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Evaluation of Exterior Insulated Panels for Residential Deep Energy Retrofits

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Abstract: This paper provides an analysis of challenges and available solutions for exterior insulated panels suitable for deep energy retrofits of existing building envelopes. The analysis covers a review of available technologies that provide flexible retrofit insulated panels suitable for multiple climates and building typologies. Moreover, the paper proposes a new design for insulated retrofit panels that account for the majority of identified technical risks including cost, architectural diversity, climate variations, structural concerns, moisture resilience, air sealing, and water sealing. Additionally, the proposed design can be easily installed with minimal disruption to the occupants. A series of parametric and optimization analyses is carried out to identify the optimal design specifications for insulated panels suitable for deep retrofits of existing US housing stocks. The analysis results show that the optimal design criteria for the insulated panels can reduce heating and cooling energy consumption by up to 80% and HVAC capacities by 70%. Moreover, the results indicate that these insulated panels are highly cost effective for retrofitting US housing units located in cold climates.

Keywords: building envelope; energy savings; housing prototypes; insulated panels; cost optimization

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1. Introduction

Buildings account for roughly 40% of the total annual energy consumption in the United States. The residential building stock alone accounts for approximately 21%. With ambitious climate goals being set to reduce greenhouse gas emissions, the US, like other countries, has aligned on the vision to reach a net-zero-energy building stock by 2050 [1]. Reaching this target requires sweeping changes to improve the energy efficiency of both new constructions and existing building stocks. Historically, investments have focused on improving home performance of new constructions through more stringent building standards, research and development of new construction technologies, and incentives that support clean-energy efforts. Decarbonizing the existing residential housing stocks remains a significant and unsolved challenge for several countries that requires additional research and development efforts as well as higher capital investments. Roughly half of the current 125 million US housing units were built prior to 1980, before any energy efficiency standards were enforced in buildings [2]. Some studies estimate that meeting zero climate targets requires that the pace of whole-building retrofits needs to increase from the current rate of well below 1% per year to around 3% per year by the end of the decade and must be sustained at this rate through mid-century [3]. Specifically, more than 3 million net-zero carbon retrofits will likely be needed annually to meet these goals starting from 2030 [3]. This significant retrofit undertaking will take a combination of increased adoption of energy-efficient electrification technologies, grid-interactive communities, and building envelope upgrades. Existing homes can be improved through cost-effective deep energy retrofits. One way to accelerate deep energy retrofits is through the deployment of non-disruptive and standardized retrofit insulated panel assemblies. While several products exist for prefabricated insulated wall assemblies targeted at the new construction sector, commercially available insulated panels for retrofit applications are very limited.

There is clearly a lack of panelized technology for existing envelope improvements on the market, and if the industry is going to tackle energy efficiency in the existing building stock, cost-effective and easy-to-install solutions to envelope upgrades will be needed. Research is needed to understand the technical challenges preventing market uptake of exterior insulated panels for residential deep energy retrofits. This paper explores the opportunity of building envelope upgrades via the installation of insulated panels for residential deep energy retrofits. Exterior insulated retrofit panels can be installed on the exterior façade of an existing building to dramatically improve insulation and airtightness of homes, while potentially improving aesthetics. Increasing the insulation and airtightness levels of exterior envelope elements is crucial to enable better-performing residential buildings. The precedent has been set in Europe, with successful implementation of net-zero energy retrofit programs across multiple countries. This strategy is continually growing in Europe and pilot programs in the US have already begun with the hope to replicate this success. In addition to reviewing commercially available retrofit insulated panels in Europe and the US, the main intent of this paper is to propose and evaluate the performance of a new retrofit insulated panel that addresses.

It is important to note that there are other technologies other than insulated panels for improving insulation for existing buildings. Notably, the drill-and-fill techniques involves drilling holes on either the interior or exterior of the wall and then blowing in fiberglass or cellulose insulation. While this technique is fairly common practice in the industry, it has a well-known set of disadvantages. Firstly, add blow-in insulation to the wall cavities does not significantly help improve airtightness level. Other weatherization methods would be needed to also improve the airtightness of existing building envelope elements. Secondly, it is difficult to assess and control the quality of installation. Drill and fill technique can result in incomplete filling of the cavities or sagging of the insulation, both of which can leave portions of the wall uninsulated. On the other hand, prefabricated insulated panel assemblies are built with a high level of quality control with all cavities properly insulated. Furthermore, the use of prefabricated panels has the advantage of improving insulation and airtightness to any desired levels with a high level of precision and quality.

The paper starts with a literature review of the existing market for exterior insulated retrofit panels. Next, the design specifications are outlined for new exterior insulated retrofit panels suitable for residential buildings. Finally, the energy performance of the new exterior insulated retrofit panels is assessed for various residential building prototypes and climate zones in the US.

2. Literature Review

The intent of this literature review is to shed light on the market availability of exterior insulated panels that are specifically tailored for deep energy retrofit applications. The review starts with a definition of deep energy retrofit, followed by a short overview of the current technologies suitable for deep energy retrofits in the residential market. Next, a high-level discussion of some of the major European manufacturers for exterior insulated panels is provided, along with net-zero energy initiatives across Europe and the US. Moreover, the review includes key challenges and opportunities that exist with developing exterior insulated panels suitable for residential retrofits in the US market.

2.1. Overview of Deep Energy Retrofits

According to the Office of Energy Efficiency and Renewable Energy of the US Department of Energy, there are currently over 125 million buildings in the United States with more than half of these buildings constructed before 1980, that is, before enforcement of any energy efficiency standards [2]. In the residential sector specifically, approximately 68% of the existing residential stock in the US was built before 1992 and has inadequate insulation and significant air-leakage levels [4]. These facts present a significant challenge when decarbonization of buildings is essential to meeting climate change goals. One solution to improving the energy performance and comfort of the existing building stocks is to implement "deep energy retrofit" or DER programs. While the exact definition of deep energy retrofit varies across countries and building types, deep energy retrofits can generically be defined as a holistic and integrated renovation approach of existing buildings to deliver significant energy savings, typically 50% or greater, compared to their original performance [5]. When the retrofit of a building includes upgrades of the building's energy elements including envelope, mechanical, and electrical systems as a packaged renovation project, it is typically referred to as a deep energy retrofit. When individual or less integrated measures are taken to improve the energy performance of a building on a reduced scale, for example—replacing all the fluorescent or incandescent lights with LEDs, it is referred to as a conventional or standard retrofit as opposed to a deep energy retrofit.

A 2011 study published by the Regulatory Assistant Project on Residential Efficiency Retrofits reported that roughly half of all efficiency and/or carbon emission reduction potential in North America and Europe can be achieved through retrofit improvements to existing residential buildings [6]. A US market characterization study by the Advanced Building Construction (ABC) Collaborative in July 2021 identified the single-family residential and multifamily residential markets as two of the top key market segments to target for energy demand reduction, accounting for 17% and 4% of the 2019 US energy consumption, respectively [7]. Hence, the US Department of Energy has recently launched the Advanced Building Construction Initiative, with the goal of integrating highly efficient and low-carbon innovations into the construction industry's broader modernization efforts [2]. A significant portion of this initiative is focused on improving supply chain and construction practices specifically geared to improve deep energy retrofits for the residential markets.

For a typical deep energy retrofit project, energy savings are achieved through a combination of improved insulation and airtightness, replacing heating ventilating and air conditioning (HVAC) systems with high-efficiency heat pumps and heat recovery ventilation systems, and replacing legacy domestic hot water systems and appliances with energy-efficient electric systems. An estimated 34.5 million US homes with wood studs have no wall insulation [4]. Furthermore, 71% of existing US homes have an air leakage rate of 10 or more per hour at 50 pascals [8]. Thus, improvements to the insulation and airtightness of the building envelope are considered crucial measures to achieve significant energy savings in a deep energy retrofit. Beyond the energy savings, having a high-performance envelope can improve occupant comfort, decrease indoor pollutants, and improve acoustic attenuation. A variety of methods to improve exterior wall insulation through deep energy retrofits have been considered including [4]:

- Exterior insulated sheathing;
- Thermal break shear wall assembly;
- Spray foam outer shell retrofits;
- Insulated vinyl siding systems;
- Exterior insulation and finish systems (EIFSs);
- Masonry wall retrofit applications.

Each of these techniques require demolition of the existing siding, which can create challenges to occupant comfort, construction duration, and cost.

2.2. Mitigation Solutions for Deep Energy Retrofit

Among the current existing US residential building stocks, the leading jurisdictions only report 1.75% of homes undergoing deep energy retrofits [8]. This small percentage reflects the deployment challenges of deep energy retrofit programs in the United States. Indeed, deep energy retrofits are currently characterized by highly individualized, costly, complex, and disruptive upgrades [8]. For most projects, deep energy retrofits typically require invasive renovation strategies that require occupants to seek alternative temporary accommodations while the retrofit projects are underway. Since upgrades to energy and envelope systems typically require significant demolition, this temporary accommodation can last from weeks to months, posing a significant disruption to the occupants' lives. For these reasons, deep energy retrofits are not viewed favorably by the public. Clearly, smarter, quicker, and cheaper solutions to deep energy retrofits are needed in the US market.

One potential solution to improving accessibility to deep energy retrofits in the United States, is the replication of the Dutch-inspired initiative Energiesprong. This private-public partnership has successfully begun transitioning existing affordable housing into net-zero energy homes with modernized deep energy retrofits [9]. Between 2013 and 2016, 900 Dutch homes had been successfully renovated to net-zero energy. The Energiesprong method touts net-zero renovations in under one week without having to displace the occupant from their home during the retrofit. A key enabler of this delivery style is the use of an industrialized construction supply chain with prefabricated envelopes that can be installed on the outside of the existing building façades. These exterior insulated retrofit panels are fully integrated and include insulation, structural members, new windows and doors, and new exterior finishes. The panels are prefabricated off site and then installed by a crane to wrap the house in a brand new "jacket" that is fully insulated and sealed to meet current energy standards [10]. This momentous program has the potential to alter the outlook and feasibility of deep energy retrofits in the US and other countries. In fact, organizations across the US are already starting to replicate the Energiesprong model. Most notably, the US Department of Energy, through the ABC initiative, released funding in March 2022 that specifically targets technologies that either directly or indirectly support development of industrialized and prefabricated exterior insulated retrofit panels.

2.3. Current Status of Deep Energy Retrofit Technologies

This section provides a high-level overview of existing technologies on the market for exterior insulated retrofit panels. Firstly, European technologies are discussed, specifically highlighting panels used in the early adoption of the Energiesprong program. Then, adoption options of these technologies to US markets are explored. Furthermore, because products and technologies discussed in this review are protected through intellectual property clauses, detailed specifications of the technologies are rather limited.

2.3.1. Technologies in Europe

Europe is well ahead of the US when it comes to the manufacture and installation of prefabricated exterior insulated retrofit panels suitable for existing building envelopes [11]. In 2020, the US Department of Energy conducted their own market assessment to understand the availability of prefabricated zero-energy retrofit technologies in Europe and the US. Three primary suppliers of the technologies are identified in the Netherlands. These companies helped kick-start the Energiesprong program and include RC Panels, BGDD, and Renolution [12]. Each company has its own technology and manufacturing process for retrofit panels. Table 1 summarizes the main characteristics of the technologies promoted by these three companies. It is noted that due to proprietary assemblies, technology, and manufacturing processes, it is difficult to fully describe the detailed engineering systems for each assembly. A summary of the three major manufacturers in the Netherlands is provided in the following sections [12].

- Manufacturer #1: RC Panels (Source [13]). RC Panels manufactures a ready-for-retrofit panel that is similar to the industry-familiar structural insulated panel (SIP). In this system, expanded polystyrene (EPS) foam is glued between layers of rigid polystyrene and oriented strand board (OSB). The rigid polystyrene is sprayed with a proprietary recipe to achieve airtightness and moisture protection. Like SIPs, no studs are required for ensuring structural strength as it is achieved by the panel assembly itself. The panel includes a synthetic finish veneer that mimics brick and matches aesthetics of the targeted neighborhood. The manufacturer can provide variations of exterior finish options for the RC panels. To install these panels for retrofit applications, exterior ledger brackets are first installed into the existing structure of the building. The panels can then be installed to these brackets. Due to the light weight of these panels, no additional structural support is needed for this assembly. To mitigate heat loss through the foundation, the ground is typically excavated 1 foot below grade so that the insulated panels cover the crawlspace's walls. Like the case for other manufacturers described in the following sections, windows are pre-installed in this assembly to further reduce the installation time. RC Panels have a maximum thickness of 5-1/2″ with an R-39 insulation rating and the manufacturer claims that their panels regularly achieve airtightness under 0.4 ACH at 50 Pa [11,12];

- Manufacturer #2: BGDD (Source [14]). Bouwgroep Dijkstra Draisma (BGDD) utilizes a more traditional timber-framing technique for constructing their wall assemblies. BGDD emphasizes recyclable and low embodied carbon materials. Specifically, BGDD assemblies are made of wood, cellulose, mineral wool, and similar synthetic brick veneer cladding that RC Panels uses. The panels are installed close to the existing façade with a hook system. Excess insulation is blown in between existing and new walls to fill small remaining air gaps. For further details on the BGDD manufacturing process, refer to the manufacturer descriptions [13–15];
- Manufacturer #3: Renolution (Source [16]). The third major manufacturer providing exterior insulated retrofit panels in the Netherlands for Energiesprong projects is Renolution [16]. Unfortunately, very minimal information on this system is available publicly. Renolution uses light gauge steel framing with integrated ducting for heating and/or ventilation. Like the other two manufacturers, Renolution provides a complete package that includes pre-installed windows and an exterior veneer finish with an advertised weight of 6.1–10.2 lb/ft^2.

A summary of major characteristics of these three European-based manufacturers are described in Table 1.

Table 1. Summary of wall assembly technologies used in Netherlands for Energiesprong projects (Source [11]).

Manufacturer	Structure	Insulation	Max R-Value	Installation Technique
RC Panels	SIP	foam	39	Ledger attached to existing facade
BGDD	Timber frame	Cellulose	Not declared	"Hook system"
Renolution	Light steel frame	Mineral wool	Not declared	Not declared

Pilot and demonstration programs of Energiesprong are being replicated in France, UK, Germany, and Italy; other manufacturers of exterior insulated retrofit panels are appearing on the European market [9]. However, specific details for describing the piloted assemblies are very limited. Nevertheless, the Energiesprong model is being successfully replicated across Europe and hence, the demand for exterior insulated panels for retrofit applications is growing. Information on the latest participants and pilots of Energiesprong is regularly updated on the Energiesprong website [9].

2.3.2. Deep Energy Retrofit Technologies in the US

Utilizing prefabricated and modular building techniques for new constructions has a long-standing history in the US [17]. However, exterior insulated panels tailored to retrofit applications are very limited. The only products currently on the US market are variations of nail-based panels. These nail-based panels are essentially SIPs, which utilize two panels of OSB sandwiched around a layer of poly-iso or EPS foam [18]. However, unlike their European counterparts, these products still require the existing exterior façades to be removed so that the new panels can be nailed to the structural members of the existing building. Furthermore, there are no commercially available US products specifically for retrofit applications with exterior weather barriers and finish claddings. When nail-based panels are used for retrofitting applications, the industry generally refers to them as RIPs, which is short for "retrofit insulated panels". In fact, the Structural Insulated Panel Association (SIPA) provides a recommended installation guide for this type of product [18].

While commercially available exterior retrofit insulated panels are virtually non-existent in the US, there is certainly interest in following the Energiesprong approach. Indeed, there are already two prominent regional programs in the US being piloted to replicate the Dutch-inspired Energiesprong. Retrofit NY, a program by the New York State Energy Research and Development Authority (NYSERDA), has already completed a pilot project in Brooklyn [19]. Additionally, the Rocky Mountain Institute (RMI) is currently conducting two pilot projects in Massachusetts and California [20]. Both pilot programs have identified plans to leverage exterior insulated retrofit panels which are prefabricated offsite, but details of the panel assemblies are not publicly available.

From the research conducted during this literature review, it appears that there is not a commercially available product in the US specifically for exterior insulated panels suitable for retrofit applications that meets the level of completeness as in Energiesprong. However, the US Department of Energy through the ABC initiative has provided funding for 6 teams to pilot variations of exterior insulated retrofit panels as outlined in Table 2 [21].

Table 2. US Teams selected for development and deployment of exterior insulated retrofit panels [21].

Team	**Project Description**
Fraunhofer USA Center for Manufacturing Innovation	Test prefabricated, super-insulated wall retrofit panel blocks with a suite of high-performance building technologies across four locations in Massachusetts, Vermont, and Pennsylvania.
National Renewable Energy Laboratory	Use software tools to properly size and install retrofit packages in two residential low-income, multi-family buildings in Arvada, Colorado.
Oak Ridge National Laboratory	Demonstrate 3D-printed modular overclad panels with heat pump systems in 8 to 12 single-family attached public housing homes and one commercial building in Knoxville, Tennessee.
Rocky Mountain Institute	Demonstrate an integrated retrofit package of envelope panels, a heat pump pod, and innovative financing in a mid-rise, 120-unit low-income multifamily building in Cambridge, Massachusetts.
Home Innovations Research Labs, Inc.	Test an innovative wall system with vacuum insulated panels in three residential, multi-family public housing buildings in Albany, New York.
Syracuse University	Integrate overclad panels with real-time performance monitoring capabilities and an "HVAC pod" in single-family attached dormitories in Syracuse, New York.

2.4. Summary of Literature Review

While it appears that the US market has minimal commercially available products for exterior insulated retrofit panels suitable for existing residential buildings, it is clear a significant need and interest to develop these products exists [22]. US manufacturers could capitalize on learnings from the Energiesprong approach and technologies that have been developed and demonstrated in Europe. However, several challenges exist to achieve easy-to-install and cost-effective products of insulated panels suitable for retrofitting existing building envelopes for the US market. The three main technical challenges with development of exterior insulated retrofit panels specific for residential applications include:

(1) Concerns of existing buildings to support the weight of exterior panels. One of the biggest challenges is the typical timber frame structure in US residential buildings [10]. The pilot projects in the Netherlands were conducted on homes that previously had slate roofing, which is significantly heavier than typical asphalt shingles in the US. The structures on the Netherlands pilot projects were designed to support the heavy

weight of the slate roofs. Therefore, when the slate roofing was removed for the Energiesprong pilots, there was plenty of strength in the roof and wall systems to support exterior panels. This issue will need to be addressed and evaluated for the US market to pilot exterior insulated retrofit panels [10];

(2) More varied and extreme weather in the US compared to Europe. The US has a wider range of climate zones than Europe with more extreme weather events. Specifically, the panel systems in the US will need to be designed to withstand higher wind and snow loads, depending on the climate of the region, and chosen market [10];

(3) Varied architectural styles and building types. Just like in Europe, there is a plethora of housing types and architectural styles across the US. A manufacturing strategy needs to be developed in the US where these types of panels can be standardized, but still accommodate a wide variety of architectural features. Scalability has to be considered when designing an exterior insulated panel suitable for retrofit applications.

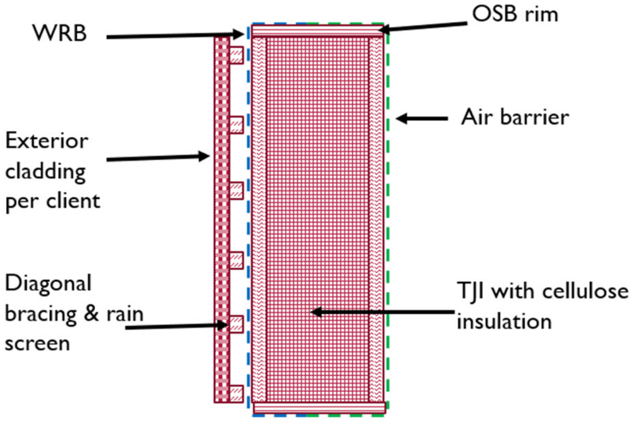
The ideal panel system will need to address and satisfy the three challenges outlined above. It is important to note that because of the wide variation in climates across the US, a strategy for panel insulation and moisture mitigation will need to be developed for a specific market. The ideal panel system will have the following characteristics:

- Lightweight so that existing housing structures can support the panels;
- Complete envelope system that includes an attachment mechanism, insulation, membranes for weatherproofing and airtightness, exterior finish, and the ability to add windows and/or doors;
- Resilient hygrothermal properties with a vapor-open strategy to allow drying to cavities between the existing façades and new panels;
- Flexibility to manufacture in multiple sizes to accommodate varying architectural features;
- Speed of installation (ideally under one week);
- Aesthetically appealing to that the product is desirable to owners and neighboring communities;
- Convenient installation that gives occupants the ability to continually occupy the retrofitted buildings while the panels are being deployed.

Finally, it is important to highlight that some of the significant challenges to implementing exterior insulated panels for retrofit applications are non-technical in nature. Non-technical challenges vary by location, labor availability, as well as local governments and policies. Key non-technical risks include warranty policies, financing, insurance, and workforce availability.

3. Proposed Insulated Panel

This section provides a new design for exterior insulated retrofit panels with specifications that meet the key challenges and opportunities discussed in Section 2. Specifically, the proposed insulated panels have the following benefits: (i) they can be prefabricated, (ii) they are easy to install from the outside without disturbing occupants, and (iii) they can accommodate various architectural features and aesthetic requirements. While the proposed panels are best suited for residential buildings in cold climates, their design is flexible enough to be adapted to buildings in warmer climates, where no significant additional insulation is needed. A section that details the components of the proposed panels is shown in Figure 1. To improve resiliency and minimize risk of condensation build-up and mold, vapor-permeable materials were chosen to promote a vapor-open design that is highly insulated while still allowing moisture movement and drying through the assembly.



Effective R-value	Thickness	Weight	Cost
~R-29	10-1/4”	5.59 lbs./ft^2	\$3.53/ft^2

Values do not include exterior cladding

Figure 1. Section for a proposed exterior insulated retrofit panel.

From interior to exterior, the wall assembly includes an air barrier, wood I-joist studs, cellulose or wool insulation, weather-resistant barrier (WRB), rain screen, and the desired exterior cladding/façade as illustrated in Figure 1. Several products can fulfill the air barrier layer, but a vapor-variable air barrier, like Intello Plus from 475 Build Supply is a recommended product [23]. An I-joist stud wall is recommended over a traditional dimensional lumber stud wall to reduce weight and minimize thermal bridging potential. Since these panels are attached to the existing structural members of the building, they do not themselves need to be structural (i.e., the wall panels do not need to withstand weights beyond their individual panel weight). Therefore, 0.61 m (i.e., 24 inches) on center spacing is acceptable. The I-joist studs are secured in place with an OSB perimeter rim board. For the WRB layer, products on the market can satisfy the purpose of this layer, but a highly permeable WRB like Mento 1000 from 475 Building Supply is recommended [24]. Rigidity of the panel is provided with diagonal wood bracing. This 1 × 3 wood bracing also serves as the rain screen, which provides a drainage plane and an air gap between the insulation and the siding to promote drying potential of any moisture buildup in the assembly. The rain screen also provides the advantage that almost any type of exterior façade can be installed, depending on the neighborhood aesthetics and building typology. The 1 × 3 battens provide a surface for the exterior façade to be secured. In theory, any type of insulation can be used in the cavities of the I-joists, but either dense pack cellulose or wool insulations is recommended. These products provide two key advantages over foam or fiberglass insulation. Firstly, both cellulose and wool have excellent hygrothermal properties that allow them to hold and release water as vapor travels through the assembly with a very good drying potential. Wool is a lighter product compared to cellulose and can even retain its insulation value when wet. However, cellulose is a much more affordable product. Therefore, if weight is the driving design parameter, then it is recommended to spend the extra money on wool insulation. If cost is the driving factor, then cellulose is recommended. Using a 0.24 m (i.e., 9-½ inches) I-joist provides an R29–R36 insulation value depending on whether cellulose or wool insulation is used. The wool insulation provides a higher insulation value but is more expensive. Without the exterior façade, the panel weight ranges from 3.3 to 5.6 pounds per square foot, depending on the insulation used. Secondly, both products have a much lower embodied carbon compared to manufactured products like fiberglass, foams, and mineral wool insulation. Because these panels are made with common materials, the size and thickness of panels can be adjusted to fit the target climate zone and building typology. A wide range of brands and thicknesses of wood

I-joists exist on the market and most of them are available off the shelf at lumber stores. Wood was chosen as the framing members so that the panels can be easily customized to the desired size. A series of isometric views of the panel can be seen in Figure 2.

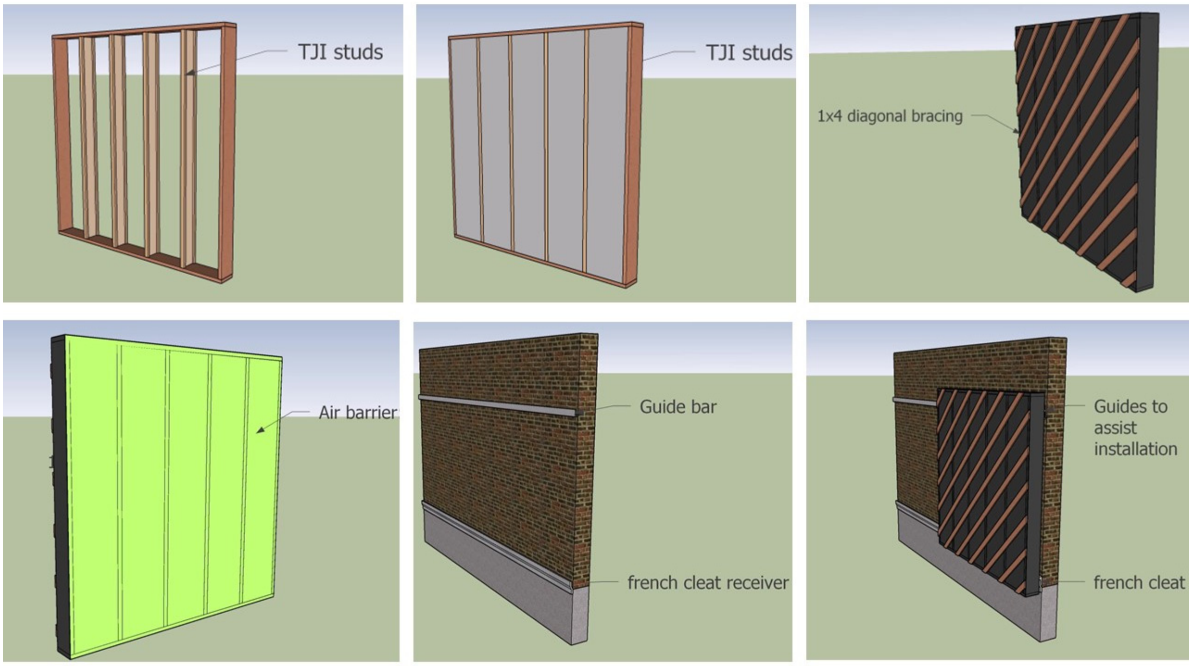
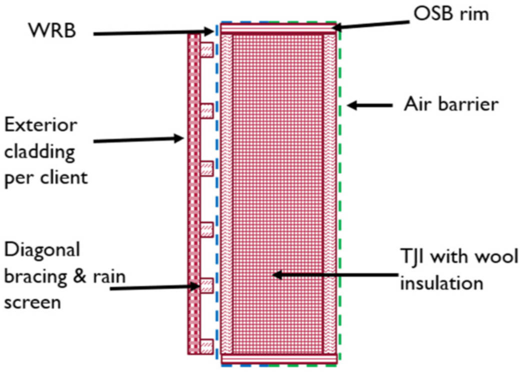


Figure 2. Isometric views of the proposed exterior insulated retrofit panel system.

The panels are designed to be installed directly to the exterior façade of the existing structure. The exact specifications of the panel depend on the building typology, construction type (i.e., masonry versus wood frame), age, and condition of existing structural components of the facades. As noted in Figure 2, the full weight of the panel rests on French cleats and guide clips attached on the back of the panels. The guide clips are only installed to assist in installation of the panels. The weight of the assembly will be supported by the French cleat receivers installed on the exterior facades of the building and secured to existing structural members. Once the panels are fully landed on the French cleat receivers, L-brackets are used to secure the top of the panels to the existing structure. It should be noted that spacing of the French cleat receivers is critical to ensure that the panels are closely connected to each other when installed. Air sealing between the panels is applied using vapor-open adhesives and caulks from 475 Building Supply [25]. While, Figure 2 only shows opaque panels, the proposed panels allow for the preinstallation of windows and doors. The existing windows and doors of the building need to be removed prior to the installation of the exterior insulated retrofit panels.

Other alternatives and variations to the proposed design for the insulated panels have been considered and to retrofit building envelope elements, as illustrated in Figure 3. These design alternatives have been evaluated and compared to the primary design configuration of Figure 1 based on cost, weight, flexibility, embodied carbon, moisture resilience, and material availability in the US market as summarized in Table 3. Based on these metrics, the I-joist stud wall of Figure 1 has been selected as the most suitable exterior insulated panels suitable for deep retrofitting US residential buildings.



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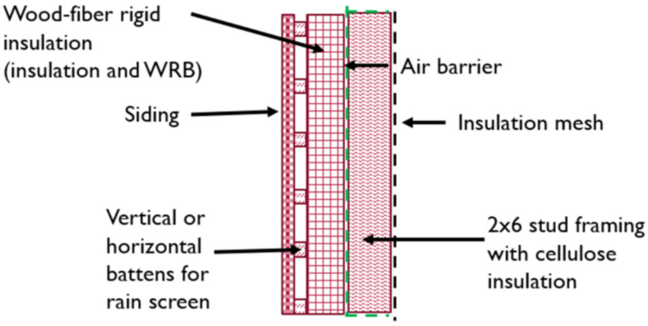

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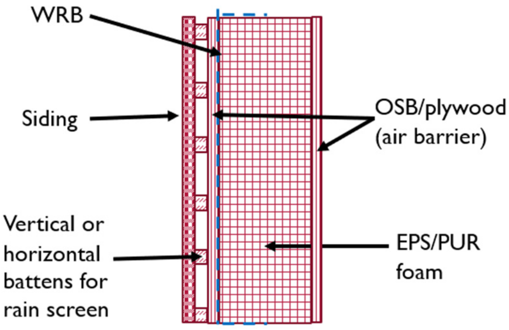


(**c**)

Figure 3. Alternatives for the proposed insulated panel including (**a**) TJI stud wall with wool insulation, (**b**) 2 × 6 stud wall with continuous insulation, and (**c**) SIP wall with rigid foam.

Table 3. Comparison of alternative design options for exterior insulated panels.

Design Option	Effective R-Value $m^2.°C/W$ ($ft^2.°F.hr/Btu$)	Weight kg/m^2 (lb/ft^2)	Cost USD/m^2 (USD/ft^2)	Moisture Resiliency (Poor, Neutral, Good, Great)	Embodied Carbon (Poor, Neutral, Good, Great)
TJI-stud wall with cellulose insulation	5.1 (29)	27.3 (5.59)	38.3 (3.56)	Great	Great
TJI-stud wall with wool insulation	6.3 (36)	16.2 (3.31)	106.1 (9.86)	Great	Great
2 × 6 stud wall with wood-fiber continuous insulation	4.9 (28)	27.5 (5.63)	73.8 (6.86)	Good	Great
SIP wall	4.9–6.7 (28–38)	17.9 (3.66)	117.9 (10.95)	Neutral	Poor

4. Analysis Approach

In this section, a detailed analysis is carried out to evaluate the energy performance of the proposed exterior insulated retrofit panels when deployed for common prototypes of US existing residential buildings. The analysis approach, outlined in Figure 4, considers various climate zones and building typologies to account for the diversity of existing housing stocks in the United States. The analysis is based on energy and cost evaluations to determine optimal R-values for the insulated panels for a variety of climate zones and residential building types in the US.

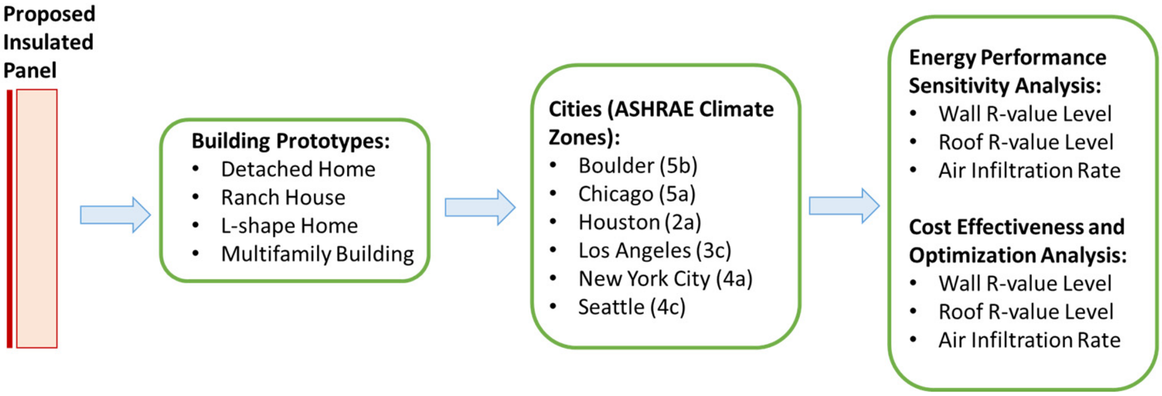


Figure 4. Flowchart for the assessments of the energy performance and cost benefits for the proposed exterior insulated retrofit panels when deployed to existing US residential buildings.

For this study, four energy models representing various prototypes of US existing residential buildings are considered, as detailed in Table 4. First, a model, referred to as PNNL SF, for a two-story single-family detached home is considered using Pacific Northwest National Laboratory (PNNL) prototypical building models [26]. In addition, three energy models are considered including ranch single family house (labeled as SF Ranch), L-shaped single-family 1-story house (referred to as L-shape), and multifamily townhouse with three floors (labeled Townhouse). The main features including geometric characteristics, floor areas, and roof types are listed in Table 4. Specific characteristics used to establish the energy models for the four US housing prototypes are listed in Table 5. In addition, the adjustments made to adjust constructions of the building envelope elements for the climate zones are listed in Table 6. The 3D renderings for the four energy models are illustrated in Figure 5. Note that the multifamily townhome is modeled as a middle unit. This means that the north and south walls are exposed to the environment while the east and west walls are considered adiabatic shared walls.

Table 4. Main features of energy models for prototypical US residential buildings.

Reference Home	Abbreviation	Square Footage m^2 (ft^2)	Floors	Roof Type	Beds/Baths
PNNL Prototypical Single Family Detached Home	PNNL SF	223 (2400)	2	Gable, 4:12 slope, unfinished vented attic	3/2
Single Family, Single Story Detached Home	SF Ranch	112 (1200)	1	Gable, 4:12 slope, unfinished vented attic	2/2
Single Family, L-shaped Detached Home	L-shape	112 (1200)	1	Gable, 4:12 slope, unfinished vented attic	2/2
Multifamily, Middle Unit Townhome	Townhome	167 (1800)	3	Flat	3/2

Table 5. Specifications of characteristics of energy models for four US housing prototypes.

	Unit	PNNL SF	SF Ranch	L-Shape	Townhome
Square footage	m^2 (ft^2)	223 (2400)	112 (1200)	112 (1200)	167 (1800)
Floors	-	2	1	1	3
Wall height	m (ft)	2.6 (8.5)	2.6 (8.5)	2.6 (8.5)	2.6 (8.5)
Roof type	-	gable	gable	gable	flat
Roof slope	rise:run	4:12	4:12	4:12	flat
# Number of bedrooms	qty	3	2	2	3
Number of baths	qty	2	2	2	2
Number of occupants	qty	default	default	default	default
Orientation	-	north	north	north	north
Neighbors	-	none	none	none	none
Heating set point	°C (°F)	21.7 (71)	21.7 (71)	21.7 (71)	21.7 (71)
Cooling set point	°C (°F)	24.4 (76)	24.4 (76)	24.4 (76)	24.4 (76)
Humidity set point	N/A	none	none	none	none
Natural ventilation	-	cooling months only, 3 days/wk	cooling months only, 3 days/wk	cooling months only, 3 days/wk	cooling months only, 3 days/wk
Int. Shading	-	Summer = 0.7, Winter = 0.7	Summer = 0.7, Winter = 0.7	Summer = 0.7, Winter = 0.7	Summer = 0.7, Winter = 0.7
Wall construction	-	Uninsulated, 2 × 4, 16″ OC	Uninsulated, 2 × 4, 16″ OC	Uninsulated, 2 × 4, 16″ OC	Uninsulated, 2 × 4, 16″ OC
Sheathing	-	OSB	OSB	OSB	OSB
Exterior finish	-	Vinyl, light	Vinyl, light	Vinyl, light	Vinyl, light
Unfinished attic	-	uninsulated, vented	uninsulated, vented	uninsulated, vented	uninsulated, vented
Finished roof	-	N/A	N/A	N/A	N/A
Roof material	-	Asphalt shingles, med.	Asphalt shingles, med.	Asphalt shingles, med.	Asphalt shingles, med.
Radiant barrier	-	none	none	none	none
Slab	-	* changes per climate zone	* Changes per climate zone	* changes per climate zone	* changes per climate zone
Carpet	-	80% carpet	80% carpet	80% carpet	80% carpet
Thermal mass—exterior wall	-	1/2″ drywall	1/2″ drywall	1/2″ drywall	1/2″ drywall
Thermal mass—interior wall	-	1/2″ drywall	1/2″ drywall	1/2″ drywall	1/2″ drywall
Thermal mass—ceiling	-	1/2″ drywall	1/2″ drywall	1/2″ drywall	1/2″ drywall
Window areas	-	15% F25 B25 L25 R25	15% F25 B25 L25 R25	15% F25 B25 L25 R25	15% F25 B25 L25 R25
Windows	-	* changes per climate zone	* changes per climate zone	* changes per climate zone	* changes per climate zone
Eaves	m (ft)	0.6 (2)	0.6 (2)	0.6 (2)	0.6 (2)
Overhangs	-	none	none	none	none
Air leakage	-	13ACH50	13ACH50	13ACH50	13ACH50
Mech. Vent.	-	exhaust	exhaust	exhaust	exhaust
Refrigerator	-	Top freezer, EF = 17.6	Top freezer, EF = 17.6	Top freezer, EF = 17.6	Top freezer, EF = 17.6
Cooking Range	-	Electric	Electric	Electric	Electric
Dishwasher	-	270 Rated kWh	270 Rated kWh	270 Rated kWh	270 Rated kWh
Clothes dryer	-	Electric, CEF-3.73	Electric, CEF-3.73	Electric, CEF-3.73	Electric, CEF-3.73
Plug Loads multiplier	-	1	1	1	1
Lighting	-	100% LED	100% LED	100% LED	100% LED
ASHP	-	SEER 14.3, 7.5 HSPF2, auto-size	SEER 14.3, 7.5 HSPF2, auto-size	SEER 14.3, 7.5 HSPF2, auto-size	SEER 14.3, 7.5 HSPF2, auto-size
Ducts		15% leakage, R-8	15% leakage, R-8	15% leakage, R-8	15% leakage, R-8
Water heater	-	Electric tank, UEF = 0.93	Electric tank, UEF = 0.93	Electric tank, UEF = 0.93	Electric tank, UEF = 0.93
WH location	-	auto	auto	auto	auto
Distribution	-	uninsulated, copper	uninsulated, copper	uninsulated, copper	uninsulated, copper
WH set point	°C (°F)	51.7 (125)	51.7 (125)	51.7 (125)	51.7 (125)

(*) The specifications for the slab-on-grade floor constructions and windows are listed in Table 6 for various climate zones.

Table 6. Adjustments made for floors and windows according to the climate zones.

Climate Zone	Slab	Windows
Cold	2-ft R-10 perimeter, R-5 gap	Double, med. Gain low-e, nonmetal frame, argon (U = 0.35, SHGC = 0.44)
Hot humid	uninsulated	Double, low gain low-e, nonmetal frame, air (U = 0.37, SHGC = 0.3)
Hot dry	uninsulated	Double, low gain low-e, nonmetal frame, air (U = 0.37, SHGC = 0.3)
Mixed	2-ft R-10 perimeter, R-5 gap	Double, med. Gain low-e, nonmetal frame, argon (U = 0.35, SHGC = 0.44)
Marine	2-ft R-10 perimeter, R-5 gap	Double, med. Gain low-e, nonmetal frame, argon (U = 0.35, SHGC = 0.44)

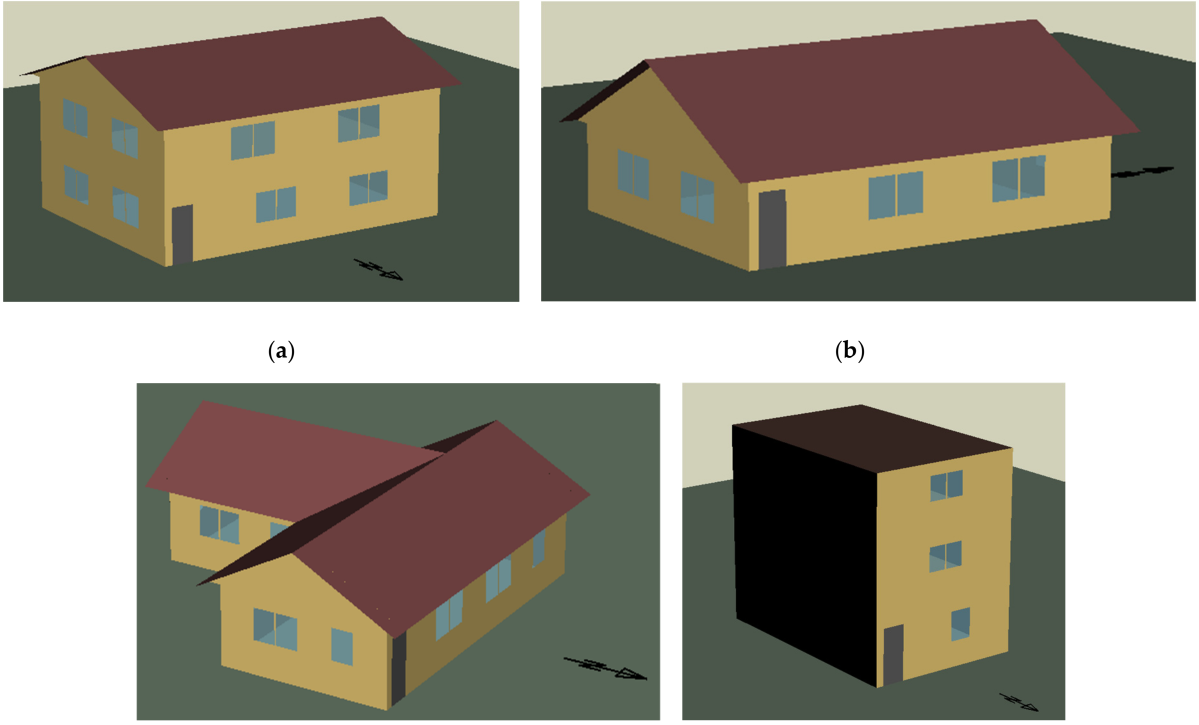

(**a**) (**b**) (**c**) (**d**)

Figure 5. 3D Renderings for four energy models for (**a**) PNNL SF, (**b**) SE Ranch, (**c**) L-shape, and (**d**) Townhouse.

Variations of the four housing units have been established for six US cities that encompass six different ASHRAE climate zones, as summarized in Table 7. The analysis is carried out using EnergyPlus version 22.2, a state-of-the-art whole building energy simulation tool [27], integrated into a user interface, BEOpt version 3.0.1, a user-friendly tool that allows both parametric and optimization analyses [28]. The series of analyses conducted for this study evaluates both the energy use and cost of various insulation levels for the insulated retrofit panels when implemented in exterior walls depending on the roof/ceiling insulation levels and air infiltration rates.

Table 7. Climate zones evaluated in energy performance analysis.

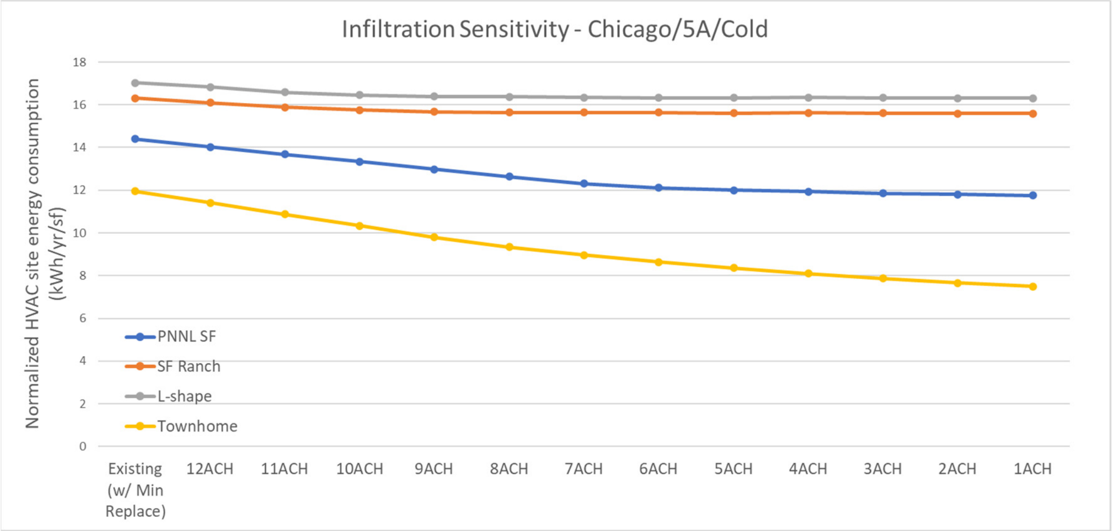
City, State	ASHRAE Climate Zone	Building America Climate Zone	Heating Degree Days (65 deg F)	Cooling Degree Days (50 deg F)
Chicago, IL	5a	Cold	5882	3806
Boulder, CO	5b	Cold	5743	3479
New York City, NY	4a	Mixed humid	4521	3977
Seattle, WA	4c	Marine	4600	2487
Houston, TX	2a	Hot humid	1210	8149
Los Angeles, CA	3c	Hot dry	1312	5593

5. Discussion of Analysis Results

Using various housing prototypes and climate zones, a series of sensitivity and optimization analyses are carried out to assess the energy efficiency and cost benefits of the proposed exterior insulated retrofit panels.

5.1. Impact of Air Infiltration Rate

In this section, the air tightness of the building was varied from 13 ACH (reference case) to 1 ACH at 50 Pa. All other variables of the reference case remained the same (uninsulated walls and roof with B10 specifications from NREL 2014 Building America Simulation Protocols). The effects of air infiltration rate on the heating, ventilating, and air conditioning (HVAC) energy use are illustrated in Figure 6 for all the climate zones and housing prototypes. As indicated by the results of Figure 6, improving the airtightness of the SF Ranch and L-shape homes has a limited impact on energy consumption for all the climate zones evaluated. However, a significant reduction in HVAC energy consumption is achieved for the PNNL SF and the townhome models located in cold climates (i.e., Chicago, Boulder, New York City, and Seattle) due to reduction in air infiltration rate. This result is due to two driving forces affecting both heating and cooling thermal loads including (i) prevalent temperature differences between indoors and outdoors which are associated with the climatic conditions, and (ii) amount of infiltrating air which is related to the volume of the housing units. The first driving force implies that air infiltration affects mostly heating loads in locations with cold climates and where the outdoor temperatures are significantly lower than indoor temperature settings. The second driving force indicates that for the same air change rate (ACH) affects more significantly the PNNL SF and townhouse as they have higher volume than the SF home and L-shape.



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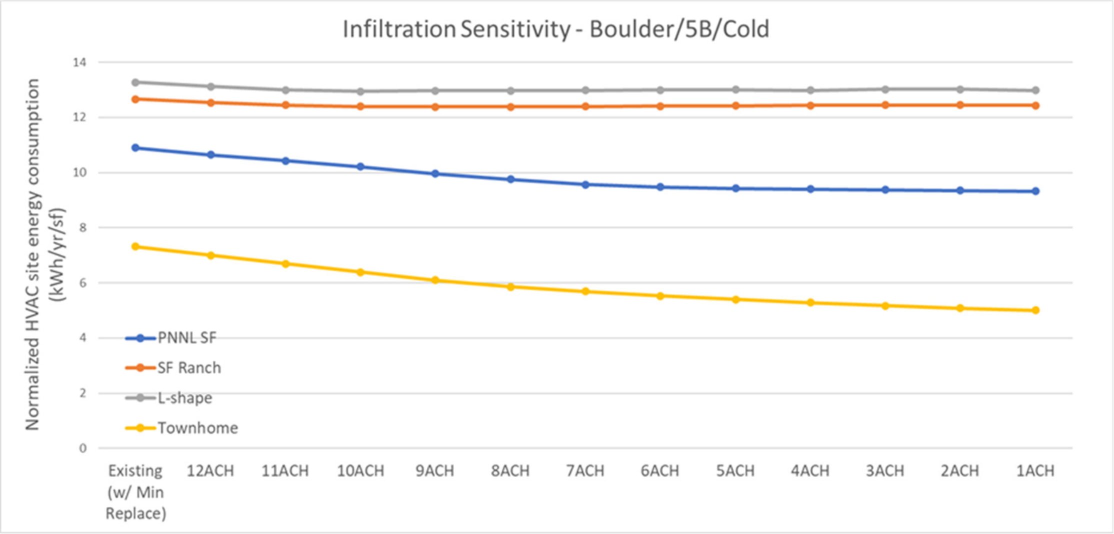

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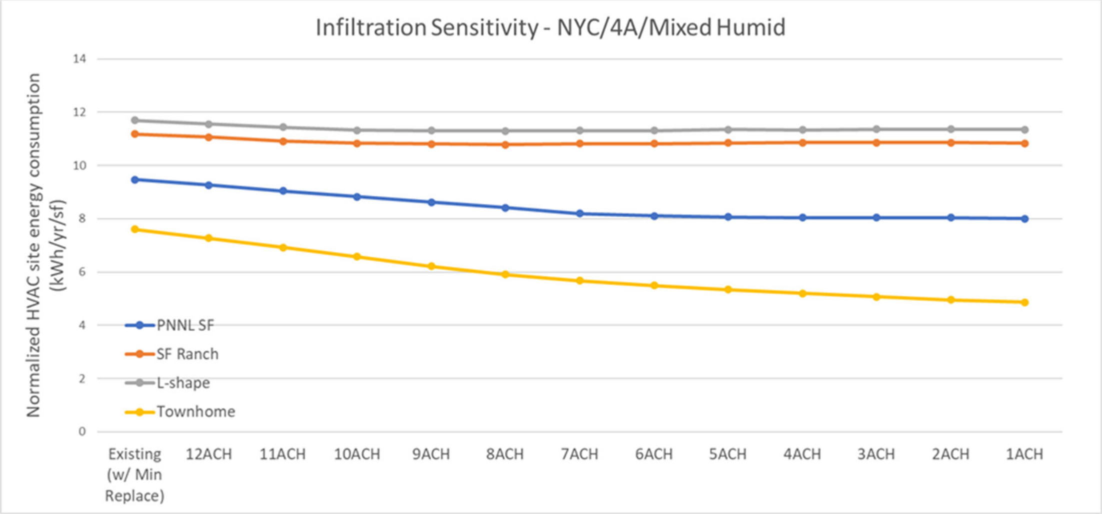
Figure 6. *Cont.*



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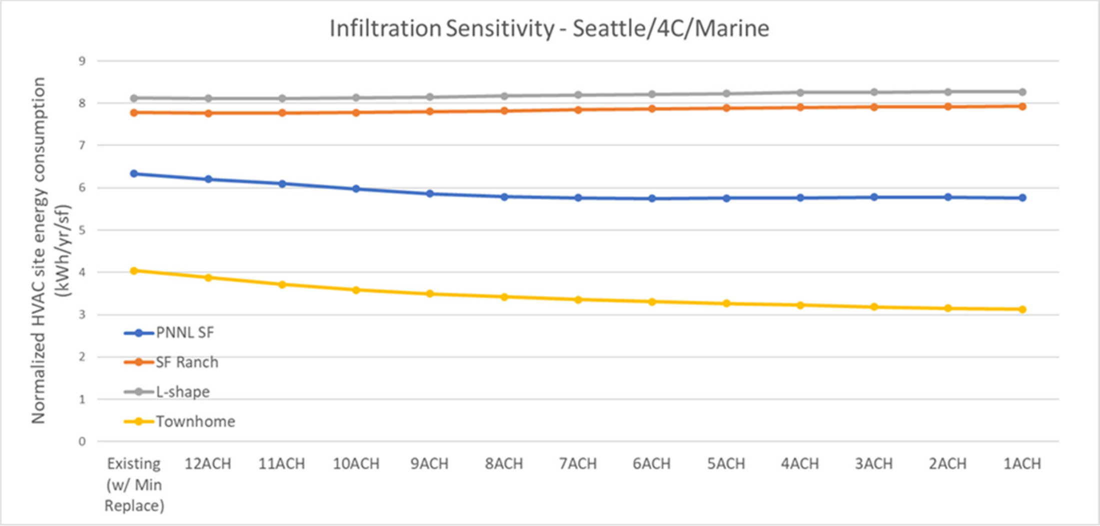

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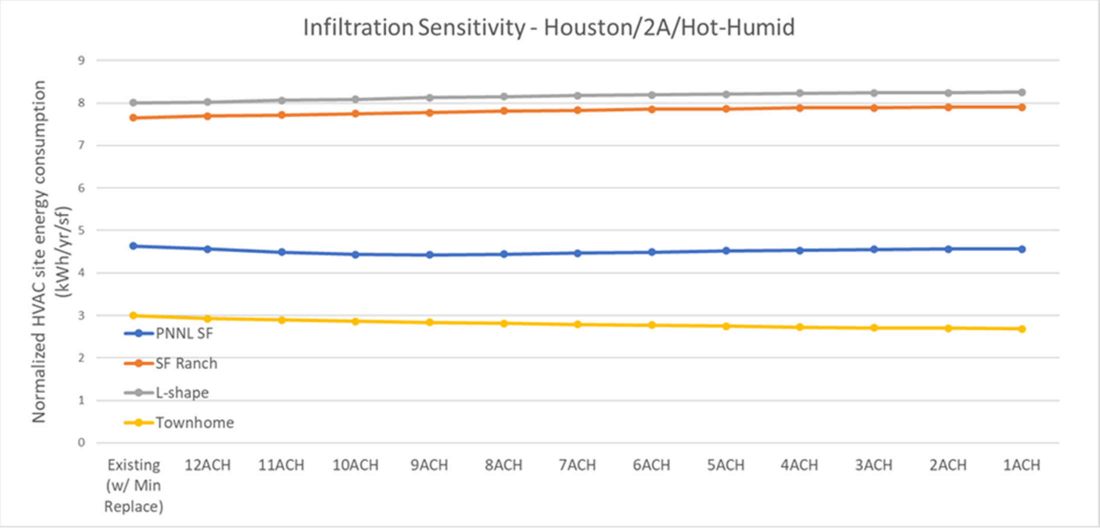

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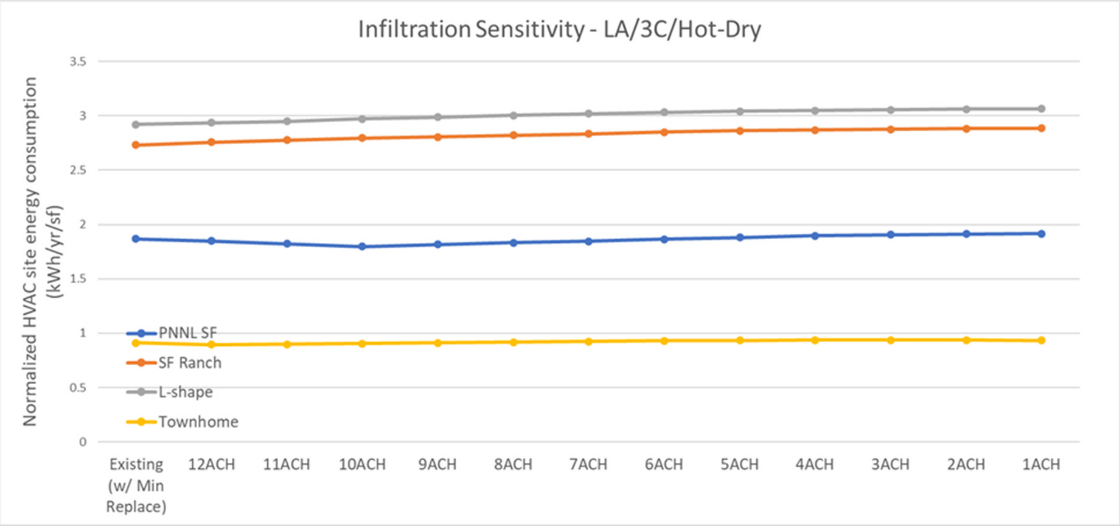
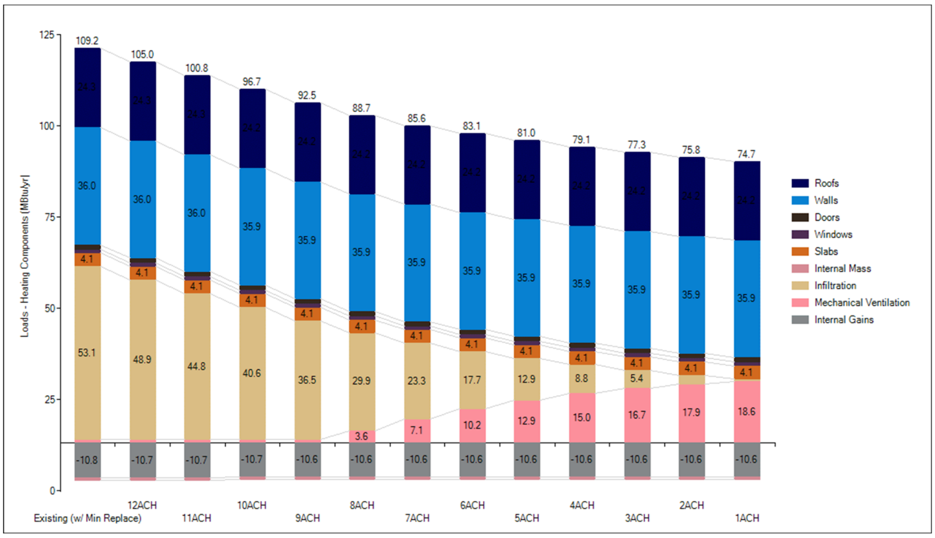


(f)

Figure 6. Impact of air infiltration rate on HVAC electrical consumption for four housing prototypes located in (**a**) Chicago, IL; (**b**) Boulder, CO; (**c**) New York City, NY; (**d**) Seattle, WA; (**e**) Houston, TX; (**f**) Los Angeles, CA.

The significance of both climate and size of the housing unit on the impact of air infiltration rate on heating and cooling loads are illustrated by Figures 7 and 8. Indeed, Figures 7 and 8 show the annual distributions of both heating and cooling thermal loads specific to a townhouse located in Chicago and Houston, respectively. For the cold climate of Chicago, IL, a significant portion of the annual heating thermal load for the townhome in its baseline design is attributed to air infiltration. This portion is reduced with lower air infiltration rate as noted in Figure 7a. However, the contribution of air infiltration in annual cooling thermal load for the townhouse located in Chicago, IL, remains low regardless of the ACH rate as depicted in Figure 7b since there are no significant differences between outdoor and indoor temperatures during the summer. For the hot climate of Houston, TX, the air infiltration results in small annual thermal loads for both heating and cooling of the townhouse as noted in Figure 8.



(**a**)

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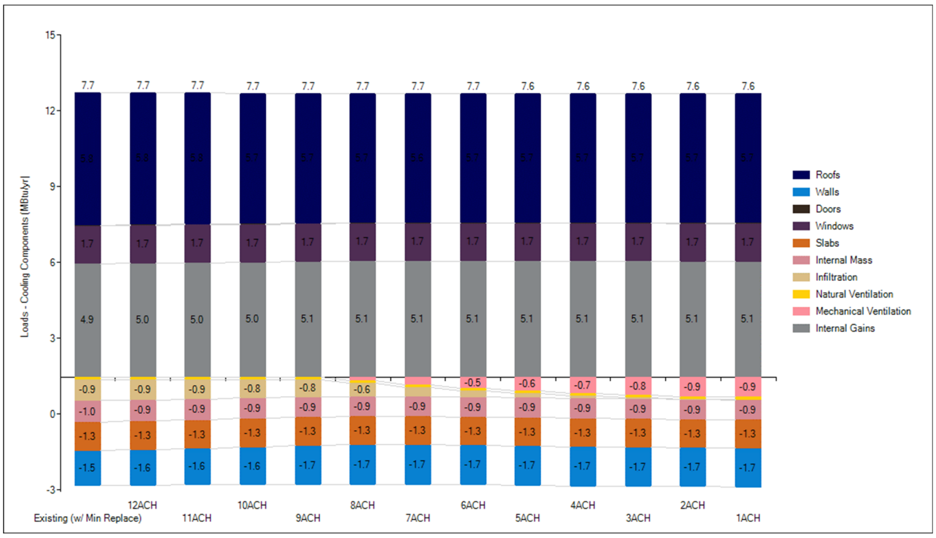

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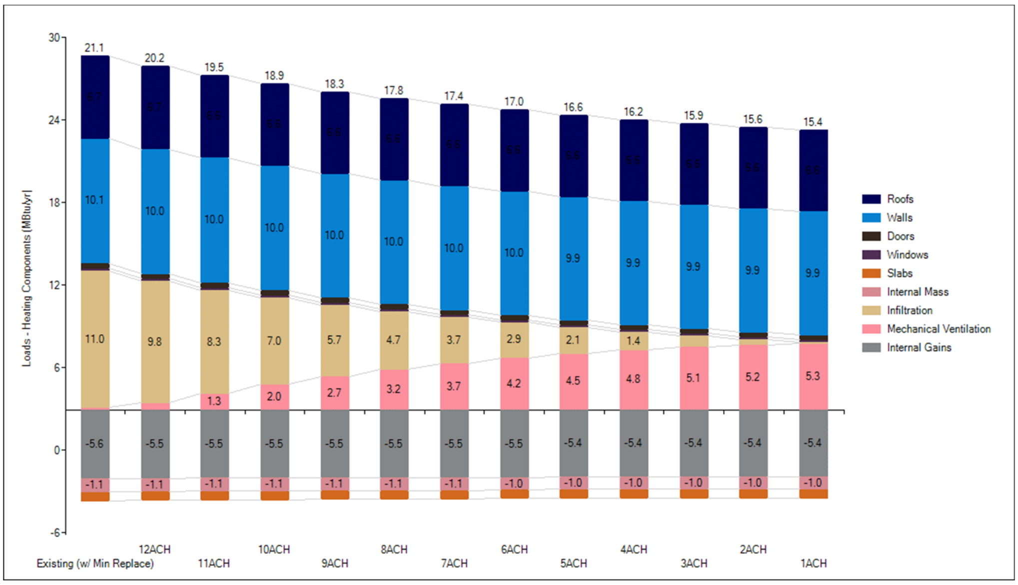
Figure 7. Impact of air infiltration rate on annual distribution of (**a**) heating load and (**b**) cooling load for townhouse in Chicago, IL.



(**a**)

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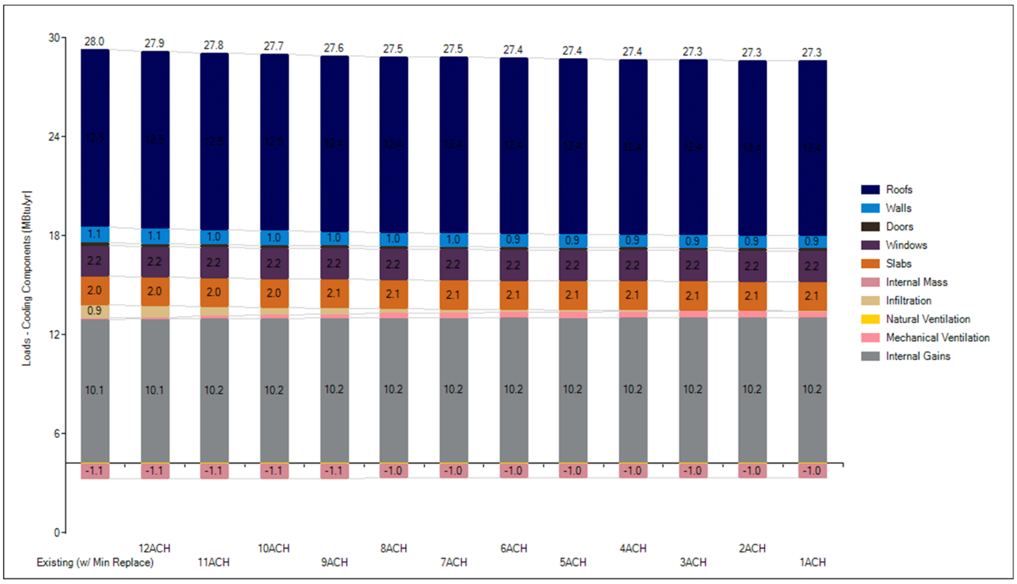


(**b**)

Figure 8. Impact of air infiltration rate on annual distribution of (**a**) heating load and (**b**) cooling load for townhouse in Houston, TX.

Figure 9 summarizes the energy impacts of air infiltration rate for all climates and housing prototypes by showing the maximum percent annual HVAC energy savings that could be achieved if air infiltration rate is reduced from 13 ACH (reference case) to 1 ACH for 50 Pa pressure differential between indoors and outdoors. Again, only the PNNL SF and townhome located in cold climates show significant reduction in HVAC energy savings from air infiltration improvements due to both higher volumes of these prototypical buildings and large differences between indoor and outdoor temperatures during the winter seasons. It should be noted that the highest possible energy savings for the townhome is almost double the highest possible energy savings in the PNNL SF, in 5 of the 6 climates. For hot climates of Houston and Los Angeles, the reduction of air infiltration rate results in little to no HVAC energy savings.

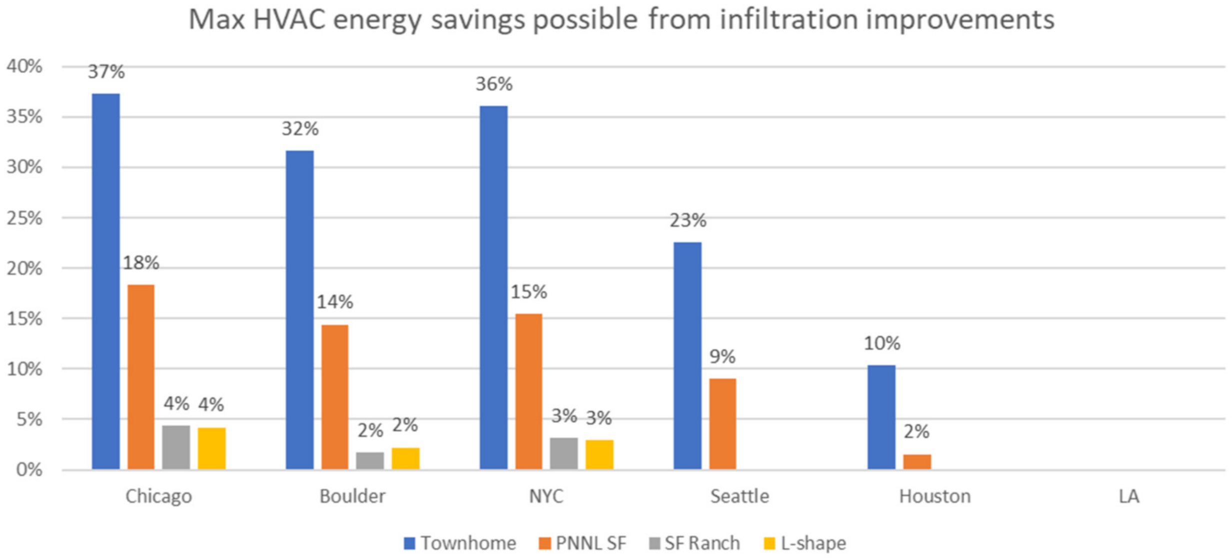
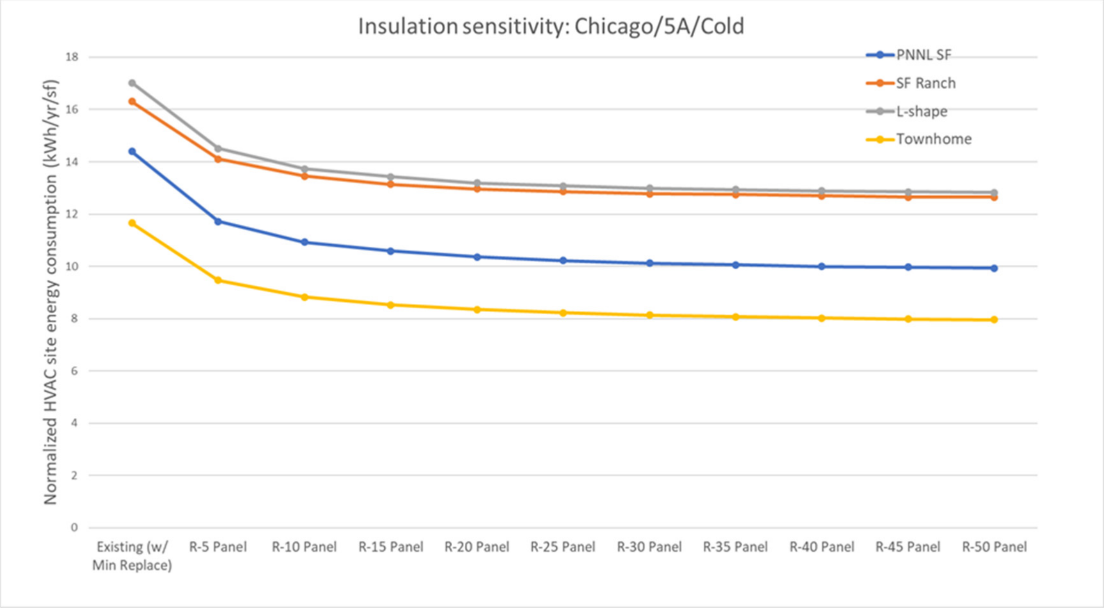


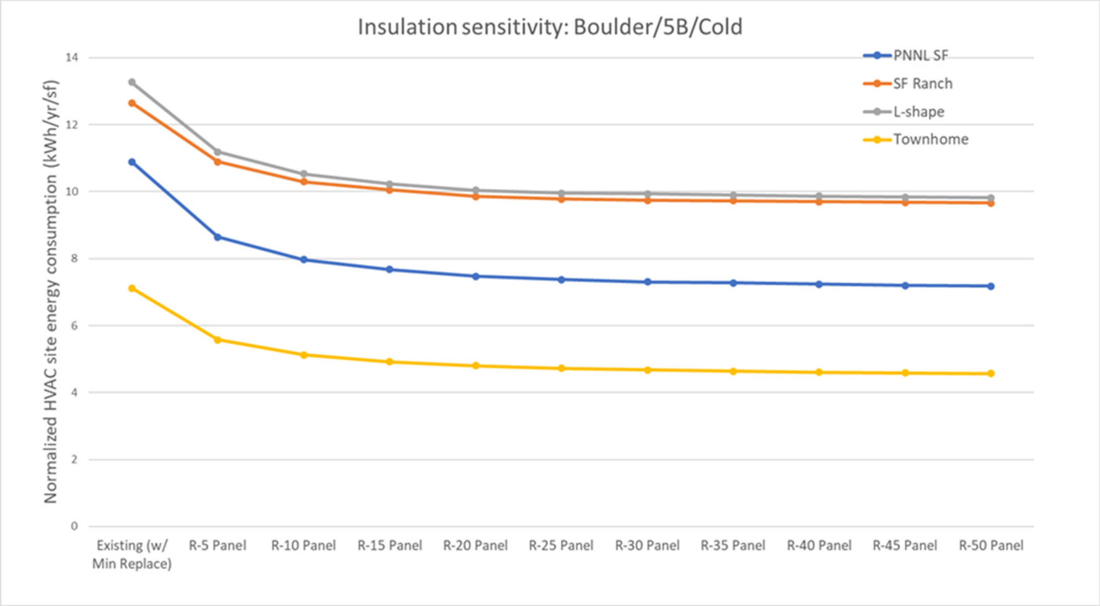
Figure 9. Potential maximum annual HVAC energy savings due to reduction of air infiltration rate from 13 ACH to 1 ACH at 50 Pa for all climates and housing prototypes.

5.2. Impact of R-Value for Wall Insulated Panels

In this section, the energy benefits of R-value of the insulated retrofit panels when deployed to exterior walls for the four housing prototypes located in six US cities are evaluated. Specifically, R-value of the insulated panels is varied from R-0 (reference case) to R-50. All other variables of the reference case remained the same (air leakage rate is set 13 ACH at 50 Pa and uninsulated roof, and specifications listed in Tables 5 and 6). Figure 10 illustrates the variations of annual HVAC energy consumption with the wall R-value for all climate zones and housing prototypes considered in this study.



(a)



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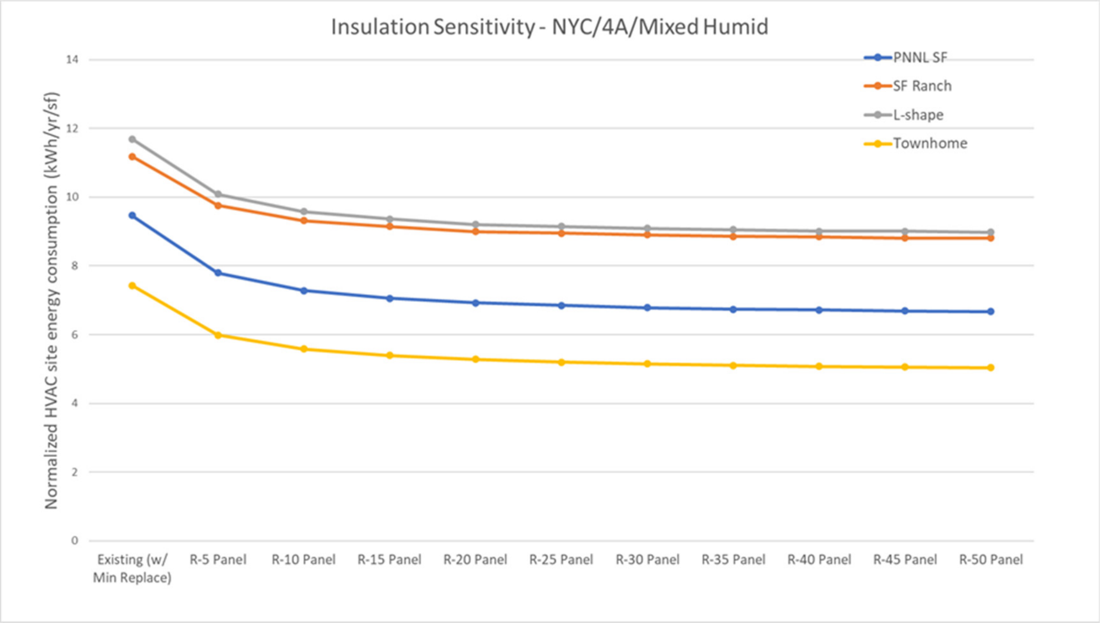

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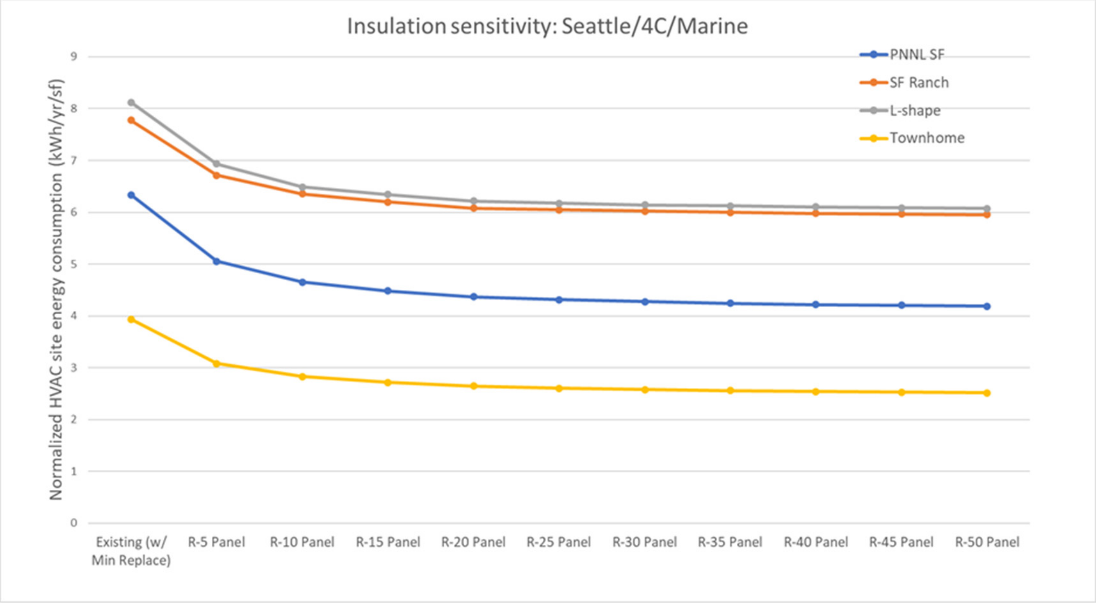

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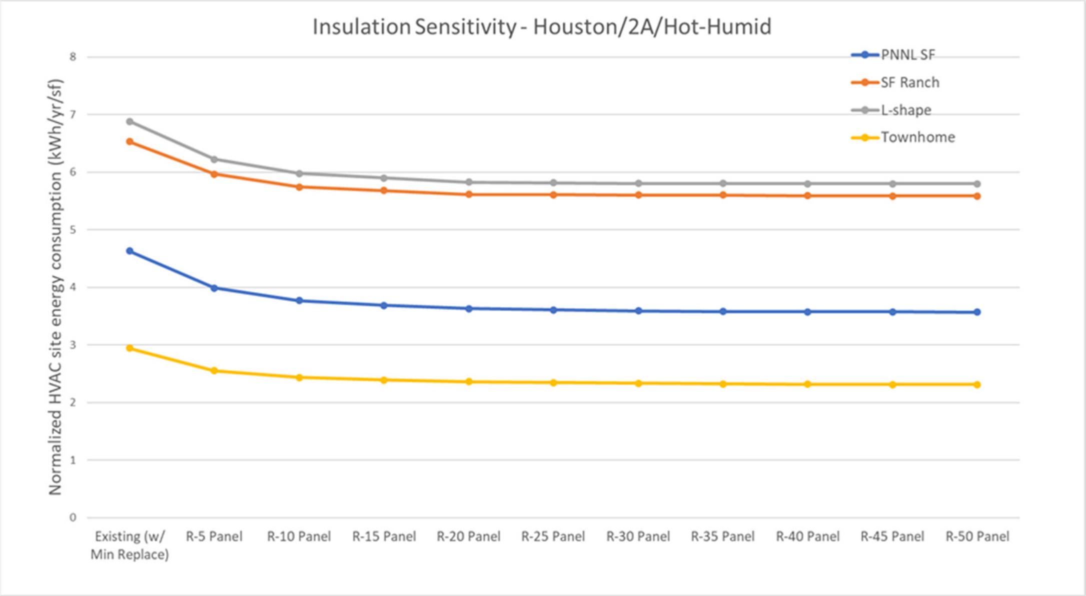

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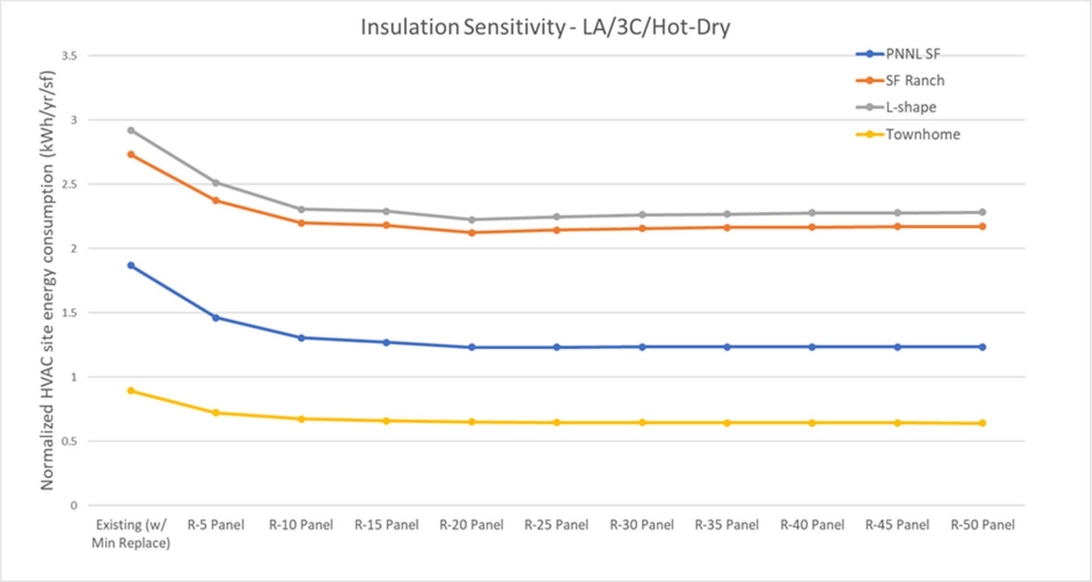


(f)

Figure 10. Impact of wall insulation R-value on HVAC electrical consumption for four housing prototypes located in (**a**) Chicago, IL; (**b**) Boulder, CO; (**c**) New York City, NY; (**d**) Seattle, WA; (**e**) Houston, TX; (**f**) Los Angeles, CA.

Unlike the case of reducing air infiltration rate, adding wall insulation reduces substantially annual HVAC energy consumption for all four housing prototypes and six climate zones. Indeed, the addition of thermal insulation affects both heating and cooling demands regardless of the building type and climate zone. As indicated by the results of Figure 10, the point of diminishing returns for the addition of wall insulation is consistent between housing prototypes for a given climate zone. For cooler climate zones, the diminishing returns for the added wall insulation range from R-25 to R-30. For warmer climate zones, the diminishing returns start around R-10 to R-20. Figure 11 shows the potential savings in annual HVAC energy savings when R-50 insulated panels are added to uninsulated walls of four housing prototypes in six US climates. The highest relative HVAC energy savings range from 32% to 36% and are achieved for both the PNNL SF and townhouse in all climates.

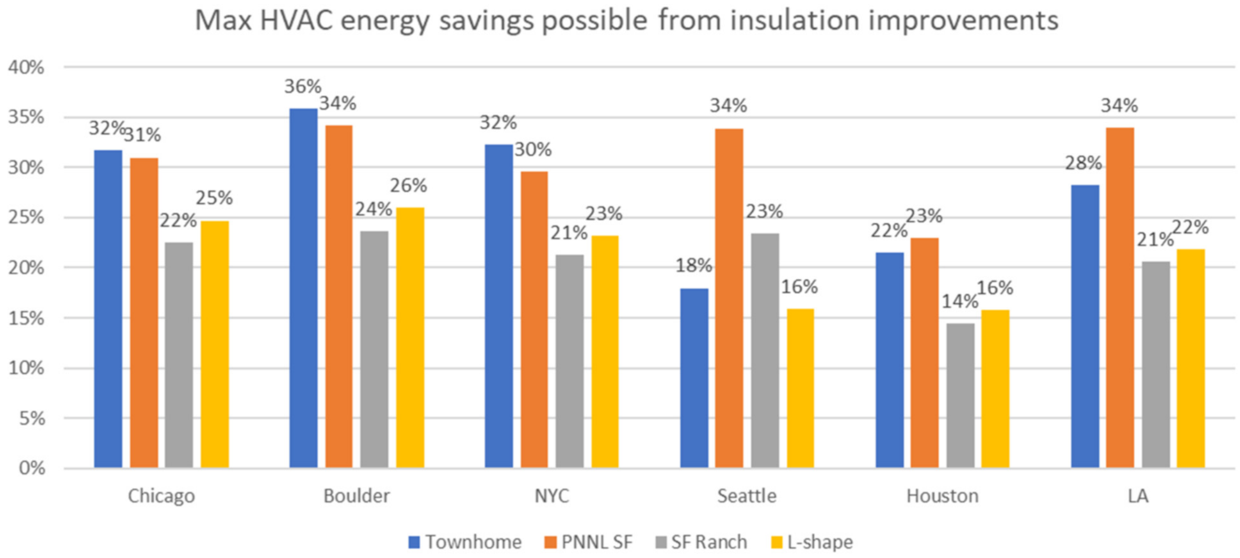
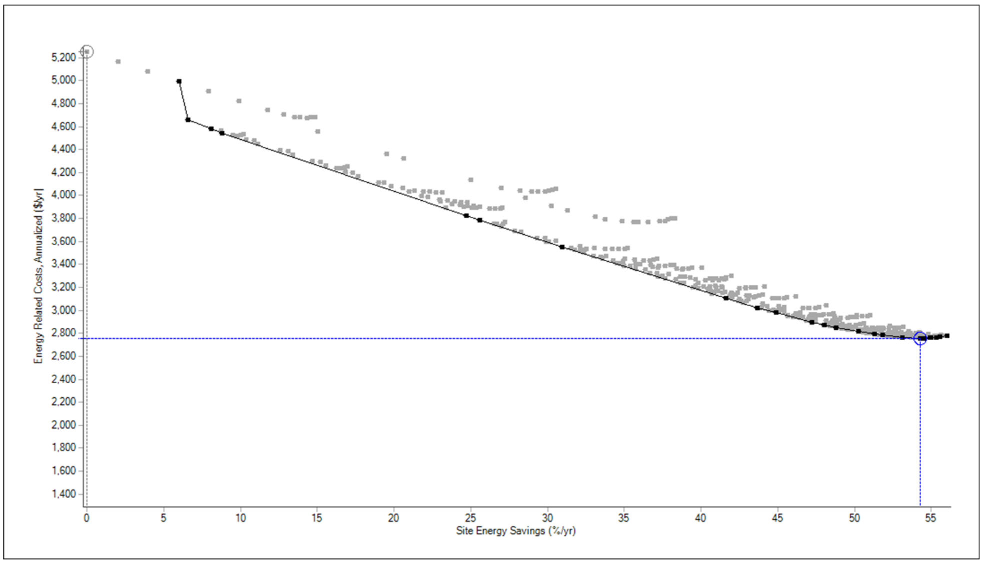


Figure 11. Potential maximum annual HVAC energy savings due to adding R-50 insulated panels to exterior uninsulated walls of four housing prototypes located in six cities.

5.3. Cost Optimization Analysis

In this section, the insulation levels for both walls and roof/ceiling as well as the air infiltration rate are optimized using life cycle costs to retrofit both PNNL SF and townhouse housing prototypes located in six US cities considered in this study. The life cycle costs are expressed in annualized energy cost which combines annual utility bills to the incremental cost associated with the implementation of the selected energy efficiency measures (i.e., R-value of insulated panels, R-value of roof/ceiling, and air infiltration rate) [29]. The cost database includes commonly used insulation R-values and air infiltration rates suitable for US residential buildings. The results of the cost optimization are illustrated in Figure 12 for the PNNL SF housing prototypes for six US cities. The optimal pareto curves of Figure 12 are obtained using the sequential optimization technique show the best combination of retrofit measures to achieve any desired annual energy savings for the housing prototype [30]. In particular, the optimal set of measures that achieve the lowest annualized cost is shown at the bottom of the pareto curve for each city. The specific values for the wall insulation, roof insulation, and air infiltration rate for the optimal set for both PNNL SF and townhouse prototypes are listed in Table 8 for all six US cities. Moreover, Table 8 provides the annual HVAC energy savings achieved by the optimal retrofit sets. These HVAC energy savings range from 49% for hot climates to 80% for cold climates. Indeed, lower air infiltration rate is consistently identified to be cost-beneficial for cold climates (with optimal ACH lower than 10) compared to that for hot climates (with optimal ACH higher than 10) leads to higher HVAC energy savings.



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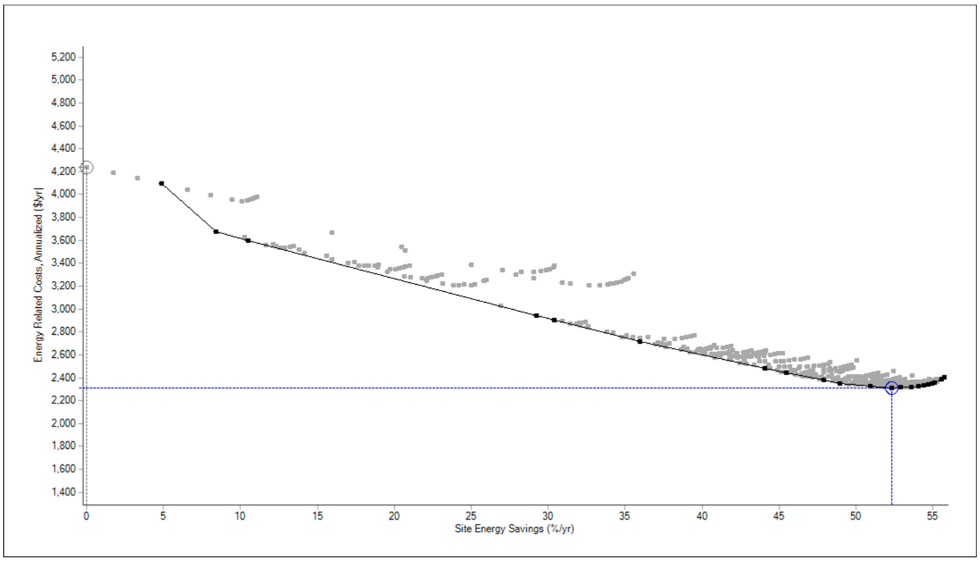

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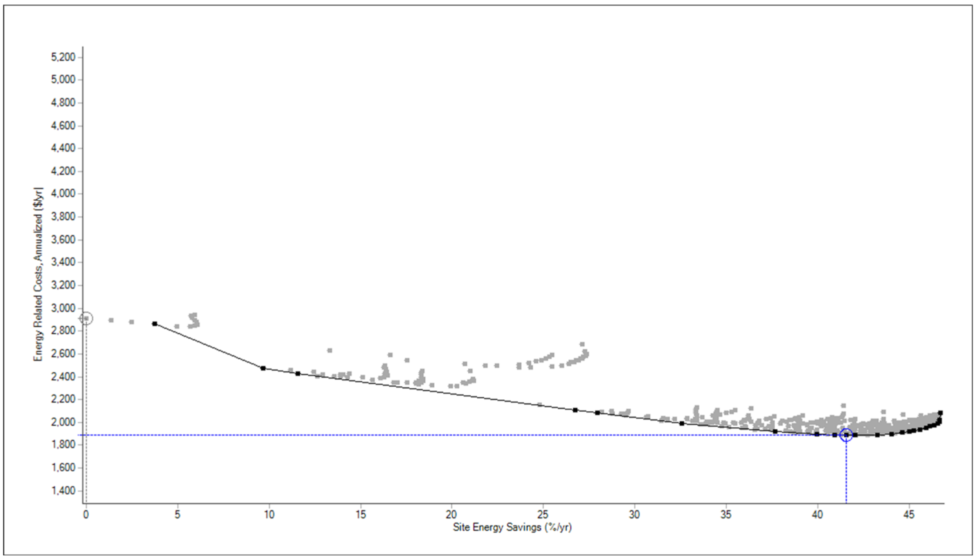

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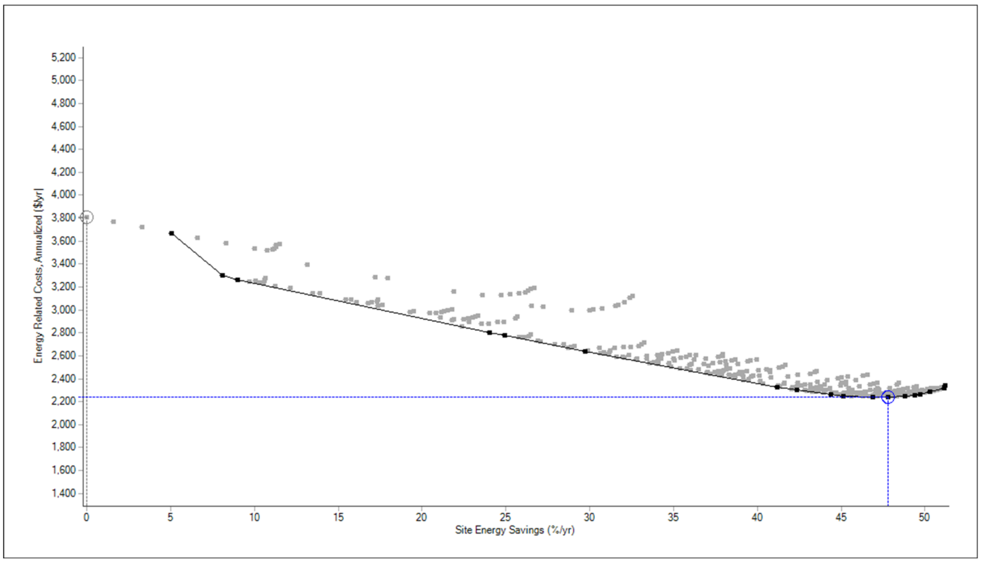

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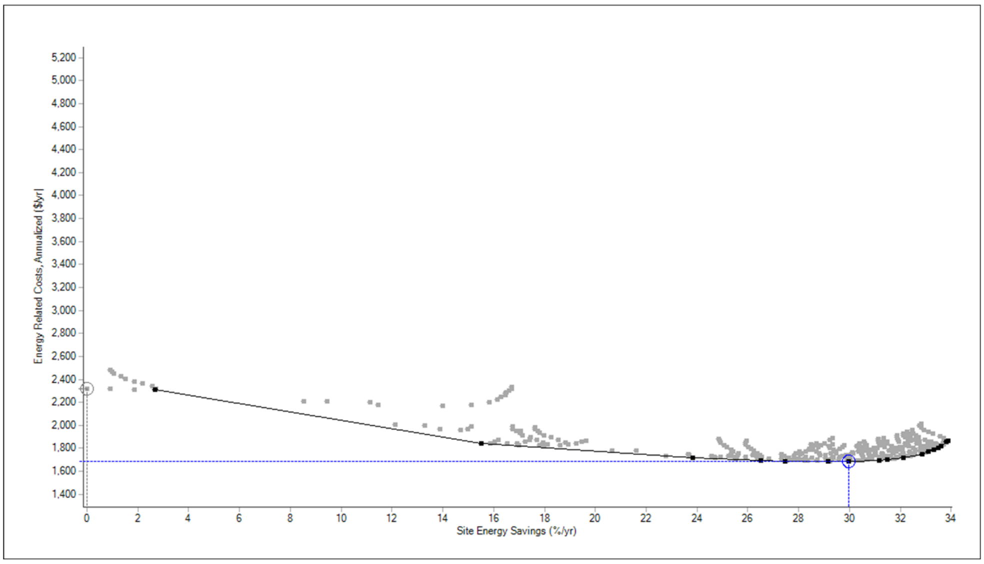

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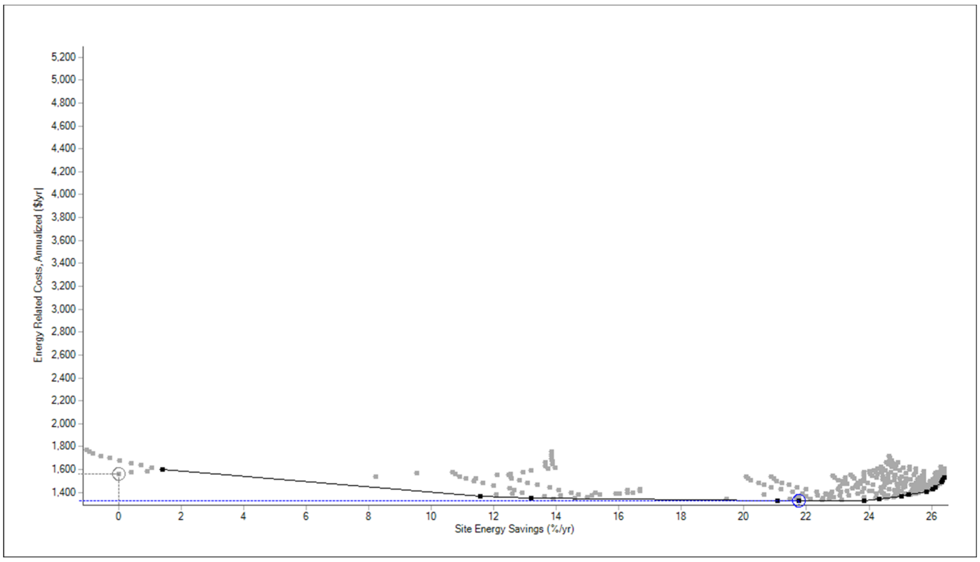

(**f**)

Figure 12. Optimization pareto curves to improve building envelope elements for PNNL SF housing prototype located in (**a**) Chicago, IL; (**b**) Boulder, CO; (**c**) New York City, NY; (**d**) Seattle, WA; (**e**) Houston, TX; (**f**) Los Angeles, CA.

Table 8. Optimal retrofit values and HVAC energy savings for PNNL SF and townhouse for all US cities.

			Infiltration	**Wall Panel**	**Roof/Attic Insulation**	**HVAC Energy Savings from Reference Case**
City	**Climate Zone**	**Reference**	**ACH50**	**R-Value**	**R-Value**	**%**
Chicago	5A/Cold	PNNL SF	2	R-35	R-38	67%
		Townhome	1	R-30	R-40	80%
Boulder	5B/Cold	PNNL SF	6	R-30	R-38	69%
		Townhome	3	R-25	R-30	76%

Table 8. *Cont.*

			Infiltration	Wall Panel	Roof/Attic Insulation	HVAC Energy Savings from Reference Case
City	**Climate Zone**	**Reference**	**ACH50**	**R-Value**	**R-Value**	**%**
New York	4A/Mixed	PNNL SF	5	R-25	R-30	64%
		Townhome	2	R-20	R-30	76%
Seattle	4C/Marine	PNNL SF	8	R-15	R-30	63%
		Townhome	10	R-15	R-20	61%
Houston	2A/Hot Humid	PNNL SF	10	R-10	R-30	49%
		Townhome	13	R-10	R-20	45%
LA	3C/Hot Dry	PNNL SF	13	R-5	R-19	57%
		Townhome	13	R-5	R-10	56%

Another benefit for retrofitting building envelope is the reduction of the heating and cooling capacities of the HVAC systems required to maintain indoor thermal comfort within the housing prototypes. This benefit can be significant when considering the electrification of existing residential buildings using heat pumps. Indeed, adding thermal insulation to the exterior walls and roof/ceiling as well as reducing air leakage rates reduces the size of the heat pumps needed to heat and cool the housing units. Figure 13 presents the reduction in HVAC design loads when the optimal building envelope retrofit packages are implemented for both the PNNL SF and townhouse located in six US cities. The HVAC capacities for both heating and cooling can be reduced from 30.8% to 74.5%.

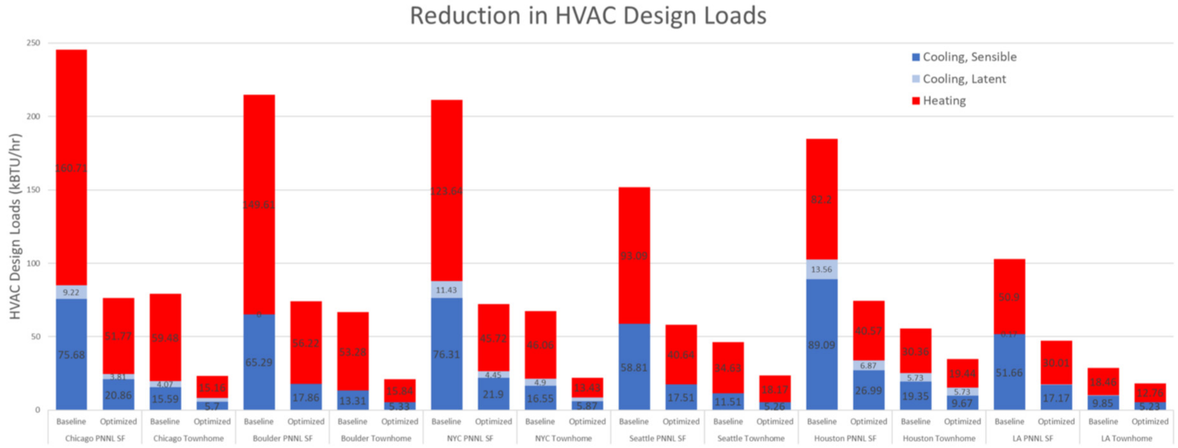

Figure 13. HVAC heating and cooling capacities of pre- and post- optimal retrofit package implementation for PNNL SF and townhouse located in six US cities.

Utilizing estimated capital costs required for implementing the optimal retrofit packages, a cost-benefit analysis can be carried out for both PNNL SF and townhouse prototypes located in six US cities. Table 9 summarizes this cost-benefit analysis results using simple payback periods. As expected, the payback periods for retrofitting the building envelope elements are significantly shorter for cold climates than those for warm climates. Moreover, Table 5 indicates the breakeven costs for the retrofit measures to make them cost-effective using a lifecycle of 30 years and a discount rate of 5% [30]. The costs for implementing the retrofit measures must be substantially lower than current estimates for upgrading building envelope elements to be cost-effective in hot climates.

Table 9. Simple payback periods and breakeven costs for optimal retrofit measures in six US cities.

Location	Home Type	Retrofit Cost USD/m^2	Retrofit Total Cost USD	Energy Cost Savings USD/Year	Payback Period Years	Breakeven Costs per Unit Area USD/m^2
Chicago, IL	PNNL	67.28	23,730	2807	8.45	122.60
	Townhouse	85.25	16,642	2031	8.19	160.28
Boulder, CO	PNNL	61.36	21,635	2159	10.02	94.29
	Townhouse	80.95	15,788	1175	13.44	92.79
New York City, NY	PNNL	61.46	21,669	1766	12.27	77.18
	Townhouse	80.95	15,787	1218	12.96	96.12
Seattle, WA	PNNL	55.44	19,563	1155	16.94	50.48
	Townhouse	69.00	13,463	518	25.99	40.90
Houston, TX	PNNL	51.99	18,312	654	28.00	28.53
	Townhouse	63.62	12,413	279	44.49	22.07
Los Angeles, CA	PNNL	46.07	16,258	311	52.28	13.56
	Townhouse	60.60	11,817	106	111.48	8.40

6. Conclusions

Decarbonizing existing US residential housing stock will require effective solutions for performing deep energy retrofits. Due to the success of the Dutch-inspired program, Energiesprong, a key component to cost-effective deep energy retrofits includes the use of prefabricated exterior insulated panels that can be installed directly to the outside of the existing cladding. While such envelope technologies have been investigated and implemented in Europe, they are just starting to be trialed and evaluated in the US. Indeed, the US market for commercially available products for exterior insulated panels tailored for retrofit applications is nascent. With recent significant investments, the US government is providing the tools necessary to identify cost-effective solutions required for deep energy retrofits especially those suitable for residential buildings.

This study has proposed and investigated the energy efficiency and cost benefits of a novel design for exterior insulated panels suitable for retrofitting US residential buildings. The proposed design can be scaled to multiple climates and building topologies. Moreover, the proposed design can overcome a set of common technical challenges prevalent for retrofitting US housing stocks including cost, architectural diversity, climate zone variations, structural concerns, moisture resilience, air sealing, and water sealing. Additionally, the proposed design could integrate windows, doors, and the exterior finish. Perhaps most importantly, the proposed insulated panels can be installed with minimal disruption to the occupants.

Based on a series of parametric and optimization analyses, optimal design criteria for retrofitting building envelope elements specific to improving air infiltration, wall insulation, and roof/attic insulation for various US housing prototypes and climates have been identified. The key findings from these energy and cost analyses include:

- Optimal design parameters for deep retrofit of building envelope elements are dependent on climate zone, building topology, construction, and existing energy systems. Each specific building should be evaluated individually when conducting a deep energy retrofit;
- Improving building airtightness is more important as the volume of the housing unit increases and the ratio of volume to exposed surface area increases;
- Improving airtightness in buildings is more important for buildings located in cold climates than those in hot climates;
- It is more economically feasible to retrofit exterior walls with high R-values in colder climates compared to those in warmer climates;
- Optimal retrofit measures for building envelope elements can reduce HVAC energy consumption by 45–80%, depending on the climate and the housing prototype;
- Adding insulation consistently reduces HVAC site energy consumption regardless of US climate and housing prototype. However, the point of diminishing returns and the optimal R-value depend closely on the climate.

In summary, the presented design for insulated panels can be a potential cost-effective solution for deep retrofit of US residential buildings, especially in cold climates. However, buildings are highly individualized and retrofit solutions need to be evaluated on a case-by-case basis. Thus, additional analyses are required to assess the suitability of the proposed insulated panels to different types of residential and commercial buildings. In addition, the energy performance and cost effectiveness of the proposed insulated panels summarized in this paper are based solely on modeling analysis. To complement the simulation-based analysis carried out in this study, a validation of the expected energy savings of the proposed design for insulated retrofit panels is proposed as future work using laboratory and field testing.

7. Patents

A patent has been submitted and is pending as a result of this study.

Author Contributions: Conceptualization, M.K.; methodology, K.B.; software, K.B.; validation, K.B.; formal analysis, K.B.; investigation, K.B.; resources, M.K.; data curation, K.B.; writing—original draft preparation, K.B.; writing—review and editing, M.K.; visualization, K.B.; supervision, M.K.; project administration, M.K.; funding acquisition, M.K. All authors have read and agreed to the published version of the manuscript.

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Nomenclature

ABC	Advanced Building Construction
ACH	Air Change per Hour
ASHRAE	American Society for Heating Refrigerating and Air Conditioning Engineers
DER	Deep Energy Retrofit
EIFS	Exterior insulation and finish system
EPS	Expanded Polystyrene
HSPF	Heating Seasonal Performance Factor
HVAC	Heating Ventilating and Air Conditioning
NREL	National Renewable Energy Laboratory
NYSERDA	New York State of Research and Development Authority
OC	Off-Center
OSB	Oriented Strand Board
PNNL	Pacific Northwest National Laboratory
RC	Reinforced Concrete
RIP	Retrofit Insulated Panel
RMI	Rocky Mountain Institute
SEER	Seasonal Energy Efficiency Ratio
SF	Single Family
SHGC	Solar Heat Gain Coefficient
SIP	Structural Insulated Panel
SIPA	Structural Insulated Panel Association
UEF	Uniform Energy Efficiency
US	United States

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