building models, detailed and hourly indoor space conditions such as relative humidity and temperature are available as outputs from the EnergyPlus simulations. The project team plans to use these hourly results as inputs to WUFI.

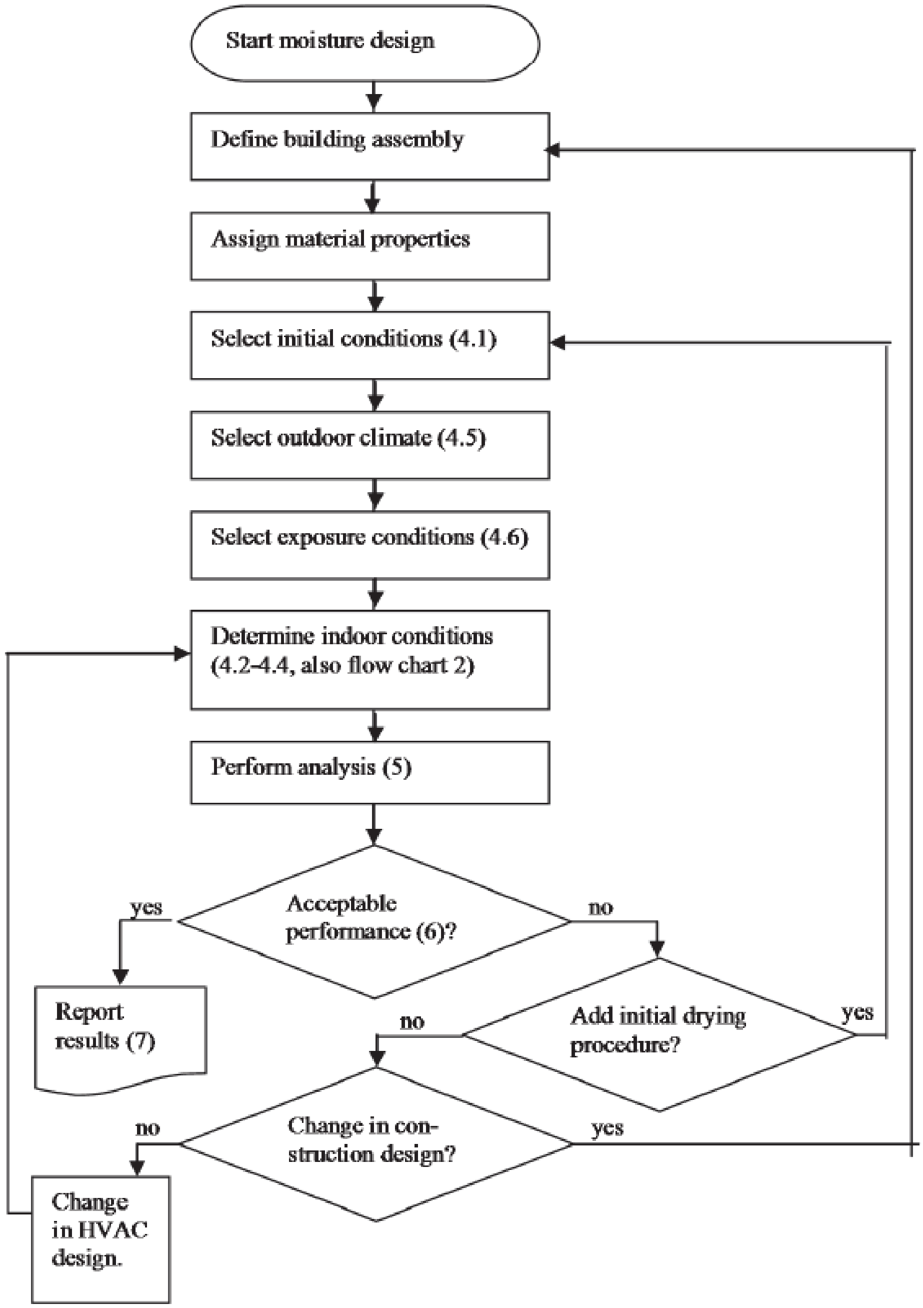

Figure 13. Flow of moisture-control design process using Standard 160-2016 (ANSI/ASHRAE 2016).

7.0 Conclusion

This literature review is part of a larger effort to identify, model, and test advanced wall systems for DERs in single-family homes. In addition, a techno-economic analysis of the wall system viability, including the opportunity for scaling into the larger market, will be conducted. This literature review represents the beginning of a multi-year research study. Ultimately, the objective of this study is to identify materials, applications, and technologies that will advance envelope retrofits and provide thermal and moisture durability for existing building stock.

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Pacific Northwest National Laboratory

902 Battelle Boulevard
P.O. Box 999
Richland, WA 99352
1-888-375-PNNL (7665)

www.pnnl.gov