An Iterative Parametric Modeling Analysis of Architectural Indicators and Associated Impacts on Energy Consumption in a Pennsylvania Single-Family Home

An Iterative Parametric Modeling Analysis of Architectural Indicators and Associated Impacts on Energy Consumption in a Pennsylvania Single-Family Home

Naim Jabbour

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Abstract

Residential buildings in the U.S. consume 21% of the total primary energy, mostly generated via conventional fossil fuels, a major contributor to environmental pollution and degradation (EIA, 2017). Hence, energy conservation measures (ECM) have become key factors in developing sustainable building and energy use policies. This thesis examined the impacts of various combinations of ECM on energy use in a Pennsylvania single-family home. A 6.9% reduction of the state's residential energy market load could be achieved by 2020 if robust optimal ECM were adopted in single-family homes (Statewide Evaluation Team, 2015). However, most research to date has focused almost exclusively on the impact of singular or cumulative building system upgrades on energy use, often neglecting to holistically investigate the impact of optimal targeted permutations of architectural indicators. To address this knowledge gap, this thesis comprehensively evaluated the correlation between various architectural indicators and energy performance in a single-family residential building. The main objective of this research was to develop and generate optimal architectural guidelines for the design of high performance detached single-family homes in Pennsylvania.

To address the research objective, the following questions were investigated: What is the impact of various iterations of architectural variables---architectural design and building system configurations---on energy consumption in single-family residential structures in Pennsylvania? What specific permutations would yield the most optimal

energy performance indicators? To assess this relationship, a consistent baseline was established for residential energy consumption and construction in Pennsylvania, an impact assessment of various design configurations and building system upgrades was then examined, and lastly, an impact assessment of the most optimal permutations encompassing combinations of building design and building system variables was evaluated. The Energy Use Intensity index (EUI) was employed as the primary energy performance indicator. The research utilized a system dynamics modeling approach to simulate the impacts of interactions among various variables. An iterative modeling analysis was employed to evaluate and determine the most optimal combinations of ECM. Two modeling stages were utilized, the first stage evaluated the impact of individual variables and the second stage assessed impacts of permutations of optimal variables. To that end, National Renewable Energy Laboratory's (NREL) building energy optimization software (BEopt) was employed as the primary building modeling and energy simulation engine. Industry references, building code databases, and Department of Energy (DOE) guidelines were sourced for all necessary data.

Simulation results showed the following three building design variables as the most important energy indicators: number of floors, roof shape, and window to wall ratio (WWR). Analysis of building systems revealed the following three as the major ECM: envelope, heating-ventilation-air-conditioning system (HVAC), and conditioning set points and schedules. Parametric permutation-modeling of the most optimal variables generated the following combination as the top energy performance indicator: high-efficiency HVAC system (ground source heat pump), complemented with a super-insulated air-tight building envelope (structural insulated panel) and a compact one-story rectangular footprint (40’ x 50’) with high percentage south-facing WWR (25%). This specific permutation of variables out-performed the other simulated combinations, yielding a 56% reduction in energy use over the modeled baseline threshold and a 27% reduction from an average U.S. detached single-family home (RECS, 2009).

This study is of value to a multitude of stakeholders including homeowners, architects, developers, and policy makers, as it further enhances the understanding of the energy impacts associated with various architectural variables. Furthermore, the research could have far-reaching significance impacting many areas such as building codes, building science, building construction, architectural practices, energy modeling, policy, and advocacy. The findings from this study have potentially substantial implications for the advancement of building science, building standards, building design, and construction practices. Moreover, the study is likely to spur further research that examines the nexus between architectural building design and systems and energy consumption/efficiency. The application of these findings provides the residential home building industry a systematic comprehensive roadmap to enact more robust sustainable, economical, and resilient building practices.

Author’s Biographical Sketch

Naim Jabbour was born in Lebanon during the height of the civil war. He migrated to the United States in the winter of 1996 seeking a safer and brighter future. While in the U.S., he earned a Bachelor of architecture degree from Louisiana State University. Naim then moved to Houston to pursue a career in the architectural sector. While practicing architecture for seven years, he was involved with the design of many projects encompassing various archetypes and typologies. In 2008, he moved to Pittsburgh to pursue graduate studies in the field of building science and sustainable design at Carnegie Mellon University. After earning his Master of Science in architecture, he accepted a position at Pennsylvania College of Technology as an Assistant Professor of Architecture and Sustainable Design. He has since been heavily invested in the field of sustainable design and energy efficiency.

Dedication

For my dad, may he rest in peace. You are a guiding light, an inspiration, and a model of excellence that I can only hope to emulate and live up to. For my loving wife and kids, I couldn't have done this without your unwavering support and encouragement. Lastly, for my mom, whose support is beyond limits, I'm the person I am today because of you.

Acknowledgments

I would like to acknowledge the following people who were instrumental in developing and ensuring the success of this thesis: Dr. Carol Lugg, my thesis director and Dean of the School of Construction and Design at Penn College; Dr. Mark Leighton, my research adviser and Associate Director and Senior Research Advisor of Sustainability at Harvard Extension School.

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Definitions of Terms

ACH – Air changes per hour

AFUE - Annual fuel utilization efficiency: a measure of a gas furnace's efficiency

BEopt - Building Optimization Tool

Btu – British thermal unit

COP – Coefficient of performance: efficiency rating of a heat pump

DHW – Domestic hot water

DOE – Department of Energy

ECM – Energy conservation measures

EER – Energy efficiency ratio: efficiency rating of air conditioners

EIA – Energy Information Administration

EPA – Environmental Protection Agency

EUI - Energy use intensity: annual amount of energy used by a building per square foot

GHG – Greenhouse gases

GSHP – Ground source heat pump

HERS – Home energy reporting system

HVAC – Heating, ventilation, and air conditioning

IECC - International Energy Conservation Code

KWh – kilowatt-hour

LEED – Leadership in Energy and Environment

NAHB – National Association of Home Builders

NBI – New building institute

NREL – National Renewable Energy Laboratory

RECS – Residential energy consumption survey

SF - Square feet

SHGC – Solar heat gain coefficient

SIP – Structural insulated panels

USGBC – United States Green Building Council

WWR – Window to wall ratio

Chapter I

Introduction

Buildings have a substantial impact on energy consumption, the environment, and overall comfort of occupants. Rapidly increasing energy use associated with residential structures is a significant and growing problem. Energy consumption in single-family homes is steadily rising, negatively impacting energy efficiency and overall greenhouse gas emissions (EIA, 2017). In 2016, residential and commercial structures consumed approximately 40% of the primary energy and nearly 70% of the electricity generated in the United States (DOE, 2016). Furthermore, the residential sector consumed approximately 21% of the primary energy, compared to just 10% in the late 1940's. Total annual U.S. residential energy swelled from a mere 6,000 trillion Btu's in the 1950's to almost 22,000 trillion Btu's in 2016 (RECS, 2009). As a result, 6% of total U.S. greenhouse gas emissions are attributed to the residential market (EPA, 2016). Current and future market trends are projecting a steady increase in home size and population growth, which will inevitably exacerbate environmental and energy use issues further. Furthermore, residential code development as it relates to energy use has reached a static level in terms of energy performance advancements (IECC, 2016). Left unaddressed, the implications of population growth, rising energy prices, prevalence of modern home appliances, steadily increasing home size, and energy shortages could be profoundly detrimental to energy consumption and the overall environment.

Architects, designers, builders, and homeowners have explored at varying degrees the adoption of green building features and practices into homes. To address this critical issue, many building professionals have resorted to a “fix all – upgrade all” approach, with the aim of drastically reducing energy use (Smeds, 2007). Green building features are of paramount significance to overall building energy consumption. However, it is not clear which permutations of architectural metrics are the most optimal as energy performance indicators in detached single-family residential buildings. As a result, there is still a substantial gap between energy performance and architectural building systems adoption. To date, neither building code nor industry guidelines provide a clear and robust delineation on best practices relating to optimal energy performance in single-family homes.

Many uncertainties exist within the industry, specifically around the impact of residential architectural building variables---building design and building system metrics---on energy performance and efficiency. Consequently, policymakers, advocacy groups, building professionals, and the general public are uninformed when it comes to issues concerning energy use and efficiency in single-family residences.

In Pennsylvania, single-family detached homes constitute 59.5% of the state’s residential housing sector (US Census, 2016). Given the significant size of this industry, there is tremendous potential to reduce energy use and associated environmental impacts. Accordingly, a study by the Pennsylvania Statewide Evaluation Team (Statewide Evaluation Team, 2015) found that 72.5% of residential energy savings potential could be achieved by 2020 if the state adopted more robust energy efficiency measures in single-family homes. Hence, improving the energy performance of the residential building industry, by adopting robust energy performance guidelines, could potentially constitute a key factor in energy independence endeavors and climate-change mitigation efforts.

Thus, it is imperative the industry undergo a paradigm shift by addressing these issues to curtail the wasteful consumption of resources and associated environmental degradation.

Research Significance and Objectives

To address these uncertainties, gaps, and opportunities, this research explored methods to optimize energy performance in Pennsylvania single-family detached buildings. The research examined a number of architectural variables to identify top energy performance indicators encompassing building design and building systems. An iterative parametric computer modeling analysis (DOE, 2016) was employed to comprehensively evaluate the impact of various architectural metrics on energy consumption. The research evaluated various permutations of indicators, assessing the relationship between architectural features and energy efficiency in single-family residential buildings. The goal of this analysis was to provide a robust roadmap guiding home owners, builders, planners, designers, and policymakers toward more sustainable building approaches. The objectives of this study were:

- To generate optimal building guidelines encompassing various architectural "building design" and "building systems" metrics
- To develop optimal inclusive architectural guidelines for the design of high performance single-family residential buildings in Pennsylvania. The state is situated in climate zone 5A
- To inform policy makers, advocacy groups, industry professionals, and the general public on robust techniques to approach energy consumption and efficiency in single-family residential buildings

Background

Buildings have a substantial impact on energy consumption and the environment. According to the Energy Information Administration (EIA), the U.S. residential building sector consumes more than half of total primary energy expenditures attributed to the building sector (Figure 1). Detached and attached single-family homes account for 69.1% of the total residential housing units (EIA, 2017). Accordingly, 80% of the total U.S. residential site energy is consumed by these single-family buildings (RECS, 2009). Statistically, detached single-family homes account for the largest energy consumption among all residential structures (EIA, 2017). The square footage of single-family homes continue to increase in size than those homes built in earlier decades, a noteworthy trend as most energy end-uses (heating, cooling, lighting, hot water, etc.) are impacted by building size and footprint. Data from the 2016 Census' *Annual Characteristics of Housing* report points to a significant spike in the number of single-family homes built in 2015 with at least 3,000 square feet (SF) of floor area, higher than any previous year. As home sizes increase, heating and cooling loads rise, lighting requirements grow, and the overall energy use surges. In 2009, estimates from the EIA's residential energy consumption survey show that space conditioning (cooling and heating) account for more than 48% of energy use in an average U.S. residence (RECS, 2009). Moreover, Department of Energy (DOE) data points to heating, water heating, lighting, and equipment end-uses as the largest drivers of residential energy demand. Collectively, these end-use energy drivers account for more than two-third of total site energy use

(Figure 2). Moreover, space heating accounted for the largest end-user of single-family residential site energy (EIA, 2017).

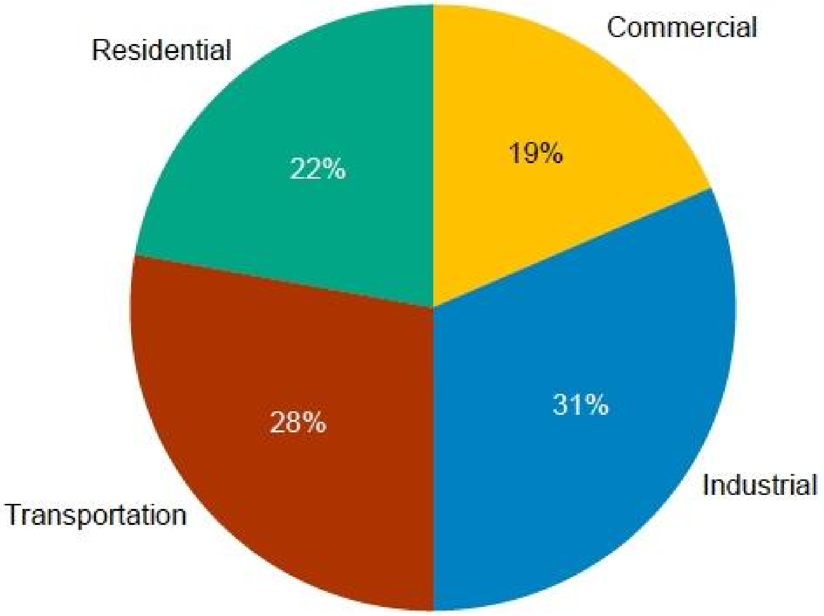
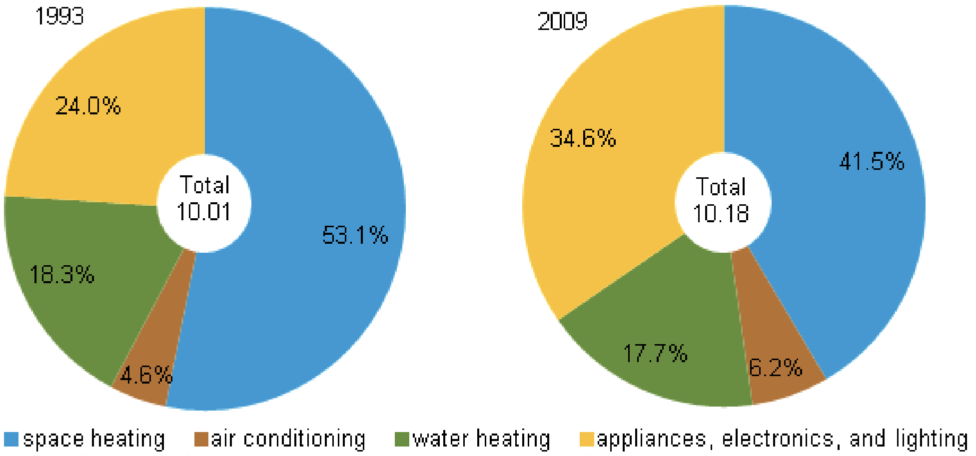


Figure 1. Breakdown of U.S. energy consumption end-uses (EIA, 2017).



Source: U.S. Energy Information Administration, Residential Energy Consumption Survey.
Note: Amounts represent the energy consumption in occupied primary housing units.

Figure 2. U.S. Home energy end-use consumption comparison (EIA, 2017).

EIA data show an increasing number of energy efficiency trends, specifically among cooling, heating, and refrigeration equipment in the U.S. (EIA, 2017). Hence, the energy consumption of these end uses has been significantly reduced compared to two decades ago. Nonetheless, these energy reductions and savings have been offset by other systems that have been incorporated into homes. Single-family homes now contain more energy-consuming devices. The agglomeration of the such products as televisions, dishwashers, clothes washers, DVDs, DVRs, cell phones, audio-video equipment, and mobile devices, have significantly impacted the energy outlook of homes. According to the EIA, the average U.S. household consumed 11,496 kWh of electricity in 2010, of which the largest portion (7,526 kWh) was for appliances, electronics, lighting and miscellaneous uses. Consequentially, energy consumption increased 24% from 1990 to 2009. This new paradigm of ever increasing energy end-uses is presenting a substantial challenge to home owners, designers, and sustainability professionals. The majority of fuel sources for that energy is derived from fossil fuels, which include coal, oil, and natural gas (DOE, 2016). As a result, U.S. residential sector contribution to greenhouse gases emissions is significant and steadily increasing. It is imperative to explore innovative approaches to reduce energy use in homes. Furthermore, Department of Energy (2016) and World Energy Council (2016) projections have alluded to somewhat of a turbulent energy market, riddled by uncertainties and insecurities. Home owners in the U.S. and specifically Pennsylvania are not immune to these market fluctuations. Uncertainties in future energy prices and availability pose a serious threat to a home owner’s bottom line and overall economic well-being. It is therefore imperative to devise more energy efficient and adaptively resilient residential building models. The following section will present an overview of the efforts undertaken by the building industry and other organizations to promote more robust and efficient building energy paradigms.

Past and Current Trends in Residential Building Industry

In 2009, the average energy use per U.S. household was 90 million Btu's compared with 138 million Btu's in 1978, a reduction of 31% (Figure 3). This in part is due to upgraded appliances and HVAC equipment that use less energy and reduced infiltration through walls, roofs, and windows due to improved insulation and construction techniques. Nonetheless, home energy consumption is still high relative to where it should and could be. Various efforts have been undertaken to address this problem via residential code improvement and industry initiatives (Figure 4). To address code and industry shortfalls, the DOE initiated a program in 1993 called "Building America" with the goal of reducing whole-house energy consumption for new homes by 50% by 2015 and 95% by 2025 (Anderson & Christensen, 2006). The program is a private-public partnership aiming at improving new and existing home energy performance across the U.S. In 2002, the DOE initiated the "Zero Energy Homes-ZEH" initiative, making available the latest research development concepts to homebuilders and homeowners across the United States. DOE's objective was to help builders and homeowners construct homes that generate as much energy as they consume over the course of a year. The DOE designated various teams, working with the National Renewable Energy Laboratory (NREL), to introduce ZEH concepts into the residential market. To date, the Building America/ZEH program has been an incubator of innovations in the residential building sector. According to the DOE, Building America scientists have worked directly with approximately 300 U.S. homebuilders and have improved the performance of more than 42,000 homes. In 2012, DOE recognized nearly 30 game-changing building accomplishments from the years 1995 through 2012 as “Building America Top Innovations”. However, most of the DOE efforts outlined above are voluntary in nature. As a result, as of 2017 only 10% of new homes in the U.S. are built to surpass minimum efficiency standards. These industry trends are reflected on a micro-scale in Pennsylvania’s residential building sector.

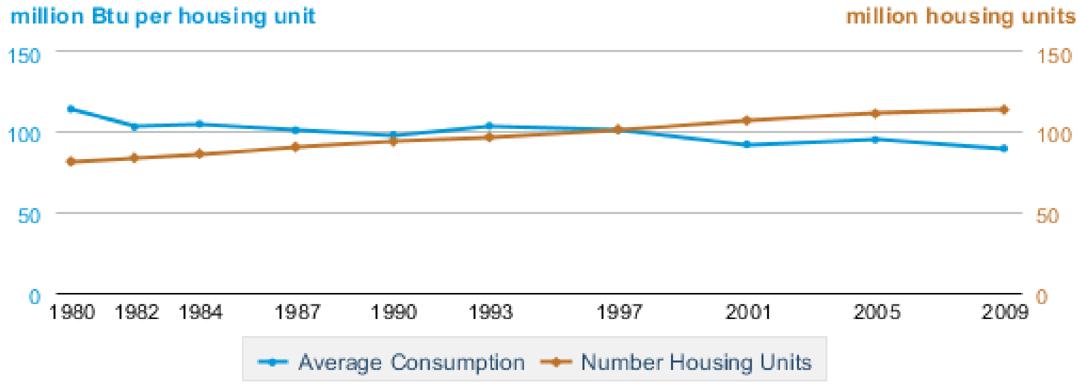


Figure 3. Average energy use per home and number of units (EIA, 2017).

Figure 4. Residential code development from 1970 to 2015 (IECC, 2016).

Residential Energy Use Trends in Pennsylvania

According to 2017 EIA data, Pennsylvania's residential sector consumed 15.7% of the state's total primary energy in 2010 (EIA, 2017). Total price of energy in the state increased 6.3% between 2000 and 2010. Consequently, Pennsylvania home owners spent $2,353 per housing unit on energy consumption in 2009, 16% higher than the national U.S. average of $2,024 (RECS, 2009) (Figure 5). Similarly, Pennsylvania homes consumed on average 96.4 million Btu per housing unit, 8% higher than the national average of 89.6 million Btu (Figure 6). EIA (2017) data showed Pennsylvania homeowners paid 9.15% above the national average on electricity and 5% more on natural gas in 2016. Furthermore, Pennsylvania's residential sector was the second largest consumer of the state's primary energy at 24.1% in 2016. Space conditioning, primarily heating, constituted the highest end user of energy in Pennsylvania households at 50%. Moreover, home-size trends have followed a similar trajectory as homes in the Northeast region and the United States. The trend is that of a steadily increasing footprint and square footage (US Census, 2016). Energy data show that majority of fuels used to power and condition Pennsylvania single-family homes are primarily fossil fuel-based (coal, oil, and natural gas) (EIA, 2017). Accordingly, 51% of Pennsylvania households utilize natural gas primarily for heating, 21% use coal, and 19% fuel oil. Coal is the leading type of fuel consumed to generate electricity in the state (EIA, 2017). Pennsylvania is the second largest producer of natural gas and the fourth largest producer of coal in the nation (EIA, 2017). Hence, there need to be a serious concerted effort to transition the area towards more sustainable and energy efficient practices.

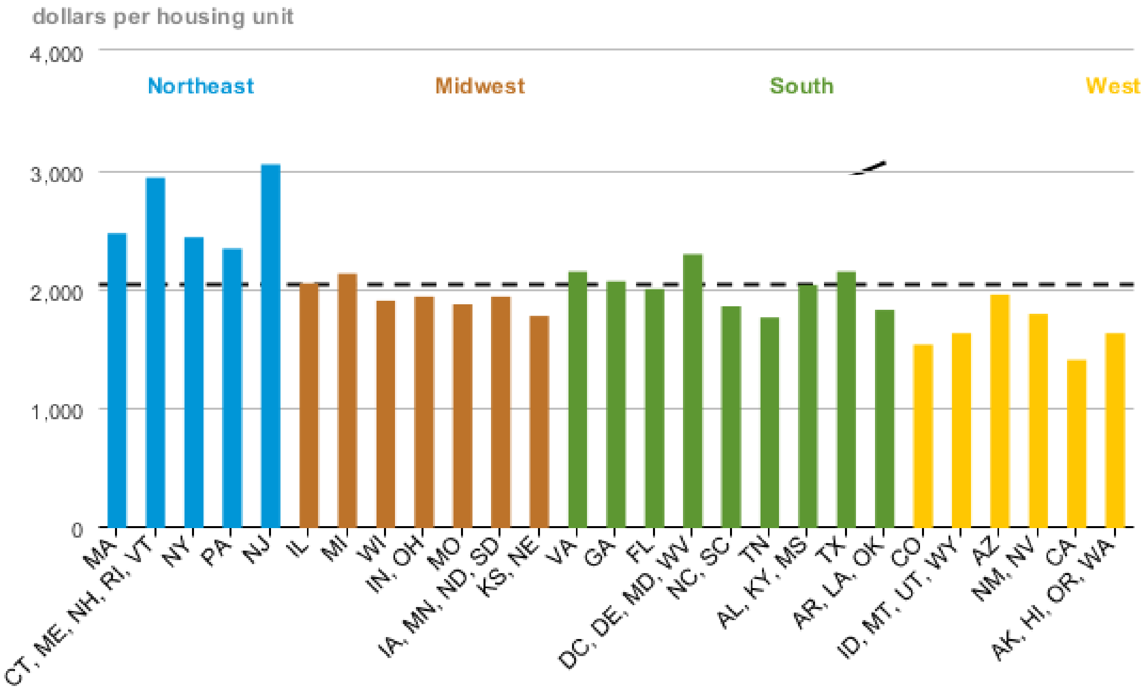


Figure 5. Average home energy expenditures in United States (RECS, 2009).

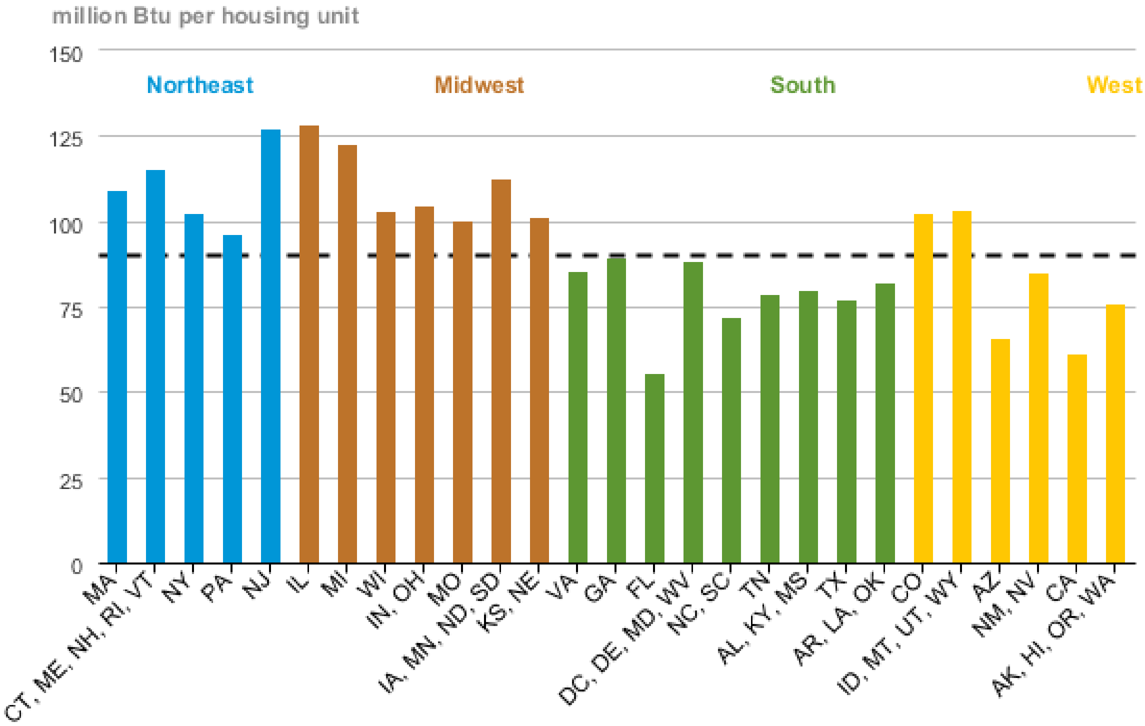


Figure 6. Average home energy consumption in United States (RECS, 2009).

Residential Energy Conservation Efforts and Initiatives in Pennsylvania

Given the age of residential housing stock and energy sources used in Pennsylvania, there is a significant need to move that market towards more sustainable practices and building approaches. In 2008, Pennsylvania's General Assembly enacted "Act 129" to mandate the state's seven major electrical distribution companies advance energy conservation and efficiency programs to reduce residential electric use. The program incentivizes the following areas: high efficiency appliances, high efficiency heat pumps, LED lighting, home audits, time-of-use and peak pricing rates, and hourly pricing options. Accordingly, the state has saved 3,383,465 MWh of electricity since the introduction of Act 129 (EIA, 2017). The Housing Alliance of Pennsylvania, in concert with several energy groups, launched in 2013 the "Energy Efficiency for All" initiative. This program is tailored to link the residential and energy sector and bring energy efficient practices to fruition. Furthermore, the DOE's "Weatherization Assistance Program" has also been available to Pennsylvania residents. Qualified participants can qualify for on-site energy audits to evaluate the most cost-effective energy efficiency practices. Pennsylvania is also currently working on its own version of the "Clean Power Plan." Furthermore, Pennsylvania has adopted the following energy conservation measures over the past decade: advanced metering, alternative and renewable energy supply programs and policies, dispersed and distributed generation systems, and green incentives and rebates. However, the state still lags behind in terms of energy efficiency in the single-family residential market. For instance, only 6% of Pennsylvania single-family residences are Energy Star rated, less than the national average of 10% (US

Census, 2016). Similarly, only 4% of Pennsylvania households earned the USGBC's LEED Homes green certification (USGBC, 2016).

Transitioning to More Sustainable Building Practices

Studies have illustrated that energy conservation measures (ECM) could potentially reduce building energy consumption by 25-50% (Crawley, 2009). Accordingly, research conducted by the U.S. Green Building Council have shown that green buildings tend to have energy use intensities on average of 69 kBtu/sf, 24% lower than their traditional counterparts at 91 kBut/sf. Research conducted by the DOE, NREL, and other groups have all alluded to a strong connection between building system upgrades and enhanced energy performance across industry spectrums (Crawley, 2009). For example, upgrades in insulation have been shown to yield significant reductions in heating loads in cold climate locations (Yılmaz, 2007). Similarly, upgrades in glazing and HVAC systems have also generated substantial savings in energy consumption in single-family residential structures in various cold climate locations (Logue, 2013). Accordingly, serious efforts have been undertaken by various groups such as NAHB, DOE, EPA, NREL, EIA, USGBC, and NBI to advance the science and the overall state of the industry (Scofield, 2009). For instance, the International Energy Conservation Code has been updated to reflect a more sustainable emphasis and approach in its 2015 iteration. Similarly, many municipalities, cities, and states in the United States have been pursuing more performance-based building codes in an effort to transition toward more sustainable practices such as Cambridge, Portland, Santa Monica, and Austin. Nonetheless, there is still a level of uncertainty in regards to what system upgrade combinations might offer the most optimal performance (NREL, 2011). Furthermore, the relationship between building design configuration and energy performance remains ambiguous and largely untested. The transition of industry standards into sustainable building practices is well documented; however, research on the impact of targeted optimal energy indicators is still considered deficient. The following section will present an overview of the state of existing literature on energy use and efficiency in the residential building sector.

Residential Energy Consumption

Literature clearly indicates a strong correlation between green building features and energy performance (Smeds, 2007). Studies have shown that certain building system upgrades, encompassing HVAC systems, envelope construction, glazing, and insulation, have a significant impact on various building energy end uses such as heating, cooling, lighting, and hot water (Christensen & Norton, 2008). Residential energy implications of varying architectural building system indictors have been thoroughly investigated by prior research (DOE, 2016). However, many studies have failed to assess the impact of targeted permutations of such indictors on energy use in detached single-family buildings in cold climate locations. Most of the existing research focuses either on the impact of singular energy conservation measures or a cumulative-all-included-approach (Logue, 2013). For example, a 2006 study of energy efficient houses in Denmark highlighted measurable reductions in energy use applying an all-inclusive approach of building system upgrades. The study measured significant improvements in energy performance when upgrading the following systems: HVAC, insulation, ventilation, glazing, and lighting (Tommerup, Rose, & Svendsen, 2007). Similarly, a Swedish study found considerable improvements in energy use via a cumulative-based approach employing building systems upgrades in insulation, building envelope, windows, and air tightness (Smeds, 2007). Another study successfully evaluated the feasibility of energy-efficient design in Vermont, while utilizing energy conservation measures encompassing windows, air/vapor barriers, insulation, ventilation, and HVAC systems (Maclay, 2015).

Nonetheless, most of the investigated studies failed to adequately isolate key optimal energy performance indicators. While it is prudent to investigate the impact of all building systems on energy consumption, it’s imperative to examine the most optimal permutations correlating to energy efficiency. Existing literature and research have not robustly analyzed the effects of optimal combinations of building system upgrades in an iterative parametric approach. Correspondingly, there’s a significant knowledge gap in assessing the efficacy of select targeted combinations of upgrades, particularly within Pennsylvania’s residential building industry (EIA, 2017). Hence, most studies failed to capture a more realistic picture of the residential energy consumption paradigm.

In addition to the lack of robust research on the impact of targeted permutations of building system upgrades, there has not been extensive data on the impact of varying building design configurations on energy performance in single-family residential buildings. For example, building geometry, footprint, and shape are often neglected as energy performance indicators. Most studies have focused on the effect of building system upgrades on overall energy use, while few have examined the impact of architectural design configuration variances on residential energy consumption (Krem, Hoque, Arwade, & Breña, 2013). Furthermore, there isn’t robust literature pointing to a clear correlation between detached single-family building morphology and energy performance. However, building science research does imply a connection between geometry of a structure and energy transmission (NREL, 2011). Building construction and design configuration variables such as “area to volume ratio” are closely related to thermal losses in single-family residential buildings. Nevertheless, most design configuration studies have focused on multi-story multi-family residential structures with three or more floors. In a study of multi-family residential structures in Turkey, Erlalelitepe (2011) found a noteworthy correlation between design configuration and energy saving potential. Similarly, another study concluded that a correlation does exist between envelope design and energy use in residential buildings (Granadeiro, Duarte, Correia, & Leal, 2013a). However, these authors indicated that energy modeling and performance information is usually absent during the early stages of design, where a building envelope is defined and shaped. The researchers concluded that it is imperative upon designers and building professionals to thoroughly investigate the impacts of architectural design variances early during the design stages. The study also recommends more resources slated toward investigating building envelope architectural shape and its correlation to energy performance optimization. Regardless, it remains unclear to what extent varying design configurations would impact energy use in detached single-family structures within the targeted region of this study. Furthermore, the impact of building design on energy consumption is relatively unknown when paired with building system upgrades. The next section outlines existing research entailing the impact of targeted architectural variables on energy consumption and efficiency.

Impact of Targeted Architectural Variables on Energy Use

This section will present an overview of the existing research on correlations between optimized architectural variables and energy use. Architectural building systems play a significant role in determining the outlook of a building's energy performance. Most research to date have focused on the impacts of building system upgrades on energy use in residential buildings, often neglecting to assess building design variables such as massing and form. Furthermore, research shows that the majority of efforts have been directed towards either singular energy conservation measures or an all-inclusive zero energy approach, overlooking targeted optimal green building features. Nonetheless, findings from these types of studies point to three primary indicators impacting energy performance and demand in residential building: super-insulated envelopes, high-performance glazing system, and mechanical systems (heating & cooling) (Parker, 2008).

Envelope upgrades. The envelope comprising the roof, walls, foundation, and glazing usually accounts for 35-40% of a home's overall energy demand (DOE, 2016). A home's envelope acts as a thermal barrier that plays a critical role in regulating interior temperatures and overall energy use, hence, impacting over thermal comfort and energy demand. A properly insulated and sealed building envelope has the potential to impact approximately 50% of building energy loads (NREL, 2011). An average home in the northeast region of the Unites States could realize a 12% reduction in total energy use and a 19% reduction in heating loads by properly sealing air leaks and adding more insulation (Center for Climate and Energy Solutions, 2017). Moreover, properly insulated and sealed roofs could save home owners 10-15% in peak heating and cooling demands. Properly air-sealed building envelopes tend to yield 20-30% reductions in heating demand (International Energy Agency, 2013). Department of Energy data shows a 10% reduction in total annual energy expenditures and 20% savings in cooling and heating costs via properly insulated and sealed building envelope (DOE, 2016). For example, building envelope systems such as structural insulated panels and insulated concrete forms have been shown to reduce overall energy demand by up to 30-40% (NAHB, 2006). Furthermore, super-insulated building envelopes such as double-stud construction tend to reduce between 20-30% of energy demands in colder climate locations (EIA, 2017). For example, insulation as a singular energy conservation measure have been shown to yield energy reductions between 10 and 25% depending on location and climate (Anderson & Christensen, 2006). A study of residential structures in mild to cold climates in the U.S. found 10-15% reductions in annual heating loads when upgrading the thermal resistance of a home's building envelope via upgraded insulation levels (Park, SrubarIII, & Krarti, 2015). A Rutgers University study analyzing single-family homes in New Jersey revealed 27% energy savings with the application of advanced framing and upgraded insulation (The Rutgers Center for Green Building, 2011). In a study of a hypothetical residential building in Sydney, the researchers were able to show energy reductions between 15-25% via upgraded insulation levels across the envelope (Tabrizi, Hill, & Aitchison, 2016).

Window upgrades. Considered one of the weakest points in a building envelope, windows are critical components in a comprehensive energy efficiency strategy. Windows consume approximately 24% of a building thermal energy loads, 19% for heating and 39% for cooling (Arasteh, Selkowitz, & Apte, 2006). Heat energy transmission through glazing systems plays a key role in determining energy demand and overall thermal comfort in residential buildings. Optimal high-performance glazing systems have the potential to reduce residential energy consumption by 10-50%, depending on application and location (Ander, 2016). Department of Energy data shows 7-24% annual energy reduction by using Energy Star rated windows (DOE, 2016). Studies by the Center of Climate and Energy Solutions echo these findings and have been able to demonstrate 10-50% reduction in energy consumption based on optimal glazing specifications and window design (Center for Climate and Energy Solutions, 2017). Key to these findings are three parameters: placement, surface area, and performance specifications. To that end, studies of homes in the northeastern United States have shown a potential 6-10% reduction in energy use when upgrading to double-pane low emissivity windows (The Rutgers Center for Green Building, 2011). Other cold-climate location pilot projects demonstrated 20-25% reductions in heating and peak electrical loads (International Energy Agency, 2013). Window to wall ratio (WWR) percentage is another key factor in determining the impact of glazing systems on energy use. Studies have shown the potential to double energy savings by increasing a façade's WWR from 10 to 30% (Ihm, Park, Krarti, & Seo, 2012), reducing annual cooling and heating loads by 25-35% with 30% WWR envelopes.

Mechanical system upgrades. Space conditioning end-uses such as cooling and heating loads account for approximately 50% of the energy consumed in an average single-family American household (DOE, 2016). In the Northeast, heating loads constitute the majority of a home's energy end-uses (40%). Energy Information Administration data shows three major equipment types used for heating in residential buildings: electric furnaces, natural gas furnaces, and heat pumps (EIA, 2017). The DOE estimates 30% savings in energy consumption with upgraded HVAC equipment coupled with appropriate insulation and air sealing (DOE, 2016). For example, Energy Star rated air conditioners are 10-15% more efficient than standard models (DOE, 2016). Moreover, it is estimated that geothermal heat pump systems could reduce a home's energy use by 30-60%. Studies have shown energy saving potential between 14 and 45% when upgrading residential HVAC systems (The Rutgers Center for Green Building, 2011). Furthermore, 37% reductions in annual energy operating costs could be achieved with high level efficient active mechanical systems. The second largest energy user in a house is water heating consuming 18% of total energy end-uses. DOE (2016) research has demonstrated energy savings between 30-50% when comparing efficient upgraded water heaters with standard units.

Multiple-paired upgrades. The impact of singular energy conservation measures is well documented. However, several studies have attempted to evaluate the impact of multiple-paired architectural variables, incorporating building systems and design configuration, on energy consumption in residential buildings (Yılmaz, 2007). For example, various residential blocks in Eastern Europe measured between 67.8% and 77.2% energy saving potential when upgrading envelope insulation and window U-values (Csoknyaia et al., 2016). Varying exterior wall insulation levels and window R-values were found to have a significant impact on energy use, specifically reducing heating and cooling loads (Croitorua, Nastasea, Sandua, & Lungu, 2016). This study also discovered 40% improvements in energy use by optimizing building orientation. Orienting a house facing south was found to be very effective in reducing energy demand in cold climates, especially heating loads. However, the researchers concluded that improving thermal resistance of both exterior walls and windows was the most optimal approach to reduce overall energy consumption. Similarly, high energy performance in Turkish residential buildings was correlated with optimal east-west axis orientation (Kazanasmaza, Uygun, Akkurt, Turhan, & Ekmenc, 2014). The study also found that lower ratios of external surface areas to net usable floor area yielded higher energy savings.

A parametric study integrating nine different simulated building geometries, assessing building footprint, shape, and volume, showed a noteworthy association between building shape and energy demand (Granadeiro et al., 2013a). Findings revealed a 28% reduction in energy loads (heating & cooling) with design iterations that had lower ratios of external surface areas to net usable floor areas. Window areas percentages and envelope insulation levels were primary drivers of energy consumption in a hypothetical study analyzing 8000 variations of a hypothetical residential building designs (Granadeiro et al., 2013b). The researchers showed a strong statistical correlation between building envelope upgrades, aimed at increasing thermal resistance and minimizing heat transfer, and overall energy demand. A study of newly constructed homes in Mexico showed 52% annual energy savings when adopting a combination of improved thermal insulation and efficient appliances (Griegoa, Krarti, & Hernández-Guerrero, 2012). Similarly, Danish researchers realized a 40% reduction in electricity consumption upon upgrading envelopes' thermal insulation and air tightness (Tommerup, Rose, & Svendsen, 2007). To that end, properly insulating a home coupled with effective air sealing have been shown to reduce energy use by 5% to 16 % depending on location (DOE, 2016). Moreover, utilizing a super-insulated envelope with virtually no leaks has yielded energy savings around 25% (DOE, 2016). Similarly, upgrading the R-value of attic insulation has resulted in a 15% reduction of a home's cooling and heating loads. It was also concluded that energy optimization is best enhanced when building envelope upgrades are sequentially selected first to be followed by HVAC upgrades, potentially yielding a 70% optimization rate (Bichiou & Krarti, 2011). Collectively, most studies have advocated the adoption of the following green building upgrades as primary energy indicators: high-performance heating systems, super-insulated envelope, high-performance glazing, and high percentage south-facing window to wall ratio. Adoption of these indicators into residential buildings have shown on average energy-use reductions between 40% and 60% (NREL, 2011). Alternatively, a large body of literature points to weak and insignificant statistical correlations between energy consumption in residential buildings and the following architectural features: architectural style and typology, shading devices, interior floor and space layout, equipment and system schedules, doors specifications, roof characteristics, ventilation system, and plug loads (DOE, 2016). In contrast, few studies have explored the correlation between architectural design variables (building footprint, shape, massing, volume, etc.) and energy use. Moreover, the impact of building design variables paired with optimal building systems has not been robustly investigated and evaluated. Consequently, a gap in the industry still exists that needs to be addressed.

Bridging the Gap

It is evident that energy conservation measures are paramount to achieving desired levels of high performance within the residential building industry, however, it is still uncertain what permutations are most effective in single-family residential structures in cold climate locations. A recent report showed that 84% of surveyed homeowners could not describe what entails an energy efficient building (Vaughan, 2017). The report also concluded that there is a lack of attention on the adoption of robust optimal solutions within the residential building industry. Similarly, little attention is devoted to the impact of design configurations on energy use. Indeed, building design is a significant unknown variable as it relates to residential energy consumption. Buildings represent very complex environments, encompassing many moving parts and variables. Therefore, it is imperative that any research be focused on a holistic investigation of all parts and systems parametrically, in an integrated, iterative, and analytical manner. Accordingly, I conducted a comprehensive impact analysis of various architectural metrics and their effect on energy performance.

Research Questions, Hypotheses, and Specific Aims

My research sought to illuminate the relationship between architectural indicators and energy performance. To address this gap in knowledge, a comprehensive modeling analysis was conducted examining the impact of targeted permutations of architectural variables on energy consumption in single-family residential buildings in cold climates. The following research questions were addressed in an effort to evaluate the correlation between architectural building components and energy efficiency:

- What impact does varying architectural design configurations have on energy consumption in a standard Pennsylvania single-family home?
- What impact does varying building system configurations have on energy consumption in a standard Pennsylvania single-family home?

- What impact does various permutations of architectural variables---architectural design and building system configurations---have on energy consumption in a standard single-family residential building in Pennsylvania? And what specific permutation would yield the most optimal energy performance indicators?

Architectural design variables investigated include the following: footprint, volume/massing, geometry, orientation, window to wall ratio percentage (WWR), roof shape and characteristic. Building system variables investigated include the following: insulation, envelope construction, glazing specifications, HVAC, hot water, lighting, conditioning set point and schedules, appliances, and plug loads.

This research was designed to examine the hypothesis that certain targeted permutations of architectural indicators would yield significant improvements in energy performance exceeding the minimum 15% improvement threshold over baseline, equivalent to LEED Homes and Energy Star criteria. As such, these indicators should be adopted as best practice guidelines for the design of high performance detached single-family residential buildings in Pennsylvania. Based on prior research as well as industry practices and guidelines, the following variables were hypothesized to significantly improve energy consumption and performance in Pennsylvania detached single-family households.

- The architectural design indicators of compact rectangular floor plan, two-story volume, and high percentage southern window to wall ratio, and
- The building systems indicators of super insulated envelope, high efficiency HVAC system, and space conditioning set points and schedules.

- Accordingly, the most optimal combination of architectural indicators was expected to be: super-insulated envelope, high efficiency HVAC system, and compact two-story rectangular floor plate with high percentage of south-facing WWR.

In contrast, the following metrics were not expected to significantly influence building energy consumption and efficiency: architectural style and typology, form and shape, orientation, interior layout, door specifications, ventilation system, lighting, appliances, and plug loads.

Specific Aims

In order to test these hypotheses, the specific aims of the research encompassed the following steps:

1. Establishing a consistent baseline for residential energy consumption and standard residential construction in Pennsylvania.
2. Modeling energy parametric runs to assess the impact of various iterations of architectural variables encompassing architectural design configurations.
3. Modeling energy parametric runs to assess the impact of various iterations of architectural variables encompassing architectural building systems.
4. Modeling energy parametric runs to assess the impact of the most optimal iterations of architectural variables encompassing combinations of building design and building systems.

Research Limitations

This thesis was developed under the conjecture that ample time would be available to conduct a comprehensive analysis of most variables encompassing architectural metrics in detached single-family residential buildings. This proved to be somewhat difficult due to the immense amount of permutations possible from such an endeavor. To address that issue, a detailed targeted list of optimal iterations and permutation was developed and established to set a clear and achievable project.

The robustness and efficacy of energy simulation tools was another potential limitation to this project. The accuracy and predictability of such tools have not yet reached a high degree of confidence. Furthermore, a recent study explored the "energy performance gap — the difference between promised energy savings in green buildings and the actual savings delivered" (Cali, 2016). The author concluded that this gap is due to inept energy modeling tools that fail to accurately depict how buildings really work under certain conditions. Furthermore, the building occupants' behavior is also a significant trigger for the energy performance gap. To circumvent these potential issues, the study employed robust energy modeling tools in an effort to normalize the data and findings across various spectrums. Results were then compared and analyzed to generate a reasonable and accurate set of data. Another area of limitation was the ability to exchange and extrapolate data seamlessly between 3-D modeling environments and energy modeling and simulation platforms. To that end, modeling tools were selected based on their interoperability and ability to exchange and share data across their respective simulation platforms (NREL, 2011). Finally, constraining the analysis to a specific geographical area limits the applicability of the study to a wider and broader audience.

Chapter II

Methods

To address the research questions, hypotheses, and specific aims, an iterative parametric energy modeling/simulation analysis was undertaken (DOE, 2016) (Figure 7). The study used an integrated building components methodology to assess energy performance and evaluate the most optimal permutations of energy conservation measures to be utilized in single-family homes (Smeds, 2007). Accordingly, the research design employed a “system dynamics modeling” approach to simulate the impacts of interactions among various architectural variables (NREL, 2011). This modeling analysis aimed to investigate the impact of targeted variations of green building features on energy consumption in a single-family Pennsylvania residential building. The study examined optimal permutations of architectural building systems and design configurations. Energy use intensity (EUI) was used as the main energy performance indicator and primary response variable. EUI was utilized as a standard normalized measure to compare results across the wide spectrums of simulated runs. The following formula was employed to generate the EUI data: Total annual site energy (KBtu) divided by total area (square feet-sf) of the house (EUI=Total Energy/Total Area). Major residential energy end-uses such as heating, cooling, lighting, hot water, ventilation, and appliances were also measured and evaluated. To that end, the analysis employed robust parametric energy modeling tools to evaluate and assess the information (DOE, 2016). Data needed for the modeling analysis was sourced from appropriate industry and building code databases. The analysis used optimized iterative 3-D computer simulations to gauge the impact of various architectural components on energy performance in the detached single-family structure.

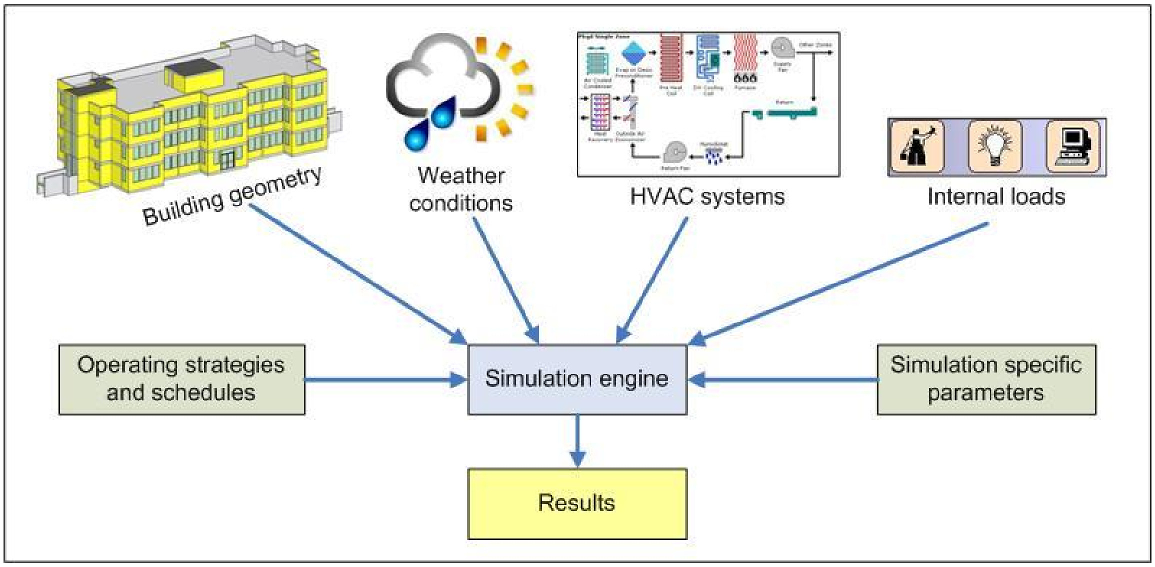


Figure 7. General overview of energy simulation engines data flow (DOE, 2016).

The research design for this analysis encompassed the following four overarching sequential steps, listed in the order in which they were executed:

1. Established a normalized energy and construction baseline model. Input data was normalized via a baseline benchmark model that addressed the following components: house size, lot size, construction specifications (envelope, HVAC, windows, insulation values), household number, number of bedrooms and bathrooms, energy use intensity (EUI), and annual total energy use. The EUI metric, a measure of annual energy consumed by a structure per unit of gross floor area, was utilized as the main energy performance indicator (baseline set at 90.75 KBtu/sf/yr). The Home Energy Reporting System index (HERS) was used to establish the minimum allowable energy improvement threshold between standard new homes and energy efficiency ones, reflected in a

minimum 15% improvement over baseline, equivalent to LEED Homes and Energy Star Homes. Industry databases such as the *New Housing Characteristics report* were tapped for all architectural baseline measures (US Census, 2016). The Energy Information Administration's "2009 Residential Energy Consumption Survey" was sourced for all energy benchmarks (RECS, 2009).

2. Simulated diverse parametric annual energy modeling runs using the EnergyPlus engine, assessing the impact of various architectural design variables. These included the following building components: footprint/layout, volume, orientation, roof characteristics and shape, window to wall ratio, glazing placement and distribution. The top three energy performance indicators to meet or exceed the minimum 5% improvement over baseline were selected as the most optimal parametric building design components.

3. Simulated diverse parametric annual energy modeling runs using the EnergyPlus engine, assessing the impact of various building system variables. These included the following building systems: insulation levels, envelope construction, glazing specification, HVAC, set points and schedules, domestic hot water, lighting, appliances, and plug loads. The top three energy performance indicators to meet or exceed the minimum 5% improvement over baseline were selected as the most optimal parametric building systems components.

4. Selected the most optimal permutations from steps two and three, and thereafter, simulated iterative parametric energy modeling runs evaluating different combinations of architectural variables encompassing building design and systems. The objective was to determine the top four top energy performance indicators, two from each

modeled category. Finally, a life cycle assessment of the top optimal permutations was conducted to evaluate the sustainability of the targeted indicators.

Research Scope and Variables

The following outlines the standard architectural and energy systems specifications assumed for the single-family residential baseline case, adopted from the 2016 US Census report on new housing characteristics: archetype (single-family detached residential), lot size (9,000SF), building size (2,000SF), built year (new construction), number of floors (2), number of bedrooms (3 to 4), number of bathrooms (2 to 3), occupancy (4), central air conditioning system, forced air furnace heating system, vinyl siding, shingle roof, full/partial basement, and location/transect zone (T3-Suburban).

The following architectural indicators served as the independent variables within the experiment: envelope construction typology, insulation levels (walls, roof, ceiling, and foundation), HVAC system, DHW system, glazing, lighting, building geometry/layout, building volume, building shape, roof characteristics, orientation, and window to wall ratio. The primary dependent response variable was the energy use intensity performance index (EUIp).

The following databases were sourced for various data pertaining to research methods and design: Energy Information Administration (EIA), U.S. Census, International Energy Conservation Code (IECC), Department of Energy (DOE)–residential building prototype models, National Renewable Energy Laboratory (NREL), U.S. Green Building Council (USGBC), and existing industry standards and guidelines.

Energy Modeling Tools

Building Energy Optimization (BEopt) was used to evaluate the relationship and impact of various architectural indicators on energy performance. BEopt is NREL's parametric building energy optimization modeling software that utilizes the Department of Energy's EnergyPlus™ simulation engine (NREL, 2011). Sketchup and BEopt were utilized as the primary architectural 3-D modeling tools. Sefaira, Energy-10, and Design Builder were employed as supplementary energy modeling tools.

EnergyPlus engine is a whole building energy program designed to model buildings energy consumption for various energy end uses such as cooling, heating, lighting, ventilation, and plug loads (DOE, 2016). It is considered one of the industry's more robust tools, offering the following capabilities: integrated parametric analysis, thermal zones, heat balance calculations, sub-hourly-hourly-monthly-annual runs, heat transfer, illuminance calculations, component-based HVAC, solar energy analysis, and energy end-use breakdown.

Energy Modeling/Simulation Framework and Workflow

Energy-efficient and green building upgrades were evaluated using BEopt's EnergyPlus simulation engine (NREL, 2011) (Figures 8 & 9) in a sequential parametric analysis approach (Figure 10). Numerous iterations of simulations were modeled to systematically analyze the interactions between different permutations of variables (Granadeiro et al., 2013a). BEopt's architectural and energy modeling environment follows this simulation sequence/protocol: (1) establish a baseline code-referenced model with proper climate and location data; (2) model various parametric simulation runs assessing respectively separate iterations of building design configurations and building system features; (3) isolate the most optimal individual energy-performing indicators; and (4) model and test the most optimal permutations of indicators in an effort to generate the top energy indicators.

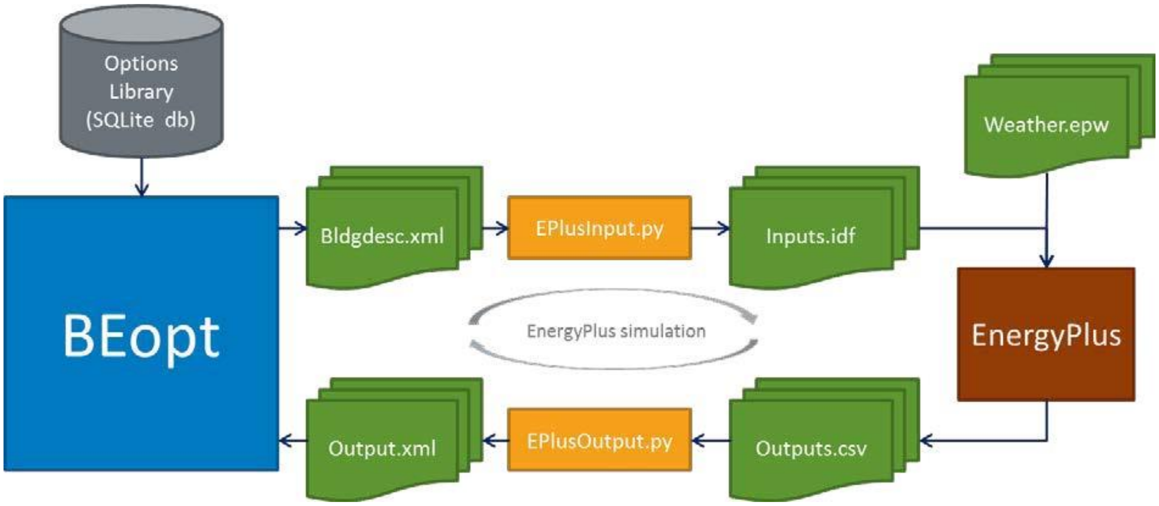


Figure 8. EnergyPlus workflow diagram for BEopt simulations (NREL, 2011).

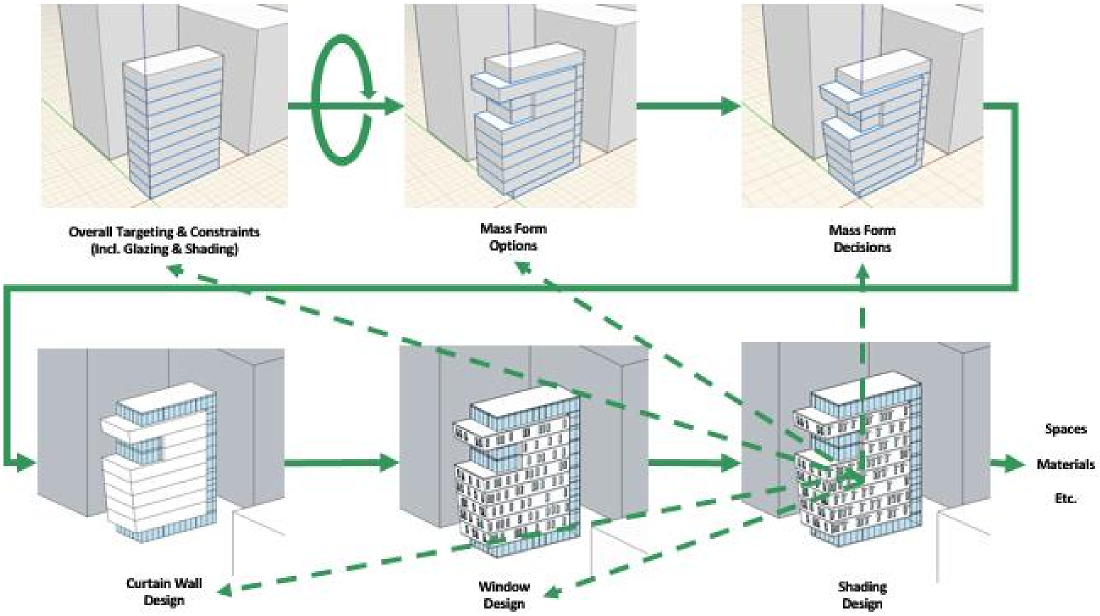


Figure 9. EnergyPlus workflow diagram for Sefaira simulations (DOE, 2016).

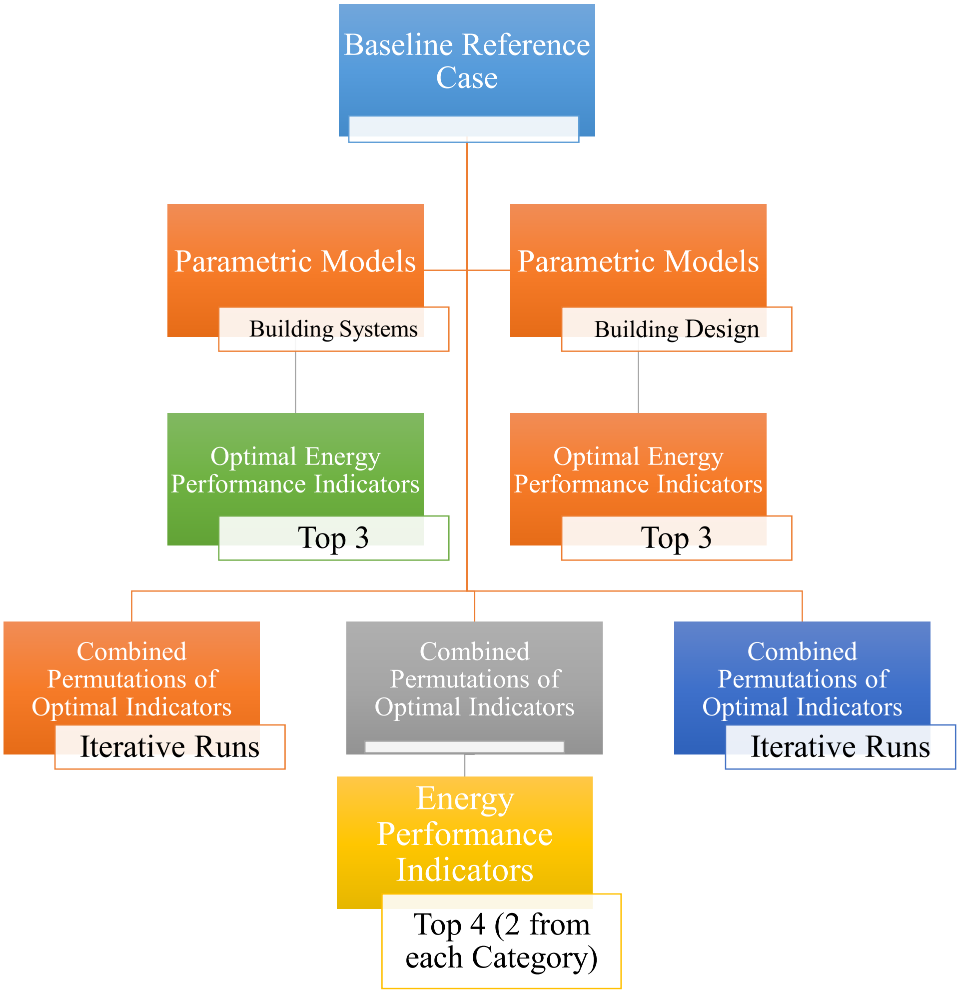


Figure 10. Project modeling framework environment.

Energy Modeling and Simulation Protocols

All baseline energy simulation assumptions were based on the “Building America Housing Simulation Protocols (Table 1),” developed by NREL and DOE (NREL, 2016). The simulation protocols followed building code guidelines and specifications. The protocols were consistent with industry references and practices. Baseline code-reference single-family building components were used to initiate the modeling process (NREL, 2016) (Table 2). DOE’s “Building America’s” optimized cold-climate building metrics were utilized for all other improved parametric runs (2016) (Table 3).

Table 1. Single-family baseline simulation protocol assumptions (DOE, 2016).

Category	**Performance**	**Options**
ENVELOPE		
Walls	R-13	• Fiberglass batt, 2x4, 16 o.c., R-5 XPS
Exterior Finish	Vinyl	• Light Colored
Ceilings & Roofs		
Unfinished Attic	Ceiling R-38	• Cellulose, Vented
Finished Roof	R-38	• Fiberglass batt, 2x12
Roof Material	Asphalt Shingles	• Medium
Radiant Barrier	None	
Slab	Uninsulated	• 2-ft R-10 perimeter, R-5 gap • Furring Strips, ½” dry wall
Finished	Wall 8-ft R-10 XPS	
Unfinished Basement	Whole Wall R-10 XPS	
HVAC SYSTEM		
Heating Equipment	Gas: 78% AFUE Furnace Electric: Heat Pump/7.7 HSPF/13 SEER	• Direct Vent Gas Furnace • Air-Source Heat Pump
Cooling Equipment	Gas: 13 SEER Central Air Conditioner Electric: Heat Pump/7.7 HSPF/13 SEER	
Water Heating	Gas, EF = 0.67 Electric, EF = 0.97	• In Basement
Water Heating Set Point	125F	
WINDOWS		
Window Area	15%	
Window Type	Double-pane	• Medium-gain low-e, nonmetal frame, argon fill (U = 0.35, SHGC = 0.44)

Table 2. IECC Specifications for baseline code-built home (IECC, 2016).

Building Components	**New Construction**
Walls	R-13
Attic	R-38 Vented
Basement Walls	R-10
Crawlspace Ceiling	R-30 Vented
Slab	R-10
Window Type	Double Pane, Low-e (U-Factor 0.35)
Ducts	7.5% leakage, R-6

Table 3. "Building America's" optimized cold-climate building metrics (DOE, 2016).

Measure	**Performance**	**Options**
High-R Ceiling	R-49	Vented & Unvented Attics • Spray Foam Underside Roof • SIP Roof • Blown-in or Batt Insulation
High-R Walls	R-20 Cavity and R-10 Continuous	• Single-Wall Cavity Insulation with Advanced Framing • Spray Foam • Exterior Rigid Insulation • Double-Wall Cavity Insulation • SIP Walls • Insulated Concrete Walls
Basement Foundation	R-15 Continuous or R-19 Cavity	• Exterior Rigid Insulation • Interior Foundation Insulation • Rigid Insulation plus Batt • Cavity with Batt or Blown-in
High-R Window	$U \leq 0.27$ ($R \geq 3.7$) $SHGC \geq 0.46$	• ENERGY STAR Certified
Heating Equipment	94% AFUE (Gas), or 10 HSPF (Electric)	• Direct Vent Gas Furnace • Air-Source Heat Pump • Geothermal Heat Pump
Cooling Equipment	13 SEER	• Air-Source Heat Pump • Geothermal Heat Pump

Baseline Home Model

The main premise of the research analysis entailed comparing a residential baseline reference case with various alternative parametric cases. Establishing a reasonable benchmark was extremely critical to the success and efficacy of the modeling analysis. The baseline case modeled a detached single-family house based on standard residential new construction practices, adopted from the DOE's Building America Housing Simulation Protocols. All modeled assumptions were consistent with guidelines outlined in the 2016 International Energy Conservation Code. The modeled baseline case served as the benchmark for all alternative scenarios. The reference single-family home was located within a suburban zone in Williamsport, Pennsylvania. The location identified for this study resides within climate zone 5A (Figure 11).

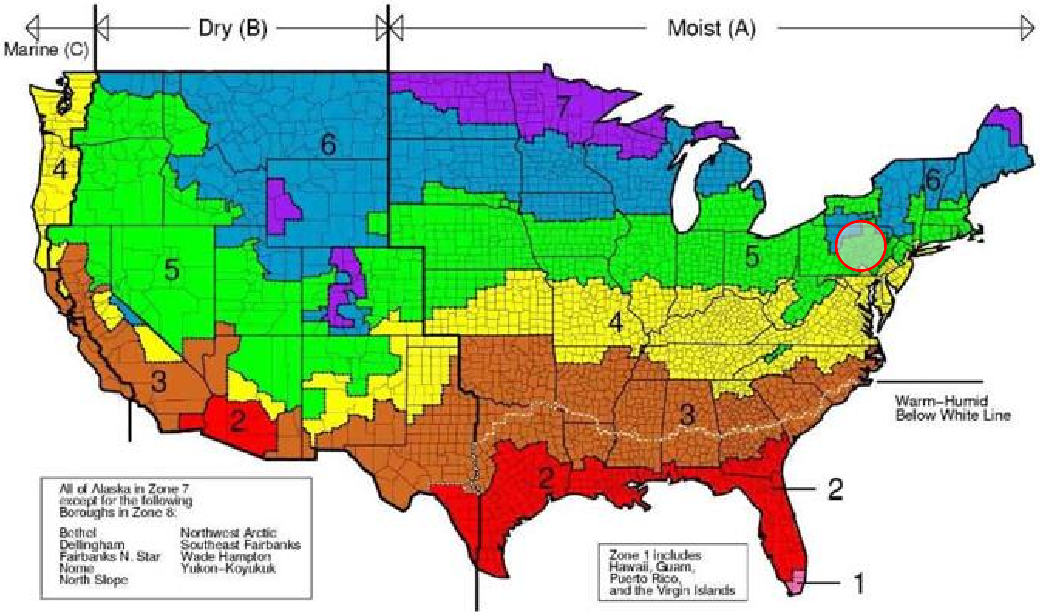


Figure 11. United States climate zones (IECC, 2016).

The single-family home was modeled and constructed using BEopt's input geometry screen. The 2000 sf detached single-family home was modeled as a two-story structure with a square footprint, measuring 32' x 32' (Figure 12). The house consisted of four bedrooms, three bathrooms, slab on grade foundation, and an unfinished attic. The house had a gable roof with a 6:12 roof pitch. Pennsylvania state averages were used for all utility assumptions including electricity and natural gas rates.

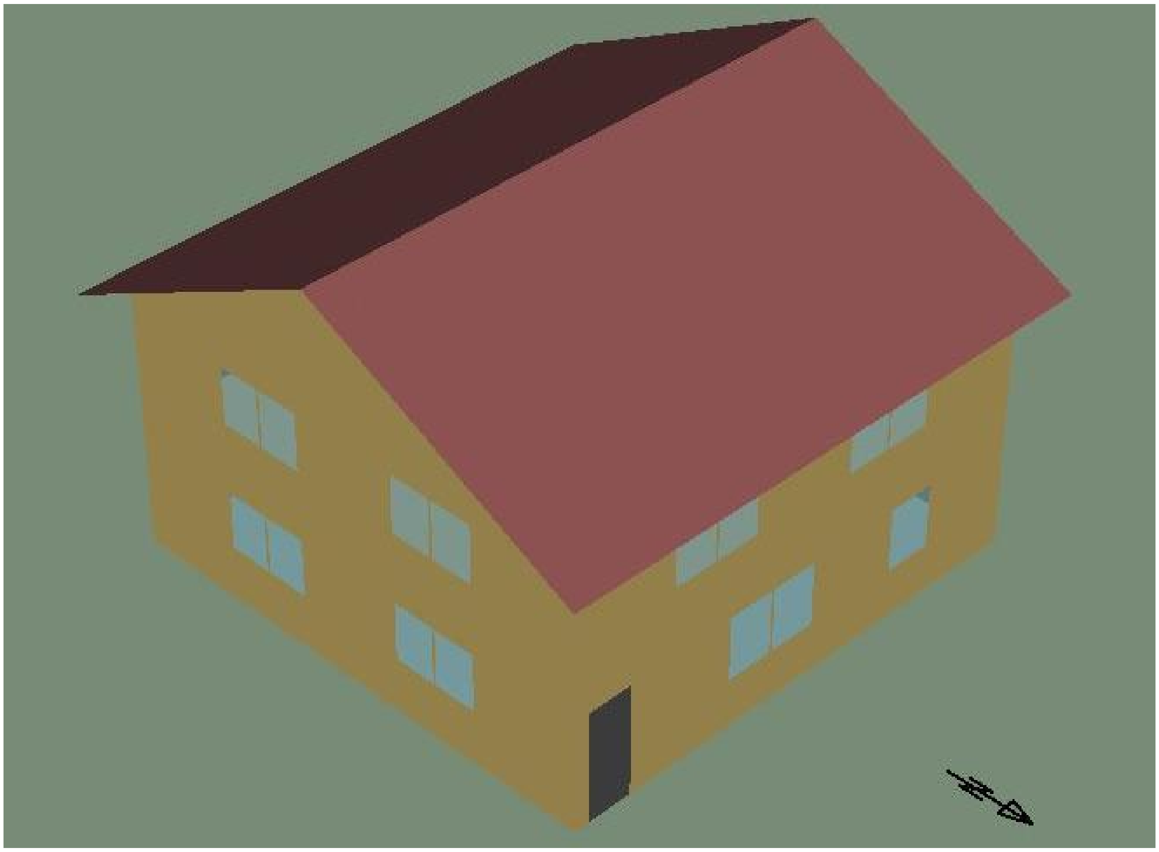


Figure 12. Baseline reference model depicted in BEopt modeling environment.

The entire home specifications and characteristics employed in modeling the baseline reference case are in Table 4.

Table 4. Baseline modeling specifications and characteristics, adopted from BEopt.

Building Components	Modeling Assumptions
Walls	R-13 Fiberglass Batt, 2x4, 16 in o.c. (8ft interior wall height)
Ceiling/Roof/Attic	R-30 Cellulose, Gr-1, Vented
Roof Material	Asphalt Shingles, Medium
Foundations/Floors-Slab	R-10
Floor Mass	Wood Surface, 0.625 in thick
Exterior Wall	½ in Drywall
Ceiling Mass	½ in Drywall
Window Type	Low-E, Double Pane, Non-metal, Argon, (U-value 0.35)
Window Area	15% of Wall Area for each façade (N, E, S, W)
Hot Water	Gas, Standard, 0.59 EF (Energy Factor)
Air Flow/Infiltration	10 ACH50 (Air Change per Hour)
Mechanical Ventilation	Exhaust, 2010 ASHRAE 62.2
Appliances	Standard
Space Conditioning	
Air Conditioner	SEER 13
Furnace	Gas, 78% AFUE, Gas
Conditioning Set Points	
Cooling	72 F
Heating	75 F
Humidity	55% RH
Plug Loads	Standard Option 4 (9597 KWh/unit/.yr)
Lighting	20% CFL
Weather File	TMY3 – Williamsport Regional Airport 725140

Modeling and Simulation Scenarios and Analyses

After establishing baseline parameters and benchmarks via NREL's BEopt platform, parametric modeling analysis commenced using the reference home as a starting point. The parametric modeling analysis targeted and explored various alternate sets of architectural variables in an effort to assess the impact on energy consumption. Modeling scenarios encompassed two main categories: (1) architectural design variables and (2) building system components. The modeling analysis examined the correlation between various architectural variable upgrades and overall performance. To that end, baseline parameters were upgraded, modeled, and simulated one variable at a time to effectively assess the significance of specific interventions on energy demand in the single-family home. Each modeling run entailed a set of independent and dependent variables. Energy consumption was deemed the dependent variable, while architectural factors constituted the independent variables.

Alternate Design-Modeling Runs

The first set of modeling scenarios encompassed the following architectural design variables: building footprint, roof characteristic (shape & pitch), building massing (number of floors), window area (WWR), building shape, and building orientation.

Parametric Design Modeling Run #1: Building Footprint

The first design runs examined the impact of building footprint variations on energy use. The exploration focused on compact design, starting with the baseline scenario (square footprint at 32' x 32' spanning two floors). All baseline assumptions, including building volume, overall size, construction specifications, number of floors, and design parameters, were maintained with the exception of the building footprint. The runs exclusively examined the impact of footprint modifications on energy use. Footprint variations were kept within a compact rectangular design approach. The parametric runs sought to examine the connection between building footprint variation and energy use intensity to assess the efficacy of such a change. Accordingly, the following run parameters (Figure 13) were then established, modeled, and evaluated using the Energy Plus simulation engine within NREL's BEopt energy simulation platform: footprint #1 (35' x 28'), footprint #2 (40' x 25'), footprint #3 (45' x 22'), and footprint #4 (50' x 20').

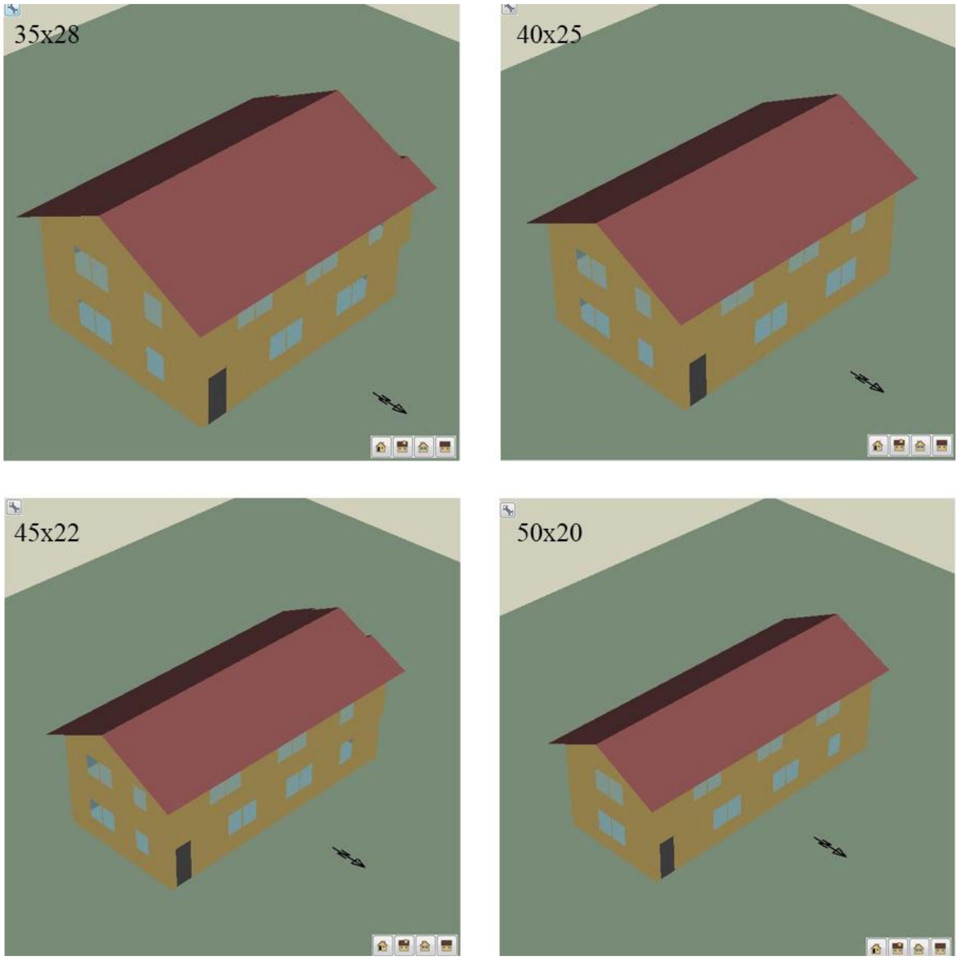


Figure 13. Images depicting the 4 modeled building footprint variations (BEopt).

Parametric Design Modeling Run #2: Roof Characteristic and Shape

The next set of parametric runs examined the impact of building roof variations on energy use. The investigation focused on roof pitch (slope & angle) and overall shape (gable & hip), starting with the baseline scenario (gable roof, 6:12 roof pitch, 32' x 32' building footprint, spanning two floors). All baseline assumptions were maintained with the exception of the building roof pitch and shape. The runs exclusively evaluated the impact of roof modifications on energy use to assess the efficacy of such a change. Accordingly, three sets of parameters were established and modeled. The first assessed gable-roof pitches variations: 1:12, 2:12, 3:12, 4:12, and 8:12 (Figure 14). The second assessed hip-roof pitch variations (flat and hip roof): 1:12. 2:12, 3:12, 4:12, 6:12, and 8:12 (Figure 15). The third examined a flat roof condition.

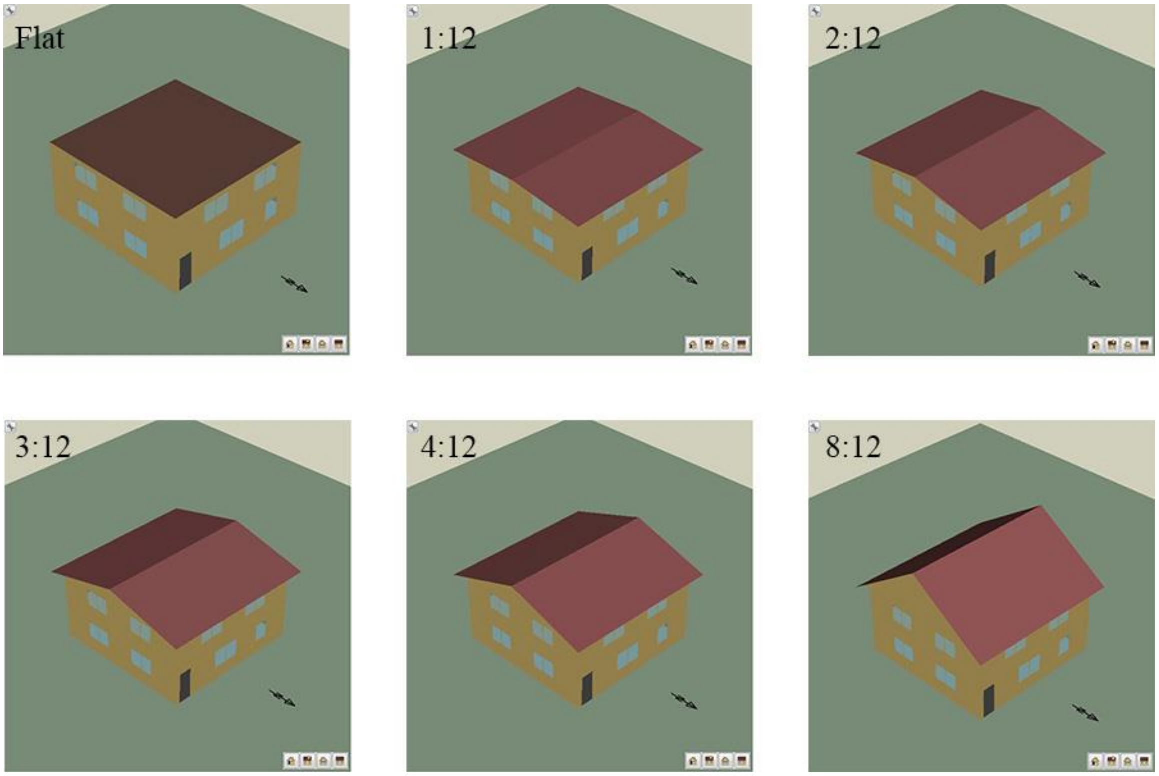


Figure 14. Images depicting the modeled gable-roof variations (BEopt).

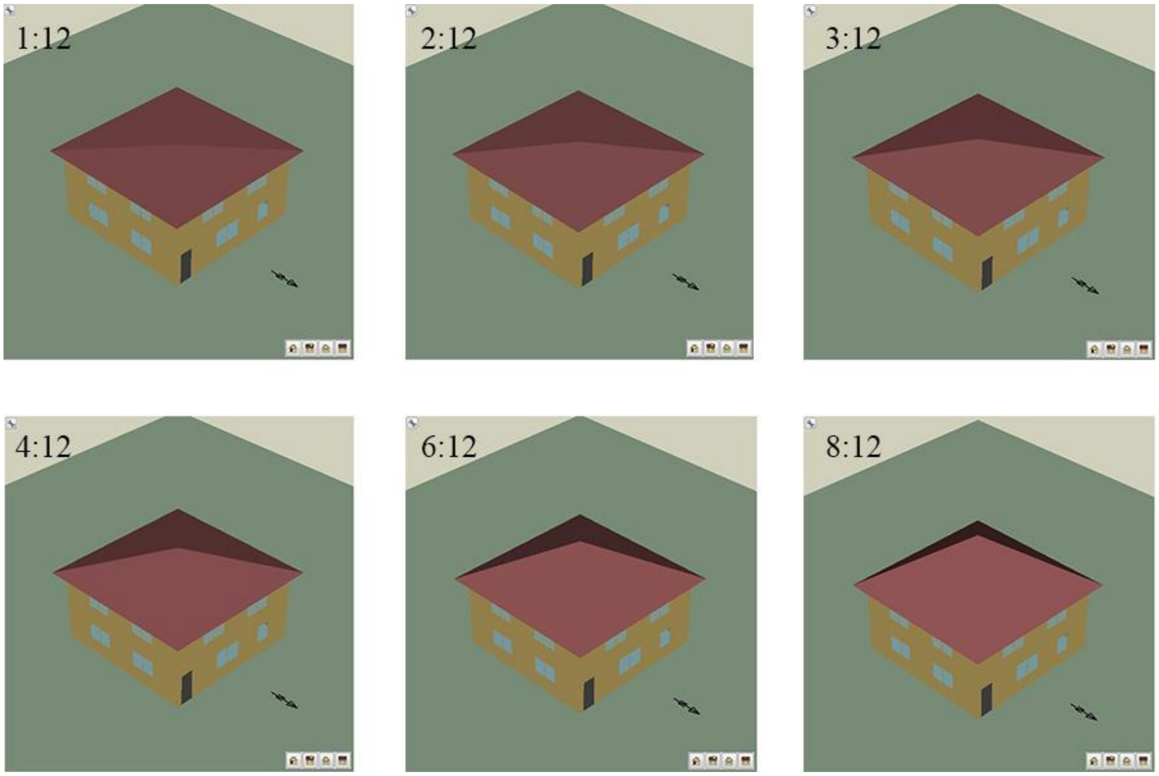


Figure 15. Images depicting the modeled hip-roof variations (BEopt).

Parametric Design Modeling Run #3: Massing (Number of Floors)

The next set of parametric runs tested the impact of varying the amount of floors on energy use. All baseline assumptions were maintained with the exception of the number of floors and associated building footprint. The runs solely assessed the impact of floor massing modifications to gauge the effectiveness of such an intervention. Two conditions were investigated encompassing one-story and three-story structures (Figure 16). Accordingly, the first set of modeled runs simulated a one-story building with the following parameters: 30’ x 60’ footprint, 35’ x 57’ footprint, 40’ x 50’ footprint, 45’ x 45’ footprint. The second set of runs modeled and simulated a three-story building with the following parameters: 27’ x 25’ footprint and 30’ x 22’ footprint.

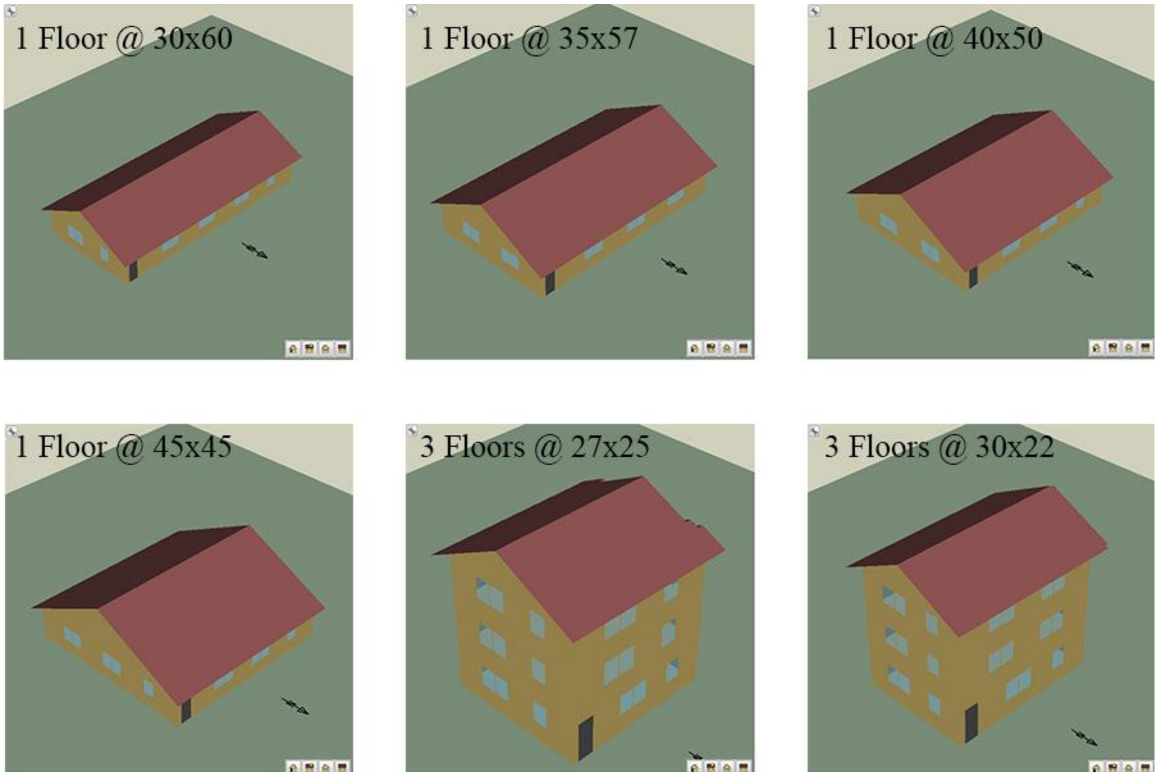


Figure 16. Images depicting the modeled number of floor variations (BEopt).

Parametric Design Modeling Run #4: Window Area Ratios (WWR)

Window area was targeted as the next set of parametric runs. Window area was defined as a fraction/percentage of each façade's exterior wall area. Window to wall ratio percentage variations were modeled to gauge the impact on energy. All baseline assumptions were maintained except for window area ratios. The runs started with the baseline assumption of 15% window area for each façade (North-N, South-S, East-E, and West-W – N15S15E15W15). The main premise of the investigation encompassed window area modifications on the southern, eastern, and western facades. The runs were modeled primarily to assess the impact of increasing the WWR on the southern envelope. Accordingly, the following iterations were modeled: N0S30E0W0, N0S30E0W5, N0S30E5W5, N0S30E0W15, N0S25E0W0, N0S25E0W5, N0S25E5W5, N0S25E5W15, N0S20E0W0, N0S20E0W5, N0S20E5W5, and N0S20E5W15 (Figure 17).

Figure 17. Images showing the modeled WWR variations (BEopt).

Parametric Design Modeling Run #5: Massing (Building Form)

The next set of runs examined the impact of varying the building shape on energy use. All baseline assumptions were maintained with the exception of building massing. The runs exclusively evaluated the impact of shape modifications, in order to assess the efficacy of such a change. Several iterations were modeled including the following building shapes: L-shape, U-shape, T-shape, and several overlapping shapes (Figure 18).

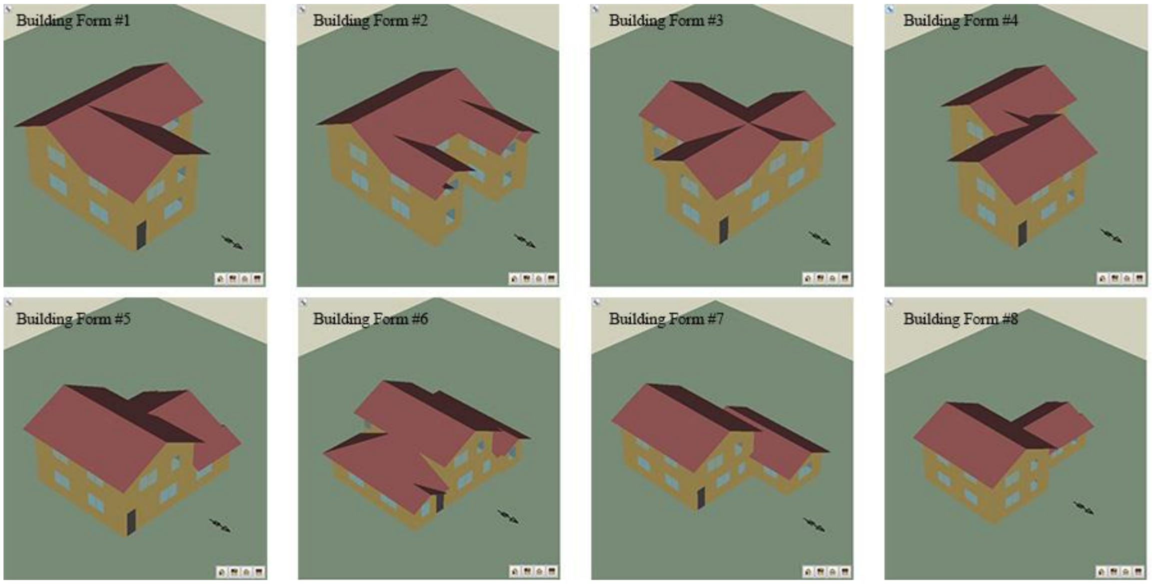


Figure 18. Models depicting simulated building shape variations (BEopt).

Parametric Design Modeling Run #6: Building Orientation

Building placement on site was the final investigated design variable. Orientation was measured via the azimuth angle in degrees, clockwise from south. Baseline orientation was defined and modeled as the direction faced by the front of the house (North facing façade, azimuth=180 degrees). All other building baseline assumptions were upheld. Accordingly, the parametric runs solely examined the impact of orientation shifts, in order to assess the usefulness of such a modification. The following iterations were modeled: south (azimuth=0 degrees), east (azimuth=270 degrees), west (azimuth=90 degrees), northeast (azimuth=225 degrees), northwest (azimuth=135 degrees), southeast (azimuth=315 degrees), and southwest (azimuth=45 degrees).

Alternate System-Modeling Runs

The second set of modeling scenarios entailed adopting upgraded building system variables including the following: envelope construction (walls, ceiling/roof, and foundation/floor), window types, HVAC specification (heating and cooling), domestic hot water systems, space-conditioning set points (heating, cooling, and relative humidity), lighting, appliances/fixtures, and plug loads.

Parametric System Modeling Run #1: Building Envelope (Walls, Roof, and Slab)

The first system-modeling runs examined the impact of building envelope variations on energy use. The runs specifically assessed the correlation between exterior envelope upgrades and overall performance. The exploration encompassed the following building envelope categories: wall construction, wall sheathing, ceiling/roof insulation, roof material, slab insulation, and exterior wall finishes. All other baseline assumptions were maintained as modeled initially. The parametric runs sought to examine the connection between building envelope variations and energy use intensity, and to assess the efficacy of such a change. Accordingly, specific targeted building envelope parameters were established, modeled, and simulated using the Energy Plus simulation engine within NREL's BEopt energy simulation platform (Table 5).

Table 5. Envelope specifications and characteristics, adopted from BEopt.

Envelope Systems	Modeling Assumptions
Wall Upgrade Options:	
1. Wood Stud	R-36 Closed Cell Spray Foam, 2x6, 24 in o.c.
2. Double Wood Stud	R-45 Fiberglass, Gr-1, 2x4 Staggered, 24 in o.c.
3. Steel Stud	R-25 Fiberglass Batt, 2x8, 24 in o.c.
4. Concrete Masonry Unit (CMU)	6" Perlite Filled, R-19 Fiberglass Batt, 2x6, 24 in o.c.
5. Structural Insulated Panels (SIPS)	R36, 9.4" EPS Core, Gypsum int.
6. Insulated Concrete Forms (ICF)	R23, 2" EPS, 12" Concrete, 2" EPS
Wall Sheathing	OSB, R-15 XPS
Exterior Finishes Options	Brick, Wood, or Vinyl
Ceiling/Roof Upgrades:	
• Ceiling Insulation	R-60 Closed Cell Spray Foam, Gr-1, Vented
• Roof Material	Asphalt Shingles, Medium color
• Radiant Barrier	Double-Sided, Foil
Foundation Upgrades:	
• Foundation/Floors	Whole Slab R40, R10 Gap XPS

Wood stud walls are standard framed walls with cavity insulation. Double wood stud walls are built from two parallel wood stud walls. Both stud walls and the space between them are filled with continuous insulation. Steel stud wall are standard steel framed walls with cavity insulation. Concrete masonry units are large rectangular concrete blocks used in wall construction. Structural insulated panels (SIPS) are a composite building material consisting of an insulating layer of rigid core insulation sandwiched between two layers of structural oriented strand board (OSB). Insulated concrete forms are another example of composite systems consisting of rigid plastic foam forms that hold concrete in place during curing and kept in place afterwards as thermal insulation for concrete wall.

Parametric System Modeling Run #2: Glazing Specifications

Given that windows are the weakest components within the building's thermal envelope, the next set of modeling runs evaluated the effect of glazing specification variations on energy consumption. The runs specifically examined the correlation between window-typology properties and overall performance. The simulation environment encompassed the following glazing categories: Thermal transmittance (U-value), number of window panes, solar heat gain coefficient (SHGC), emissivity rating (Low-E), window frame type/material, and air cavity characteristics (Table 6). Baseline window specifications were adopted as a starting point (Low-E, double Pane, non-metal, argon gas air cavity, and 0.35 U-value). All other assumptions were retained from the baseline condition. The parametric runs sought to examine the connection between building glazing upgrades and energy use intensity.

Table 6. Glazing specifications and characteristics, adopted from BEopt.

Glazing Systems	Modeling Assumptions
Window Options:	
• Typology #1	Low-E, Double Pane, Non-Metal Frame, Air cavity, High Gain, U-value @ 0.39, SHGC @ 0.53
• Typology #2	Low-E, Double Pane, Non-Metal Frame, Air cavity, Medium Gain, U-value @ 0.38, SHGC @ 0.44
• Typology #3	Low-E, Double Pane, Non-Metal Frame, Air cavity, Low Gain, U-value @ 0.37, SHGC @ 0.3
• Typology #4	Low-E, Double Pane, Non-Metal Frame, Argon Gas cavity, High Gain, U-value @ 0.37, SHGC @ 0.53
• Typology #5	Low-E, Double Pane, Non-Metal Frame, Argon Gas cavity, Low Gain, U-value @ 0.34, SHGC @ 0.3
• Typology #6	Low-E, Double Pane, Insulated Frame, Air cavity, High Gain, U-value @ 0.32, SHGC @ 0.56
• Typology #7	Low-E, Double Pane, Insulated Frame, Air cavity, Medium Gain, U-value @ 0.3, SHGC @ 0.46
• Typology #8	Low-E, Double Pane, Insulated Frame, Air cavity, Low Gain, U-value @ 0.29, SHGC @ 0.31
• Typology #9	Low-E, Double Pane, Insulated Frame, Argon Gas cavity, High Gain, U-value @ 0.29, SHGC @ 0.56
• Typology #10	Low-E, Double Pane, Insulated Frame, Argon Gas cavity, Medium Gain, U-value @ 0.27, SHGC @ 0.46
• Typology #11	Low-E, Double Pane, Insulated Frame, Argon Gas cavity, Low Gain, U-value @ 0.26, SHGC @ 0.31
• Typology #12	Low-E, Triple Pane, Non-Metal Frame, Air cavity, High Gain, U-value @ 0.3, SHGC @ 0.38
• Typology #13	Low-E, Triple Pane, Non-Metal Frame, Air cavity, Low Gain, U-value @ 0.29, SHGC @ 0.26

• Typology #14	Low-E, Triple Pane, Non-Metal Frame, Argon Gas cavity, High Gain, U-value @ 0.29, SHGC @ 0.38
• Typology #15	Low-E, Triple Pane, Non-Metal Frame, Argon Gas cavity, Low Gain, U-value @ 0.27, SHGC @ 0.26
• Typology #16	Low-E, Triple Pane, Insulated Frame, Air cavity, High Gain, U-value @ 0.21, SHGC @ 0.4
• Typology #17	Low-E, Triple Pane, Insulated Frame, Air cavity, Low Gain, U-value @ 0.19, SHGC @ 0.27
• Typology #18	Low-E, Triple Pane, Insulated Frame, Argon Gas cavity, High Gain, U-value @ 0.18, SHGC @ 0.4
• Typology #19	Low-E, Triple Pane, Insulated Frame, Argon Gas cavity, Low Gain, U-value @ 0.17, SHGC @ 0.27

Parametric System Modeling Run #3: HVAC Specifications

Heating and cooling account for approximately 48% of a typical household energy consumption (DOE, 2017). Efficient heating, ventilation, and air conditioning systems (HVAC) are paramount to ensuring optimal energy performance. Accordingly, the next set of modeling runs specifically examined the impact of HVAC system variations on energy consumption. All other baseline assumptions were kept as modeled originally. The parametric modeling runs sought to examine the connection between HVAC system variations and overall energy use intensity. A concerted effort was paid to heating systems specifications since the site of the study has a heating-dominated climate. The simulation encompassed the following categories: seasonal energy efficiency ratio (SEER/EER), annual fuel utilization efficiency (AFUE), heating and seasonal performance factor (HSPF), coefficient of performance (COP), duct leakage and insulation, dehumidifier energy factor, and ceiling fans ratings (Table 7).

Table 7. HVAC specifications and characteristics, adopted from BEopt.

HVAC Systems	Modeling Assumptions
System Options:	
1. Central Air Conditioner Furnace	SEER 24.5, EER 19.2Kbtu/KWh (E)-Electric, 100% AFUE, 1.0Btu/Btu (G)-Gas, 98% AFUE, 0.98 Btu/Btu (O)-Oil, 96% AFUE, 096Btu/Btu (P)-Propane, 96% AFUE, 096Btu/Btu
2. Air Source Heat Pump	SEER 22, 22Btu/W-h 10 HSPF Variable Speed Compressor
3. Ground Source Heat Pump	#1-EER 20.2, COP 4.2, Low-K soil, Standard grout #2-EER 20.2, COP 4.2, Low-K soil, Enhanced grout #3-EER 20.2, COP 4.2, High-K soil, Enhanced grout
Ducts	8 CFM25 per 100ft2, R-8
Ceiling Fans	Premium Efficiency, 100% Coverage
Dehumidifier	150 pints/day Ducted 3.7L/KWh Energy Factor

Parametric System Modeling Run #4: Hot Water System

The next set of modeling runs evaluated the impact of domestic hot water (DHW) system variations on overall energy performance. In an effort to determine the efficacy of such an intervention, the parametric runs specifically examined the correlation between hot water system specifications and the home’s energy use intensity. All other modeling assumptions were maintained as simulated in baseline conditions. The modeling investigation encompassed the following categories: water heater type, energy factor

(EF), volume, location, storage capacity, pipe insulation, pipe material, pipe layout, and fuel type (Table 8).

Table 8. DHW specifications and characteristics, adopted from BEopt.

DHW Systems	Modeling Assumptions
System Options:	
1. Electric Premium	0.95 EF, 66 gal/unit Tank, Electric Fuel
2. Electric Tankless	0.99 EF, Tankless, Electric Fuel
3. Gas Premium, Condensing	0.82 EF, 50 gal/unit Tank, Gas Fuel
4. Gas Tankless, Condensing	0.96 EF, Tankless, Gas Fuel
5. Propane Premium, Condensing	0.82 EF, 50 gal/unit Tank, Propane Fuel
6. Propane Tankless	0.82 EF, Tankless, Propane Fuel
7. Heat Pump Water Heater #1	2.35 EF, 50 gal/unit, Electric Fuel, 140F
8. Heat Pump Water Heater #2	2.35 EF, 50 gal/unit, Electric Fuel, Confined
9. Heat Pump Water Heater #3	2.30 EF, 80 gal/unit, Electric Fuel
Distribution Systems	Pipe Insulation: R-5 Pipe Layout: Trunk Branch Pipe Material: PEX pipes Recirculation Type: Timer Controls
Location	Interior Living Space

Parametric System Modeling Run #5: Space-Conditioning Set Points & Schedules

The next set of parametric runs assessed the impact of space-conditioning schedule and set point changes on overall energy consumption. The runs specifically examined the relationship between heating and cooling conditioning temperature variations and energy use intensity, in an effort to evaluate the effectiveness of such a change. All other baseline assumptions were retained as modeled initially, including conditioning systems and their associated humidity set points. The simulation analysis investigated the following measures: cooling set points and setbacks, heating set points and setbacks, relative humidity set points, programmable thermostat, and space-conditioning weekday and weekend schedules (Table 9).

Table 9. Conditioning set points and schedules, adopted from BEopt.

Conditioning Set Points	**Schedule Assumptions**
Cooling Set Points Options:	**Schedule Options**
Setting #1 - 76 F	With Setback @ 85F Weekday: 9am-5pm
Setting #2 - 76 F	With Setback @ 81F Daily: 9am-4pm
Setting #3 - 76 F	Demand Response w/ Direct Load Control
Setting #4 - 76 F	Demand Response w/ Direct Load Control With Setback @ 85F Weekday: 9am-5pm
Setting #5 - 76 F	Demand Response w/ Direct Load Control-Precooling
Heating Set Points	**Schedule Options**
• 71 F	With Setback @ 65F Weekday: 9am-5pm & 11pm-6am, and @ 65F Weekend: 11pm-6am
Humidity Set Points	55%

Parametric System Modeling Run #6: Lighting

Lighting upgrades were modeled next to assess the impact of such an intervention on overall energy consumption. The parametric runs explicitly tested the correlation between lighting system variations and energy use intensity. All other assumptions were retained from baseline conditions. The modeling analysis started from the baseline scenario of 20% compact fluorescent lights (CFL). Thereafter, the simulation evaluated the following three categories: first-100% CFL, second-100% light-emitting diodes (LED), and third-100% LED with low efficacy.

Parametric System Modeling Run #7: Appliances and Fixtures

The next set of runs examined the impact of appliance and fixture upgrades on energy performance in the single-family home. The parametric runs sought to assess the significance of appliance variations on overall energy use intensity. All other baseline assumptions were kept. The simulation analysis evaluated the following fixtures: refrigerator, cooking range, dishwasher, clothes washer, and clothes dryer (Table 10).

Table 10. Appliances and fixtures specifications, adopted from BEopt.

Appliances	**Modeling Assumptions**
Refrigerator	Top Freezer, EF=21.9 lb/KWh, Electric use 348KWh/yr
Cooking Range	Gas, 80% usage, Gas use 27therms/unit/yr
Dishwasher	290 rated KWh, DR Control. Electric use 96.9KWh/yr
Clothes Washer	EnergyStar, 80% usage, Electric use 32.6KWh/unit/yr
Clothes Dryer	1. Electric Premium, EF=3.93lb/KWh 2. Electric, Heat Pump, Ventless. EF=4.2lb/KWh 3. Gas Premium, EF=3.48lb/KWh

Parametric System Modeling Run #8: Plug Loads

The final set of parametric system runs assessed the effect of plug loads on energy consumption. Plug loads constitute energy consumed by equipment powered via an alternate current plug. This include all electric loads excluding major end uses such as HVAC, water heating, and lighting. The BEopt platform also excluded appliances and fixtures from plug load energy calculation. Simulation analysis assumed a plug-load annual electric use of 600KWh/unit/yr.

Chapter III

Results

Energy modeling results of the baseline scenario are presented first, to be followed by findings from the parametric runs. Simulation results from each category of variables are presented with a brief description and summary of findings, including data charts on energy use intensity (EUI), site energy (energy measured at the meter), site electricity, source energy (energy measured at the power plant-3 times the site energy), energy rating index (HERS rating-a score from 0 to 150, with 0 reflecting a net zero rating compared to a standard newly constructed home at 100), and greenhouse gas emissions (CO^2).

Baseline Modeling Run Results

The baseline modeling run yielded an EUI of 90.75KBtu/sf/yr, which is equitable with the industry standard of newly constructed home's EUI of 100 KBtu/sf/yr (Figure 19). Similarly, total annual site energy was 181.5 MMBtu (Figure 19). Furthermore, site electricity and source energy results are within the predictable range of an average newly code-constructed single-family detached home. Baseline simulation results are within the margin of error for acceptable data points as compared to an actual built home (EIA, 2017). Nonetheless, baseline results show heating as the dominant and prevalent end-use consuming energy load (Table 11).

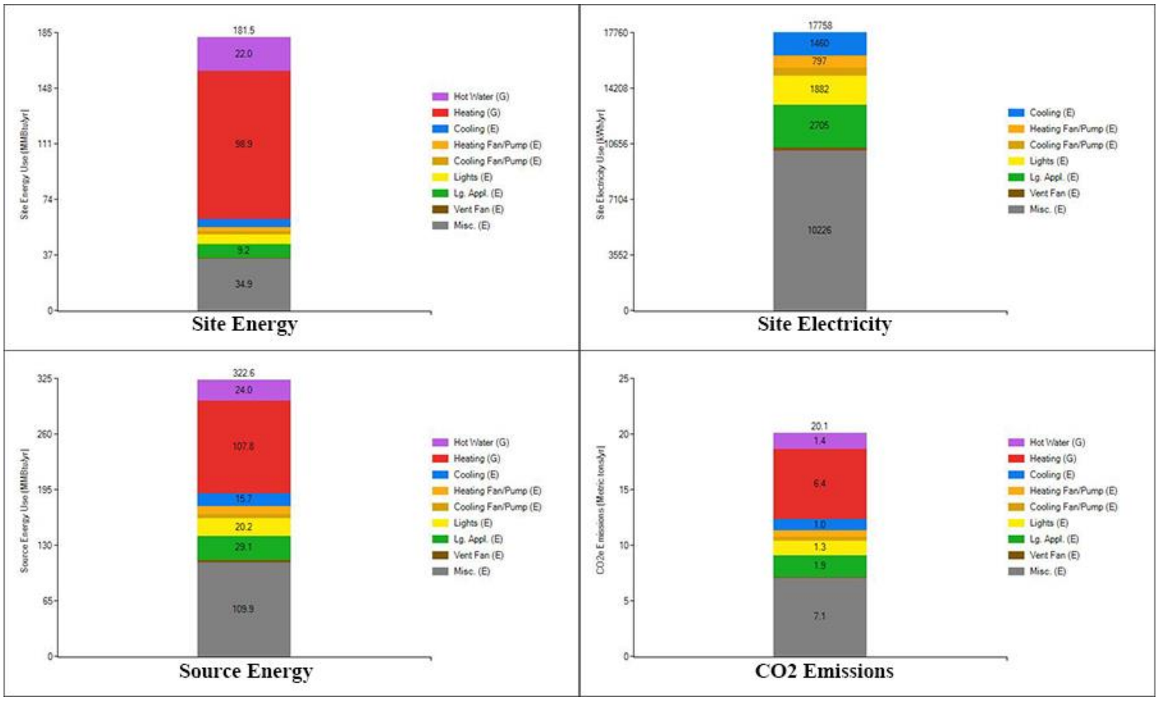


Figure 19. Total annual baseline energy consumption result, adopted from BEopt.

Table 11. Total annual baseline site energy use, adopted from BEopt.

Energy End Use	**Site Energy Consumption (MMBtu)**
Hot Water (Gas)	22.01
Heating (Gas)	98.86
Cooling (Electricity)	4.98
Heating Fan/Pump (Electricity)	2.72
Cooling Fan/Pump (Electricity)	1.74
Lights (Electricity)	6.42
Large Appliances (Electricity)	9.23
Ventilation Fan (Electricity)	0.61
Miscellaneous (Electricity)	34.89
Total	**181.5**

Parametric Design Modeling Run #1 Results: Design-Building Footprint

Simulation results revealed reductions in total annual energy consumption in two (40’ x 25’ footprint, and 35’ x 28’ footprint) of the four modeled parametric runs; the other two runs (45’ x 22’ footprint, and 50’ x 20’ footprint) showed an increase in energy use, compared to the baseline condition (Figure 20). Nonetheless, the 40’ x 25’ building footprint iteration proved to be the largest energy saver among all 4 runs, yielding a 5.39% reduction from the baseline (Table 12). Accordingly, the 40’x 25’ footprint option was the only run able to clear the required set benchmark of 5% improvement over baseline, the stated optimal energy performance indicator metric (Figure 21).

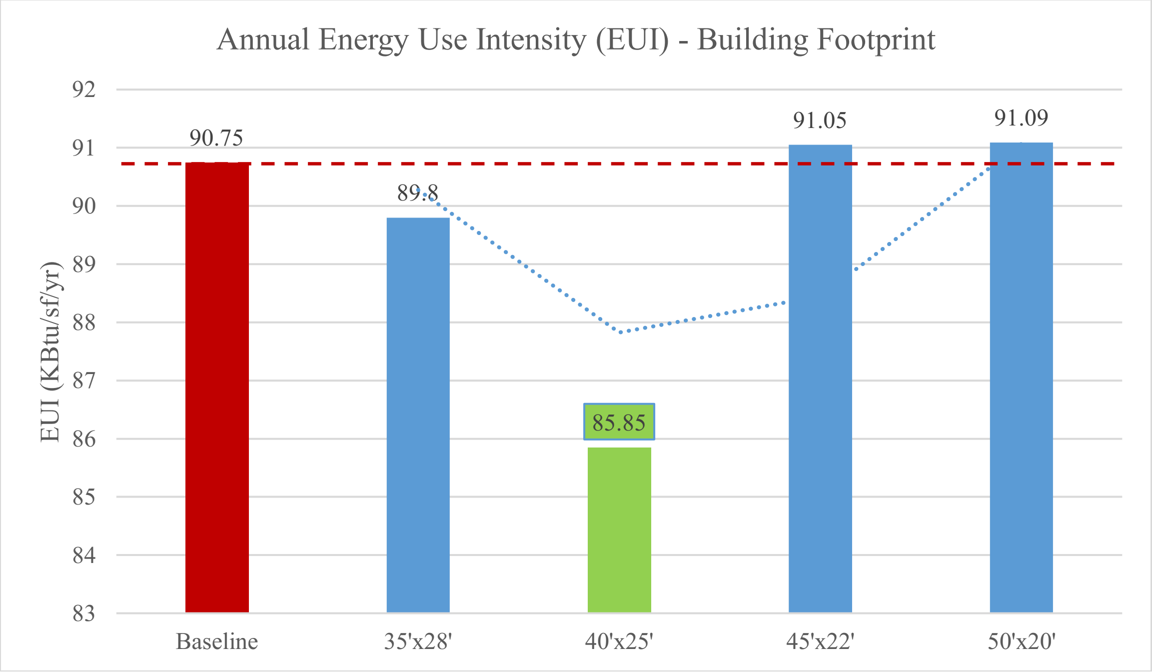


Figure 20. Energy use intensity for modeled footprint parametric runs. Baseline energy consumption indicated by dashed red line.

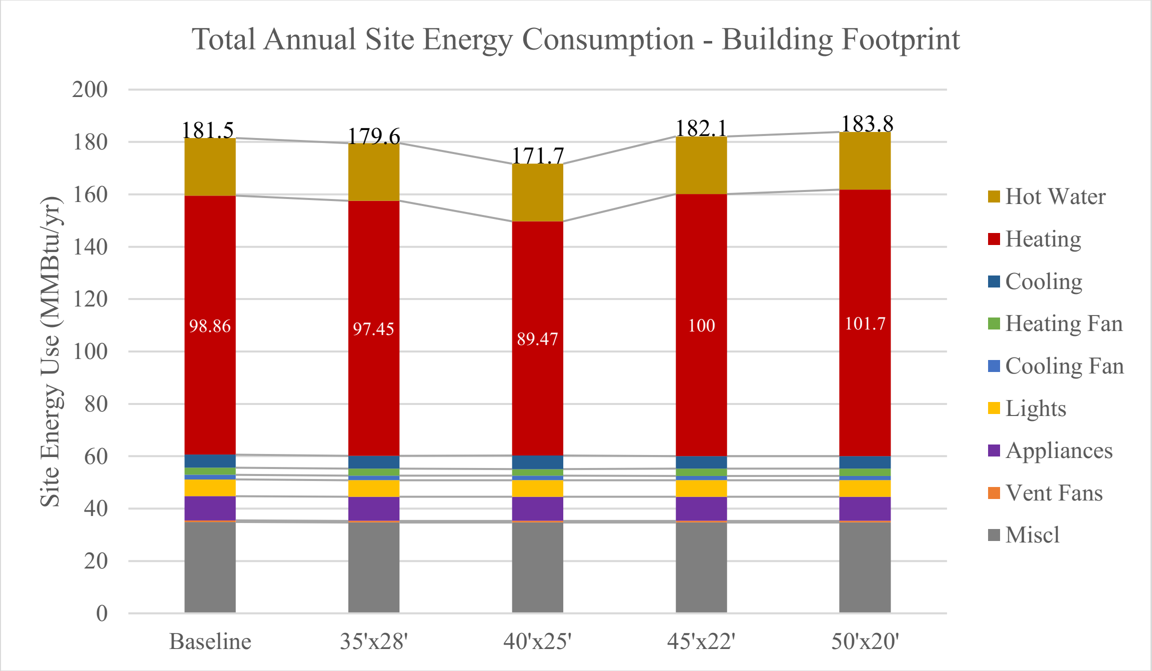


Figure 21. Site energy use for modeled footprint parametric runs.

Table 12. Building footprint simulation results.

Building Footprint Options	Site Electricity	Source Energy	CO2 Emissions	HERS Rating
35’ x 28’	17614 KWh	319.5 MMBtu	19.9 Metric Tons/yr	111.5
40’ x 25’	17652 KWh	311.2 MMBtu	19.4 Metric Tons/yr	107.8
45’ x 22’	17594 KWh	322.2 MMBtu	20 Metric Tons/yr	111.3
50’ x 20’	17597 KWh	324.1 MMBtu	20.2 Metric Tons/yr	111.3

Parametric Design Modeling Run #2 Results: Roof Characteristic and Shape

The flat roof performed most optimally compared to all other runs, yielding a 10.3% energy reduction over the baseline (Figure 22). All other runs failed to break the required 5% improvement over baseline threshold (Figure 23). Findings showed a correlation between roof flatness and overall energy consumption (Table 13).

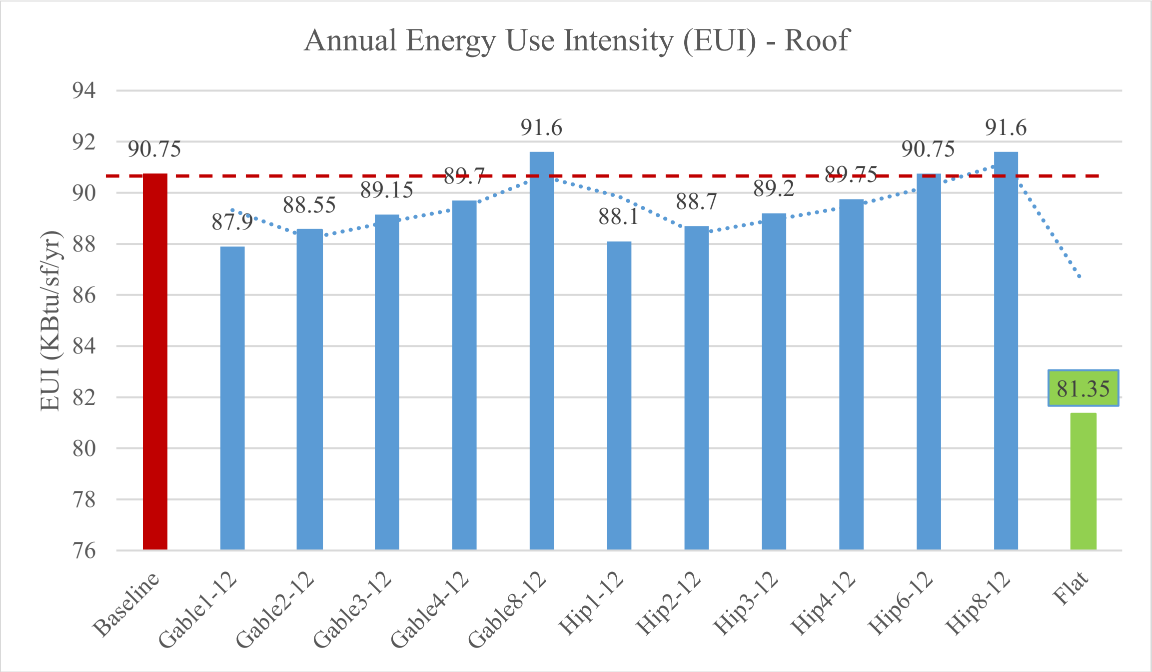


Figure 22. Energy use intensity for modeled roof parametric runs.

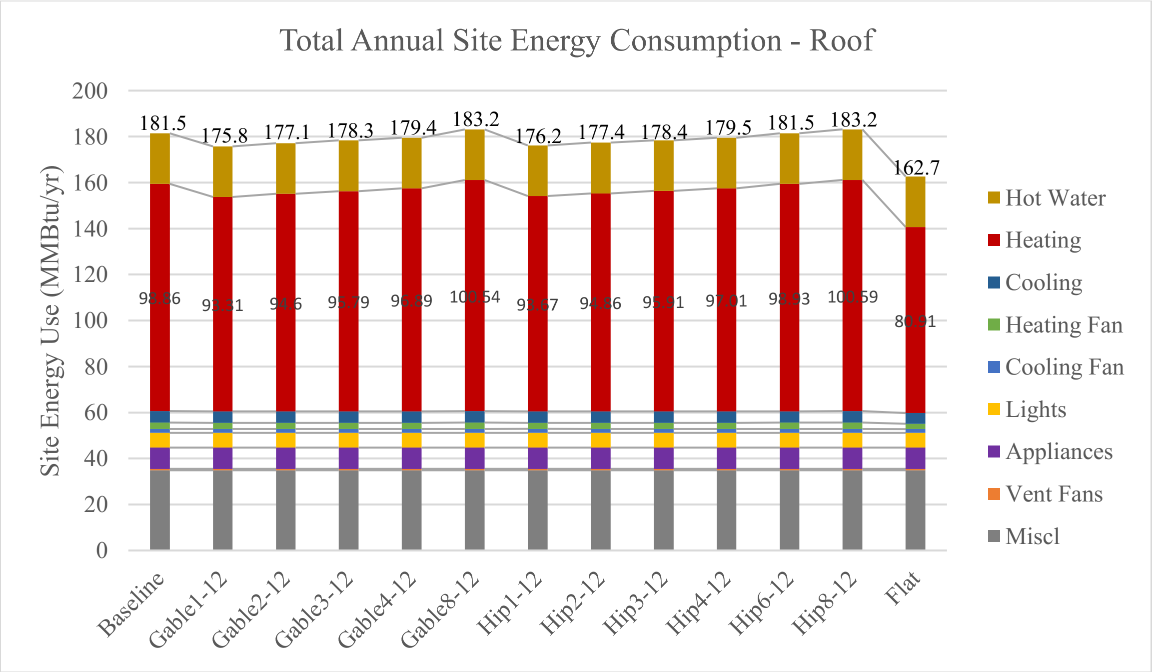


Figure 23. Site energy use for modeled roof parametric runs.

Table 13. Building roof simulation results.

Building Roof Options	Site Electricity	Source Energy	CO2 Emissions	HERS Rating
Gable 1-12	17717 KWh	316.1 MMBtu	19.7 Metric Tons/yr	108.2
Gable 2-12	17726 KWh	317.6 MMBtu	19.8 Metric Tons/yr	109.2
Gable 3-12	17734 KWh	319.1 MMBtu	19.9 Metric Tons/yr	110
Gable 4-12	17743 KWh	320.3 MMBtu	19.9 Metric Tons/yr	110.8
Gable 8-12	17761 KWh	324.5 MMBtu	20.2 Metric Tons/yr	113.2
Hip 1-12	17726 KWh	316.6 MMBtu	19.7 Metric Tons/yr	108.2
Hip 2-12	17726 KWh	317.9 MMBtu	19.8 Metric Tons/yr	109.1
Hip 3-12	17723 KWh	319 MMBtu	19.9 Metric Tons/yr	109.9
Hip 4-12	17732 KWh	320.3 MMBtu	20 Metric Tons/yr	110.6
Hip 6-12	17740 KWh	322.5 MMBtu	20.1 Metric Tons/yr	111.9
Hip 8-12	17752 KWh	324.4 MMBtu	20.2 Metric Tons/yr	113.1
Flat	17512 KWh	300.4 MMBtu	18.8 Metric Tons/yr	99.8

Parametric Design Modeling Run #3 Results: Massing (Number of Floors)

The one-story structure performed better than its three-story counterpart. Specifically, the one-story 40’ x 50’ massing option yielded energy reductions of 12.3% compared to the baseline. All other options were unsuccessful in attaining the required 5% improvement over baseline threshold (Figures 24 & 25). Furthermore, the three-story options caused a considerable spike in energy consumption over the baseline. Simulation results point to a clear advantage in overall energy performance when adopting a one-story building approach with a compact and slightly rectangular building footprint (Table 14). A one-story house is typically easier to heat and cool due to the laws of physics governing the movement of air.

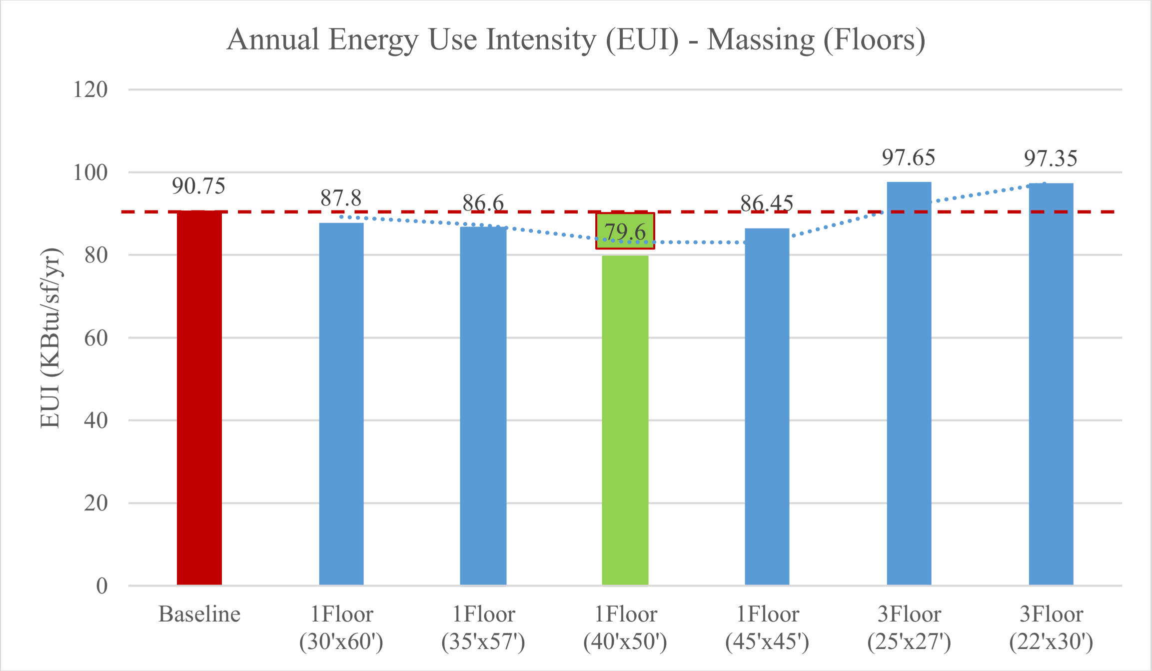


Figure 24. Energy use intensity for modeled floor massing runs.

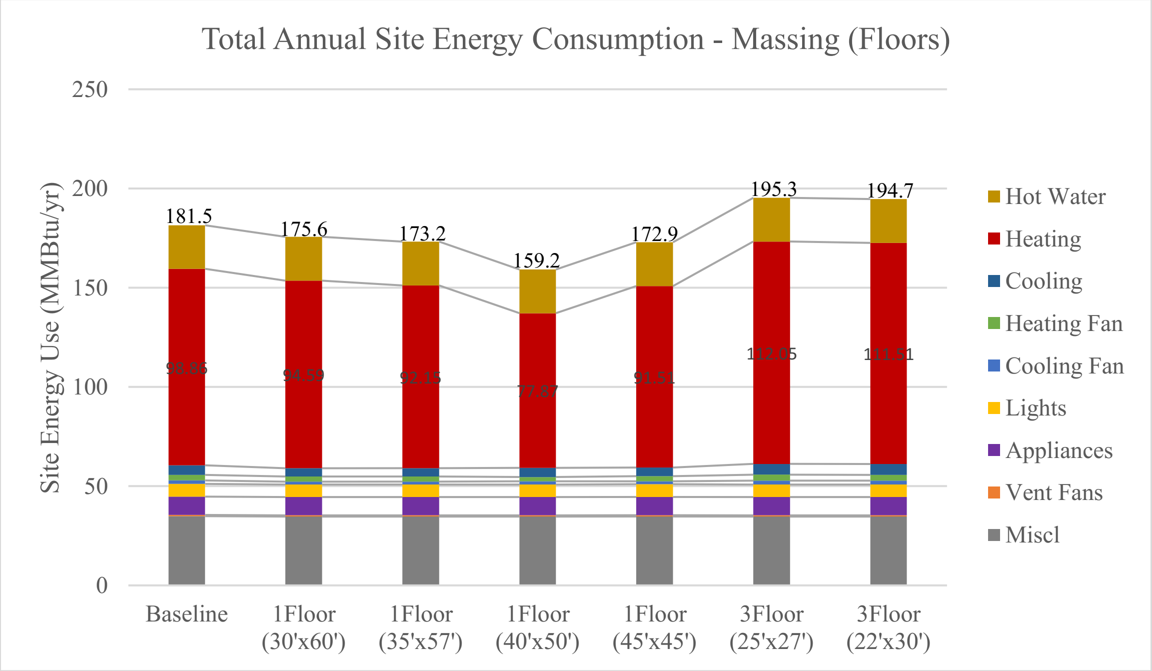


Figure 25. Site energy use for modeled floor massing runs.

Table 14. Floor massing simulation results.

Floor Massing Options	Site Electricity	Source Energy	CO2 Emissions	HERS Rating
1Floor (30’ x 60’)	17301 KWh	313 MMBtu	19.5 Metric Tons/yr	111.3
1Floor (35’ x 57’)	17307 KWh	310.5 MMBtu	19.3 Metric Tons/yr	111
1Floor (40’ x 50’)	17383 KWh	295.7 MMBtu	18.5 Metric Tons/yr	104.7
1Floor (45’ x 45’)	17400 KWh	310.8 MMBtu	19.4 Metric Tons/yr	111.2
3Floor (25’ x 27’)	17948 KWh	339 MMBtu	21.1 Metric Tons/yr	113.5
3Floor (22’ x 30’)	17919 KWh	338.1 MMBtu	21 Metric Tons/yr	113.1

Parametric Design Modeling Run #4 Results: Window Area (WWR)

All runs were able to meet the required 5% improvement over baseline threshold (Figure 26). Furthermore, all options performed relatively equally (Figure 27). However, the largest energy reductions were experienced with three specific runs, yielding a 7.7% reduction over baseline: 30%, 25%, and 20% south-facing WWR with no windows on the 3 remaining sides (Figure 26). Results revealed a trend of higher energy use with more east and west-facing windows (Table 15).

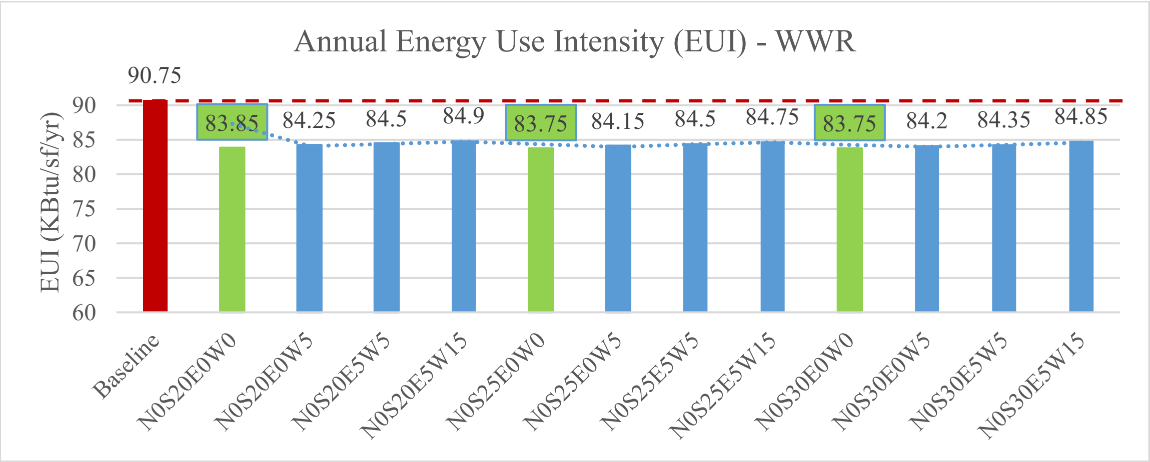


Figure 26. Energy use intensity for modeled window area runs.

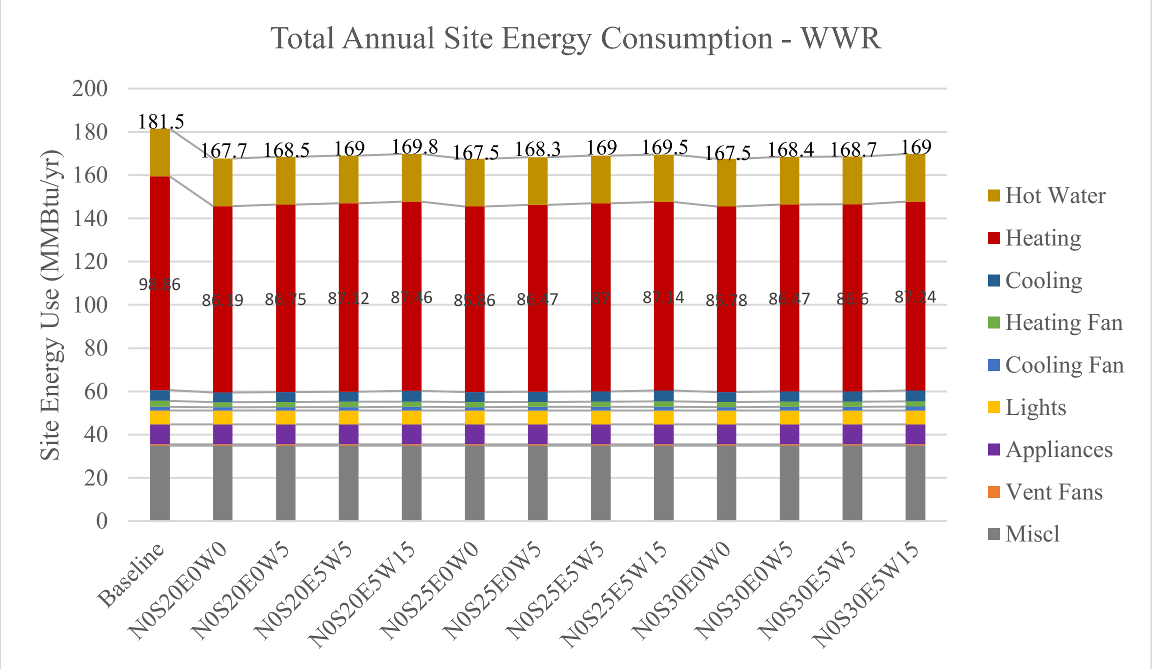


Figure 27. Site energy use for modeled window area runs.

Table 15. Window area simulation results.

WWR Options	Site Electricity	Source Energy	CO2 Emissions	HERS Rating
N0S20E0W0	17430 KWh	305.3 MMBtu	19 Metric Tons/yr	103.1
N0S20E0W5	17494 KWh	306.6 MMBtu	19.1 Metric Tons/yr	103.7
N0S20E5W5	17550 KWh	307.6 MMBtu	19.2 Metric Tons/yr	104.2
N0S20E5W15	17670 KWh	309.2 MMBtu	19.3 Metric Tons/yr	105.5
N0S25E0W0	17474 KWh	305.4 MMBtu	19.1 Metric Tons/yr	102.9
N0S25E0W5	17535 KWh	306.7 MMBtu	19.1 Metric Tons/yr	103.6
N0S25E5W5	17585 KWh	307.8 MMBtu	19.2 Metric Tons/yr	104.1
N0S25E5W15	17691 KWh	309.1 MMBtu	19.3 Metric Tons/yr	105.5
N0S30E0W0	17506 KWh	305.6 MMBtu	19.1 Metric Tons/yr	102.9
N0S30E0W5	17564 KWh	307.1 MMBtu	19.2 Metric Tons/yr	103.5
N0S30E5W5	17608 KWh	307.7 MMBtu	19.2 Metric Tons/yr	104
N0S30E5W15	17723 KWh	309.6 MMBtu	19.3 Metric Tons/yr	105.5

Parametric Design Modeling Run #5 Results: Massing (Building Form)

The parametric runs explored the impact of changing the compact house design via multiple iterations of volumetric spatial studies. Most options yielded a larger building mass and ground-level footprint. Accordingly, all simulated runs failed to meet or exceed the required 5% improvement over baseline threshold (Figures 28 & 29). Results revealed a significant spike in energy use when deviating from a compact building mass into a more sprawling spatial form and footprint (Table 16). The introduction of more surface area to the home's overall form and mass, relative to volume, resulted in significantly higher energy use and lower performance. Consequently, energy consumption seemed to be strongly correlated with building form and shape alteration, albeit in a negative way when deviating from a compact form.

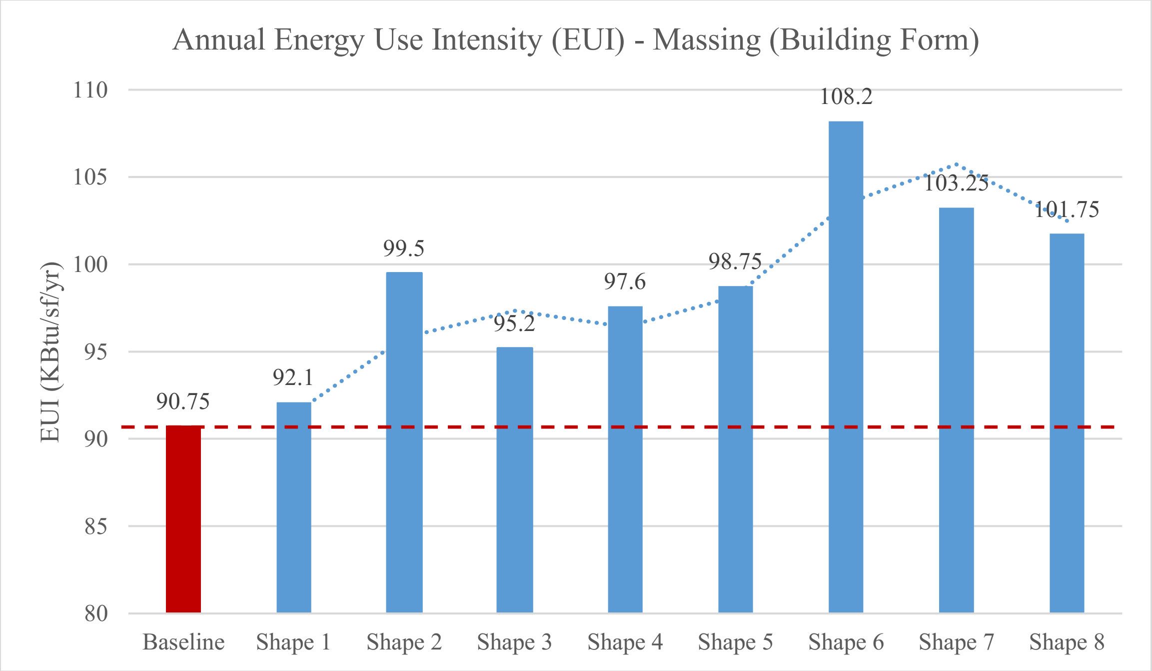


Figure 28. Energy use intensity for modeled massing form runs.

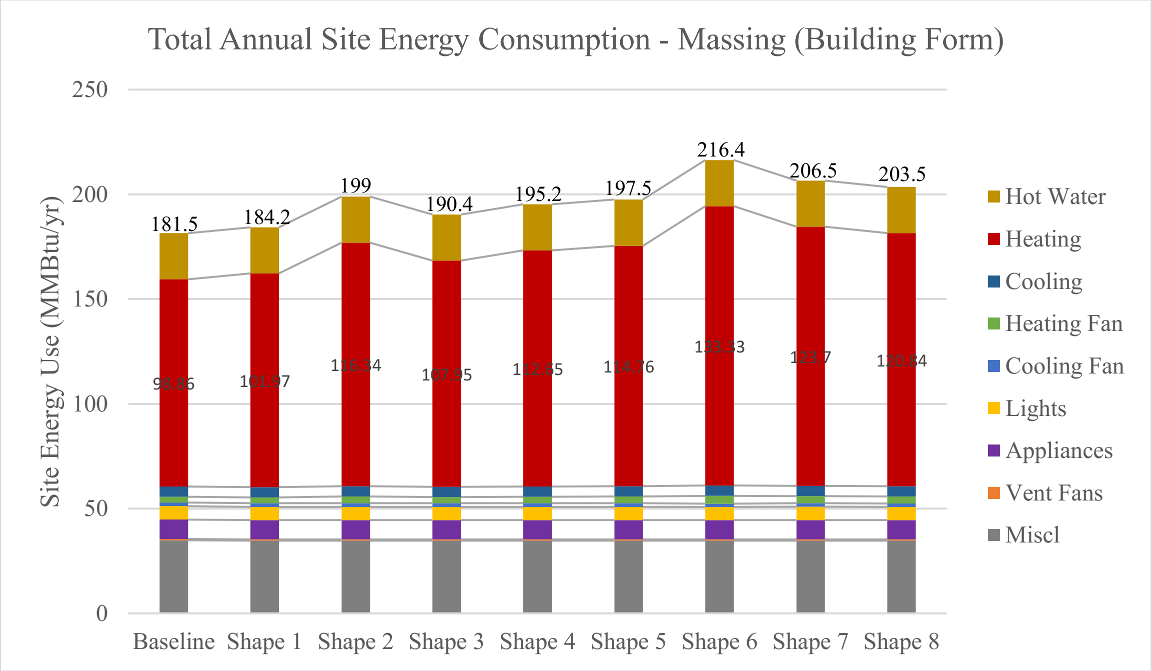


Figure 29. Site energy use for modeled massing form runs.

Table 16. Building massing form simulation results.

Massing Form Options	Site Electricity	Source Energy	CO2 Emissions	HERS Rating
Shape 1	17655 KWh	324.9 MMBtu	20.2 Metric Tons/yr	112
Shape 2	17770 KWh	341.8 MMBtu	21.2 Metric Tons/yr	114.7
Shape 3	17696 KWh	331.9 MMBtu	20.6 Metric Tons/yr	112.7
Shape 4	17743 KWh	337.5 MMBtu	21 Metric Tons/yr	113.6
Shape 5	17790 KWh	340.3 MMBtu	21.1 Metric Tons/yr	117.8
Shape 6	17890 KWh	361.6 MMBtu	22.4 Metric Tons/yr	122.9
Shape 7	17825 KWh	350.4 MMBtu	21.7 Metric Tons/yr	119.6
Shape 8	17773 KWh	346.8 MMBtu	21.5 Metric Tons/yr	118.9

Parametric Design Modeling Run #6 Results: Building Orientation

The last design modeling iterations encompassed building orientation analysis. All runs failed to meet the required 5% improvement over baseline threshold (Figures 30

& 31). Moreover, the findings revealed minimal impacts on energy consumption when deviating from the baseline condition (Table 17).

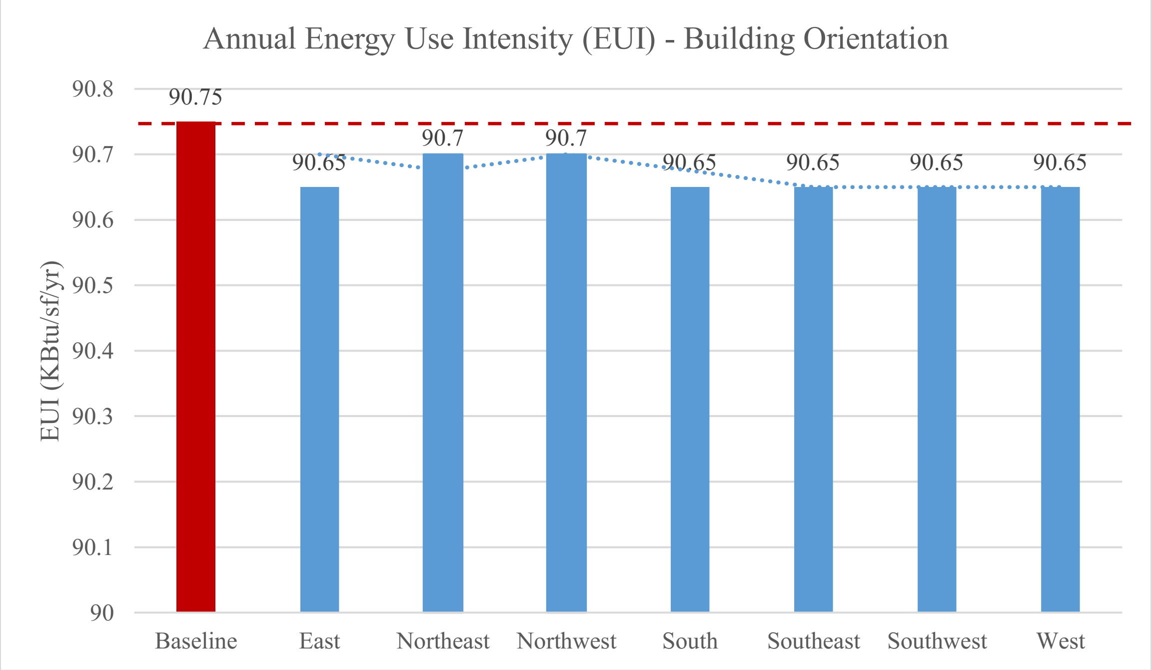


Figure 30. Energy use intensity for modeled building orientation runs.

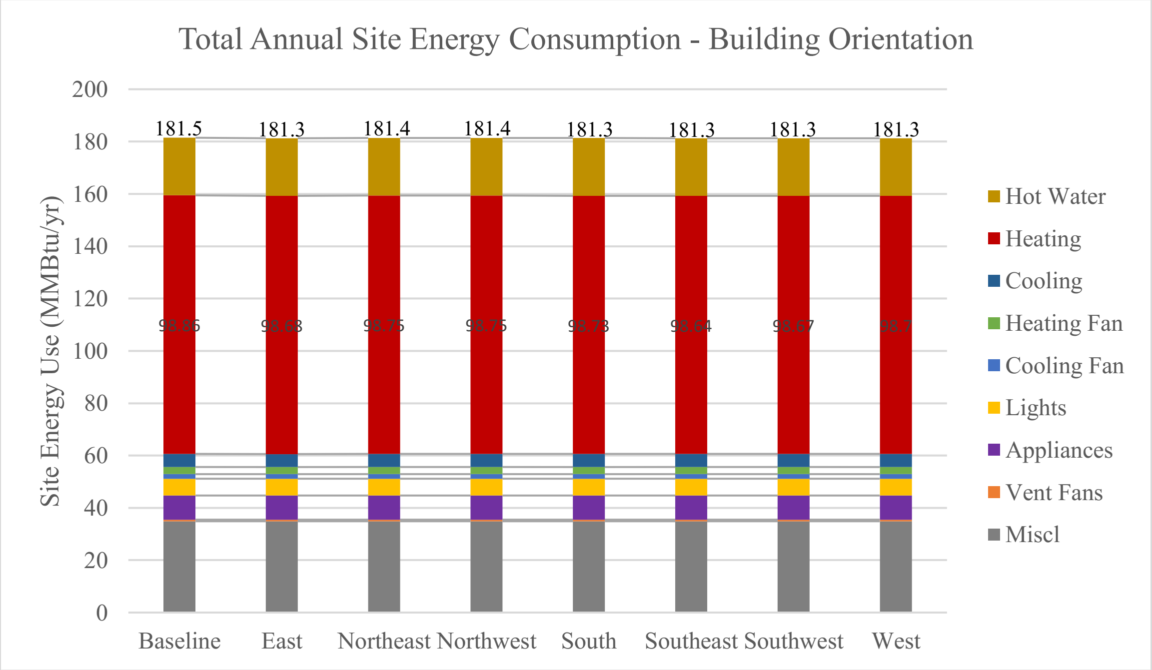


Figure 31. Site energy use for modeled building orientation runs.

Table 17. Building Orientation simulation results.

Building Orientation Options	Site Electricity	Source Energy	CO2 Emissions	HERS Rating
East	17752 KWh	322.4 MMBtu	20.1 Metric Tons/yr	112
Northeast	17770 KWh	322.6 MMBtu	20.1 Metric Tons/yr	112.2
Northwest	17770 KWh	322.6 MMBtu	20.1 Metric Tons/yr	112.3
South	17755 KWh	322.5 MMBtu	20.1 Metric Tons/yr	112
Southeast	17770 KWh	322.5 MMBtu	20.1 Metric Tons/yr	112.2
Southwest	17767 KWh	322.5 MMBtu	20.1 Metric Tons/yr	112.2
West	17755 KWh	322.4 MMBtu	20.1 Metric Tons/yr	112

Parametric System Modeling Run #1 Results: Building Envelope

The first set of system runs examined the impact of envelope modifications on energy use. The analysis examined exterior walls, roof, and slab. All runs consistently surpassed the required 5% improvement over baseline threshold (Figures 32 & 33). Moreover, the structural insulated panel (SIP) wall system yielded the largest energy savings, a 25% reduction from the baseline condition (Table 18).

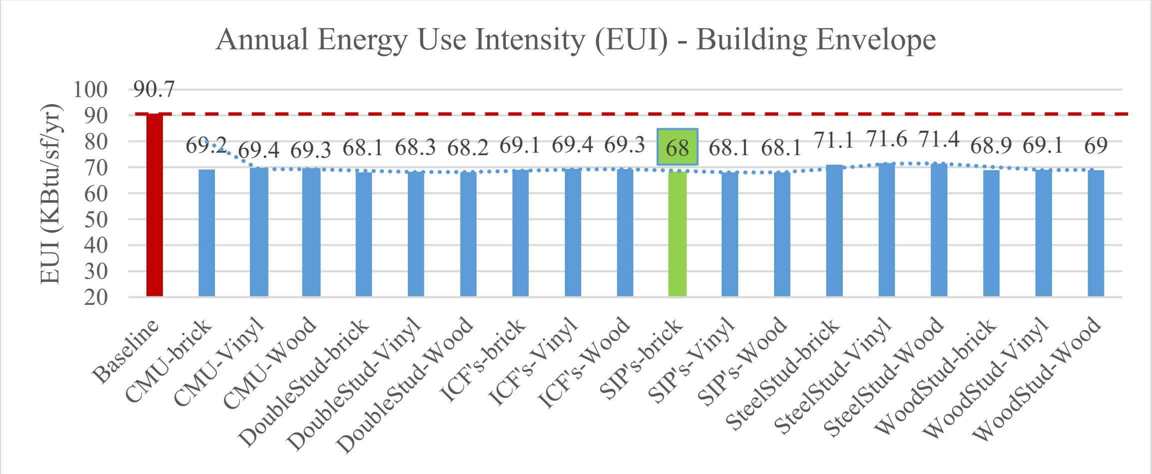


Figure 32. Energy use intensity for modeled building envelope runs.

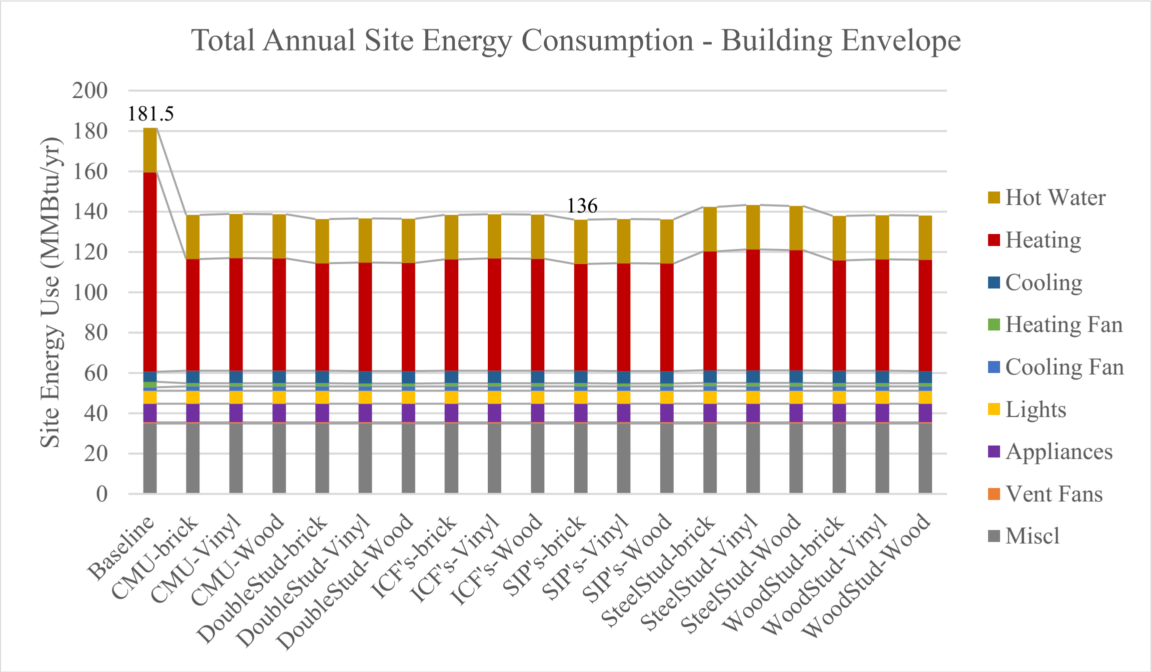


Figure 33. Site energy use for modeled building envelope runs.

Table 18. Building envelope simulation results.

Building Envelope Options	Site Electricity	Source Energy	CO2 Emissions	HERS Rating
CMU-brick	17925 KWh	276.9 MMBtu	17.4 Metric Tons/yr	90.4
CMU-Vinyl	17893 KWh	277.2 MMBtu	17.4 Metric Tons/yr	90.5
CMU-Wood	17893 KWh	276.9 MMBtu	17.4 Metric Tons/yr	90.4
Double Stud-brick	17893 KWh	274.4 MMBtu	17.3 Metric Tons/yr	89.2
Double Stud-Vinyl	17866 KWh	274.5 MMBtu	17.3 Metric Tons/yr	89.2
Double Stud-Wood	17866 KWh	274.4 MMBtu	17.3 Metric Tons/yr	89.2
ICF's-brick	17919 KWh	276.7 MMBtu	17.4 Metric Tons/yr	89.9
ICF's-Vinyl	17893 KWh	277 MMBtu	17.4 Metric Tons/yr	90
ICF's-Wood	17890 KWh	276.8 MMBtu	17.4 Metric Tons/yr	89.9
SIP's-brick	17893 KWh	274.1 MMBtu	17.2 Metric Tons/yr	88.9
SIP's-Vinyl	17866 KWh	274.2 MMBtu	17.3 Metric Tons/yr	88.9
SIP's-Wood	17863 KWh	274.1 MMBtu	17.2 Metric Tons/yr	88.9
Steel Stud-brick	17966 KWh	281.4 MMBtu	17.7 Metric Tons/yr	93
Steel Stud-Vinyl	17948 KWh	282.3 MMBtu	17.7 Metric Tons/yr	93.5

Steel Stud-Wood	17940 KWh	281.8 MMBtu	17.7 Metric Tons/yr	93.2
Wood Stud-brick	17907 KWh	276.2 MMBtu	17.4 Metric Tons/yr	90.1
Wood Stud-Vinyl	17887 KWh	276.5 MMBtu	17.4 Metric Tons/yr	90.3
Wood Stud-Wood	17878 KWh	276.2 MMBtu	17.4 Metric Tons/yr	90.1

Parametric System Modeling Run #2 Results: Glazing Specifications

The second set of system runs evaluated the impact of glazing specification changes on energy consumption. Results showed window typology #18 as the only option surpassing the required 5% improvement over baseline threshold (Figures 34 & 35). The Low-E, triple pane, insulated frame, argon gas cavity, and high gain window typology yielded a 5.6% reduction in energy use compared to the baseline condition (Table 19).

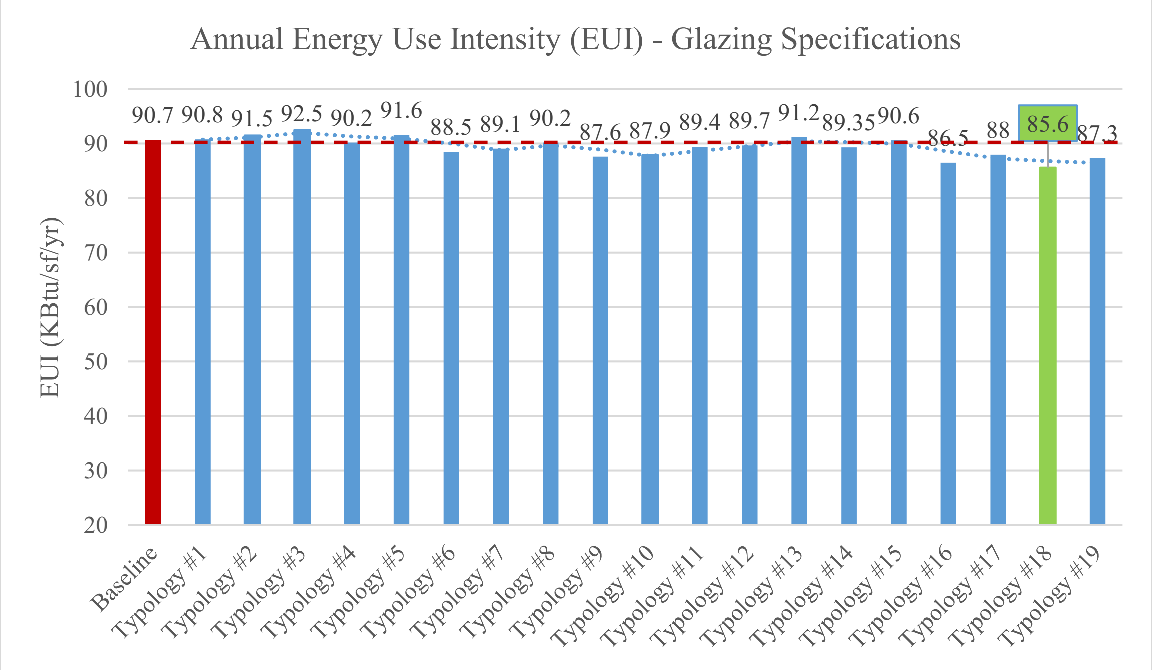


Figure 34. Energy use intensity for modeled glazing runs.

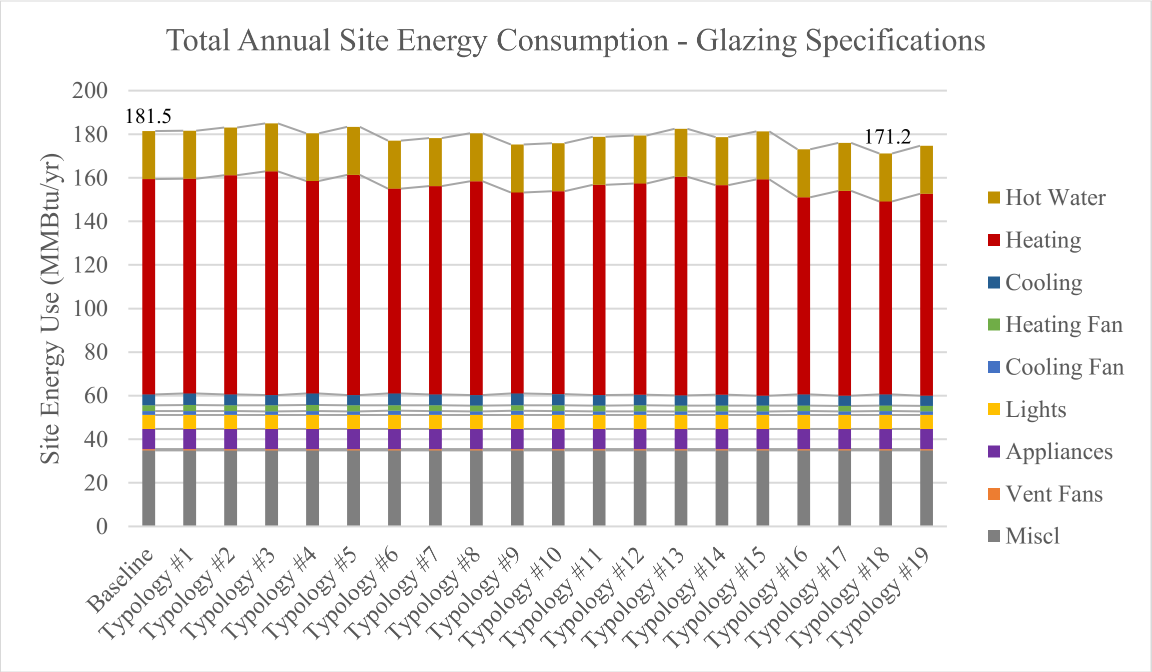


Figure 35. Site energy use for modeled glazing runs.

Table 19. Building glazing simulation results.

Building Glazing Options	Site Electricity	Source Energy	CO2 Emissions	HERS Rating
Typology #1	17872 KWh	323.6 MMBtu	20.1 Metric Tons/yr	112.4
Typology #2	17761 KWh	324.5 MMBtu	20.2 Metric Tons/yr	113
Typology #3	17673 KWh	325.8 MMBtu	20.3 Metric Tons/yr	114
Typology #4	17866 KWh	322.3 MMBtu	20.1 Metric Tons/yr	111.7
Typology #5	17661 KWh	324 MMBtu	20.2 Metric Tons/yr	113
Typology #6	17890 KWh	318.8 MMBtu	19.9 Metric Tons/yr	109.8
Typology #7	17764 KWh	319.1 MMBtu	19.9 Metric Tons/yr	110.4
Typology #8	17661 KWh	320.8 MMBtu	20 Metric Tons/yr	111.4
Typology #9	178844 KWh	316.8 MMBtu	19.8 Metric Tons/yr	108.9
Typology #10	17790 KWh	316.8 MMBtu	19.7 Metric Tons/yr	109.3
Typology #11	17655 KWh	319 MMBtu	19.9 Metric Tons/yr	110.3
Typology #12	17705 KWh	320 MMBtu	19.9 Metric Tons/yr	111.1
Typology #13	17611 KWh	322.7 MMBtu	20.1 Metric Tons/yr	111.8
Typology #14	17711 KWh	319.3 MMBtu	19.9 Metric Tons/yr	110.7

Typology #15	17603 KWh	321.3 MMBtu	20 Metric Tons/yr	111.1
Typology #16	17746 KWh	313.4 MMBtu	19.5 Metric Tons/yr	107.6
Typology #17	17591 KWh	315.6 MMBtu	19.7 Metric Tons/yr	108.2
Typology #18	17737 KWh	311.3 MMBtu	19.4 Metric Tons/yr	106.6
Typology #19	17588 KWh	314.1 MMBtu	19.6 Metric Tons/yr	107.5

Parametric System Modeling Run #3 Results: HVAC Specifications

The next set of system parameters examined the impact of HVAC system modifications on energy consumption in the single-family home. All runs were able to meet and far surpass the required 5% improvement over baseline threshold (Figures 36 & 37). Furthermore, simulation results revealed energy use reductions of 40% over baseline, when employing ground source heat pump systems (Figure 36, Table 20).

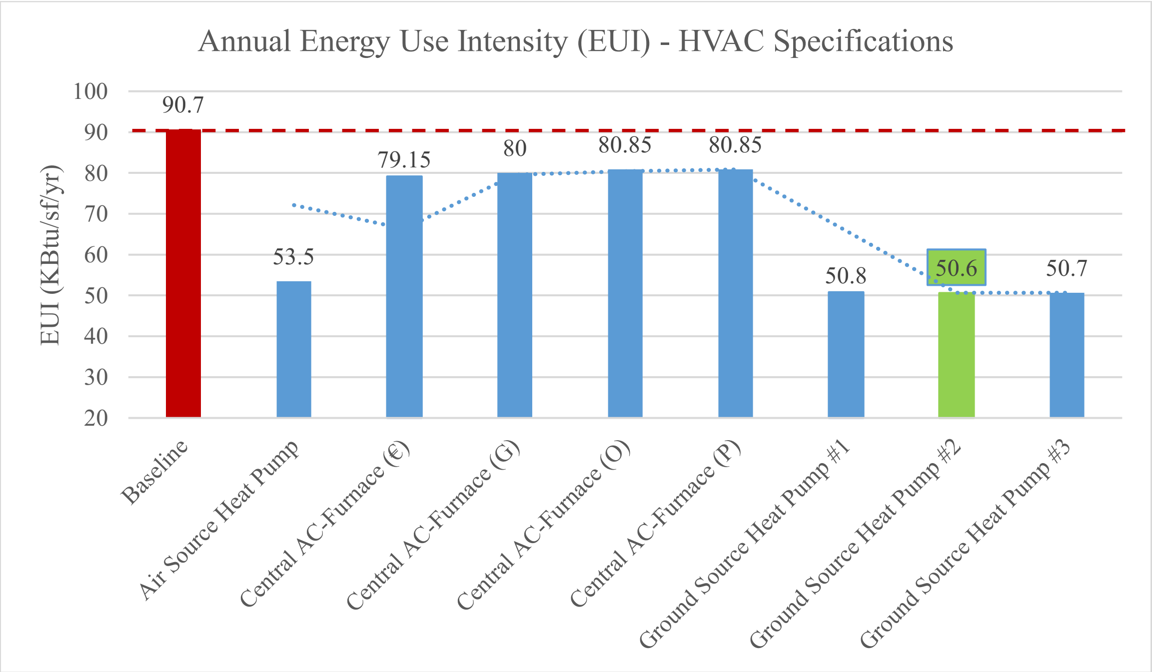


Figure 36. Energy use intensity for modeled HVAC runs.

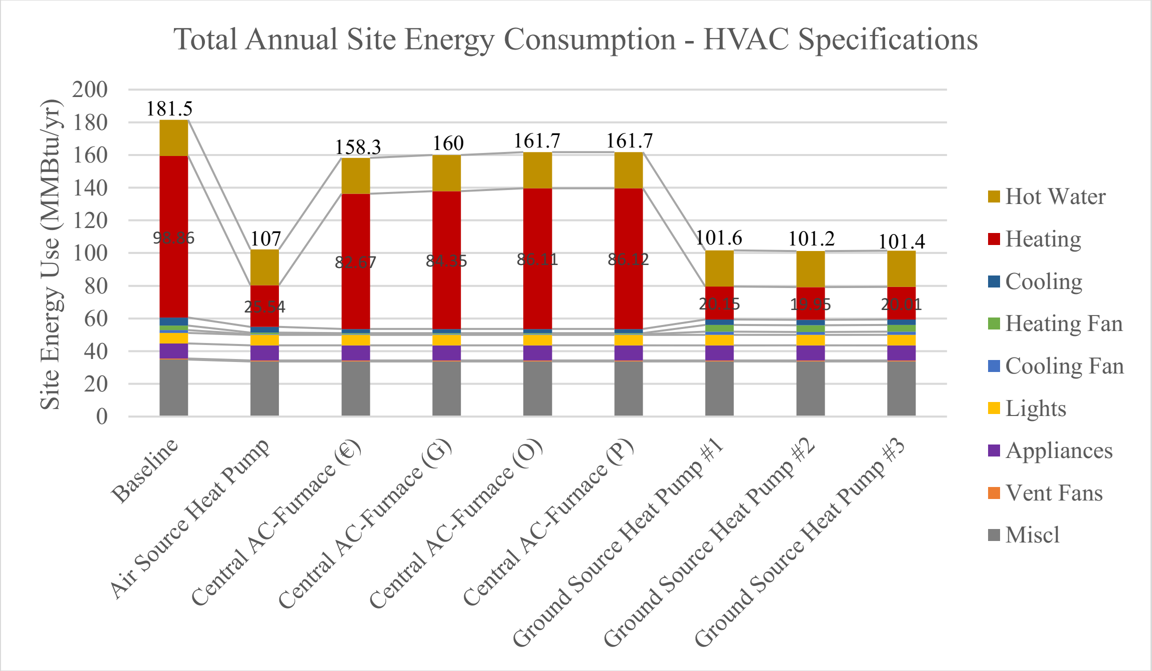


Figure 37. Site energy use for modeled HVAC runs.

Table 20. Building HVAC simulation results.

Building HVAC Options	Site Electricity	Source Energy	CO2 Emissions	HERS Rating
Air Source Heat Pump	24921 KWh	291.9 MMBtu	18.7 MetricTons/yr	91.7
Central AC-Furnace (E)	39938 KWh	453.3 MMBtu	29.1 MetricTons/yr	160.8
Central AC-Furnace (G)	15709 KWh	284.8 MMBtu	17.7 MetricTons/yr	91.6
Central AC-Furnace (O)	15709 KWh	295.4 MMBtu	20 MetricTons/yr	93
Central AC-Furnace (P)	15709 KWh	291.9 MMBtu	19 MetricTons/yr	93
Ground Source Heat Pump #1	23332 KWh	274.8 MMBtu	17.6 MetricTons/yr	79.1
Ground Source Heat Pump #2	23215 KWh	273.6 MMBtu	17.5 MetricTons/yr	78.6
Ground Source Heat Pump #3	23265 KWh	274.1 MMBtu	17.6 MetricTons/yr	78.8

Parametric System Modeling Run #4 Results: Hot Water System

Eight out of the nine modeled runs did not meet the required 5% improvement over baseline threshold (Figures 38 & 39). Nonetheless, the heat pump water heater option #2 did yield a 5.4% reduction in energy consumption over the baseline (Table21).

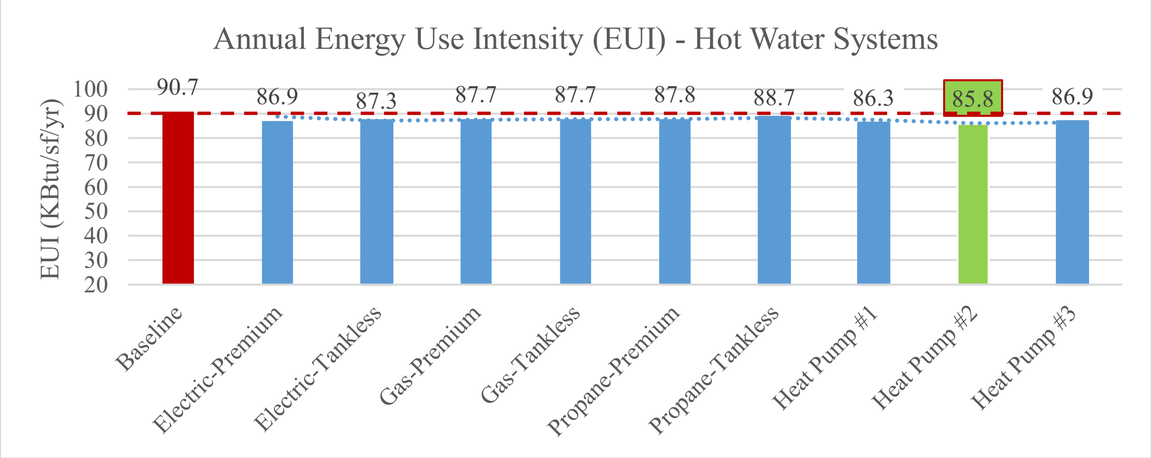


Figure 38. Energy use intensity for modeled hot water runs.

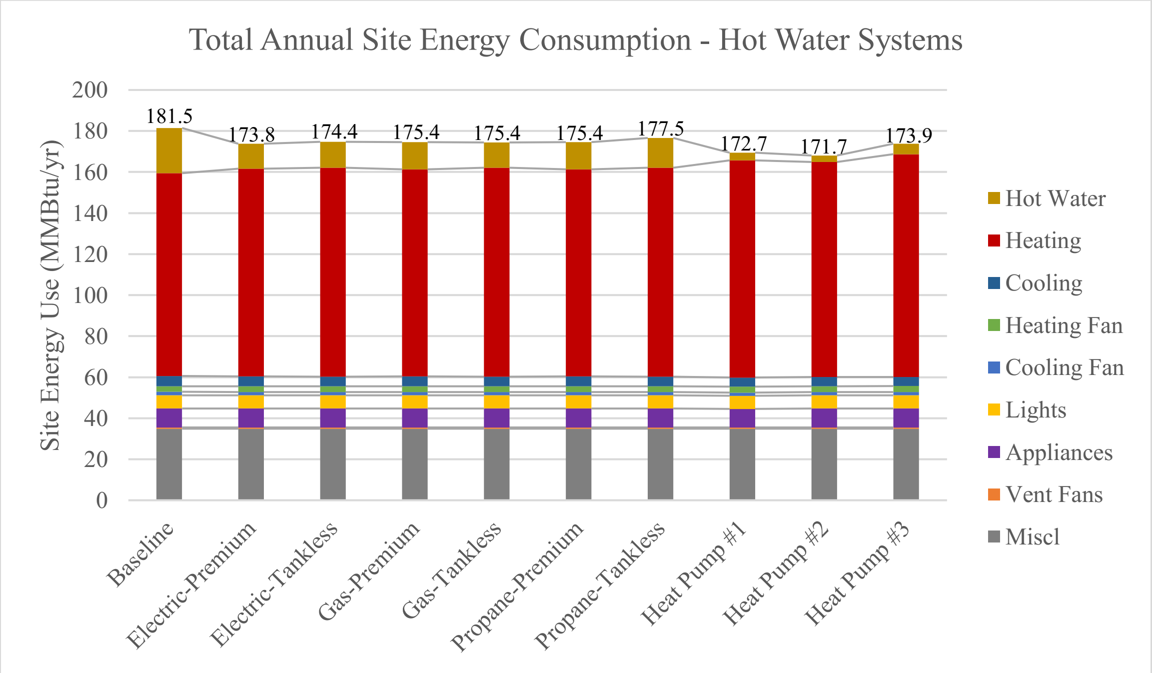


Figure 39. Site energy use for modeled hot water runs.

Table 21. Building DHW simulation results.

Building DHW Options	**Site Electricity**	**Source Energy**	**CO2 Emissions**	**HERS Rating**
Electric-Premium	21225 KWh	338.6 MMBtu	21.3 MetricTons/yr	129.9
Electric-Tankless	21348 KWh	340.5 MMBtu	21.4 MetricTons/yr	131.1
Gas-Premium	17940 KWh	317.3 MMBtu	19.8 MetricTons/yr	112.1
Gas-Tankless	17934 KWh	317.3 MMBtu	19.8 MetricTons/yr	108.9
Propane-Premium	17937 KWh	318.1 MMBtu	20 MetricTons/yr	112.1
Propane-Tankless	17934 KWh	320.4 MMBtu	20.1 MetricTons/yr	116.4
Heat Pump #1	19572 KWh	325.9 MMBtu	20.4 MetricTons/yr	119.3
Heat Pump #2	19628 KWh	325.2 MMBtu	20.4 MetricTons/yr	117.5
Heat Pump #3	19112 KWh	323.8 MMBtu	20.3 MetricTons/yr	116.5

Parametric System Modeling Run #5 Results: Conditioning Set points and Schedules

The next set of variables examined temperature set points and modified conditioning schedules. The modeled runs yielded a 20% reduction in energy use, easily meeting the required 5% baseline threshold (Figures 40 & 41 and Table 22).

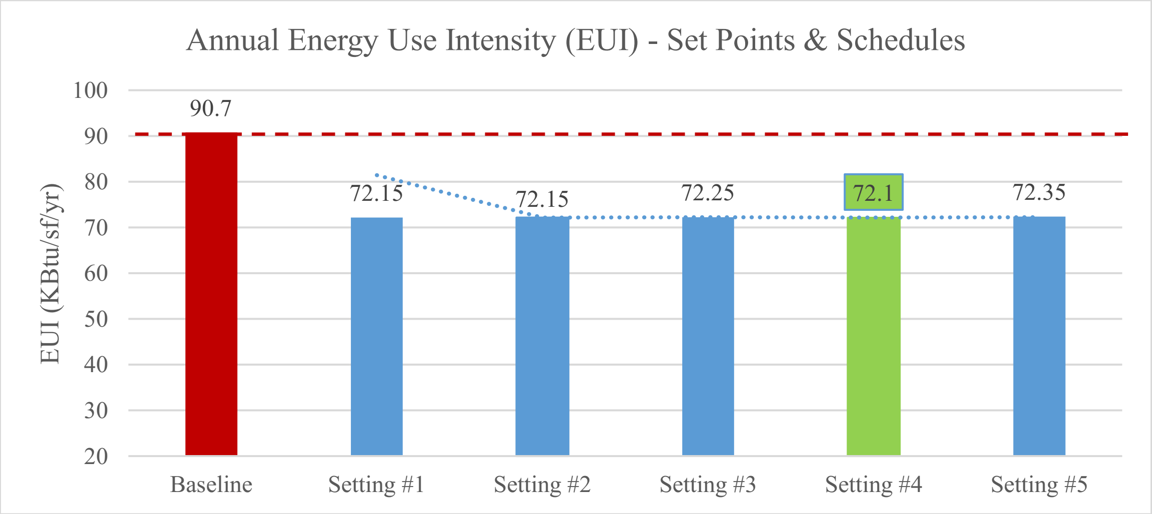


Figure 40. Energy use intensity for modeled setpoint-schedule runs.

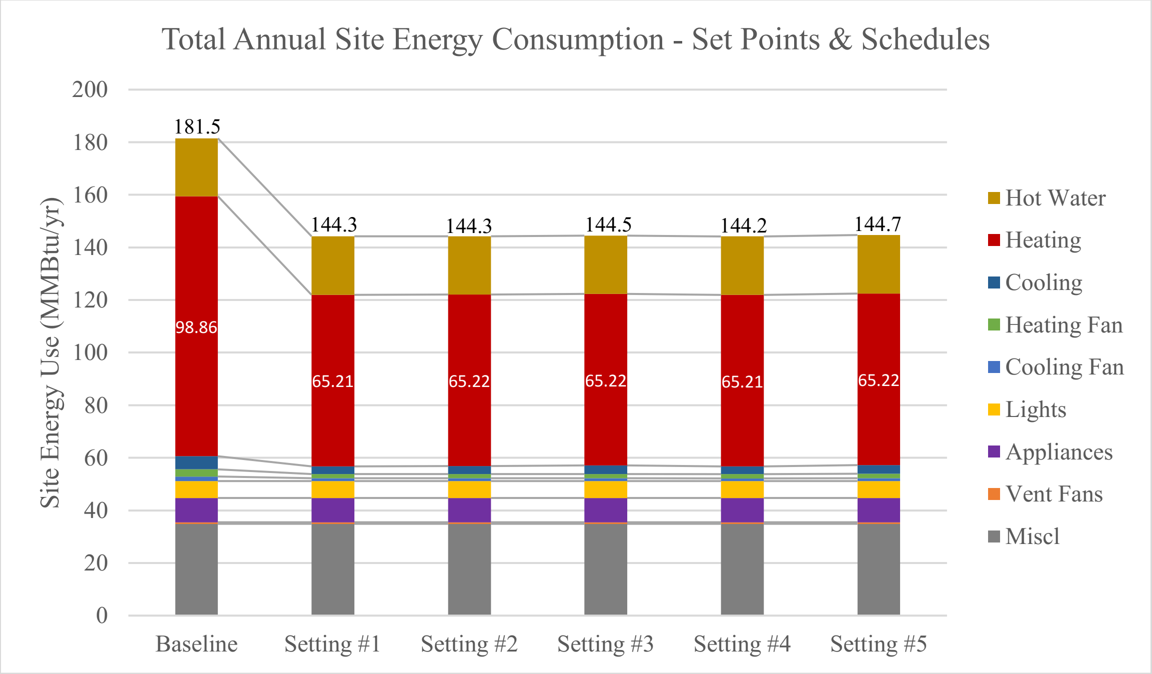


Figure 41. Site energy use for modeled setpoint-schedule runs.

Table 22. Space conditioning setpoint-schedule simulation results.

Set Point & Schedule Options	Site Electricity	Source Energy	CO2 Emissions	HERS Rating
Setting #1	16647 KWh	274.3 MMBtu	17.2 MetricTons/yr	109.5
Setting #2	16656 KWh	274.4 MMBtu	17.2 MetricTons/yr	109.5
Setting #3	16723 KWh	275.1 MMBtu	17.2 MetricTons/yr	109.7
Setting #4	16627 KWh	274 MMBtu	17.2 MetricTons/yr	109.7
Setting #5	16764 KWh	275.5 MMBtu	17.3 MetricTons/yr	110

Parametric System Modeling Run #6 Results: Lighting

The modeling analysis explored the connection between changing lighting parameters and specifications and overall energy consumption. Simulation results revealed a very insignificant improvement in energy performance (Figures 42 & 43). Furthermore, all three runs failed to meet the required 5% improvement over baseline threshold (Table 23).

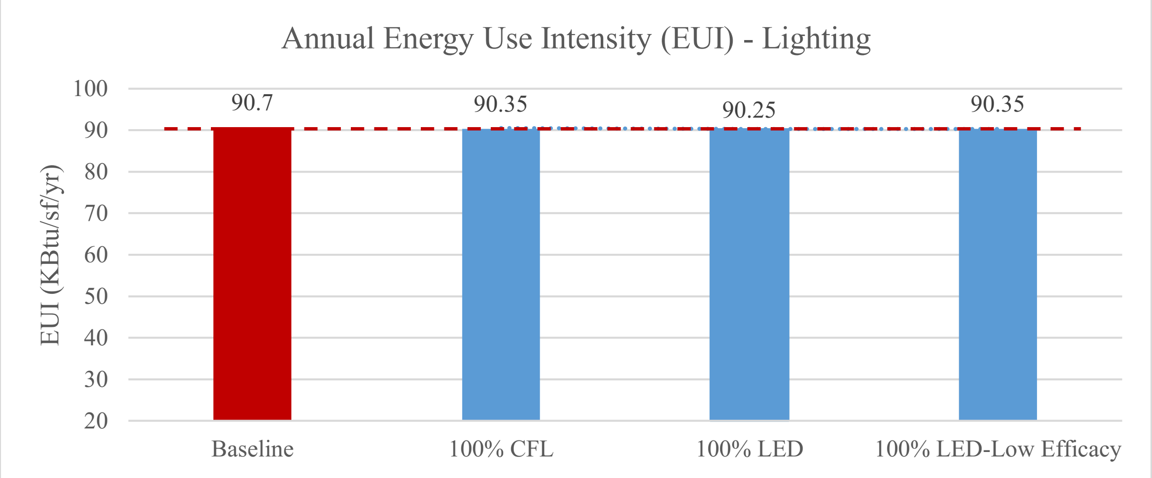


Figure 42. Energy use intensity for modeled lighting runs.

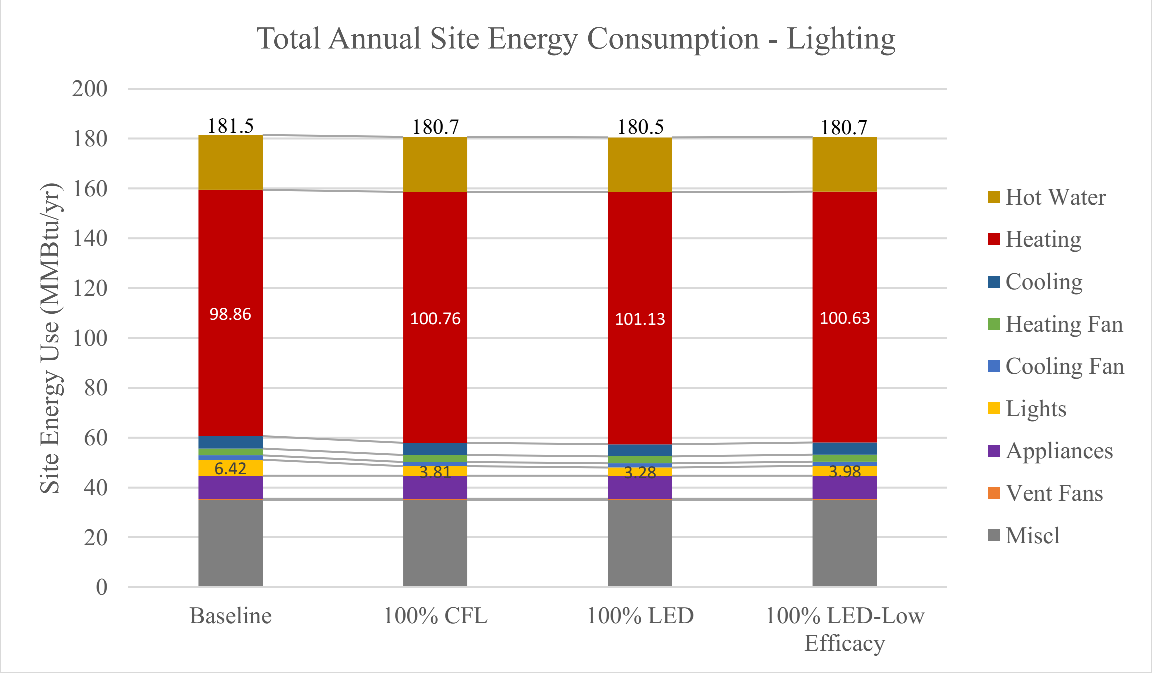


Figure 43. Site energy use for modeled lighting runs.

Table 23. Lighting simulation results.

Lighting Options	Site Electricity	Source Energy	CO2 Emissions	HERS Rating
Baseline	16967 KWh	316.2 MMBtu	19.7 MetricTons/yr	109
100% CFL	16805 KWh	314.9 MMBtu	19.6 MetricTons/yr	109
100% LED	17016 KWh	316.6 MMBtu	19.7 MetricTons/yr	109

Parametric System Modeling Run #7 Results: Appliances & Fixtures

The next set of runs evaluated the impact of home appliance and fixture upgrades on overall energy consumption. The modeling analysis employed energy efficiency measures across a wide spectrum of home appliances. Accordingly, simulation results revealed a 5.8% improvement in energy performance over baseline condition (Figure 44).

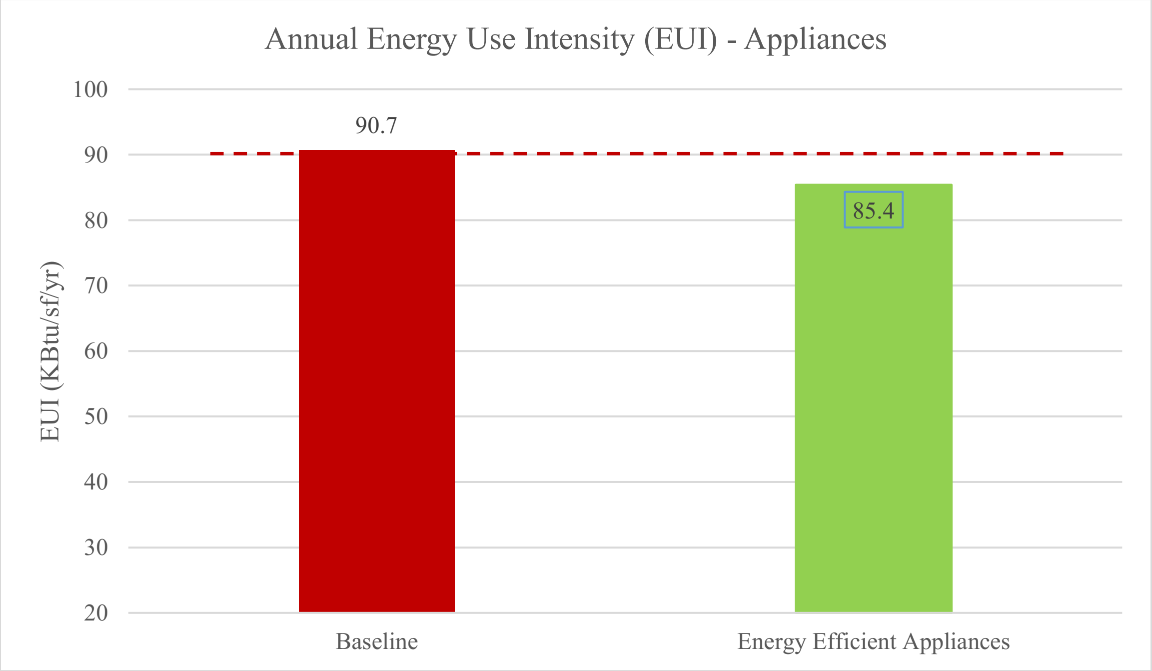


Figure 44. Energy use intensity for modeled appliances.

Parametric System Modeling Run 8 Results: Plug Loads

The final set of system runs examined the effect of plug load variations on overall energy use. Simulation results yielded only a 2% reduction in energy consumption, hence, failing to meet the required 5% improvement over baseline threshold.

Chapter IV

Discussion

Results from the modeled alternative parametric runs revealed a wide spectrum of impacts associated with varying architectural variables. Findings varied considerably between architectural design and building system variables. Simulation data revealed a stronger connection between building systems and overall energy consumption. Nonetheless, architectural design parameters had a significant impact on energy use. In total, fourteen architectural parameters were modeled and simulated, encompassing six architectural design and eight building system variables. The parametric iterative modeling analysis evaluated correlations between upgraded architectural variables and energy performance. Findings revealed energy use reductions ranging between 5% and 40% over the modeled baseline. This chapter will outline major findings from each of the modeled categories, including both architectural design and building systems variables.

Architectural Design Variables

The impact of individual architectural design variable modifications on energy use in the single-family home ranged between 5% and 12% reduction over the baseline. The majority of the modeled design variable runs (four out of six, 66%) yielded a 5% or larger energy use reduction, hence, meeting the required established improvement benchmark (Figures 45 & 46). The remaining runs failed to meet the required energy performance threshold. The most effective architectural design variables encompassed roof shape and characteristic changes as well as allocated number of floors associated with the home. On the other hand, the least effective strategy entailed building massing from modifications, whereby results revealed a considerable spike in energy consumption compared to the compact building form modeled in the baseline condition.

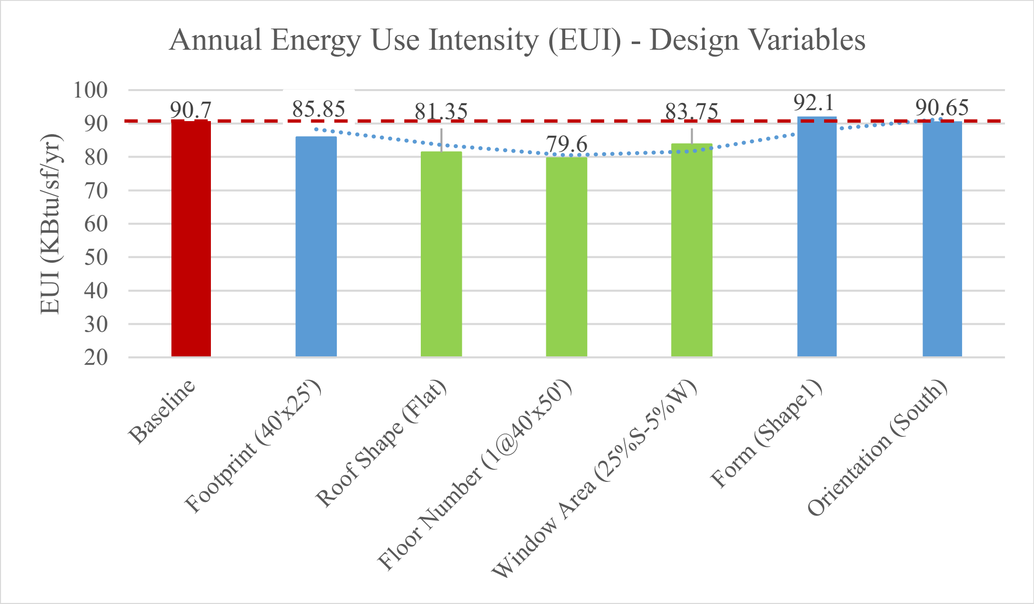


Figure 45. Energy use intensity for the identified optimal design variable runs.

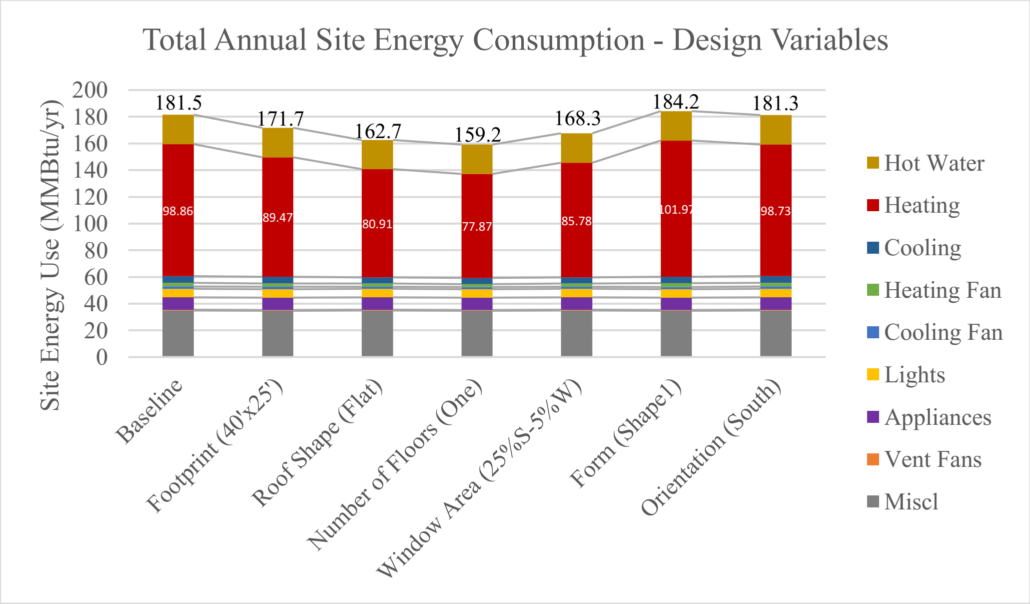


Figure 46. Site energy use for the identified optimal design variable runs.

Analysis

The effect of design variations on energy use intensity was mostly evident throughout the various spectrums of modeled parametric runs. Some variables had greater significance on overall energy performance than others. Results revealed heating loads as the primary driver of energy use within the house. As such, the most optimal variables were those that drove the heating demand considerably lower. The performances of the design runs are outlined in the section below.

Building footprint. Four options were modeled, examining diverse deviations from the square baseline footprint (32’ x 32’). The 40’ x 25’ option yielded the best results in terms of overall energy reductions and thermal performance. Results revealed a 5.4% improvement over the baseline condition. Altering the building footprint into a more rectangular form allowed for more south-facing exposure while reducing eastern and western exposures, prone to larger and more frequent energy migration (heat loss or gain). On the other hand, delineating a longer south-facing building axis allowed for the introduction of more daylighting and passive solar energy gains into the house, decreasing overall heating and electrical demands. As a result, the 40’ x 25’ option generated the most optimal run in terms of energy performance.

Building roof. Several roof shapes with various pitches and slopes were examined in order to assess the correlation between roof characteristic and energy consumption. Simulation results showed the flat (low-sloped) roof option as the most optimal iteration, yielding a 10.3% reduction in overall energy use compared to the baseline condition. Flat roofs have better thermal performance than pitched ones due to insulation and material differences. Unlike pitched roofs that employ cavity insulation systems pressed between ceilings joists, flat roofs have a membrane system applied atop rigid insulation boards, effectively eliminating gaps within the insulation layer. The result is a more efficient and insulated roof envelope. Furthermore, since flat roofs must be covered with a roofing membrane by design, material choices are usually more efficient in terms of thermal insulation. For example, Ethylene Propylene Diene Monomer roofing membranes (EPDM) are significantly more energy efficient than their traditional pitched-roof counterparts (NREL, 2011). Accordingly, structures with flat roofs tend to have lower overall cooling and heating demands.

Number of floors. Two iterations of floor numbers were modeled, including one-and three-story options. The 40’ x 50’one story run yielded the most optimal results, reducing energy use 12.3% over the baseline. Energy improvements could be attributed to the fact that one-story structures are usually more energy efficient and thermally balanced. In a two-story home heat is continuously rising onto the second floor, causing an imbalance in the first floor, ultimately increasing heating and cooling loads. As a result of this imbalance, the HVAC system is constantly trying to reach a state of equilibrium between the first and second floor, which in turn drives energy demand higher. Thermal imbalance is usually absent in a one-story building, whereby heating and cooling is equitably dispersed along the entire volume of the structure. Hence, a one-story home is easier to cool and heat, resulting in an overall more energy efficient building.

Window area. Twelve window typologies were evaluated, entailing variations in WWR percentages. The primary focus was south and west facing building envelopes. Simulation results showed a strong correlation between varying south-facing window area percentages and overall energy use. Accordingly, all modeled runs yielded relatively similar results, meeting and exceeding the set threshold of 5% improvement over the baseline. Nonetheless, one run performed slightly better, resulting in approximately 7.5% reduction in energy consumption. The run was modeled based on the following criteria: 25% south-facing WWR and 5% west-facing WWR. The increase in south-facing glazing allowed for more direct solar gain and daylighting, thus, reducing the heating and lighting loads. As a result, thermal loads were reduced causing a significant reduction in energy use intensity.

Building form & massing. Building shapes were modeled, evaluating deviations from the baseline's compact building massing form. All runs failed to significantly improve energy performance. On the contrary, simulation results showed an increase between 1 and 19% in energy consumption. The deviation from a compact form into a multi-prong sprawling mass generated more surface areas relative to volume, resulting in larger thermal loads and overall energy use.

Building orientation. Building siting options were analyzed in an effort to examine the relationship between orientation and energy use intensity. However, results didn't demonstrate a measurable improvement in energy consumption. In fact, energy reductions averaged around 0.11% compared to the baseline condition. This could likely be attributed to the fact that the baseline scenario had the house sited along a south-facing direction, considered an optimal orientation.

Synopsis

Results from the modeled parametric design runs revealed three top performers in terms of overall energy reductions and efficiency. All three runs surpassed the required 5% improvement threshold (Table 24). The one-floor (40' x 50') run option yielded the best results at 12.3% reduction in energy consumption over baseline. The flat-roof option was second at 10.3%. The 25% WWR percentage option was third at 7.5% reduction in energy use over baseline. Accordingly, those three top individual design variables were employed in the next and final stage of parametric energy simulation runs, evaluating the most optimal permutations of both architectural design and building system variables.

Table 24. Results revealing the top three optimal individual design variables.

Top Three Optimal Design Variables	EUI	Site Energy	% Reduction over Baseline
1. One-story (40' x 50')	79.6KBtu/SF/Year	159.2MMBtu	12.3%
2. Flat Roof Option	81.3KBtu/SF/Year	162.7MMBtu	10.3%
3. Window Area Option: 25% South-facing WWR 5% West-facing WWR 0% North-facing WWR 0% East0facing WWR	84.1KBtu/SF/Year	168.3MMBtu	7.5%

Building System Variables

Simulation results from the various building system variable runs revealed a substantial decrease in energy use. The impact of individual building system upgrades on energy use reduction fluctuated between 5 and 40% over the baseline. Significant energy savings were attained with systems targeting primary heating loads. Findings show 75% (six out of eight) of the modeled building system variables yielded energy use reductions equivalent to 5% or higher, hence, meeting the required performance benchmark (Figures 47 & 48). Moreover, 37% of variables yielded energy improvements beyond 20%, a four-fold increase over the threshold. Only two out of eight runs failed to meet the established threshold. Nonetheless, the most effective building system variables included envelope, HVAC, and conditioning set points-schedule upgrades. On the other hand, the least effective options involved lighting system and plug load upgrades.

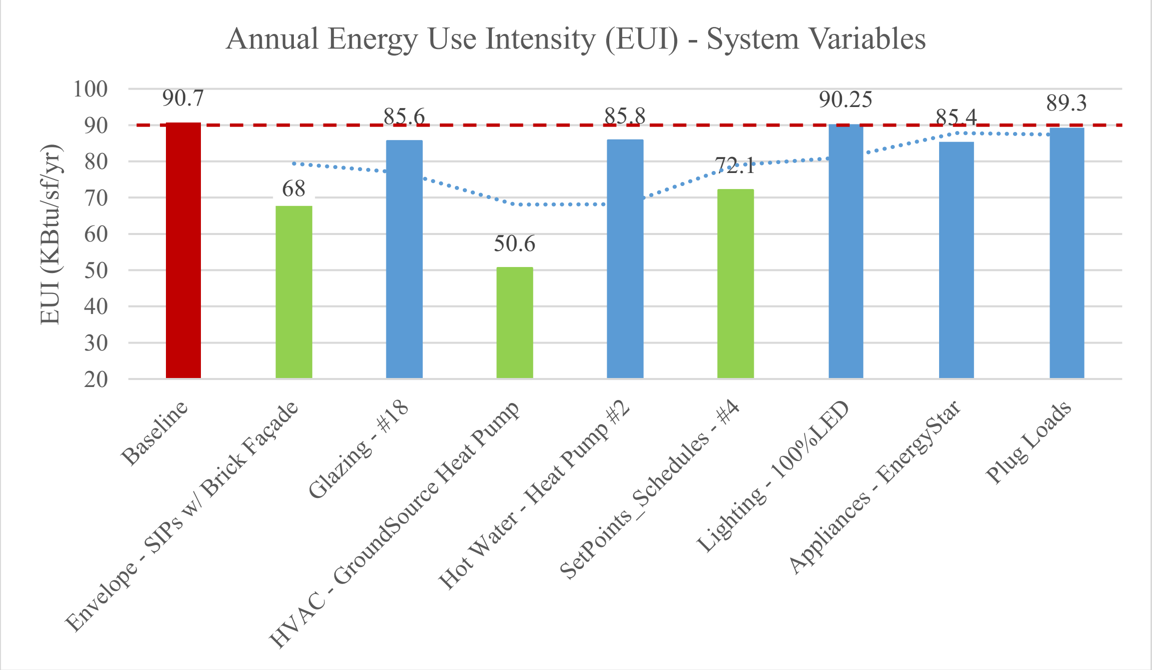


Figure 47. Energy use intensity for the identified optimal systems variable runs.

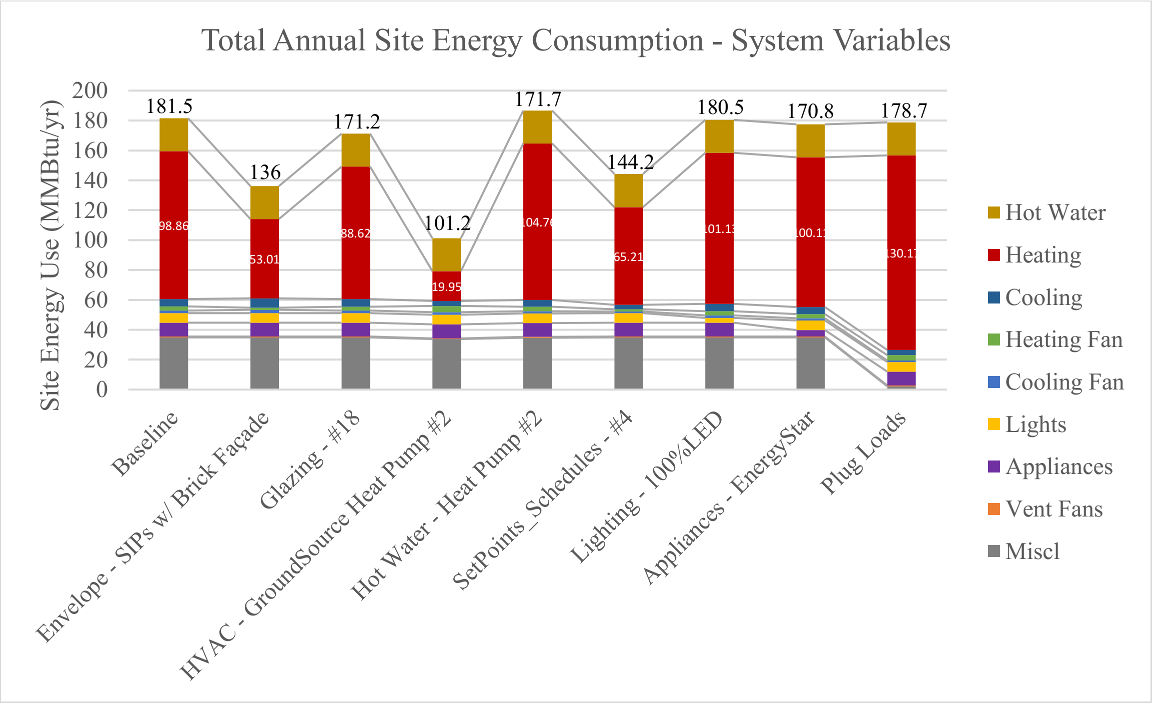


Figure 48. Site energy use for the identified optimal systems variable runs.

Analysis

The influence of building system upgrades on energy use intensity was apparent throughout the majority of the modeled parametric runs. Most simulated variables had a substantial impact on overall energy performance, while few were not as significant. Heating loads were again the major driver of energy consumption within the structure. Furthermore, overall thermal performance was primarily dominated by heating load requirements. Accordingly, the most optimal system options were variables that addressed and impacted heating demands directly. The section below outlines the performance of the various building system runs.

Building envelope. Thermal load losses via the building envelope are estimated to range between 15% and 35%, based on the envelope surface (EIA, 2017). Accordingly, six exterior wall options were modeled, examining a variety of construction typologies. The structural insulated panel system yielded the most optimal result compared to other envelope systems. Simulation results revealed a 25% reduction in energy use over the baseline. SIPs are known to be a super-insulated building material with significantly high R-values and superior thermal performance. The result is an extremely air tight building envelope, that significantly minimizes heat gains, losses, and overall energy loads.

Glazing specifications. Nineteen glazing options were modeled, assessing window specifications and typologies. Upgrade parameters included U-values, solar heat gain coefficients, and most importantly, number of windows panes. The low emissivity triple pane argon filled window option performed most optimally, yielding a 5.6% reduction in energy consumption. Windows are considered one of the weakest components of the building envelope. As a result, glazing upgrades are paramount to ensuring an optimal thermal environment.

HVAC specifications. Three diverse HVAC system options were examined, specifically targeting heating and cooling space conditioning systems. Heating and cooling loads constitute about half of the energy loads of a typical single-family home (EIA, 2009). It's imperative to install energy efficient HVAC systems to significantly impact overall energy consumption. Accordingly, the ground source heat pump performed far above the rest of the modeled HVAC systems. This is due to the fact that heat pump systems employ mechanisms that move/transfer energy in lieu of creating it. Accordingly, simulation results showed energy use reductions around 40%, by far the largest improvements over the baseline amongst all modeled variables. Most of the realized gains could be attributed to massive reductions in heating loads, considered the primary driver of energy use in residential structures located in heating-dominated climate zones.

Hot water system. Four different hot water systems were evaluated. The analysis encompassed various typologies ranging from electric, gas, propane, and heat pumps. Results revealed the heat pump systems as the most optimal option, reducing energy use over the baseline by approximately 5.4%. Water heating constitutes around 18% of the energy use in a single-family home, third behind space heating, lighting and appliances (EIA, 2009). Therefore, achieving measurable reductions is paramount to ensuring optimal thermal performance.

Conditioning set points & schedules. Set point and schedule modifications yielded the third most optimal result amongst all modeled system variables. Establishing a defined programmed preset schedule, with various heating and cooling set points, resulted in 20% reduction in energy use over the baseline.

Lighting. The modeling analysis encompassed an examination of the following typologies: light emitting diodes (LED) and compact fluorescent light (CFL). Simulation analysis revealed a negligible improvement in energy performance, yielding only a 0.5% reduction over the baseline. The baseline condition was initially modeled using an efficient lighting system, as a result, the upgrades employed thereafter didn’t generate significant and measurable improvements.

Appliances & fixtures. Upgrading the home's appliances into more energy efficient models, such as EnergyStar, resulted in a 5.8% reduction in energy consumption over the baseline condition. Therefore, it is critical to utilize this approach, given the large number of appliances installed within single-family homes.

Plug loads. Variations and upgrades in the plug load system did not yield significant improvements in energy performance. Results show only a 1.5% reduction in energy use over the baseline. Even though plug loads tend to drive cooling and electrical loads higher, its overall impact on thermal performance and energy use intensity is usually offset by reduction in heating loads.

Synopsis

The impact of building system variable upgrades was evident in many of the modeled iterative runs. Simulation results from the various parametric building system runs revealed three top performers in terms of overall energy reductions and performance. All three runs surpassed drastically the required 5% improvement threshold (Table 25). Mechanical system (HVAC) upgrades generated the most optimal result, yielding a 40% reduction in energy consumption over baseline. Building envelope upgrades yielded 25% reductions. The third best system variable entailed space conditioning set point and schedule changes. Consequently, those three top individual system variables were chosen to advance into the final stage of parametric energy simulation runs, evaluating the most optimal permutations of both architectural design and building system variables.

Table 25. Results revealing the top three optimal individual system variables.

Top Three Optimal System Variables	EUI	Site Energy	% Reduction over Baseline
1. HVAC: GSHP Ground Source Heat Pump	50.6KBtu/SF/Year	101.2MMBtu	40%
2. Building Envelope: SIPs	68KBtu/SF/Year	136MMBtu	25%
3. Set Points & Schedules	72.1KBtu/SF/Year	144.2MMBtu	20%

Design & System Variables Modeling Permutations

The next stage of the analysis entailed an iterative parametric modeling investigation of the top six performing variables generated from the individual parametric runs as identified in the results section (Tables 24 & 25). Hence, the simulation process utilized the top three variables generated from the architectural design and building systems categories. As outlined in Figure 49, the study sought to isolate the top four energy performance indicators via an analytical examination encompassing various permutations of factors, aimed at identifying the top two variables from each architectural category. Accordingly, modeling parameters adopted a pairing of two variables from each category to generate a comprehensive list of four energy indicators, yielding nine different permutations of variables (Table 26). Each permutation of variables was modeled and simulated independently in order to evaluate the variable’s overall efficacy and impact on energy use in the single-family home. To that end, National Renewable Energy Laboratory’s (NREL) building energy optimization modeling package (BEopt) was employed as well for this phase of the simulation analysis. Site energy consumption and energy use intensity were used as the primary energy performance indicators.

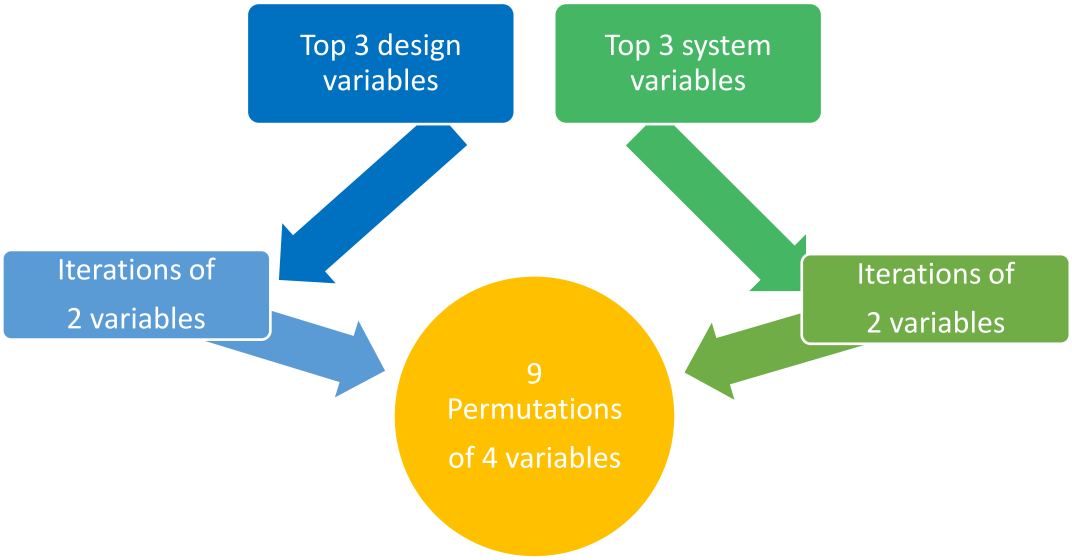


Figure 49. Flow outline of the modeling and simulation permutation framework.

Table 26. Optimal design and system variable permutation runs.

Permutation Runs	Design Variables (Combination of Two)	System Variables (Combination of Two)
Run #1	One-story (40’ x 50’) + Flat Roof	GSHP + SIPs
Run #2	One-story (40’ x 50’) + Flat Roof	GSHP + Set Points/Schedules
Run #3	One-story (40’x50’) + Flat Roof	SIPs + Set Points/Schedules
Run #4	**One-story (40’ x 50’) + 25% S-WWR**	**GSHP + SIPs**
Run #5	One-story (40’ x 50’) + 25% S-WWR	GSHP + Set Points/Schedules
Run #6	One-story (40’ x 50’) + 25% S-WWR	SIPs + Set Points/Schedules
Run #7	Flat Roof + 25% S-WWR	GSHP + SIPs
Run #8	Flat Roof + 25% S-WWR	GSHP + Set Points/Schedules
Run #9	Flat Roof + 25% S-WWR	SIPs + Set Points/Schedules

Permutation-Modeling Run Results

Simulation results revealed energy reductions ranging between 52% and 56% (Figure 50). All nine modeled runs significantly surpassed the established 15% improvement threshold (Figure 51). Furthermore, findings showed improvements across the board including EUI, site and source energy, carbon emissions, and HERS rating (Table 27). However, permutation run number four included the most optimal combination of variables, yielding a 56% reduction in energy consumption over the bassline. The run produced a EUI of 40 KBtu/sf/yr, approximately 23% lower than the U.S. national average of 51.6 KBtu/sf/yr for a similar size single-family home (RECS, 2009). The run included the following architectural design and building system variables: compact rectangular one-story structure with a gable roof, 25% south-facing and 5% west-facing window to wall ratio, ground source heat pump HVAC system, and a structural insulated panel building envelope system with minimal air flow leakage rates.

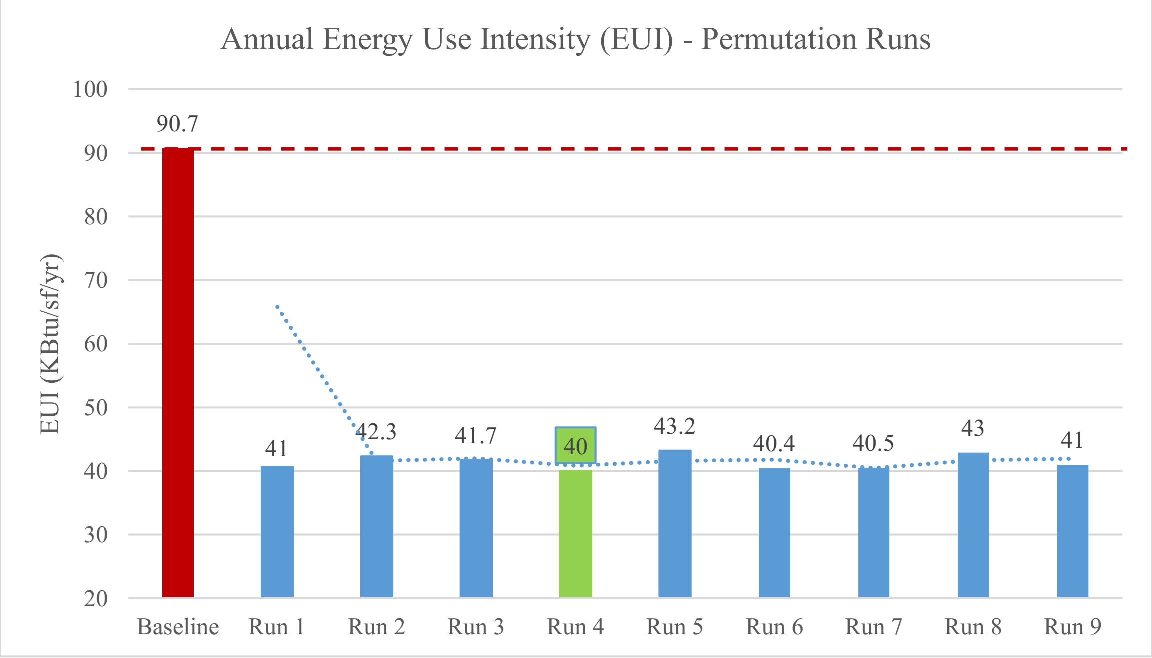
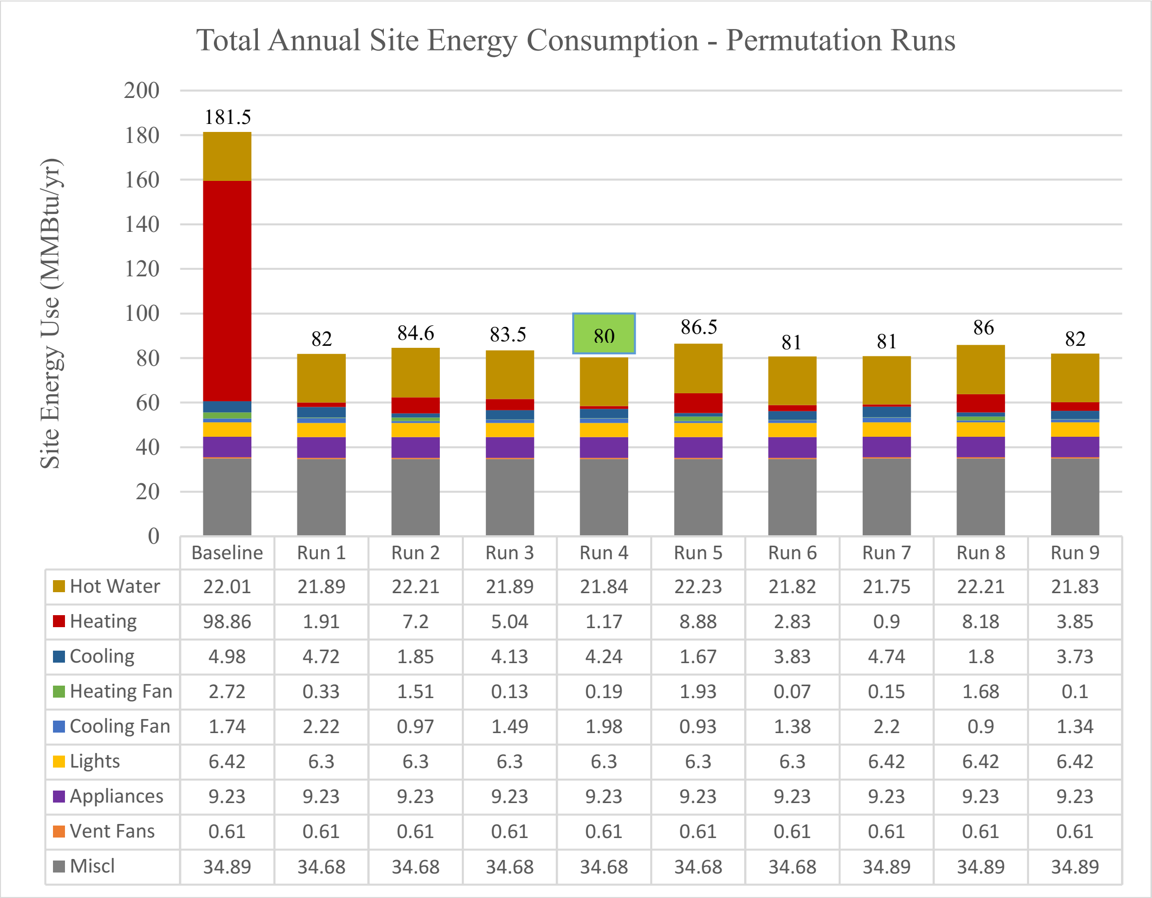


Figure 50. Energy use intensity for the identified optimal permutation runs.



	Baseline	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9
Hot Water	22.01	21.89	22.21	21.89	21.84	22.23	21.82	21.75	22.21	21.83
Heating	98.86	1.91	7.2	5.04	1.17	8.88	2.83	0.9	8.18	3.85
Cooling	4.98	4.72	1.85	4.13	4.24	1.67	3.83	4.74	1.8	3.73
Heating Fan	2.72	0.33	1.51	0.13	0.19	1.93	0.07	0.15	1.68	0.1
Cooling Fan	1.74	2.22	0.97	1.49	1.98	0.93	1.38	2.2	0.9	1.34
Lights	6.42	6.3	6.3	6.3	6.3	6.3	6.3	6.42	6.42	6.42
Appliances	9.23	9.23	9.23	9.23	9.23	9.23	9.23	9.23	9.23	9.23
Vent Fans	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61
Miscl	34.89	34.68	34.68	34.68	34.68	34.68	34.68	34.89	34.89	34.89

Figure 51. Site energy use for the identified optimal permutation runs.

Table 27. Permutation modeling-run results

Permutation Runs	Site Energy	Source Energy	CO2 Emissions	HERS Rating	% Reduction Over Baseline
Baseline	181.5MMBtu	322.6MMBtu	20.1mt/yr	112.1	
Run #1	82MMBtu	212.9MMBtu	13.6mt/yr	63.2	54.8%
Run #2	84.6MMBtu	220.6MMBtu	14.1mt/yr	70.4	53.3%
Run #3	83.5MMBtu	207.5MMBtu	13.2mt/yr	73.4	53.9%
Run #4	**80MMBtu**	**207MMBtu**	**13mt/yr**	**60**	**56%**
Run #5	86.5MMBtu	226.6MMBtu	14.5mt/yr	76.5	52.3%
Run #6	81MMBtu	203.6MMBtu	13mt/yr	69.3	55%
Run #7	81MMBtu	210MMBtu	13.4mt/yr	58	55%
Run #8	86MMBtu	225MMBtu	14.4mt/yr	68.5	52.6%
Run #9	82MMBtu	205.4MMBtu	13.1mt/yr	66.7	54.8%

Analysis

Results from the parametric simulation analysis revealed that building system upgrades had greater impacts on energy use over building design changes. To that end, individual building design alterations yielded energy reductions between 5% and 12 %. On the other hand, building system upgrades generated reductions between 5% and 40%. Accordingly, building system improvements such as envelope and HVAC upgrades were significant drivers of energy reductions in the single-family home. In aggregate, combined iterations of upgraded architectural building design and systems variables revealed energy savings over 50% compared to the baseline. Accordingly, all nine permutation runs performed substantially better than the baseline and the individually modeled parametric runs. Nonetheless, the fourth permutation run was the most optimal in terms of overall energy consumption and efficiency (Table 27). The run's building design parameters, which encompassed a one-story structure with a high percentage of south-facing glazing, proved to be the most optimum design option. Additionally, the combination of a super air-tight insulated building envelope with a high-efficiency HVAC system provided an exceptionally energy resilient and efficient structure. Paired together, these four variables generated the best and most optimal energy performance indicators amongst all other modeled and simulated variables.

Residential structures are primarily skin-load dominated buildings, whereby thermal loads are significantly driven by exterior climatic conditions. Hence, the building envelope and HVAC systems are critical components of the overall thermal boundary. Heat gains and losses are significantly impacted by a structure's overall footprint and envelope construction. Studies have shown building envelope thermal load fluctuations ranging between 15% and 35% in a code-built single-family home (Bichiou & Krarti, 2011). Simulation results revealed similar trends in the modeled home. Energy demand was heavily driven by the home's overall surface area, footprint, and envelope type. Furthermore, analysis of the individually simulated building design and systems parameters showed that energy loads were predominantly driven by heating demand. Similarly, data analysis of the various permutation runs exhibited a noteworthy trend as it relates to overall energy performance, revealing heating loads as the primary driver of energy consumption in the modeled single-family home. Statistical regression analysis confirmed that trend and showed a positive correlation between energy use intensity and heating demand. The analysis yielded a 0.98 coefficient of determination (Figure 52). Accordingly, passive and active energy conservation measures, targeting heating demand, proved to be the most optimal approach in reducing overall thermal loads and energy consumption.

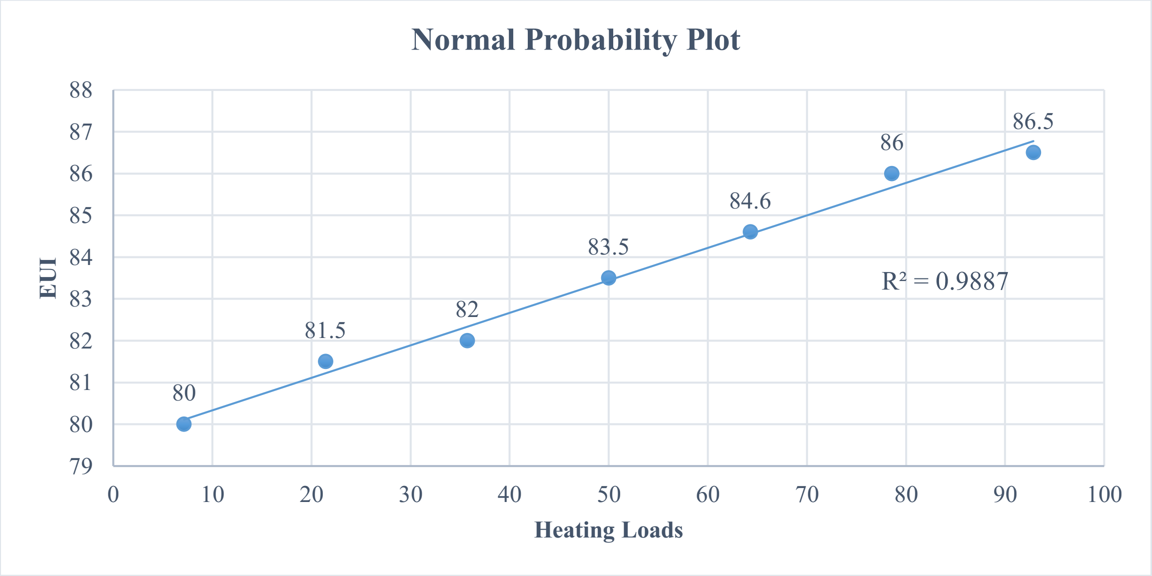


Figure 52. Plot showing the significant correlation between heating loads and EUI.

Since heating loads were determined to be the primary driver of energy use in the single-family home, the fourth permutation run provided the most optimal conditions for enhancing the building's energy performance. The one-story compact design generated an extremely efficient conditioned space, with balanced thermal loads throughout the structure. As a result, heating and cooling loads were evenly distributed and dispersed throughout the space, resulting in an ideal thermal environment. Additionally, the increased south-facing window area generated larger passive solar gains, reducing overall energy loads, specifically electrical and heating loads. Furthermore, envelope upgrades via the structural insulated paneling system yielded a super air-tight building envelope with significantly high R-values and very low leakage rates. The higher levels of insulation enhanced the envelope's overall thermal resistance, drastically minimizing infiltration and leakage rates. Thermal conditions were further improved via the high efficiency HVAC system. The ground source heat pump's high COP provided for an ideal thermal environment, ultimately driving energy loads substantially lower than the baseline. Collectively, the increased levels of thermal resistance throughout the building envelope, high-efficiency HVAC system, compact one-story structure, and augmented glazing area produced a super-efficient structure (Table 28). Daily, monthly, and annual energy profile data showed consistently lower thermal loads (Figure 53). The result was a 56% reduction in energy use over the modeled baseline. Furthermore, simulation results showed a 30% improvement in energy performance when compared to a B10 benchmark reference case, defined as a newly-constructed 2009 IECC code building (Figure 54). Permutation run #4 also generated a HERS index of 60, a 46% reduction from the simulated baseline and 29% lower than a standard EnergyStar certified home (Figure 55).

Table 28. Top energy performance indicator variables from Permutation run #4.

Permutation Run # 4 Architectural Parameters	**Specifications**
Building Design: Number of Floors	• One-story with Gable roof • Compact 40'x 50' Footprint
Building Design: Window Area	• 25% South-facing WWR & • 5% West-facing WWR
Building Systems: HVAC	• Ground Source Heat Pump • COP 4.2, EER 20.2
Building Systems: Envelope	• Walls: Structural Insulated Panels, 9.4 inch EPS Core, R-45 • Wall Sheathing: OSB, R-15 XPS • Exterior Finish: Brick • Roof: R38 Fiberglass Batt, R-25 XPS, Grade-1 • Slab: Whole Slab, R-10 Gap XPS • Infiltration/Leakage: 1 ACH50, 0.04 ACHn/hr

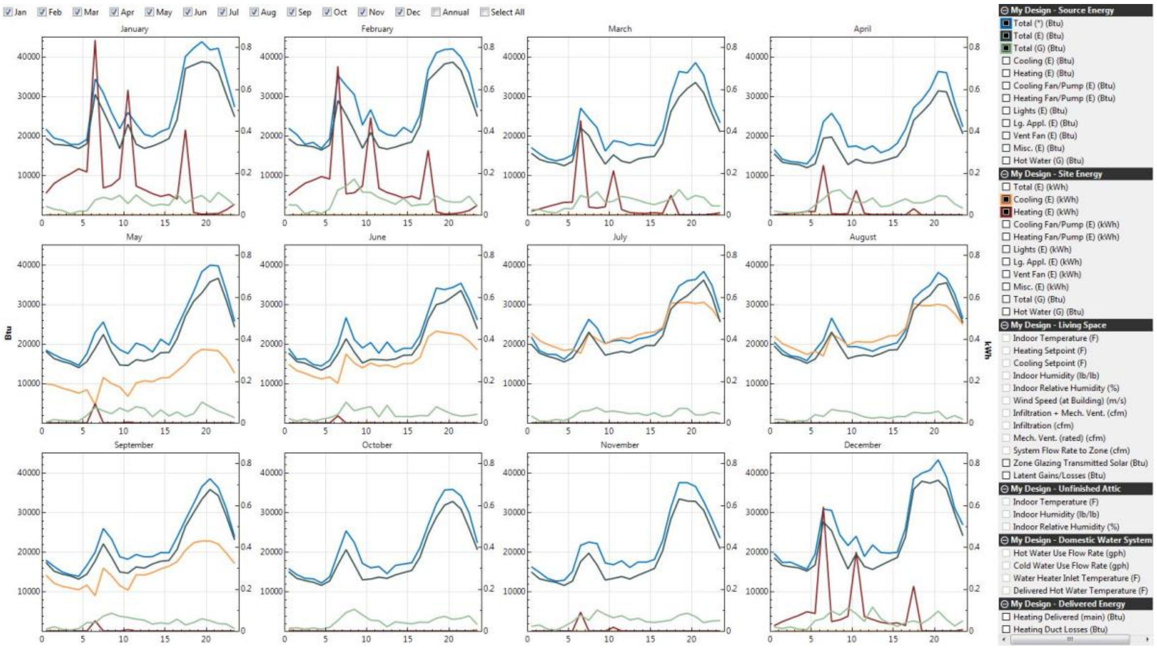


Figure 53. Monthly graphs illustrating average daily energy use profiles from run #4.

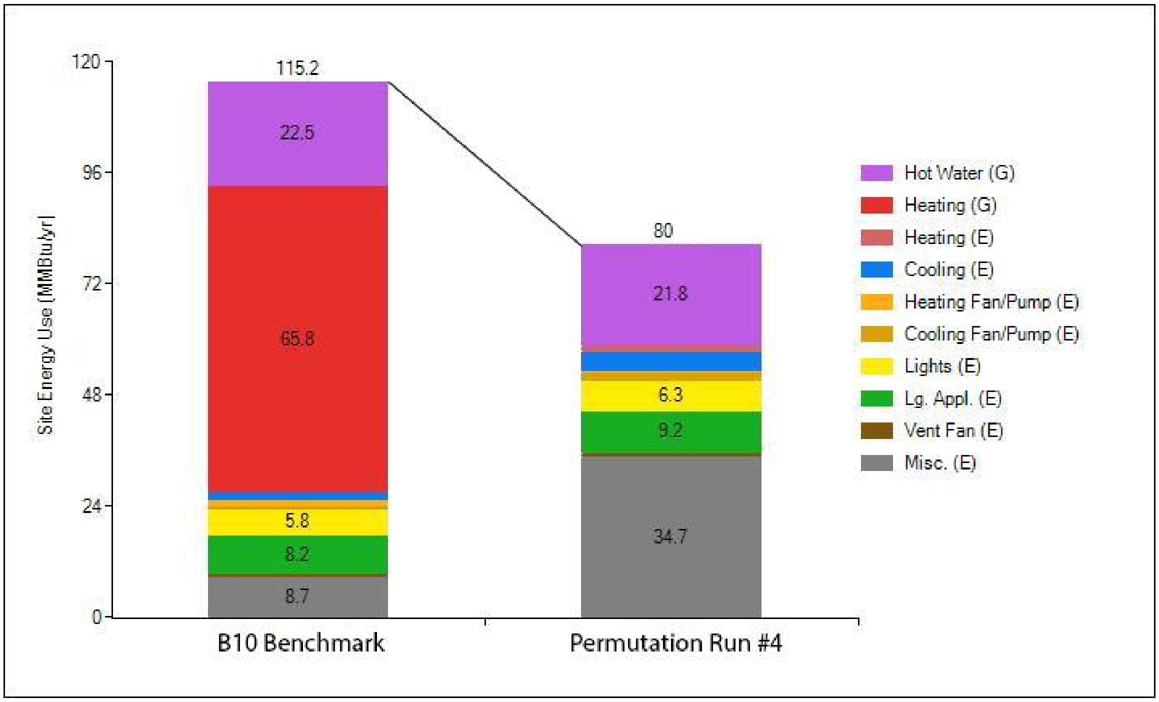


Figure 54. Site Energy use comparison between run #4 and B10 reference case.

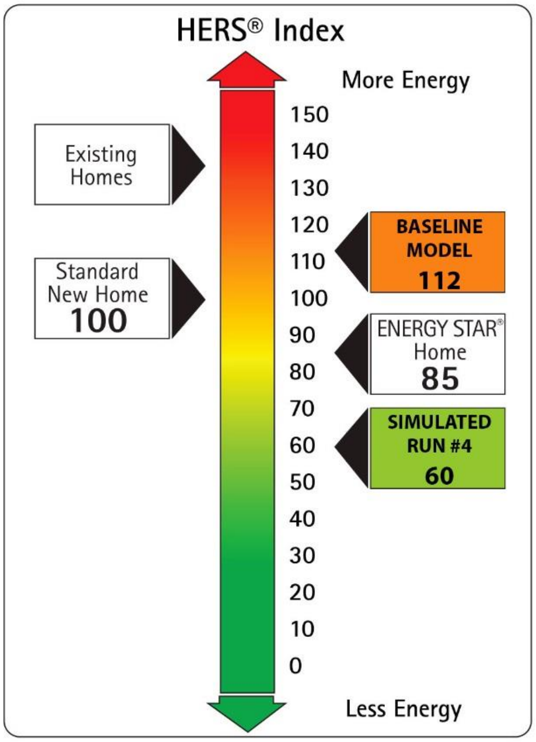


Figure 55. HERS index illustrating the various energy ratings (modified by author).

Life Cycle Assessment and EIU of Design and Systems Decisions

A life-cycle assessment was conducted to further understand the ramifications of design and systems decisions made throughout the modeling process. All nine permutation runs were analyzed using the Tally life-cycle assessment package. Tally is a whole building analysis tool used to quantify and asses the environmental impact of building materials and systems. The software accounts for the full cradle to grave life-cycle of the building, including systems and materials manufacturing, maintenance, replacement, end of service, and energy used across all life-cycle stages. Tally employs NREL's GaBi life-cycle inventory databases and modeling principles, considered industry best practices (2011). The analysis methodology is compliant with life-cycle assessment standards ISO 14040-14044. Assessment results showed run #4 as the least environmentally impactful scenario as it relates to acidification, eutrophication, global warming, ozone depletion, smog formation, and primary energy demand (Figure 56). Furthermore, run #4 had 25% smaller environmental footprint then the baseline.

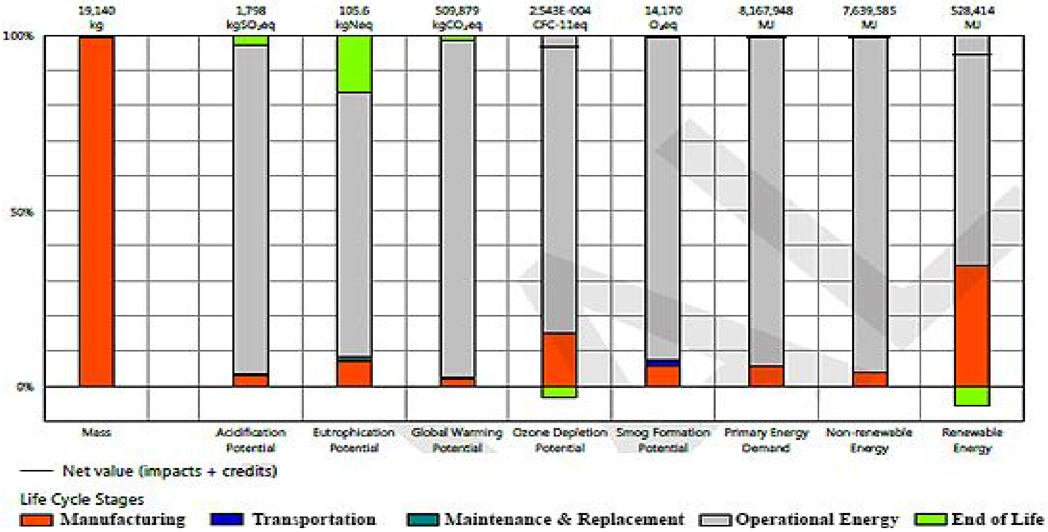


Figure 56. Results depicting life-cycle assessment analysis of permutation run #4, showing significant reductions in operational energy over the lifetime of the building.

Lastly, several energy simulation tools were employed as a measure to assess the validity of the results across the nine different permutation runs. The tools were used to normalize the findings across a broad spectrum of simulation engines. To that end, Design Builder, Energy-10, Home Energy Saver, Green Building Studio, and Sefaira were utilized as supplementary simulation packages to evaluate the efficacy of the data. Accordingly, simulation results from the various tools revealed approximately similar energy use intensities as generated in BEopt, hence confirming the accuracy and validity of the modeling and simulation analysis. Comparison results from permutation run #4 showed a 5% maximum data variance across the various energy modeling and simulation platforms (Figure 57), considered within the allowable margin of error (DOE, 2016).

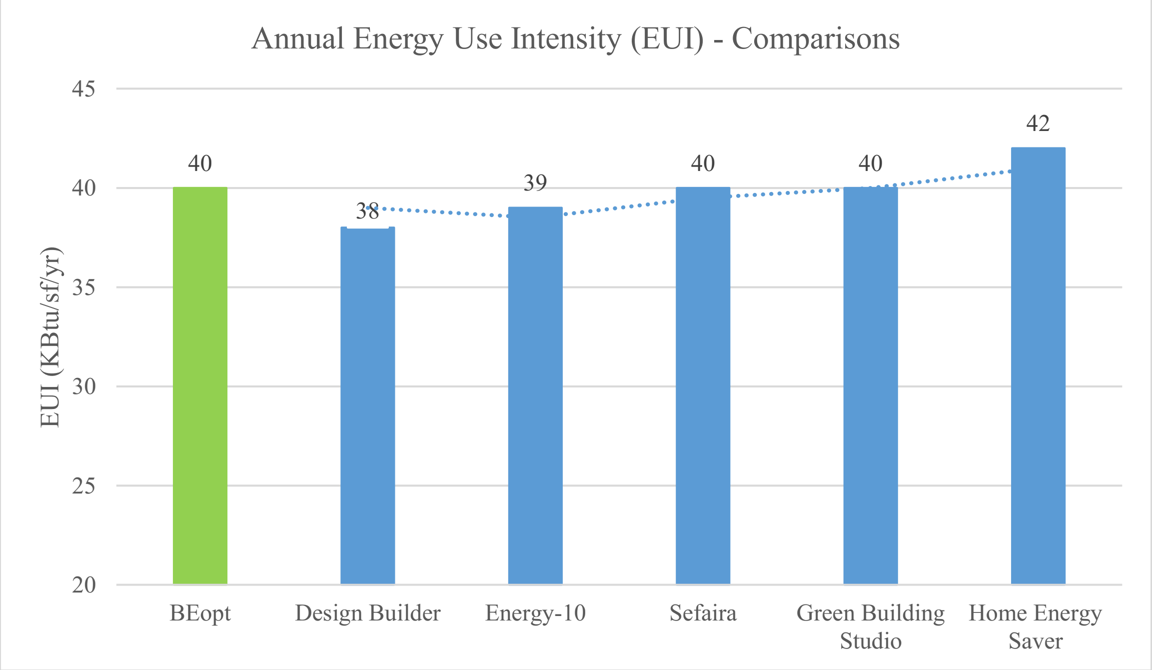


Figure 57. EUI comparison across various modeling platforms for permutation #4.

Conclusions

Residential structures have a substantial impact on energy consumption and the environment. The residential building sector consumes approximately 21% of total U.S. primary energy, predominately generated from conventional fossil fuels (EIA, 2017). Attached and detached single-family homes account for approximately 70% of total residential housing units in the U.S. Accordingly, 80% of the total U.S. residential site energy is consumed by these single-family structures (RECS, 2009). Furthermore, detached single-family homes are the largest energy users among all residential structures. DOE’s single-family home energy consumption projections are forecasted to steadily increase over the next decade, adversely impacting overall energy efficiency and associated greenhouse gas (GHG) emissions (2016). Furthermore, current residential market data reveal an ever-increasing trend in single-family home size, whereby homes today are 38% larger then ones built prior to 1950 (DOE, 2016). Furthermore, larger home sizes coupled with more electronics and appliances have all but wiped energy efficiency gains realized through better insulation, equipment, and overall building practices. Accordingly, total annual U.S. residential energy use increased from 6,000 trillion Btu’s in 1950 to around 22,000 trillion Btu’s in 2016 (EIA, 2017). As a result, 6% of total U.S. GHG emissions are attributed to the residential building sector (EPA, 2016). Therefore, energy conservation measures have become key factors in developing and promoting sustainable building practices and energy efficiency polices.

To address these issues, this thesis examined the impacts of various architectural variables on energy consumption in a standard Pennsylvania detached single-family home. The study targeted specific architectural design parameters and building systems upgrades. An iterative dynamic modeling analysis was employed to evaluate the correlation between the various architectural variables and overall energy use. The modeling analysis was performed using NREL's BEopt energy simulation package. Two modeling stages were utilized, the first stage evaluated the impact of individual variables and the second stage assessed impacts of permutations of optimal variables. For comparison, results were presented in term of annual site energy consumption and overall energy use intensity. First phase simulation results revealed six top optimal energy performing indictors. The top three architectural design variables included compact one-story volume/footprint, flat roof condition, and high ratio south-facing window area. The top three building system variables included high efficiency heat pump HVAC system, structural insulated panel super-insulated air-tight building envelope, and pre-set space conditioning schedules and set points. Thereafter, the second phase of simulation results revealed four top optimal energy performing indicators represented in one permutation of variables. The top four optimal variables were high efficiency HVAC system, super-insulated air-tight building envelope, compact one-story volume/footprint, and high ratio south-facing WWR. The top most optimal permutation yielded an EUI of 40 KBtu/sf/yr, a 27% reduction from an average U.S. detached single-family home at 55 KBtu/sf/yr. Furthermore, results showed a 45% reduction in energy consumption compared to an average detached single-family home in the Northeast region (EIA, 2017). The heating-dominated climate of the region played a critical component in the overall energy outlook forecast. As a result, substantial energy savings were primarily realized due to significant reductions in heating loads, which constituted the largest energy demand in the investigated single-family home. Addressing the building's overall thermal envelope and heating system proved to be key factors in achieving the desired energy performance. Paired with the architectural design modifications, the combination of variables provided an ideal optimal thermal scenario.

Based on the generated results, the initial hypothesis was mostly accepted with one caveat. The initial hypothesis predicted a two-story structure as one of the four optimal energy performance indicators. However, simulation results revealed a one-story residence as one of the most optimal energy efficiency indicators. Nonetheless, all other hypothesized parameters were successfully predicted.

It is important to highlight the limitations of the study. The analysis didn’t take into account user habits, which could constitute a significant factor in energy use patterns. Moreover, the research only tackled a detached single-family home typology, neglecting to address the other residential archetypes. Also, additional data is required regarding various building system upgrades and energy conservation measures. Furthermore, more robust and accurate energy modeling tools are warranted to address certain gaps within simulation platforms. It’s also important to note that as residential energy end use patterns change, a paradigm shift in energy evaluation must occur. 2009 EIA data shows a consistent trend of higher energy consumption by appliances, electronics, and lighting. Accordingly, appliances and electronics energy end use spiked from 21% in 1980 to 35% in 2009. It’s therefore imperative to consider these new parameters in any future energy evaluation analysis.

The goal of this research was to provide a robust roadmap guiding home owners, builders, planners, designers, and policymakers toward more sustainable building approaches and practices. The study aimed to inform advocacy groups, industry professionals, and the general public on optimal techniques to approach energy consumption and efficiency within single-family residential buildings. Furthermore, the research sought to provide optimal architectural guidelines for the design of high performance detached single-family residential buildings. Based on the simulation results, the following list encompasses the top optimal energy performance variables recommended for adoption in detached single-family residential construction in Pennsylvania and similar climate zone regions (Figure 58):

- Design - Massing: compact one-story building volume and footprint
- Design - Glazing: high percentage of high-performance south-facing windows
- Systems - Enclosure: super-insulated air-tight building envelope with high R-values and low infiltration rates
- Systems - HVAC: high efficiency heat pump with a smart thermostat

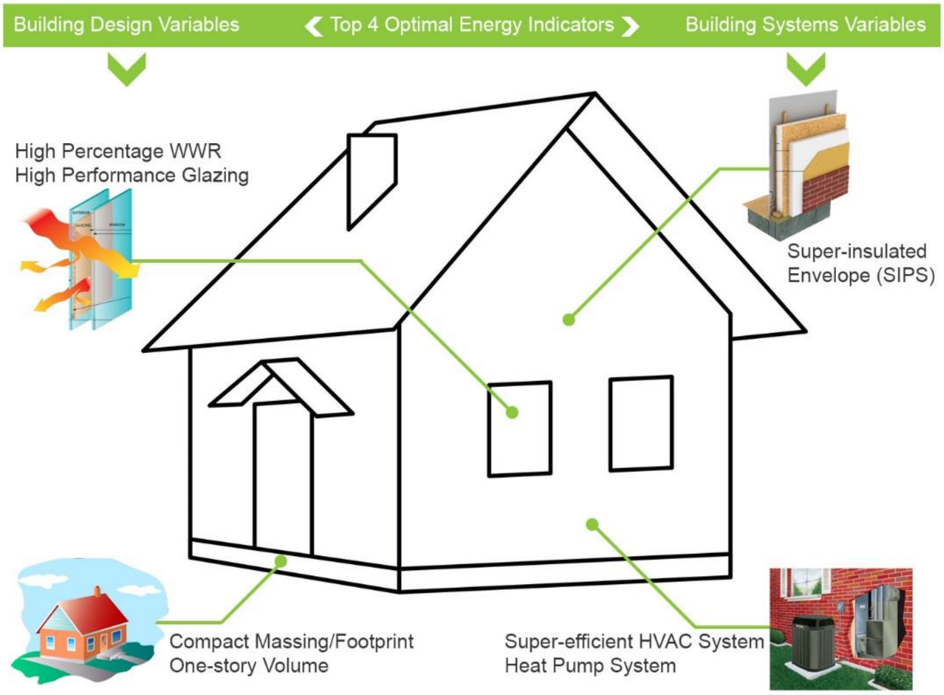


Figure 58. 3d diagram highlighting the top four optimal energy performance indicators.

The aim of this thesis was to provide an alternative path towards residential energy efficiency via a paradigm shift in single-family home design and construction. The road map provided by this study provides a foundational starting point for industry professional, owners, and policy makers. Results are in line with findings from NREL's residential stock energy analysis report, which found a potential minimum of 28% energy savings in Pennsylvania single-family homes via adoption of energy-efficiency measures and improvements (NREL, 2017).

The amount of energy consumed in a single-family home is heavily dependent on climate and location. Accordingly, a possible future research area could encompass a modeling and simulation analysis across various U.S. climate zones, coupled with a financial impact and life-cycle cost examination. Such an investigation would potentially provide a more robust analysis of residential energy use patterns and trends across a wide spectrum of climatic conditions. Nonetheless, this research provides a starting and foundational platform that aims to help policy makers, industry professionals, and various interested parties develop more optimal policy actions and sustainable building practices. It is the hope of this study to advance building science and industry standards, paving the way to more sustainable, economical, and resilient building practices.

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