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A Parametric Modeling Analysis of Architectural Variables and their Impacts on Energy Consumption in a Baseline Pennsylvania Single-Family Home

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Abstract

Buildings have substantial impacts on energy consumption, the environment, and overall comfort of occupants. Rapidly increasing energy use associated with the building sector is a significant and growing problem. Despite advances in energy efficiency and building technology, U.S. energy consumption and resources use per capita continue to increase. This paper examines residential energy performance in a Pennsylvania (PA) single family home, to assess the impact of the most optimal options of building upgrades. Energy consumption in the residential sector has remained relatively steady for several years as increased energy efficiency gains has offset the surge in the number and average size of housing units. To that end, the average area of a U.S. home increased 45% from 1970s. Alternatively, the average number of occupants per household decreased 15% from 1970s. Both of these are alarming trends as it pertains to overall energy use outlooks. As a result, the steady downward energy consumption patterns are threatened to be offset by those trends. Hence, these trends could have negative impacts on energy efficiency gains and greenhouse gas (GHG) emissions. In 2018, the residential sector consumed approximately 21% of the total primary energy produced in the U.S., compared to just 10% in the late 1940's. Furthermore, 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. As a result, 6% of total U.S. GHG emissions are attributed to the residential sector. Given the significant size of this industry, there is tremendous potential to reduce energy use and associated environmental impacts. For example, Pennsylvania could yield a 6.9% reduction of the state's residential energy market load by 2020 if robust optimal energy conservation measures (ECMs) are adopted in single-family homes. 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. Left unaddressed, the implications of population growth, rising energy prices, proliferation of modern home appliances and electronics, steadily increasing home sizes, and energy shortages could be profoundly detrimental to overall energy consumption patterns and the environment. This paper reviews the state of residential energy consumption patterns in the US and Pennsylvania specifically, to understand the underlying mechanisms of energy saving mechanisms and methodologies. Furthermore, the paper examines a myriad of energy efficiency measures available to homeowners. Lastly, the study assesses the impacts of building upgrades on energy use in a baseline PA single-family home via a parametric modeling approach, to provide comprehensive energy conservation and efficiency recommendations.

Keywords: architectural variables, building upgrades, energy efficiency, building performance, energy modeling and simulation, building energy analysis, iterative parametric runs

1 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 the residential sector has remained relatively steady for several years as increased energy efficiency gains has offset the surge in the number and average size of housing units. To that end, the average area of a U.S. home increased 45% from 1970s. Alternatively, the average number of occupants per household decreased 15% from 1970s. Both of these are alarming trends as it pertains to overall energy use outlooks. As a result, the steady downward energy consumption patterns are threatened to be offset by those trends, 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 variables are the most optimal as energy performance indicators in detached single-family residential buildings. As a result, there is still a gap between energy performance and architectural building systems adoption. Many uncertainties exist within the industry, specifically around the impact of combinations of residential building upgrades on energy performance and efficiency. Consequently, policymakers, advocacy groups, building professionals, and the general public are not adequately informed 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. This paper examines residential energy performance in a Pennsylvania (PA) single family home, to assess the impact of the most optimal options of building upgrades.

2 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 continues 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).

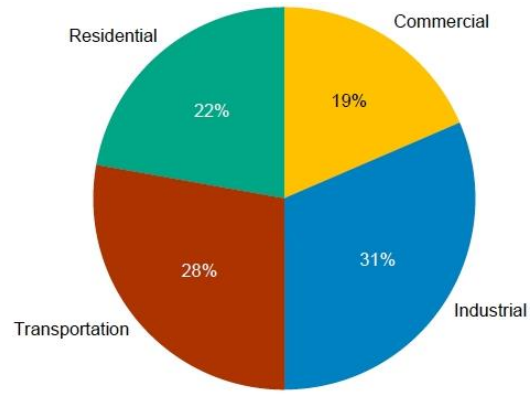

Fig 1. Breakdown of U.S. energy consumption end-uses (EIA, 2017).

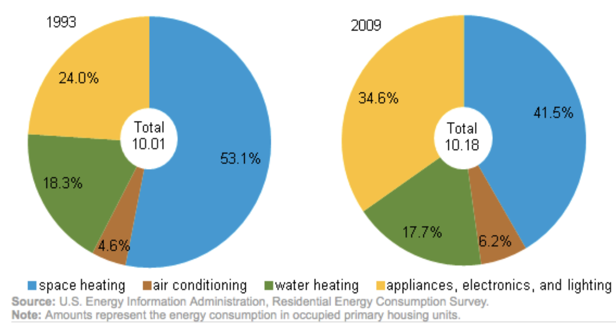

Fig 2. U.S. Home energy end-use consumption comparison (EIA, 2017).

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 homeowners, 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. Homeowners 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 homeowner's bottom line and overall economic well-being. It is therefore imperative to devise more energy efficient and adaptively resilient residential building models.

3 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 homeowners 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 3). 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 4). 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 towards more sustainable and energy efficient practices.

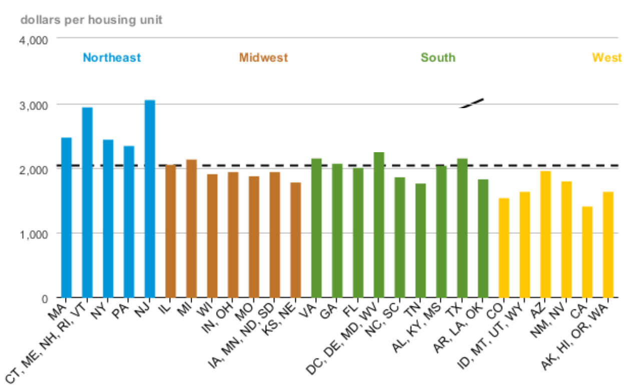

Fig 3. Average home energy expenditures in United States (RECS, 2009).

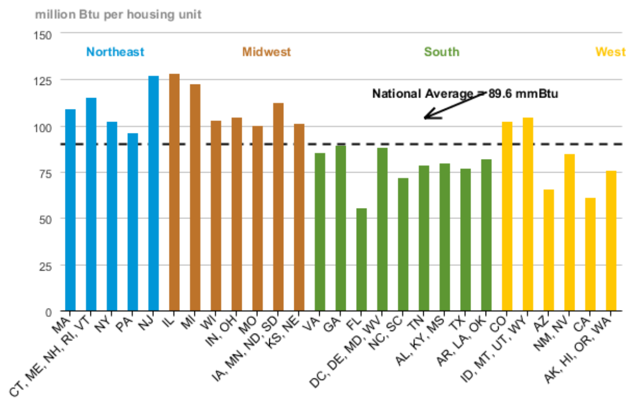

Fig 4. Average home energy consumption in United States (RECS, 2009).

4 Transitioning to more sustainable 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 regard to what system-upgrade combinations might offer the most optimal performance (NREL, 2011). 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. 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. 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 architectural building upgrades and their effect on energy performance.

5 Research questions, hypothesis, and specific aims

The research sought to illuminate the relationship between building upgrades and energy performance. Accordingly, 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 is the impact of itemized building system upgrades on energy consumption in a standard detached Pennsylvania single-family home?
- What impact does various permutations of building upgrades have on energy consumption in a standard detached single-family residential building in Pennsylvania?
- And what specific permutation would yield the most optimal energy performance indicators?

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.

5.1 Hypothesis

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 most optimal combination of architectural indicators was expected to be super-insulated envelope, high efficiency HVAC system, and a high percentage of south-facing window to wall ration (WWR).

5.2 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 consumption and standard residential construction in PA.

(2) Modeling energy parametric runs to assess the impact of itemized iterations of architectural variables encompassing architectural building systems upgrades.

(3) Modeling energy parametric runs to assess the impact of the most optimal iterations of architectural variables encompassing combinations of building systems upgrades.

6 Methods

To address the research questions, hypotheses, and specific aims, an iterative parametric energy modeling/simulation analysis was undertaken (DOE, 2016) (Figure 5). 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. 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). NREL's Building Energy Optimization (BEopt) was used as primary modeling and energy simulation engine. Data needed for the modeling analysis was sourced from appropriate industry and building code databases.

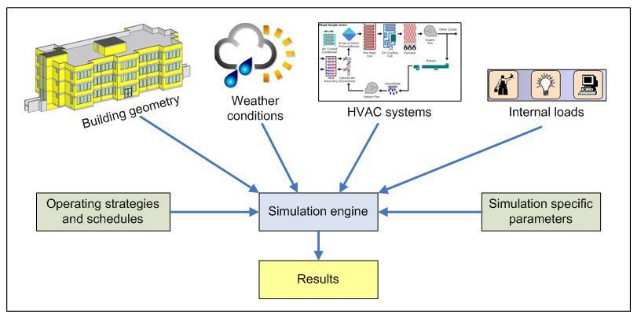

Fig 5. General overview of energy simulation engines data flow (DOE, 2016).

The modeling scenarios entailed adopting upgraded building components 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. The research design for this analysis encompassed the following three overarching sequential steps, listed in the order in which they were executed:

First, 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).

Second, simulated diverse parametric annual energy modeling runs using the EnergyPlus engine, assessing the impact of various building system variables. These included the following eight 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.

Third, selected the highest performing variables from steps two, and thereafter, simulated iterative parametric energy modeling runs evaluating different combinations of architectural variables. The objective was to determine the top two energy performance indicators from each modeled category.

7 Results

The Simulation results from the various building upgrade 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 6 & 7). 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 upgrades included envelope, HVAC, and conditioning set points-schedule upgrades. On the other hand, the least effective options involved lighting system and plug load upgrades. 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 impact of building system 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 1). 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 upgrade entailed space conditioning set point and schedule changes. Consequently, those three top individual building upgrades were chosen to advance into the next stage of parametric energy simulation runs, evaluating the most optimal permutations of building system upgrades.

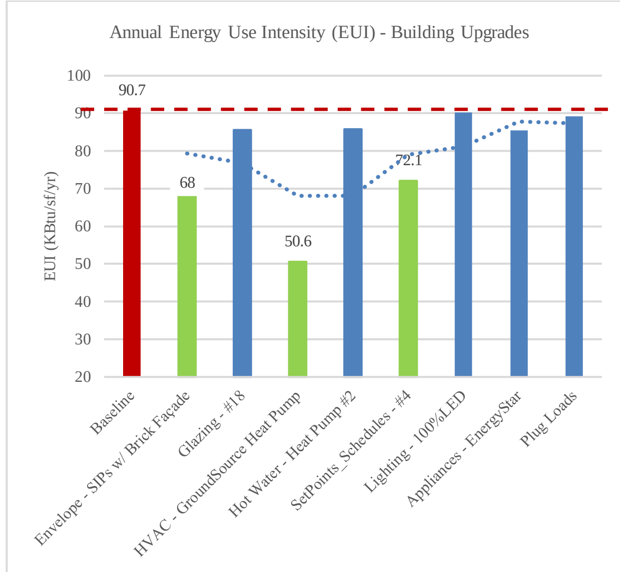

Fig 6. Energy use intensity for the identified optimal systems variable runs.

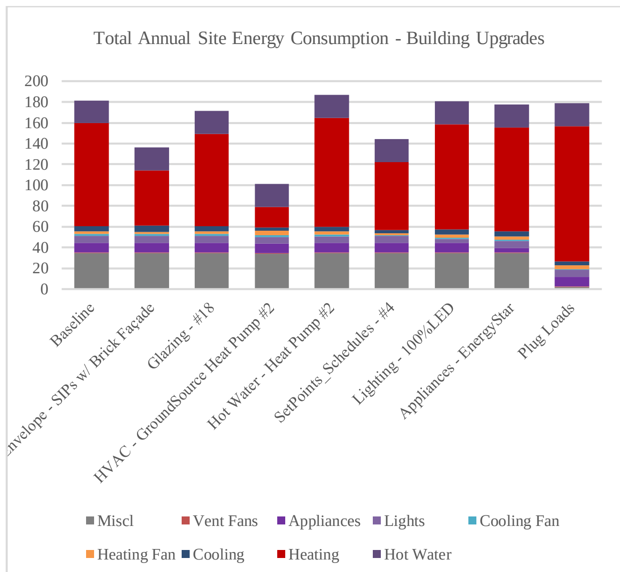

Fig 7. Site energy use for the identified optimal systems variable runs.

Table 1. The top three optimal individual Building Upgrades

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

The next stage of the analysis entailed an iterative parametric modeling investigation of the top three performing variables generated from the individual parametric runs as identified in the results section (Table 1). The study sought to isolate the top two energy performance indicators via an analytical examination. Accordingly, modeling parameters adopted a parametric pairing of two variables yielding nine different permutations of variables (Table 2). 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.

Table 2. Optimal design and system variable permutation runs.

Permutation Runs	System Variables (Combination of Two)
Run #1	GSHP + SIPs
Run #2	GSHP + Set Points/Schedules
Run #3	SIPs + Set Points/Schedules
Run #4	GSHP + SIPs
Run #5	GSHP + Set Points/Schedules
Run #6	SIPs + Set Points/Schedules
Run #7	GSHP + SIPs
Run #8	GSHP + Set Points/Schedules
Run #9	SIPs + Set Points/Schedules

The Simulation results revealed energy reductions ranging between 52% and 56% (Figure 8). All nine modeled runs significantly surpassed the established 15% improvement threshold (Figure 9). Furthermore, findings showed improvements across the board including EUI, site and source energy, carbon emissions, and HERS rating (Table 3). 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 two variables: ground source heat pump HVAC system and a structural insulated panel building envelope system with minimal air flow leakage rates.

Results from the parametric simulation analysis revealed that building system upgrades have a significant impact on energy use, yielding 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 building upgrades generated 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 3). 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 two variables generated the best and most optimal energy performance indicators amongst all other modeled and simulated variables.

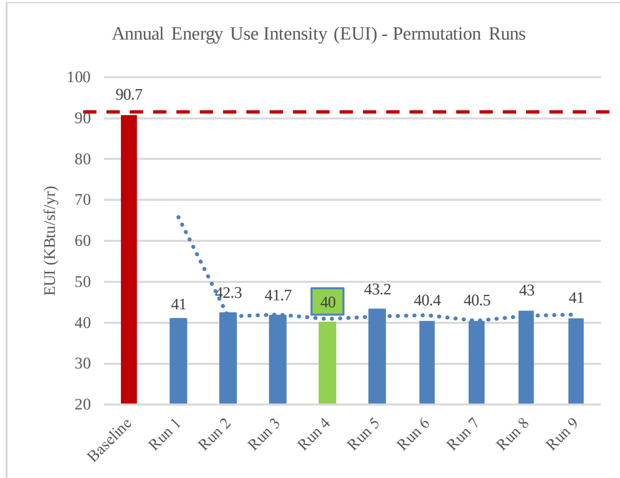

Fig 8. Energy use intensity for the identified optimal permutation runs.

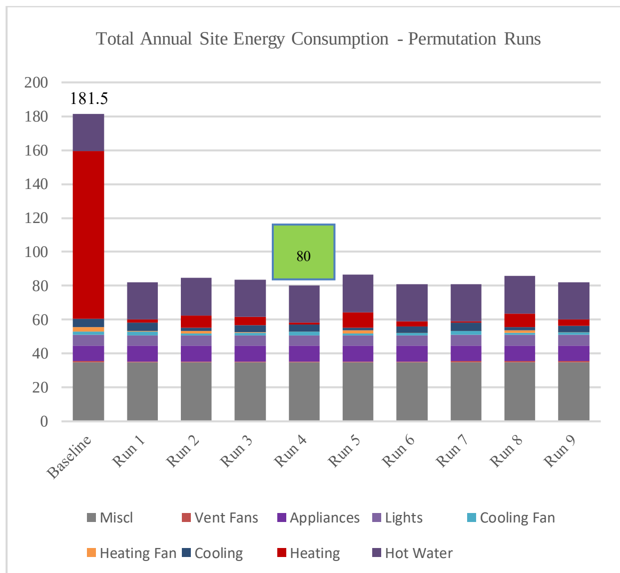

Fig 9. Site energy use for the identified optimal permutation runs.

Table 3. Permutation modeling-run results

Permutation Runs	Site Energy	HERS Rating	% Reduction Over Baseline
Baseline	181.5MMBtu	112.1	
Run #1	82MMBtu	63.2	54.8%
Run #2	84.6MMBtu	70.4	53.3%
Run #3	83.5MMBtu	73.4	53.9%
Run #4	**80MMBtu**	**60**	**56%**

Run #5	86.5MMBtu	76.5	52.3%
Run #6	81MMBtu	69.3	55%
Run #7	81MMBtu	58	55%
Run #8	86MMBtu	68.5	52.6%
Run #9	82MMBtu	66.7	54.8%

8 Results

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 than 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.

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 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. 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. 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.

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 homeowners, 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:

- Envelope Upgrades: super-insulated air-tight building envelope with high R-values and low infiltration rates
- Systems Upgrades: HVAC: high efficiency heat pump with a smart thermostat

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