Embodied and Operational Energy Analysis of Passive House-Inspired High-Performance Residential Building Envelopes

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Abstract

High-performance building envelopes are designed to achieve target reductions in operational energy (OE). However, these wall assemblies often require initial, up-front investments in material cost and manufacturing energy. To this end, this study assessed the total lifecycle energy (LCE) and lifecycle cost (LCC) of five Passive House-inspired building envelopes in the United States (US) *via* lifecycle assessment (LCA) and lifecycle cost analysis (LCCA), respectively across four US climate zones. The results indicate that, regardless of climate, wood-framed wall systems were most cost-effective and exhibited lower LCE and LCC compared to the other wall assemblies investigated herein. Double-stud walls in particular were found most environmentally and economically cost-effective in all climates. In addition, the results specifically highlight the law of diminishing returns in terms of OE reduction through more insulative envelopes, as the impacts of embodied energy (EE) outweighed the benefits of a reduced OE in some cases. Finally, depending on climate and building archetype, total EE of the residential buildings accounted for 22%-91% of total LCE over a 60-year period—a result that highlights a grand opportunity to reduce EE and, thus, total LCE of high-performance residential construction in the US.

Keywords: Passive House; Embodied energy; Operational energy; Energy efficiency; Building envelope; Lifecycle assessment.

Introduction

Approximately 39% of all energy in the United States (US) is consumed by buildings (D&R International, Ltd 2012). In 2018, residential buildings alone are responsible for 28% of total US primary energy demand (US Energy Information Agency 2018). Past research has shown that building envelopes impact the total lifecycle energy (LCE) performance of residential buildings more than any other component (Takano et al. 2015). These findings have since prompted recent technological advances in low-energy residential construction, including high-performance appliances, water systems, and heating, ventilating, and air-conditioning (HVAC) systems, as well as airtight, highly insulative building envelope materials and assemblies. El-Darwish and Gomaa (2017), for instance, demonstrated that, by simply replacing a poorly insulated building envelope in Egypt (CZ2) with a tighter, more highly insulative envelope, building operational energy (OE) consumption could be reduced up to 33%.

Passive House criteria, which champion energy-efficient solutions that result in reduced OE consumption (Passive House Institute 2014), are widely recognized as the gold standard in residential construction. Recent work by Lewandowska et al. (2013) confirmed that OE consumption of the average Passive House is approximately 72% lower than a standard home. The Passive House concept was originally conceived by Adamson and Feist (Feist 1988) and resulted in the founding of the PassivHaus Institute in Durmstadt, Germany. The European metrics serve as a one-size-fits-all design target for all climates, requiring a combination of superior envelope insulation, airtight construction, efficient mechanical equipment, and heat recovery ventilation technologies (Feist et al. 2007).

Alternative Passive House criteria were released in 2015 by Passive House Institute US (PHIUS+) for use in North America after Straube (2009) reported that in climate zones 5-7 in the US, as defined by ASHRAE, the current European standard and its metrics were generally not economically justifiable and often led to poor design decisions. Therefore, new criteria were developed to modify the international requirements based on local climate factors and energy prices (Wright and Klingenberg 2015). Basic characteristics of PHIUS+ Certification are listed in **Table 1**.

Additional requirements that apply to both European and North American Passive House standards include the following measures (at a minimum) in cold and temperate climates:

- **Insulation:** Opaque building envelope components should have a heat transfer coefficient (U-value) no higher than 0.15 $W/m^2/K$ (0.09 $Btu/h/ft^2/F$).

- **Windows:** Window frames must be well insulated, with low-e glazing filled with argon or krypton to reduce heat transfer. This measure generally requires a U-value of 0.80 $W/m^2/K$ (0.14 $Btu/h/ft^2/F$) or less, with solar heat gain coefficients (SGHC) around 50%.
- **Ventilation:** Efficient heat recovery ventilation (HRV) is essential to enable good indoor air quality without wasted energy. At least 75% of the heat from exhaust air must be transferred to the fresh air again by means of a heat exchanger.
- **Thermal bridges:** All edges, corners, connections, and penetrations must be planned and executed carefully so that thermal bridging is minimized.

Embodied vs. Operational Energy

Previous studies (Chau et al. 2015; Ramesh et al. 2010; Thormark 2002; Winther and Hestnes 1999) consider only OE when evaluating a buildings total LCE. OE is defined as the amount of energy used by a building to meet the demands for heating, cooling, hot water, ventilation, lighting, and appliances. While Passive House designs aim to reduce OE and thus LCE, other studies illustrate that OE represents only 40-60% of the total LCE consumption in residential buildings when all life cycle stages of a building are considered from cradle to grave (Gustavsson and Joelsson 2010; Verbeeck and Hens 2010). The remaining energy is attributable to embodied energy (EE), which represents the total energy consumed during manufacture, transportation, construction, maintenance, and disposal of building materials and assemblies. The sum of EE and OE is considered herein to be the total lifecycle energy (LCE).

Passive House Paradox

In low-energy residential buildings, achieving reductions in OE often necessitates increases in initial manufacturing energy, negating some savings in total LCE consumption realized through high-performance design. This tradeoff is a result of an increase in both quantity and energy-intensity of materials used in high-performance envelope assemblies (Sartori and Hestnes 2007). Despite achieving marked improvements in OE consumption, Passive House standards currently address only the use-phase of building energy efficiency and negate the increased up-front energy demand at the manufacture and construction stage. In fact, recent research has elucidated that Passive Houses do not always provide net-energy savings and, depending on expected lifetime, can exhibit total LCE consumption (OE + EE) similar to a standard building built to the "Belgian Energy Performance of Buildings Directive" (Crawford and Stephan 2013; Stephan et al. 2013). Crawford and Stephan (2013) assessed two homes in Belgium and found that a Passive House consumed 3.8% more energy over an 80-year period than a new standard home of the same geometry. The study concluded that the additional materials required in a Passive House increased the EE, resulting in higher net total energy consumption than supposedly less energy-efficient buildings. A similar study by Stephan et al. (2013) found that the EE of Passive Houses contributes up to 77% of total LCE over a period of 100 years. Together, both of these studies emphasize an important and timely need to include EE in building energy-efficiency certifications, as this can otherwise paradoxically result in a net increase of total LCE.

From a LCE perspective, the Passive House paradox illustrates an important now-or-later energy tradeoff in high-performance residential building design and construction. It follows that understanding the energy contributions of EE and OE to total LCE in high-performance residential buildings is vital to achieve surefire, cost-effective reductions in total LCE over the lifespan of a building.

Scope of Work

In recognition of the Passive House paradox, the purpose of this study is to quantify the lifecycle environmental and economic performance of five US Passive House-inspired wall assemblies and compare them to a typical low-energy residential building standard. First, a comparative cradle-to-grave lifecycle assessment (LCA) was conducted to quantify and examine the relationships between EE and OE for all of the considered wall assemblies. Next, OE consumption of each home was measured in four US climate zones using whole building energy simulation over the course of a 60-year period. Finally, a lifecycle cost analysis (LCCA) was conducted for each wall assembly. Since the building envelope is a key feature of energy efficient design, a primary outcome of this study was to elucidate best practices and informed approaches for cost-efficient, low LCE residential buildings in the US.

Methodology: LCA and LCCA

The following sections provide details on the goal and scope, inventory analysis, and impact assessment of the LCA, as well as specific aspects, models, and assumptions of the LCCA.

LCA Goal and scope

LCA Goal

The goal of this LCA is to quantify and compare the environmental cost of six (6) residential wall assemblies – five that are Passive House-inspired and one typical of low-energy residential homes. The results from this LCA report total cradle-to-gate fossil fuel consumption in terms of embodied fossil fuel consumption (i.e., EE) (MJ) and operational fossil fuel consumption (i.e., OE) (MJ). Five of the six wall types examined in this study were based on those used in Passive House construction and represent a variety of residential framing methods, insulation materials, and the associated costs. The findings of this assessment can be used by architects, engineers, and green building professionals to inform design decisions pertaining to high-performance residential wall assemblies.

LCA Scope

The functional unit used in this analysis is a 6.10 m x 6.10 m x 12.20 m (20 ft x 20 ft x 40 ft) single-family residential building consisting of two stories and three bedrooms. While actual Passive Houses often have complex geometries, this simplified building archetype was chosen to be representative of a passive residential building.. The building envelope consists of an insulated attic (RSI 6.69, R-38), insulated slab-on-grade floor (RSI 7.04, R-40), and a service life of 60 years. Despite that in cold climates, actual Passive Houses are designed with large areas of glazing on the south façade to maximize solar heat gains, the functional unit in this analysis assumes equal 15% window-to-wall ratio (WWR) ratio at each orientation. This assumption ensures consistency in the energy modeling and enables easier comparisons across locations and climates. With these assumptions, the whole building modeled in each case study is identical with the exception of the exterior wall assemblies. Environmental performance of the homes are evaluated in four locations representing the range of US climate zones from hot and humid to very cold. Representative cities were chosen for each climate zone considered herein: Los Angeles, CA (CZ3B), Orlando, FL (CZ2A), New York City, NY (CZ5A), and Minneapolis, MN (CZ6A) (ASHRAE 169-2006). Minneapolis and Orlando were chosen to represent extremes in the range of climate zones found in more highly populated areas of the US. New York City and Los Angeles, though milder in climate, represent the most highly populated cities on either coast, presenting an opportunity to provide relevant and useful data to a large number of residential building designers. Climate zones 1 and 7 were left out of the analysis since they are sparsely populated areas within the contiguous US.

This study is a cradle-to-grave LCA carried out according to the ISO 14040/14044 (Finkbeiner et al. 2006) framework and includes lifecycle stages A, B6, and C, as specified by EN 15978:2011 (CEN 2011), as shown in **Figure 1**. OE is defined to only be the energy consumed during Stage B6, while all EE is defined as stages A1-A3, A4-A5, and C1-C4 as depicted in **Figure 1**. Lifecycle stages B1-B5, which relate to recurring EE, were excluded from the system boundary, since these impacts are difficult to quantify and are assumed to be identical across all building archetypes. While the inclusion of these stages would result in more robust results, these lifecycle stages do not directly support the goal of the study and thus are excluded from the scope and the system boundary.

Greenhouse gas (GHG) emissions associated with material manufacture and building energy use are a primary contributor to climate change and an important environmental impact metric for residential and commercial buildings. However, GHG emissions were not considered as an environmental impact metric in this study due to Passive House certification's emphasis on LCE.

Wall assembly archetypes and inventory analysis

Figure 2 illustrates wall section details of six wall assemblies investigated herein. Sections through the whole-building functional unit, including sections showing roof and foundation details, are included in **Figure 1S**, **Figure 2S**, and **Figure 3S** in the **Supplementary Information**, along with a detailed floor plan and written description of each Passive House. The characteristics of each assembly are summarized in **Table 2**. The Passive Houses selected to inspire the wall assemblies in this study are the (1) Maple Leaf House (Seattle, WA), (2) Abbate House (Austin, TX), (3) Isabella Ecohome (Isabella, MN), (4) Eco-panel Construction, and (5) the Passive House in the Woods (PHITW) (Hudson, WI). The model for the archetypical high-performance, low-energy home is based on the design of the Flatirons Habitat for Humanity (H4H) home construction based in Boulder, Colorado US, which follows 2015 International Energy Conservation Code (IECC) guidelines and achieves a US Green Building Council (USGBC) Leadership in Energy and Environmental Design (LEED) v4 Platinum certification. While new residential construction codes vary by region across the US, more than 70% of states as of 2017 follow earlier versions of IECC that are less stringent than the latest 2015 update. A home built to 2015 IECC standards that also achieves LEED Platinum certification is assumed representative of typical high-efficiency residential construction.

To maximize comparability while isolating the contribution of the external wall assembly, identical quantities of the following building materials and components were included in all models:

a. Vinyl siding for exterior cladding;
b. Interior finishes:
    1) 12.7 mm (½ inch) Gypsum wall board;
    2) Alkyd solvent-based paint;
c. Ceiling, roof, and floor components:
    1) Wood truss floors and ceilings;
    2) RSI 6.69 (R-38) attic insulation (cellulose);
    3) Asphalt shingles; and

d. 20.3 cm (8 inch) slab-on-grade foundation with Expanded Polystyrene (EPS) insulation.

Limitations of the lifecycle inventory (LCI) database of the LCA modeling software discussed in the following section necessitated assumptions regarding some wall characteristics. For example, proprietary construction products such as Tyvek housewrap are represented as 3mm polyethylene vapor barriers in the software. Since product-specific LCI data was not used in this study, the closest counterpart available in the inventory was used based upon the authors' engineering judgment. For transparency, these modeling assumptions are explicitly noted in **Table 2**.

Effective R-Values determined for each archetypical wall assembly were based on the cumulative value of thermal resistance for each material within the assembly. A complete list of materials, thicknesses, and insulation values for each of the assemblies are provided in **Table 3, Table 4, Table 5, Table 6, Table 7, and Table 8**. Overall effective R-value for each wall assembly was determined *via* summation of the individual R-values of each layer of the wall:

$$R = \frac{1}{\left(\frac{1}{\sum_{j=1}^{N_L} R_{j,f}} * a_{j,f}\right) + \left(\frac{1}{\sum_{j=1}^{N_L} R_{j,c}} * a_{j,c}\right)} \quad (1)$$

where N_L is the number of layers including the convection boundary layers that are part of the wall construction, and R_j is the R-value of each homogenous layer, j, of the wall construction, which includes the R-value due to convection of air at both the inner and outer surfaces of the wall. a_j is the path area ratio at framing, f, and between framing (i.e., cavities, c) to account for difference in heat transfer through studs and through insulation cavities. The effective R-value accounts for differences in framing types, convective air currents, and additional wall components (ASHRAE 2017). Single-stud walls are generally less efficient than double-stud walls due to the transfer of heat through the studs between interior and exterior spaces. Double-stud systems, by contrast, allow for insulated space between the studs, which eliminates thermal bridging and results in a higher effective R-value.

Lifecycle Assessment (LCA)

The LCA software tool Athena Impact Estimator for Buildings (IE4B v5.2) (*Athena Impact Estimator for Buildings* n.d.) was used to conduct this LCA. As previously discussed, substitutions were made where specific product types were not available (see **Table 2**). In its calculations, IE4B follows a process-based method and uses a proprietary primary database developed by Athena Sustainable Materials Institute, as well as the US LCI database developed by the National Renewable Energy Laboratory (NREL) (Athena Sustainable Materials Institute 2014; Trusty and Meil 2002a; b). This database uses only North American data and is compliant with ISO 14040/14044 unit processes related to basic materials, building products and components, fuel use, and transportation. All data are reportedly less than 10 years old.

Each wall assembly modeled in IE4B also included the impact of fasteners (e.g., nails, screws, staples), paints, adhesives, sealants, and other necessary construction details that are not included in cost estimations. The software also applies the local electricity grids, modes of transportation, distances, and manufacturing technologies relevant to each building location. The transportation impacts of each wall component are typical weighted averages of the distances from the material source location and takes into account the different modes of transportation used (diesel road/rail, residual fuel oil barge/ship). The software reports data for a variety of environmental impact measures consistent with the latest US Environmental Protection Agency (EPA) TRACI methodology.

Operational Energy (OE) Analysis

The whole-building energy simulation program BEopt v2.7.0.0 (with EnergyPlus v8.6) was used to estimate OE consumption for lifecycle stage B6 (see **Figure 1**). BEopt is a residential building-based graphical user interface for EnergyPlus developed by the NREL (Christensen et al. 2006). The program quantifies energy use as a function of building envelope and HVAC equipment using fundamental heat balance principles. The OE measurement includes only space heating and cooling. Baseloads from the water heater, lighting, ventilation and other plug loads were assumed constant for each location and were omitted to provide greater comparison detail for each case study home. 30-year average weather data for the four different US cities were used for all simulations (NREL n.d.).

OE due to heating and cooling loads were converted from site energy to source energy using a conversion factor of 3.4 (Deru and Torcellini 2007). The conversion factor for natural gas was assumed to be 1.0. The LCA excludes the impacts associated with manufacturing, transport, maintenance and disposal of the central heating boiler and air conditioner. Annual OE of the building was assumed to be identical for each year of its service life.

An adiabatic floor was modeled to accentuate the impact of the wall assembly on OE usage. Thus, the foundation was modeled as slab-on-grade with the highest available insulation of RSI 7.04 (R-40) EPS placed horizontally below the slab. The interior floor was modeled as a wood surface. 12.7mm (½ inch) drywall was included in the exterior and interior partition walls and ceiling. The attic was insulated with RSI 6.69 (R-38) cellulose (Grade 1, vented). The roof consisted of medium asphalt shingles. Each wall (with a window-to-wall ratio of 0.15) has low-e, low-gain, triple-paned, air-filled glazing with a shading fraction of 0.50 in the summer and 0.95 in the winter. Infiltration rates were set at 0.05 CFM50 per square foot of envelope area to meet the PHIUS+ standard.

All cases for each climate zone use the same mechanical system. The heating source was a natural gas furnace with a 98% annual fuel utilization efficiency (AFUE). The air conditioner was a variable speed split-system with a Seasonal Energy Efficiency Ratio (SEER) of 24.5, the highest available efficiency. Mechanical ventilation uses an ERV with an efficiency of 72%. Natural ventilation was used every day during cooling months. The duct system experienced 7.5% leakage and was insulated up to RSI 1.41 (R-8). The thermostat setpoints were 25.6°C (78°F) when occupied with a setback of 29.4°C (85°F) when unoccupied for cooling, and 21.1°C (70°F) when occupied and 16.7°C (62°F) when unoccupied for heating, based on recommendations by ENERGY STAR®. The schedule assumed occupancy from 5pm-9am for weekdays and weekends, and no occupancy from 9am-5pm on weekdays only. Lighting was provided by 100% LEDs. All other miscellaneous plug loads, appliances, and fixtures were excluded (default setting).

LCCA

The LCCA conducted in this study included the initial cost of materials, as well as the costs related to OE consumption for an assumed 60-year lifespan. Additional details and assumptions regarding the LCCA are discussed in the following sections.

Initial material cost

Using material takeoff quantities exported from IE4B, GoldenSeal Estimating Software ("Goldenseal Estimating Software" n.d.) was used to quantify the initial material costs of each exterior wall assembly. While the results presented here include only the aggregated total initial cost, a list of materials from the material takeoffs, unit cost, material quantity, and total aggregated cost of each constituent in the wall system is included in **Table S1** of the **Supplementary Information**. For this analysis, an additional base cost of $86,550 was added to each wall assembly to account for the remaining materials and components that comprised the whole building. These additional costs included materials for 12.7mm (½ inch) drywall on every interior surface including the ceiling, alkyd solvent-based paint, framing for interior partition walls (73.15 meters total length), a 20.3cm (8 inch) thick foundation slab, 2x10 floor and ceiling joists, 12.7mm (½ inch) oriented strand board (OSB) sheathing for the floor and roof, asphalt shingles, 25.4 cm (10 inch) cellulose insulation in the attic, and 25.4 cm (10 inch) EPS insulation below the slab.

Total LCC

The total LCC of each house was calculated as the sum of initial cost (materials) and energy cost (OE over a period of 60 years). The analysis considers a number of economic parameters, including interest, inflation, and tax rates. The following equation proposed by Krarti (2011) was used to calculate total LCC:

$$LCC = IC + USPW(d, N) \times AC \qquad \text{Eq. 1}$$

where *IC* is the initial material cost, *AC* is the annual energy cost (quantified through OE simulation), and *USPW(d,N)* is the uniform-series present worth factor based on a discount rate. The energy cost was calculated based on average 2016 US prices of residential gas usage ($118.14/MJ, $1.12/therm) and electricity ($0.109/kWh) (US Department of Energy n.d.). In this study, an effective discount rate (*d*) of 5% and 60 years of service (*N*) was assumed. The *USPW(d,N)* allows determination of the ratio of initial investment (*P*) to cost savings (*A*) based on service life and the discount rate, and is expressed as follows:

$$USPW(d, N) = \frac{P}{A} = \frac{(1+d)^N - 1}{d(1+d)^N} \qquad \text{Eq. 2}$$

This LCCA method is the most commonly accepted method to assess the economic benefits of energy conservation projects over their lifetime (Krarti 2011).

Given the primary focus on LCA for this study, construction (i.e., labor) cost and its effect on the LCCA are excluded. The omission of construction costs is potentially significant; for some materials, high initial costs are offset by a reduction in construction costs and vice versa. For example, structural insulated panel (SIP) walls are more costly than wood-framed walls, but estimated labor costs can be reduced by up to 55% compared to standard wood construction (Drain et al. 2006). Therefore, a more comprehensive LCCA including construction costs may yield different conclusions in results of overall cost-effectiveness.

Results and Discussion

EE of Passive House wall systems

Average EE and effective R-values of the five Passive House and the typical low-energy home envelope assemblies (wall systems only) are shown in **Figure 3**. As anticipated, the effective R-values for all Passive House assemblies are higher than the standard low-energy baseline. While wall systems with higher effective R-values generally result in higher initial EE, some wall assemblies exhibit similar EE to the low-energy baseline, yet achieve a higher effective R-value. As expected, the average EE of the highest effective R-value assembly (Case 5) is higher compared to the other wall systems. However, Case 2, Case 3, and Case 4 assemblies exhibit improved effective R-values but similar EE to the low-energy home (Case 1), whereas the Eco-Panel construction (Case 4) achieved only marginal improvements over the baseline home.

The data in **Figure 3** also illustrate that, generally, with the exception of Case 1, wood-framed walls exhibit lower EE compared to the SIP (Case 4) or insulated concrete forms (ICF) (Case 5) wall systems. Of the wood-framed walls, the double-stud wall systems in Case 2 and Case 3 in particular have lower EE. Case 2 and Case 3 differ only in insulation type and are otherwise identical, indicating that the marginally lower EE for Case 3 is due to the lower environmental impact of blown-in cellulose, which is a recycled paper material, compared to fiberglass, which has higher energy density.

Case 5 embodies more than three times the energy of the next highest case (Case 1). The main component of the Case 5 wall assembly consists of ICFs. The high EE associated with the production of concrete is likely responsible for the disproportionately large impact of the ICF wall. The high EE of cement-based materials is attributable to the combustion of fuels required to heat raw materials during cement manufacture for the calcination and clinkering reactions to occur (Venkatarama Reddy and Jagadish 2003). The additional layer of exterior insulation finishing systems (EIFS), which includes 22.86 cm (9 inch) EPS, also contributes to higher of EE of the Case 5 wall system.

Contributory analysis

The percent contribution of EE of each major building component to the total whole building EE for each case study building in Minneapolis, MN is shown in **Figure 4.** On average, the exterior wall contributes approximately 33% to the total EE of the low-energy and Passive House residential buildings. This result aligns well with the previous study (Stephan et al. 2013) which found that, due to the high quantity of materials required for insulation and triple-glazed windows, the building envelope is a significant contributor to the EE of Passive Houses, accounting for up to 34.4% of the total EE. Excluding windows and doors, the external wall assembly of Case 3 contributes 26% of the total EE, while the external wall assembly in Case 5 contributes 56%. If glazing at a 15% window-to-wall ratio (WWR) with triple-paned windows and two solid wood doors are included, the exterior wall assemblies are responsible for, on average, 46% of the total EE.

High contributions to total EE from the roof and foundation are attributable to the use of asphalt roofing shingles and the quantity of concrete used in the 8” slab-on-grade, both of which embody high quantities of energy due to the energy intensity of their manufacture. Asphalt shingles is among the cheapest roofing materials available in the US and, consequently, one the most commonly used roofing systems in US residential homes (National Association of

Home Builders 1998). However, in addition to moderate durability and poor recyclability, the environmental impacts of asphalt shingles are high compared to other building materials. Contrastingly, the utilization of wood trusses and framing results in low contribution of the wood floor and roof systems to total whole building EE.

OE performance of Passive Houses

The total 60-year OE consumption of the considered building archetype across four US climates is shown in **Figure 5**. It is clear that in mild or cooling-dominated climates, like Los Angeles or Orlando an effective thermal wall value above RSI 4.05 (R-23) has little impact on reducing lifetime OE. In Los Angeles, for example, the difference in OE was negligible and varied only by 3% across all wall systems, which range from an effective RSI 4.05 (R-23) for the Case 0 home to an effective RSI 12.68 (R-72) for Case 5. Similarly, in Orlando, while the energy load increases by over 5 times due to cooling, the net energy savings between the highest and lowest OE amounted to only $142 over a 60-year period.

In colder climates, however, differences in OE between case study buildings are evident (**Figure 5**). As anticipated, OE consumption decreases with an increase in R-value in heating-dominated climates, and, the colder the climate, the more effective increased R-values achieve reductions in OE. In New York City, a climate zone with high heating loads, the energy consumption from Case 0 to Case 5 is reduced by 325,995 MJ. Minneapolis, the coldest climate assessed in this study, offers the greatest potential of savings in OE, with a difference of 493,740 MJ between the highest and lowest OE options (Case 0 and Case 5, respectively). Previous studies (Bojic et al. 2002; Kim and Moon 2009) have also found that benefits of wall insulation in hot climates are far less effective than in cold climates. Bojic et al. (2002) found that an increase in thermal insulation in the building envelope, while reducing heat transfer into the walls from the outdoors, is counteracted by the reduction in the rate at which the internally gained heat dissipates to the outdoors. Furthermore, the difference in indoor and outdoor temperature is also greater in cold climates than in hot climates, so wall insulation has a greater effect on indoor temperature control in climates such as Minneapolis and New York City rather than Orlando or Los Angeles (Kim and Moon 2009). Therefore, while a minimal level of insulation is beneficial, any additional insulation does not contribute to cooling energy savings and can, in some instances, even increase the cooling load.

For Case 5, reduced OE costs in heating-dominated climates are directly attributable to the high thermal value of ICF walls, while lighter-weight materials, such as a typical timber frame of the same R-value, perform less efficiently. Diminishing savings, however, are observable in **Figure 5** for the highly insulative wall systems in temperate and mild climates. This result suggests that, beyond an R-value of a typical low-energy home (RSI 4.05, R-23), further investments in increasing insulation may not always save energy, depending on the climate.

A more detailed breakdown summary of EE and OE impacts for each case study residential building per lifecycle stage and climate region is included in **Table S2** of the **Supplementary Information**.

Contribution of EE to total LCE

Figure 6 shows the total LCE for each case study residential building in four different US cities and climate zones, while **Figure 7** shows the percentage contribution of EE from the exterior wall assembly, the non-exterior wall components, and OE to total LCE of the residential buildings analyzed herein over a 60-year design life. As shown in **Figure 6**, total LCE is at a minimum in mild climates and a maximum in heating-dominated climates, as expected, with the lowest LCE in Los Angeles and the highest in Minneapolis, regardless of building archetype. As anticipated, LCE was highest in Minneapolis for Case 0. Case 3 achieved the lowest LCE in all climates, except Minneapolis, where it was outperformed by Case 1 from a total LCE perspective.

Together, the data presented in **Figure 6** and **Figure 7** indicate (1) the importance of climate-appropriate design and (2) how over-design can be revealed when total LCE is considered. In Los Angeles, for example, the differences in total LCE are marginal between all cases, except Case 5 (**Figure 6**). Predictably, given that the ICF wall system is not intended for a mild climate, Case 5 is overdesigned for the geographic location and results in a LCE approximately 40% higher than Case 0. In comparison, the total LCE of Case 5 is lower than either Case 0 or Case 4 in Minneapolis, suggesting that, in the coldest climates, the high EE of ICF walls can result in a lower LCE compared to standard low energy construction (Case 0). However, in both New York City and Minneapolis, the wood-frame assemblies (Case 1, Case 2, and Case 3) exhibit the lowest LCE of all residential buildings, indicating that wood-frame construction is sufficient to achieve maximum reductions in total LCE in comparison to more sophisticated envelope systems like SIPs or ICFs in those climates.

The data illustrate a greater impact of location on the EE-to-LCE ratio than type of wall assembly. Data in **Figure 7** show that the EE of the non-ICF exterior wall systems alone account for a maximum of 16% of total LCE in mild- or cooling-dominated climates and up to 9% in heating-dominated climates. The total EE of double-stud wall homes, which contribute 86% to total LCE in Los Angeles, contributed as low as 24% of total LCE in Minneapolis (**Figure 7d**). ICF walls account for a maximum of 45% and minimum of 17% of total LCE, which corresponded to mild and heating-dominated climates, respectively. This result implies that, in mild or cooling-dominated climates, there is high potential for total energy reductions if buildings are designed with careful consideration of the EE associated with building components. In colder climates, however, the ratio of OE increases, and the use-phase becomes more dominant (**Figure 6**). Nevertheless, with an average EE to LCE ratio 27% in one of the coldest climate zones, total EE remains a significant fraction of total LCE and represents an opportunity to reduce total LCE by implementing best-practice design strategies to achieve sufficient, yet not overdesigned, high-performance building envelopes.

LCCA of Passive House Assemblies and Buildings

Figure 8 shows results from the LCCA of each of the case study buildings by (a) exterior wall assembly and (b) whole building calculated using Equation 1. The data show that, regardless of climate, double-stud wall systems, such as those used in the Case 2 and Case 3 wall assemblies, exhibit the lowest total cost over the anticipated operating lifespan of the building. For the double-stud wall systems, both initial costs and OE costs were low (**Figure 8a**), primarily due to the price of cellulose insulation and the high effective R-value achieved by those systems. The initial cost of Case 2 is marginally lower than Case 3, again due to the relative price between cellulose and fiberglass insulation. Double-stud walls notwithstanding, Case 0 and Case 1 represent climate sensitivities in regard to tradeoffs in total LCC. For example, in mild and cooling-dominated climates, total LCC of Case 0 is lower than Case 1, while the inverse is true for the heating-dominated climates of New York City and Minneapolis. These data illustrate that the investment in additional insulation is worthwhile only in colder climates, where the higher initial cost is offset by lower OE costs over the building's service life. If these in-service OE savings are not realized, then the initial cost penalty is not overcome.

The results further illustrate that the non-wood-frame assemblies, such as SIPs and ICFs, are not as cost-effective in any climate as compared to the wood-based assemblies. This result does not imply that SIP and ICF walls would not ever be preferred to wood-frame walls, but rather suggests that, above a thermal value of RSI 4.05 (R-23), these wall systems become less cost-effective, especially in mild and cooling-dominated climates. While high thermal mass of ICFs contributes to reductions in OE in heating-dominated climates, the data indicate that this energy reduction may not be enough to offset the high EE associated with its production. A previous study (Marceau and VanGeem 2006) showed that, at lower thermal values, ICF walls can exhibit lower LCE than wood-framed walls. The authors analyzed R-values in that study were RSI 2.11 (R-12) for the wood frame system and RSI 3.17 (R-18) for the ICF system. For all climates, ICF walls showed a higher EE, but the OE was reduced such that the total LCE was lower than the wood-framed walls in each case.

The results of this study, by comparison, show that there is a limit to the efficiency of ICF walls and that, given a specific climate, when the exterior wall assembly reaches a certain insulation value, ICF walls may not be the lowest LCE option. However, the results presented herein are not part of a full scope economic analysis, and the implications for neglecting construction and labor costs may prove significant. The initial costs considered only material prices and excluded any construction labor. An inclusion of the full construction process may reveal that high material costs, for example in the case of the SIP system, could be offset by reduced construction costs.

Finally, in analyzing the LCE data with the results from the LCC, investments in high thermal insulation may not always pay off in regard to cost and energy savings over the lifetime of the building. For example, while Case 2 and Case 3 exhibited the lowest LCE for any wall system in any climate, the total LCE consumption was higher for these two cases in the coldest climate in comparison to Case 1, as previously discussed. However, the LCC of Case 1 was ~1-2% higher than either than Case 1 or Case 2 in the coldest climate, illustrating the tradeoff that exists for this system in terms of cost and energy savings. While this particular tradeoff is marginal, it suggests that utilizing only a LCE or a LCC analysis in decision-making might, in fact, lead to misinformation on total cost and energy savings for high-performance residential building envelopes.

Limitations of Study

There are several limitations in this study that building designers and decision-makers should take into consideration. Some important metrics were considered outside the scope boundary, which may affect the findings, recommendations, and results presented herein:

1) Labor costs during construction were omitted. Labor costs are presumed to vary with each wall assembly and would likely impact initial construction costs. For example, double-stud walls exhibit the lowest LCC in this study but require additional labor to erect compared to single-stud walls, which increases construction time and total cost. In contrast, the SIP wall, which exhibited the highest material cost, has relatively low labor costs due to the simplicity of its modular design and subsequent decrease in construction time. If the labor costs are known or able to be estimated for each system, these costs could be incorporated into the results *via* simple addition to total LCC.

2) A durability assessment was also beyond the scope of this study. Conducting a hygrothermal analysis, for example, would provide another useful metric for measuring long-term efficacy and cost efficiency of these wall systems. For instance, double-stud walls are prone to condensation within the wall system, due to the typical lack of exterior insulation outside of the sheathing. This lack of insulation promotes a drop in wall temperatures below the dew point, triggering condensation.
3) Additional materials to achieve identical infiltration rates for all wall systems were neglected. ICF and SIP wall systems have naturally low infiltration rates, while wood-framed walls, in order to achieve similar rates, require extra materials to seal edges and openings. The extra sealants, adhesives, and foam materials required would in increased initial costs and higher EE that are not reflected in this study. If known, these data could also be incorporated into the results presented herein.
4) Only the exterior walls of each Passive House were modeled in detail in this study. Thus, the impacts and actual costs associated with the case studies do not necessarily reflect the true impacts and costs of individual high-performance and Passive House constructions. The Isabella Ecohome Passive House, for example, reported a final building cost of $3659/m^2$ as a result of additional high-performance materials ("Isabella Lake House" 2012). This cost is 2-3 times the national average of $1338/m^2$ for new residential construction in the U.S (Zillow n.d.).

Significance and Recommendations

The results of this study suggest that US Passive Houses, even those designed and built for specific climates, may be overdesigned. The typical low-energy wall assembly with a RSI 4.05 (R-23) thermal rating (Case 0) resulted in low OE consumption, depending on the climate, such that changes in wall systems or increases in R-value were not always economical or environmentally beneficial. More specifically, the results from this work highlight the low impact and energy efficiency of wood-framed walls in comparison to SIP and ICF systems at a thermal value of RSI 4.05 (R-23) or higher. Since achieving high R-values is possible with any framing type, a wood-framed wall is recommended over other wall systems from a total LCE and LCC standpoint. Double-stud wall constructions in particular are suitable for any climate in the US and are among the most cost-effective options available. Double-stud walls were found to have the lowest EE and total LCE, suggesting that they are a good choice for a high-performance wall system, especially in colder climates.

For insulation, cellulose is an affordable, effective, low-impact option, with a lower EE than fiberglass. Cellulose requires at least 15.24 cm– 17.78 cm (6-7 inches) to achieve RSI 4.05 (R-23) or higher and is therefore most effective in a double-stud wall system as it allows for greater thicknesses. However, in a conventional single-stud system, cellulose as the main cavity insulation can still achieve high thermal values when paired with additional exterior insulation, such as polyisocyanurate, as was the case in the low-energy baseline home investigated herein. While the high cost of ICF and SIP systems may be offset by benefits in constructability, given the results presented here, high environmental impacts associated with their production limit approbation as preferred wall assemblies in high-performance wall assemblies in US residential construction.

Conclusions

This study presents the results of a LCA and LCCA of a single-family home modeled with five different types of high-performance exterior wall assemblies inspired by US Passive House construction. The LCA was carried out in accordance with ISO 14040/14044 standards. Archetype homes were modeled in US four cities, representing a range of climates: Los Angeles, New York City, Orlando, and Minneapolis. The system boundary included an output of embodied energy (EE) from the manufacturing, processing, transportation, construction, operation, and disposal of building components. Operational energy (OE) was based on an expected service life of 60 years.

Results indicate that, for all climates considered herein, wood-framed walls demonstrated the lowest environmental and economic impact compared to other highly insulative wall systems. The double-stud walls in particular exhibited the lowest cost, lowest EE, and, due to a high potential for thermal insulation, low lifetime OE. In addition, double-stud walls were the most cost-effective option in any location. In contrast, SIPs and ICF walls exhibited high environmental and economic costs, and, therefore, were considered the least cost-efficient option. Utilization of cellulose as an insulation material achieved marked improvements in total EE compared to polyisocyanurate, fiberglass, or EPS insulation.

The findings of this study confirm the importance of including the energy-intensity of materials, as neglecting them could potentially lead to consequential increases in LCE due to over-engineered envelopes. The total EE of the residential buildings investigated herein accounted for 22%-91% of total LCE, depending on climate and building archetype. Some wall constructions, including the SIPs and ICFs were not suited well for mild or cooling-dominated climates, while others, including the double-stud wall systems, outperformed Passive House wall assemblies designed for heating-dominated climates from a LCC and total LCE perspective. The findings also suggest that the perceived necessity for highly insulative envelopes may result in higher LCC and total LCE than wall assemblies that achieve minimum insulation values, beyond which marginal, if not negative, cost and energy savings benefits are realized. Finally, the data presented herein support the conclusion that, while EE has traditionally been neglected in Passive House construction, it represents not only a non-trivial percentage of total LCE, but also a grand opportunity to reduce total LCE in the design and construction of high-performance residential buildings in the United States.

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Data Availability Statement

Some or all data, models, or code generated or used during the study are available from the corresponding author by request.

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Table 1. Performance requirements of the US Passive House according to PHIUS+ Certification (Wright and Klingenberg 2015).

Performance	**Requirement**
Space Heating Energy Demand	Energy demand limits are climate-specific, but result in a ~77% reduced peak heat load and ~86% reduced annual heating from the 2009 Building America benchmark.
Space Cooling Energy Demand	~69% reduced peak cooling, ~46% reduced annual cooling.
Primary Energy Demand	Total primary (source) energy (heating, cooling, hot water, lighting, appliances, etc.) must not exceed 6200 kWh per person per year, with a source energy factor for grid electricity at the US national average of 3.16.
Airtightness	Airtightness must be a maximum of 0.05 CFM50 per square foot of gross envelope area (or 0.08 CFM75).
Thermal Comfort	Thermal comfort must be met for all living areas during winter and summer, with not more than 10% of hours per year over (25°C) (77°F).

Table 2. Summary of Passive House-inspired wall assemblies and actual versus modeled characteristics.

Case	Passive House	Description	Wall Details			Original Location	Effective R-value
				Actual	Modeled		
0	Typical Low-Energy	2x6 / cellulose + EPS[1]	*Wood studs*	38x140mm @ 60.96 cm O.C.[2] (2x6 @ 24" O.C.)	38x140mm @ 60.96 cm O.C. 2x6 @ 24" O.C.	Boulder, CO	23
			Insulation	13.97 cm (5.5") blown-in cellulose	13.97 cm (5.5") blown-in cellulose		
			Sheathing	1.27 cm (1/2") OSB[3]	1.27 cm (1/2") OSB		
			WRB	Tyvek housewrap	3mm polyethylene vapor barrier		
			Siding	Vinyl	Vinyl		
1	Maple Leaf	2x8 / fiberglass + polyiso	*Wood studs*	38x184mm @ 60.96 cm O.C. (2x8 @24" O.C.)	38x184mm @ 60.96 cm O.C. (2x8 @24" O.C.)	Seattle, WA	51
			Insulation	18.42 cm (7.25") dense-packed fiberglass	18.42 (7.25") fiberglass batt		
				10.16 cm (4") paper-faced polyisocyanurate	10.16 cm (4") polyisocyanurate		
			Sheathing + WRB	1.27 cm (1/2") ZIP system sheathing	1.27 cm (1/2") OSB		
					3mm polyethylene vapor barrier		
			Siding	Vinyl	Vinyl		
2	Abbate	Double stud / fiberglass	*Wood studs*	38x89mm @ 60.96 cm O.C. (2x4 @24" O.C.) (staggered)	38x89mm @ 60.96 cm O.C. (2x4 @24" O.C.) (staggered)	Austin, TX	47
				38x89mm @ 40.64 cm O.C. (2x4 @16" O.C.)	38x89mm @ 40.64 cm O.C. (2x4 @16" O.C.)		
			Insulation	30.48 cm (12") fiberglass	30.48 (12") fiberglass batt		
			Sheathing	OSB	OSB		
			WRB	Unknown	3mm polyethylene vapor barrier		
			Siding	Unknown	Vinyl		
3	Isabella	Double stud / cellulose	*Wood studs*	38x89mm @ 60.96 cm O.C. 2x4 @24" O.C. (staggered)	38x89mm @ 60.96 cm O.C. 2x4 @24" O.C. (staggered)	Isabella, MN	47
				38x89mm @ 40.64 cm O.C. (2x4 @16" O.C.)	38x89mm @ 40.64 cm O.C. (2x4 @16" O.C.)		
			Insulation	30.48 cm (12") blown-in cellulose	30.48 cm (12") fiberglass batt		
			Sheathing	OSB	OSB		
			WRB	Unknown	3mm polyethylene vapor barrier		
			Siding	Unknown	Vinyl		
4	Eco-panels	SIP[4]	*SIP*	1.27 cm (1/2") OSB	SIP with 8.89 cm (3.5") EPS	N/A	28
				8.89 cm (3.5") EPS			
				1.27 cm (1/2") OSB			
			WRB	N/A	3mm polyethylene vapor barrier		
			Siding	N/A	Vinyl		
5	Passive House in the Woods	ICF[5] + EIFS[6]	*ICF 27.94 cm (11")*	6.35 cm (2.5") EPS	25.4 cm (10") ICF	Hudson, WI	72
				15.24 cm (6") concrete			
				6.35 cm (2.5") EPS			
			EIFS 27.94 cm (11")	Air barrier	Air barrier		
				Drainage cavity	9" EPS		

				EPS	Stucco over metal mesh		
				Textured finish			

1. Expanded polystyrene (EPS)
2. On center (O.C.)
3. Oriented strand board (OSB)
4. Structural insulated panel (SIP)
5. Insulated concrete form (ICF)
6. Exterior insulation finishing system (EIFS)

Table 3. Effective R-values for Case 0 of the archetypical wall assemblies calculated using thermal properties at and in between framing (ASHRAE 2017; "R-Value Table - Insulation Values for Selected Materials" 2016).

Wall component	**Thickness (cm)**	**RSI/ cm**	**R-value**	**R-value**
2x6 wood studs (24"OC)	13.97	0.07	-	0.99
Blown-in cellulose	13.97	0.26	3.68	-
OSB	1.27	0.09	0.11	0.11
EPS	2.54	0.27	0.69	0.69
Gypsum board	1.27	0.06	0.08	0.08
Vinyl siding	2.54	0.04	0.11	0.11
Exterior Conditions (15 mph)			0.03	0.03
Inside Convection			0.12	0.12
(Nominal) Total R-Value			**4.81**	2.12
Path area ratio			0.15	0.03
Total			4.09	0.32
Effective RSI-Value	*(m.K/W)*		4.05	

Table 4. Effective R-values for Case 1 of the archetypical wall assemblies calculated using thermal properties at and in between framing (ASHRAE 2017; "R-Value Table - Insulation Values for Selected Materials" 2016).

Wall component	**Thickness (cm)**	**RSI-value / cm**	**R-value between framing**	**R-value at framing**
2x8 wood studs (24"OC)	18.54	0.07	-	1.30
Fiberglass batt (high density)	18.54	0.26	4.85	-
OSB	1.27	0.09	0.11	0.11
Polyisocyanurate	10.16	0.43	4.37	4.37
Gypsum board	1.27	0.06	0.08	0.08
Vinyl siding	2.54	0.04	0.11	0.11
Exterior Conditions (15 mph)			0.03	0.03
Inside Convection			0.12	0.12
(Nominal) Total R-Value			**9.66**	6.11
Path area ratio			0.85	0.15
Total			8.21	0.92
Effective R-Value	*(m.K/W)*		**8.89**	

Table 5. Effective R-values for Case 2 of the archetypical wall assemblies calculated using thermal properties at and in between framing (ASHRAE 2017; "R-Value Table - Insulation Values for Selected Materials" 2016).

Wall component	**Thickness**	**RSI-value / cm**	**R-value**	**Interior frame**	**Exterior frame**
2x4 wood studs (16"OC)	8.89	0.07	-	-	0.63
2x4 wood studs (24"OC)	8.89	0.07	-	0.63	-
Fiberglass batt (high density)	30.48	0.26	8.03	5.69	5.69
OSB	1.27	0.09	0.11	0.11	0.11
Gypsum board	1.27	0.06	0.08	0.08	0.08
Vinyl siding	2.54	0.04	0.11	0.11	0.11
Exterior Conditions (15 mph)			0.03	0.03	0.03
Inside Convection			0.12	0.12	0.12
(Nominal) Total R-Value			**8.47**	6.76	6.76
Path area ratio			0.9	0.033	0.066
Total			7.63	0.22	0.45
Effective R-Value	*(m.K/W)*		**8.27**		

Table 6. Effective R-values for Case 3 of the archetypical wall assemblies calculated using thermal properties at and in between framing (ASHRAE 2017; "R-Value Table - Insulation Values for Selected Materials" 2016).

Wall component	**Thickness**	**R-value / cm**	**R-value between framing**	**Interior frame**	**Exterior frame**
2x4 wood studs (16"OC)	6.69	0.071	-	-	0.63
2x4 wood studs (24"OC)	6.69	0.071	-	0.63	-
Blown-in cellulose	30.48	0.263	8.03	5.69	5.69
OSB	1.27	0.087	0.11	0.11	0.11
Gypsum board	1.27	0.062	0.08	0.08	0.08
Vinyl siding	2.54	0.042	0.11	0.11	0.11
Exterior Conditions (15 mph)			0.03	0.03	0.03
Inside Convection			0.12	0.12	0.12
(Nominal) Total RSI-Value			**8.47**	6.76	6.76
Path area ratio			0.9	0.033	0.066
Total			7.63	0.22	0.45
Effective RSI-Value	*(m.K/W)*		**8.03**		

Table 7. Effective R-values for Case 4 of the archetypical wall assemblies calculated using thermal properties at and in between framing (ASHRAE 2017; "R-Value Table - Insulation Values for Selected Materials" 2016).

Wall component	**Thickness (cm)**	**R-value / in**	**R value (no additional framing)**
SIPs (4.5" polyurethane, OSB)	11.43	1.80	4.58
Gypsum board	1.27	0.06	0.08
Vinyl siding	2.54	0.04	0.11
Exterior Conditions (15 mph)			0.03
Inside Convection			0.12
(Nominal) Total R-Value			**4.91**
Path area ratio			1
Total			4.91
Effective R-Value	*(h*ft2*F / Btu)*		**4.91**

Table 8. Effective R-values for Case 5 of the archetypical wall assemblies calculated using thermal properties at and in between framing (ASHRAE 2017; "R-Value Table - Insulation Values for Selected Materials" 2016).

Wall component	**Thickness (cm)**	**RSI-value / cm**	**RSI value (no additional framing)**
ICF+ EIFS	55.88	4.85	12.32
Gypsum board	1.27	0.06	0.08
Vinyl siding	2.54	0.04	0.11
Exterior Conditions (15 mph)			0.03
Inside Convection			0.12
(Nominal) Total R-Value			**12.66**
Path area ratio			1
Total			12.66
Effective RSI-Value	*(m.K/W)*		**12.66**