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Feasibility Study for Sustainable Residential Development in the United States

A Major Qualifying Project

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Table of Contents

Abstract

Global climate change is a phenomenon that affects different regions of the world in various ways. The United States specifically, but not exclusively, is affected by natural and human-made conflicts that threaten energy security and human health. A social shift acknowledging the need for greener building practices globally has been most evident in the last decade. Through energy modeling and site-specific design strategies, architects are increasingly basing their work on a variety of local and international wellness and sustainability standards. Data shows that a majority of future and existing green building development largely favors larger-scale commercial construction over smaller residential projects. A residential environment during an energy crisis can have devastating effects on the quality of life if resiliency measures are not already in place. In today's rapidly evolving social, political, and natural climates, building professionals require more resources and guidance in order to choose the appropriate renewable technologies and methods through analyzing sites. Our remedy for this problem involves looking at a variety of energy-saving strategies for the continental United States and developing guidelines to make green building practices for residential development more prevalent.

Acknowledgement

Our team would like to thank our advisors, Soroush Farzin and Stevan Van Dessel for their expertise, constructive criticism, and support. We would also like to thank Ali Fallahi, for his advice and expertise on building information modeling softwares utilized in this project.

List of Abbreviations

BIM	-	Building Information Modeling
CBP	-	Combustion by-product
DSIRE	-	Database of State Incentives for Renewables and Efficiency
EPS	-	Expanded Polystyrene Insulation
HVAC	-	Heating, ventilation, and air conditioning
IEA	-	International Energy Agency
ICF	-	Insulated Concrete Forms
LEED	-	Leadership in Energy and Environmental Design
LBNL	-	Lawrence Berkeley National Laboratory
NZEB	-	Net-Zero Energy Buildings
OPEC	-	Organization of Petroleum Exporting Countries
USDHUD	-	U.S. Department of Housing and Urban Development
USDE	-	United States Department of Energy
USGBC	-	United States Green Building Council
XPS	-	Extruded Polystyrene Insulation

List of Tables

List of Figures

Design Statement

In today's rapidly evolving social, political, and natural climates, building professionals require more resources and guidance in order to choose the appropriate renewable technologies and methods through analyzing sites. If residents wish to start a new home development or retrofitting project, how can they utilize current digital assets to design, implement and simulate a functional model? How can we further educate the general public on strategies and systems for achieving a resilient net-zero home in the United States?

Our remedy for this problem involves looking at a variety of energy-saving strategies for the continental United States and developing a guide to make green building practices for residential development more prevalent. While commonly implemented in large commercial and institutional buildings, costly building automation retrofits are progressively becoming more attainable and realized in residential applications. By enabling a home system to recognize the building environment inside and out, unobstructive technologies can be implemented to move smart home movement into an autonomous system that can prepare for environmental changes hours or even days ahead.

In the scope of data collection and unpredictability in physical building environments, simulation software and offsite construction methods can have the potential to increase productivity while reducing overall costs. Taking on ecological approaches rather than engineering-dominated solutions, residential green building construction practices aided us in our engineering design process. Utilizing local materials and buildings to relate to the wider environment can reduce environmental impacts. Implementing the use of contemporary technology to enable low energy and water demand results in a process that is safe to build and easy to adapt for future generations. By evaluating the objective and assessing the outcomes of our solutions, we were able to determine the effectiveness of the models by building information modeling softwares and simulations.

A synthesis (design) level of building mechanical systems was reached in the scope of our project through the use of modeling energy-efficient technologies and systems in the software Design Builder. Extensive research proved the applicability of a GSHP Geothermal HVAC system for the proposed net-zero conceptual residential development. Within Design Builder, these systems and mechanical system load settings can be controlled to simulate their effect on the energy use (EUI) of the model.

An application level of construction was reached through the study conducted on various wall assemblies per climate and material type. A comparative analysis was done through the software WUFI and THERM focusing on ICF (Insulated Concrete Forms) and Wood-Stud Wall assemblies. An application level of construction management was reached through the use of the software RSMeans in completing a cost estimation of the wall assemblies and the overall residential model.

Building structures was demonstrated to achieve a comprehension level by looking at new and innovative materials' use and structural durability, notably ferrock and timbercrete in future applications once more data can be gathered on them and popularity increases enough to lower the costs associated with these materials. Structural design criteria for our proposed wall assembly of ICF influenced the overall design and energy modeling.

A comprehension level in building electrical systems was met by gaining a larger understanding of the effect of lighting types and loads on overall energy usage. Additionally testing the effect of outlet/room loads when put on an adjusted schedule in Design Builder was used to simulate habitual changes. Solar energy generation was calculated through the website tool PV Watts to determine if Net-Zero was achieved after significantly reducing energy use in the models.

This project considers mechanical systems and processes within the built residential environment that can make all aspects of the design greener while maximizing resources on a budget. These systems include the implementation and analysis of next-generation renewable energy sources such as ground source heat pumps, building automation systems, and solar panel systems.

In collaboration with Worcester Polytechnic Institute professors who are adjunctly working in the field of building mechanical systems, our project was able to identify and utilize building information modeling and simulation software to aid in our design process. This included assistance in developing and analyzing WUFI, THERM, and Design Builder models and data.

Along with the utilization of computer-based building information modeling and simulations, our project utilizes applicable IBC, ASHRAE, and various sustainability assessment standards. Applicable site-specific codes and standards were also obtained through local municipality resources as well as a Database of State Incentives for Renewables and Efficiency. Furthermore, an online codes and standards tool called ResStock aids in identifying resources where states, municipalities, utilities, and manufacturers can identify which building stock improvements save the most energy and money.

With increasing geopolitical tensions and uncertainty, it is clear that residential infrastructure without resiliency to energy insecurity is not a viable option for the environment or occupants well-being. Understanding the U.S. relationship with environmental consciousness and how energy usage has evolved allows us to predict the direction current policies and efforts will advance residential development in the future. For typical homeowners, coping with the consequences of energy insecurity comes with its own negative consequences, such as loss of social networks, institutional ties, and living in unhealthy or unsafe conditions. Neighboring factors including physical home improvement needs and economic expenditures are paramount in supporting residents with high energy insecurities. Regardless of a pandemic status, the survival of the most vulnerable depends on their ability to control their home environments, whether it is air conditioning to ease respiratory distress, refrigerate medicine, or operate medical equipment, living with energy insecurity is not an option.

Each member in the project group successfully collaborated with each other and adjunct faculty to develop and analyze thoughtful solutions to the problems and objectives outlined in the problem statement.

Professional Licensure Statement

Licensure is an essential aspect of any professional field. The definition of licensure is the granting of a license, particularly when it pertains to professional practice. For AREN, this refers to the Architectural Engineering PE License.

In order to obtain the Architectural Engineering PE License, the engineer is required to have a bachelor's degree in a related field from a program that is ABET-approved. There is also a minimum requirement of four years of qualifying work experience. In addition, engineers are required to pass two competency exams successfully: the Fundamentals of Engineering or FE exams, and the Principles and Practice of Engineering or PE exams. Only when these requirements have been met can an individual receive their PE license.

To maintain the PE license, many states require engineers to maintain and improve their skills through educational courses, webinars, and other approved methods of professional development. These opportunities allow the engineer to earn professional development hours (PDHs), which are needed to maintain their PE license.

For the AREN profession, the licensure provides a threshold that allows the standards and professionalism of the position to be upheld/ Otherwise, without the license the skills of the professionals are less trustworthy and easier to doubt.

For the individual, the license certifies them to service directly to the public, which is a privilege given to the professional engineer. This means they hold themselves to the highest engineering standards and are competent enough to provide the service. Also, many positions require the engineer to be licensed before they can be hired.

Lastly for the public, licensure protects the people, who will receive the services of the licensed engineer. If licensure did not exist, the public is at risk of injury, or even death when utilizing a building created by someone who is not skilled enough for the job. With licensure, the service will only be provided if the engineer is able to meet all the stringent requirements of the PE license.

1 Introduction

With today's climate change dilemma and race for renewable energy, the gravity of energy insecurity has been a topic of increasing importance. Today, countries in Europe are suffering from a lack of on-site renewable energy generation relying on foreign energy delivery. The United States, the largest global producer of crude oil and the second largest electricity-producing country, faces the risk of intangible cyberattacks on energy infrastructure.[1] Residential homes face a greater risk than commercial buildings where resilience measures and green building practices are more prominent both globally and in the U.S. A lack of new residential construction with renewable energy and resilient design features could put the lives and livelihoods of occupants at risk amidst a future energy or climate change crises. Having homes with comfortable environmental conditions is imperative to maintaining the quality of life for occupants. Looking into the next decade, this project aims to understand historical energy crises, building trends, and built environment solutions to showcase how homeowners and building professionals can innovate and implement green building methods.

[1] "U.S. Energy Facts Explained - Consumption and Production - U.S. Energy Information Administration (EIA)," accessed December 1, 2022, https://www.eia.gov/energyexplained/us-energy-facts/.

2 Background

2.1 Introduction

While much of the global community continues to set goals towards renewable and environmentally conscious initiatives, disparities exist between residential and commercial green building development. There is ample opportunity to increase efficiency of residential green building development. As a growing number of new commercial developments are investing in green building solutions, the same innovation and progress has not occurred for residential developments. To begin the process of realizing effective solutions, we must understand what is hindering the potential progress within the industry, more specifically why we need more green residential development in the first place.

2.2 A Lack of Green Building Practices

2.2.1 Green Building

The U.S. Green Building Council (USGBC) defines green building as a holistic concept where the built environment can have profound effects, both positive and negative, on the natural environment, as well as the people who inhabit buildings every day. Green building is an effort to amplify the positive while mitigating the negative effects of pollution and waste that is prevalent throughout the entire life cycle of a building.[2]

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[2] "What Is Green Building? | U.S. Green Building Council," accessed October 19, 2022, https://www.usgbc.org/articles/what-green-building.

2.2.2 Green Building Trends

According to a 2021 World Green Building Trends report, global green building activity over the next three years shows a continuing disparity between commercial and residential construction.[3] While 49% of new commercial construction plans on utilizing green building practices, new low rise and high rise residential development rates of green implementation sit at around 31%.[4] [5] In the United States the gap between residential and commercial green building activity between 2018 and 2021 is even more divergent. With green building activity at 51% for new commercial compared to new residential high rise and low rise construction at 30% and 35%.[6] Buildings play an essential role in the daily lives of people, they are places we eat, sleep, work, learn, and congregate, while also acting as a reflection of our communities. While Americans spend more than 90% of their lives indoors, they live and work in buildings without the latest energy-efficiency and resiliency measures.[7]

The construction industry itself is confronting critical challenges, including lagging productivity, undersupply of quality trades, and insufficient pace of innovation. The housing industry invests only 0.4% of its revenue into research and development, where the average rate for other, non-farm industries is nearly 4%. In addition, the uptake of new technology is lower than in other US sectors; only agriculture is less digitized. However, new solutions such as Building Information Modeling (BIM) and augmented reality are becoming more popular among

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[3] Stephen A. Jones, "World Green Building Trends 2021" (Dodge Data & Analytics, 2021), https://www.corporate.carrier.com/Images/Corporate-World-Green-Building-Trends-2021-1121_tcm558-149468.pdf.

[4] High rise residential is 4 or more floors

[5] Low rise residential is 1-3 floors

[6] Stephen A. Jones, "World Green Building Trends 2021" (Dodge Data & Analytics, 2021), https://www.corporate.carrier.com/Images/Corporate-World-Green-Building-Trends-2021-1121_tcm558-149468.pdf.

[7] Neil E. Klepeis et al., "The National Human Activity Pattern Survey (NHAPS): A Resource for Assessing Exposure to Environmental Pollutants," *Journal of Exposure Science & Environmental Epidemiology* 11, no. 3 (July 2001): 231–52, https://doi.org/10.1038/sj.jea.7500165.

contractors. Materials used in construction have a big impact on the productivity of the industry. An increasing pressure of green construction is encouraging the development of new construction materials and advances in construction automation technology. Estimates suggest that the construction sector could automate 47% of the tasks carried out - one of the highest shares of any sector - and that, therefore, there is a significant scope to improving productivity through these means as well. Activities with the largest automation potential include data collection and dealing with unpredictable physical environments.[8] While automation may produce great benefit to the industry, the financial burden of implementing state of the art automation to a residential home is not attractive for the majority of people

Respondents to a Dodge Data & Analytics report sponsored by the USGBC shows one of the biggest incentives for owners of green buildings is to lower operating costs. In the scope of data collection and unpredictability in physical building environments, simulation software and offsite construction methods can have the potential to increase productivity while reducing overall costs.

2.3 The Next Generation of Renewable Energy Infrastructure

In 2020, 27% of U.S. households reported difficulty meeting their home energy needs. Nearly 10% of U.S. homes reported having to keep their home at unhealthy or unsafe temperatures due to energy insecurity.[9] While economic energy insecurity is a large representation of the overall energy insecurity in the United state, it is also a sign of

[8] "A FUTURE THAT WORKS: AUTOMATION, EMPLOYMENT, AND PRODUCTIVITY" (Mckinsey Global Institute, January 2017), https://www.mckinsey.com/~/media/mckinsey/featured%20insights/digital%20disruption/harnessing%20automation%20for%20a%20future%20that%20works/mgi-a-future-that-works_full-report.pdf.

[9] "In 2020, 27% of U.S. Households Had Difficulty Meeting Their Energy Needs," accessed November 4, 2022, https://www.eia.gov/todayinenergy/detail.php?id=51979.

building-level inefficiencies that increase the cost for homeowners who may already be burdened by unstable employment and low wages. Physical energy insecurity results from deficiencies in the physical infrastructure of the home environment that impacts overall thermal comfort and increases energy costs. Energy-specific inefficiencies can derive from passive design faults, such as a lack of insulation or drafts through windows and doors. Deficiencies can also result from active strategies in the home such as faulty thermostats or hvac systems. Energy insecurity comes with adverse consequences relating to residents' environmental quality and health. Poor physical conditions as a result of energy insecurity are prone to chronic stress and mental health disorders.[10] Trying to cope with the consequences of energy insecurity comes with its own negative consequences, such as loss of social networks and institutional ties. Overall, neighboring factors including physical home improvement needs and economic expenditures are paramount in supporting residents with high energy insecurities. Implementing renewable energy sources can enhance the reliability, security, and resilience of residential structure and its occupants.

2.3.1 What is renewable energy?

Renewable energy is energy produced from sources that are naturally replenished and do not run out.[11] Renewable energy sources such as biomass, geothermal resources, sunlight, water, and wind, are natural resources that can be converted into clean, usable energy. Energy dependent systems that utilize renewable energy strategies benefit from enhanced reliability, security, and resilience of the nation’s power grid. Adopting renewable energy systems also increases their affordability by allowing producers of renewable technologies to compete with

[10] Diana Hernández, “Understanding ‘Energy Insecurity’ and Why It Matters to Health,” *Social Science & Medicine (1982)* 167 (October 2016): 1–10, https://doi.org/10.1016/j.socscimed.2016.08.029.

[11] “Renewable Energy,” Energy.gov, accessed December 8, 2022, https://www.energy.gov/eere/renewable-energy.

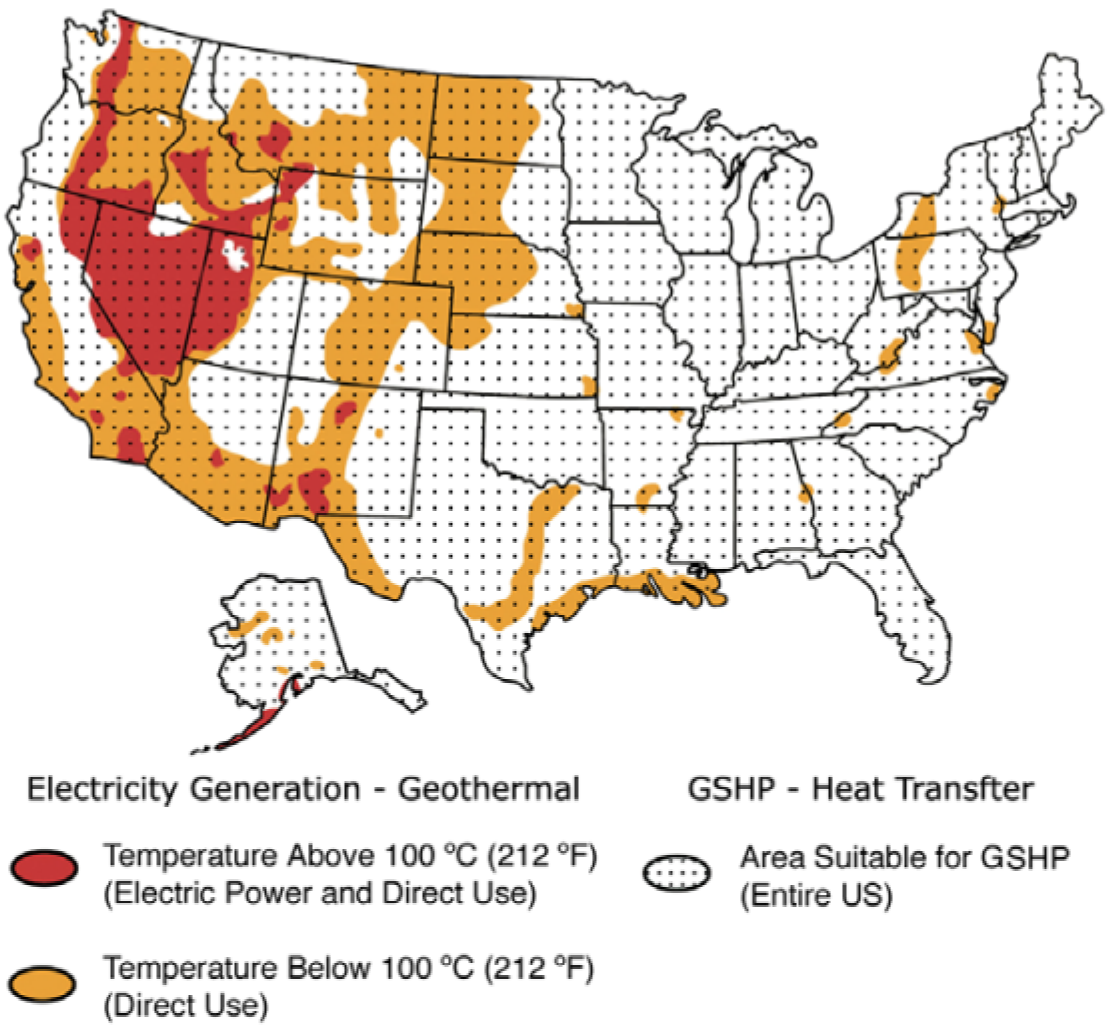
traditional energy source providers. Lastly, the reduction in carbon emissions and air pollution from energy production benefits the surrounding environment of those who adopt renewable energy strategies. While most renewable technologies are known to the general population and market, such as PV panels, some solutions are not as prevalent as they have the ability to be concealed inside or underneath a building envelope.

2.3.2 Ground Source Heat Pumps

In residential applications, a ground source heat pump transfers long loops of underground pipes filled with liquid in a closed or open loop configuration depending on the water content and soil characteristics of the ground below. When the loop returns to the building, it disperse its thermal energy through an air handling unit, radiators or hydronic flooring. The most ideal of these systems for a new development being hydronic floor heating, where the system is quiet, efficient, and unobtrusive. The implementation of geothermal technology is sustainable and becomes more efficient over time. For example, in the winter months heat can be extracted and cold thermal energy is exchanged and naturally stored in the ground. In the cooling months, that same cold thermal energy from the previous heating season is able to be extracted more efficiently in a process called seasonal thermal energy storage.

GSHP systems are preferred in locations with a more balanced climate, lower drilling costs and/or higher energy prices. In moderate climate zones such as Los Angeles (Zone 3C) a standard ground source heat pump can sufficiently meet heat and cooling demands. In colder climates such as Minneapolis (Zone 6). In this case hybrid ground source heat pumps (HGSHP's) can be implemented for any lack of efficiency in thermal load performance.[12] While there are many software applications able to analyze and model geothermal technologies, the Design Builder software is more accessible and able to design and model these systems for optimal residential building performance based on numerous parameters and properties of the development.

Figure 1: Large-scale geothermal and GSHP potential in the United States[13]



[12] G. Riyan Aditya et al., "Comparative Costs of Ground Source Heat Pump Systems against Other Forms of Heating and Cooling for Different Climatic Conditions," *Sustainable Energy Technologies and Assessments* 42 (December 1, 2020): 100824, https://doi.org/10.1016/j.seta.2020.100824.

[13] "J Hanova and H Dowlatabadi 2007 Environ. Res. Lett. 2 044001," n.d.

While the environmental and performance benefits of GSHP are superior to traditional HVAC systems, the high upfront costs and landscape alteration requirements are cons that should not be overlooked when considering residential applications. As geothermal technology advances the cost of GSHP has only increased. In the U.S. rebates and tax credits are one way to lessen this burden along with a soil mechanic analysis to see if a GSHP is a viable option to begin with..

In urban environments where land may be scarce and land alterations may not be possible, the implementation of a large ground heat exchanger (GHE) facility could supply heating and cooling needs of many residential homes. Although the energy needed to supply such a facility would be large, the use of large solar arrays or other sustainable electricity sources could reduce reliance on the grid.[14] As a U.S. environmental research study of geothermal resources indicates the entire country is suitable for GSHP and that both residents in Los Angeles and Minneapolis can benefit from the implementation of a GSHP. According to the U.S. Bureau of Labor and Statistics (USBLS) the average cost of electricity is 47% greater than Minneapolis and 33% greater than the national average.[15] The average cost of natural gas is also greater, costing 30% more per therm than Minneapolis and 14% greater than the national average. Understanding this disparity, for the purposes of the section objective, we will utilize Los Angeles as the site of interest for calculating the important factors of below grade soil necessary for understanding the efficacy of implementing a GSHP system..

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[14] Hansani Weeratunge et al., "Feasibility and Performance Analysis of Hybrid Ground Source Heat Pump Systems in Fourteen Cities," *Energy* 234 (November 1, 2021): 121254, https://doi.org/10.1016/j.energy.2021.121254.

[15] "Average Energy Prices, Los Angeles-Long Beach-Anaheim – October 2022 : Western Information Office : U.S. Bureau of Labor Statistics," accessed December 8, 2022, https://www.bls.gov/regions/west/news-release/averageenergyprices_losangeles.htm.

2.3.3 Selected Residential Building Technologies

With an implementation of new on site renewable options for single and multi-family residential buildings, the use of automation systems that can track occupancy and self-adapt to their preferences is the next major step for the future of sustainable green building practices. While commonly implemented in large commercial and institutional buildings, these costly building automation retrofits are progressively becoming more attainable and realized in residential application. By enabling a home system to recognize the building environment inside and out, unobstructive technologies can be implemented to move smart home movement into an autonomous system that can prepare for environmental changes hours or even days ahead. Utilizing a similar but less intensive methodology outlined in Harvard University's House Zero case study, interconnected active design strategies could be controlled through AI algorithms that can predict building environment needs through past data, upcoming weather, and occupancy loads. A less intensive method could involve utilizing existing electrical infrastructure such as a wall socket to create a powerline communication (PLC) between a home's active systems where powerline adapters can connect wirelessly or wired to a router and send network data through the electrical wiring of a home. Initial results from DOE research shows that the PLC is a viable low-level protocol layer solution for fine-grained power monitoring of the appliances in green building environments.[16] Regardless of the solution, green building practices need to efficiently communicate and regulate the energy they use. PLC is a cost effective way of making this communication happen without the need to install costly infrastructure.

[16] Nirmalya Roy et al., "Performance of the Latest Generation Powerline Networking for Green Building Applications," in *Proceedings of the 5th ACM Workshop on Embedded Systems For Energy-Efficient Buildings*, BuildSys'13 (New York, NY, USA: Association for Computing Machinery, 2013), 1–8, https://doi.org/10.1145/2528282.2528298.

2.4 Energy Crises & Shifting Climates

2.4.1 Historical Crises

Before the 1970's, utility companies enjoyed complete control over energy productions and transmission methods. The oil crisis of 1973/1974, triggered by the Arab-Israeli War and Organization of Petroleum Exporting Countries (OPEC) oil embargo reflected the tightening of global oil markets, disrupting energy supplies to the member states of the European Community. Energy reforms in the United States aimed to cap domestic oil prices in 1971 as part of economy-wide wage and price controls intended to fight rising inflation. Capping oil prices to help consumers ended up encouraging consumption and lowered supply, causing heating oil shortages in the winter of 1992 and 1993 that deepened the sense of an impending energy crisis. Residential energy conservation became a political and popular priority by the mid-1970's, the United States Department of Energy (USDE) funded the Lawrence Berkeley National Laboratory (LBNL) to establish an energy-efficient buildings research program. Since then, the LBNL has pioneered scientific study of the complex relationship between residential energy efficiency and indoor air quality.[17] Understanding how the U.S. relationship with environmental consciousness and energy usage has evolved will allow us to predict the direction current policies and efforts will take residential development in the future.

[17] "Climate Change and Indoor Air Quality: Lessons from the Energy Crisis of the 1970s | Joint Center for Housing Studies," accessed October 31, 2022, https://www.jchs.harvard.edu/blog/climate-change-and-indoor-air-quality-lessons-from-the-energy-crisis-of-the-1970s.

2.4.2 Recent Crises

Throughout recent years, the COVID-19 pandemic has exposed many underlying and ongoing social crises throughout the U.S. Crises that involve a direct correlation between a lack of energy services and quality of life. Studies show a clear geospatial correlation between coal fired power plants and mortality from air pollution responsible for over 52,000 premature American deaths each year.[18] Many of these deaths stem from access inequity, for example, the Navajo Nation in Dinetah, Arizona is affected by a lack of running water and households without electricity. Despite a coal power plant on the Navajo land, citizens are still without power despite the coal power emissions increasing premature death, heart and lung diseases.[19] Regardless of a pandemic status, survival of the most vulnerable depend on their ability to control their home environments, whether it is air conditioning to ease respiratory distress, refrigerate medicine, or operate medical equipment, living with energy insecurity is not an option.

2.4.3 Future Outlook

With the United States 2030 goal to reduce CO2 emissions by 50-52% below 2005 levels, it is clear that multiple pathways will be needed to achieve a net-zero economy goal by 2050. While the total energy imports to the U.S. has declined in recent years, a new age of energy management is more vulnerable to cyber threats. Current trends in energy will persist in the near future due to global initiatives like the Paris Climate Agreement. Following these trends,

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[18] Jennifer A. Burney, "The Downstream Air Pollution Impacts of the Transition from Coal to Natural Gas in the United States," *Nature Sustainability* 3, no. 2 (February 2020): 152–60, https://doi.org/10.1038/s41893-019-0453-5.

[19] Kathleen Brosemer et al., "The Energy Crises Revealed by COVID: Intersections of Indigeneity, Inequity, and Health," *Energy Research & Social Science* 68 (October 2020): 101661, https://doi.org/10.1016/j.erss.2020.101661.

renewable energy will gradually claim a larger share of the national energy consumption as these technologies become more economically available and integrated into industry. With the U.S. being the largest oil and natural gas producer in the world, the status of energy insecurity is unlikely to come from supply shortages.[20] There are three interconnected transmission grids covering the contiguous U.S. divided into western states, Texas, as well as the eastern and Midwest regions of the U.S. According to the Director of National Intelligence's 2022 Annual Threat Assessment nations and criminal groups are becoming increasingly capable of attacking the grid.[21] To make matters more tense, in 2021 the U.S. imported 3.5% of its crude oil from Russia, the greatest percentage in at least two decades. The U.S. also relies heavily on Russia for gasoline, accounting for 21% of imports, more than any other country.[22]

2.5 Site Selection

2.5.1 Selection Process

In our site selection process we decided to select sites in two different U.S. climate zones to demonstrate the differences in net zero strategies and achievability of this goal considering various sites specific factors and impacts. We selected cities in Climate Zones 6 and 3 due to their dissimilar geographical location and availability of data.

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[20] "Frequently Asked Questions (FAQs) - U.S. Energy Information Administration (EIA)," accessed October 26, 2022, https://www.eia.gov/tools/faqs/faq.php.

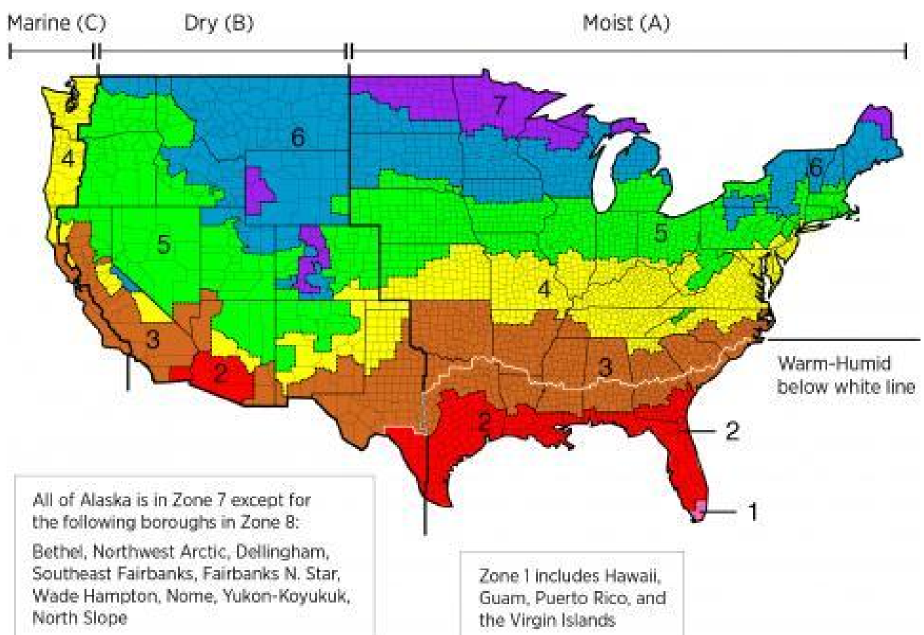
[21] U. S. Government Accountability Office, "Securing the U.S. Electricity Grid from Cyberattacks," accessed November 5, 2022, https://www.gao.gov/blog/securing-u.s.-electricity-grid-cyberattacks.

[22] "Natural Gas Imports and Exports - U.S. Energy Information Administration (EIA)," accessed December 4, 2022, https://www.eia.gov/energyexplained/natural-gas/imports-and-exports.php.

2.5.2 Climate Zone

To properly reflect the way different climate regions play a factor in the achievability of sustainable net-zero housing, this project focuses on two large climate zones in the US: climate zone 6 and climate zone 3. More specifically, the Minneapolis, MN metropolitan area of climate zone 6 and the Los Angeles, CA metropolitan area of climate zone 3.

Figure 2: US Climate Zone Map[23]



Climate Zone 6 experiences freezing cold winter temperatures and warm summers. Minneapolis receives the majority of its rain from May to August with dry periods in January and February as opposed to Los Angeles which receives the majority of its rainfall over November to April. Climate Zone 3 is a mild climate with cool winters and warm to hot summers depending on coastal proximity.

[23] "IECC Climate Zone Map | Building America Solution Center," accessed December 10, 2022, https://basc.pnnl.gov/images/iecc-climate-zone-map.

2.5.3 Energy Breakdown

The residential sector consumed 117 Bcf, Billion Cubic Feet, of natural gas in 2016, making up 26% of total natural gas consumption, falling second largest in consumption to the Industrial sector at 36%. Commercial and Electric Generation followed at 21% and 14% respectively. This 26% comes from two thirds of homes using natural gas as their main source of heating. One sixth of homes use electric heat and the remaining one sixth uses other sources of heating such as wood furnaces, geothermal heat pumps, and gas boilers.

Figure 3: Minnesota Natural Gas Consumption by Sector, 2016[24]

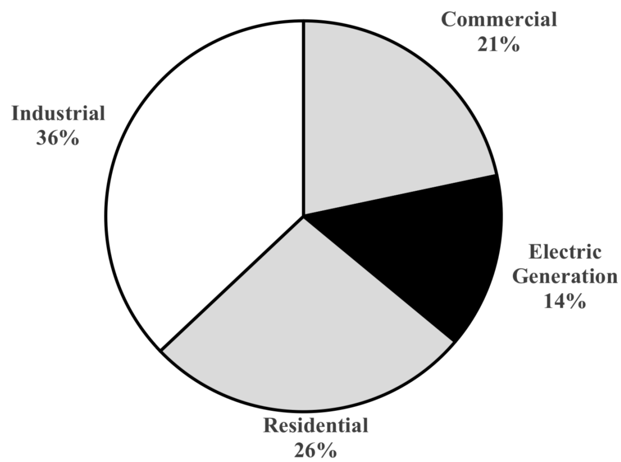
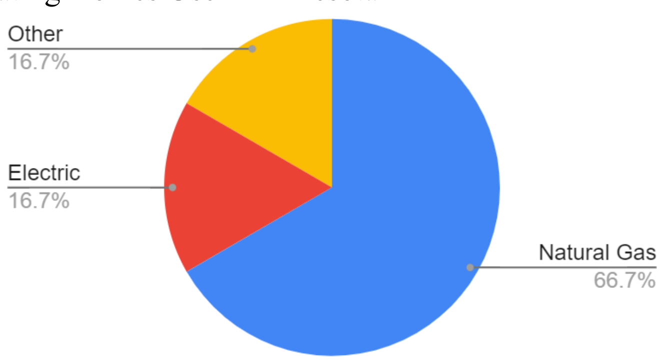


Figure 4: Types of Heating Homes Use - Minnesota[25]

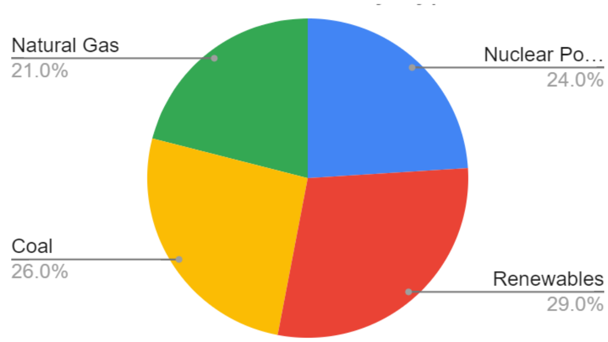


[24] "U.S. Energy Information Administration - EIA - Minnesota - Profile State Profile and Energy Estimates," accessed December 10, 2022, https://www.eia.gov/state/analysis.php?sid=CA.

[25] "U.S. Energy Information Administration - EIA - Minnesota - Profile State Profile and Energy Estimates."

A total of 18-31% of Minnesota's annual electricity supply comes from out-of-state generation. In terms of in-state generation however, the largest sector comes from renewable energy at 29%. . Minnesota's majority of renewable energy generation comes from wind farms in the southwest of the state. As a state they are among the top five states with greatest potential for residential small-scale wind installations. A small-scale wind installation is any that generates less than one megawatt. The most widely recognized renewable energy is solar, however only 4% of Minnesota's energy generation comes from solar, roughly 13.7% of the total renewable energy generation. 90% of this solar energy is generated on a utility-scale. This means that only 0.4% of all of Minnesota's energy generation comes from residential on-site solar. With an average of 198 sunny days per year, the US average comes in at 205, the Minneapolis metropolitan area has a clear potential for increased residential on-site solar generation.

Figure 5: Total In-State Generation by Type - Minnesota[26]



Looking at Los Angeles, CA's climate and energy use for comparison, the residential sector made up 23% of California's total natural gas consumption; 124 Bcf compared to MN's 117 Bcf. This 23% comes largely from two-thirds of homes using natural gas as the predominant

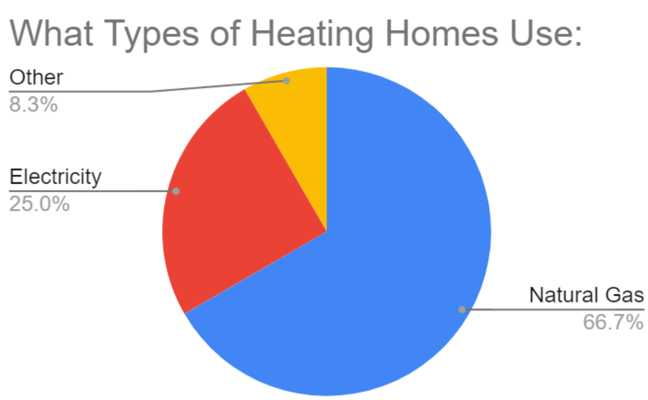
[26] "U.S. Energy Information Administration - EIA - Minnesota - Profile State Profile and Energy Estimates."

heating source. One-fourth comes from electric heat and one-twelfth comes from other heating sources such as the aforementioned wood furnaces, boilers, etc.

Similarly to Minnesota, 30% of California's energy is generated out-of-state. Their largest sector of in-state generation is Natural Gas at 50.2%. Renewables fell second at 34.8% with Nuclear at 8.5% and Large Hydropower making up 6.2%. In 2021 solar, wind, and geothermal ranked top 3 in renewable energy sources. Each generating 49.3%, 22.5%, and 16.5% of the state's renewable energy respectively.

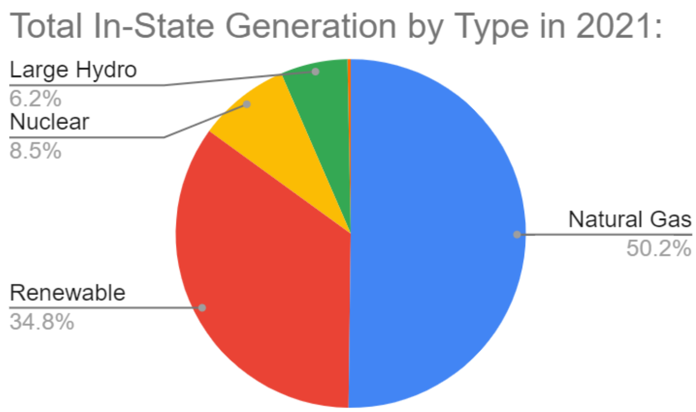
These statistics are important in understanding what potential renewable energy sources can be implemented at this site. In a residential setting, solar and geothermal of these three would be the best option. Natural Gas was the largest in-state energy generation sector. This could potentially decrease with an increase in electric heating powered by solar energy or geothermal heating coming from Ground Source Heat Pumps (GSHP).

Figure 6: Types of Heating Homes Use - California[27]



[27] "U.S. Energy Information Administration - EIA - CALIFORNIA California Profile State Profile and Energy Estimates," accessed December 10, 2022, https://www.eia.gov/state/analysis.php?sid=CA.

Figure 7: Total In-State Generation by Type - California[28]



2.5.4 Housing Statistics on the selected sites

This project focuses on the majority of housing in Los Angeles and Minneapolis. According to the US Census, of the reported 1,468,900 homes in Minneapolis - St. Paul, 77.4% of them are classified as single family or small-scale multi-family homes, excluding high-rise apartment buildings.[29] A single family home is classified as "1, detached" meaning one unit within the building and separate from any other structures. For purposes of this study multi-family will look at data as a collective total from the categories of "1, attached" such as a horizontally-attached multi-unit structure and "2-4 units" to account for shifts in housing types over the decades. Of the 4,544,900 homes in Los Angeles - Long Beach, 65.6% are single family or multi-family. The following table breaks this down further to show what percent of each city is composed of single family versus multi-family in addition to how many homes of each category are from each decade dating back to 1939 and before.

[28] "U.S. Energy Information Administration - EIA - CALIFORNIA   California Profile State Profile and Energy Estimates."

[29] US Census Bureau, "Housing Patterns," Census.gov, accessed December 11, 2022, https://www.census.gov/topics/housing/housing-patterns.html.

Figure 8: Scope of Housing - Minneapolis

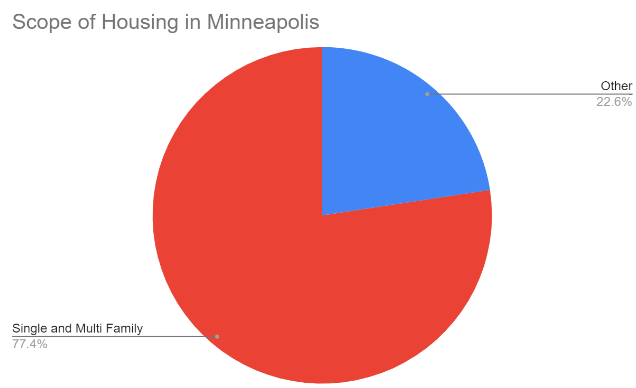


Figure 9: Scope of Housing - Los Angeles

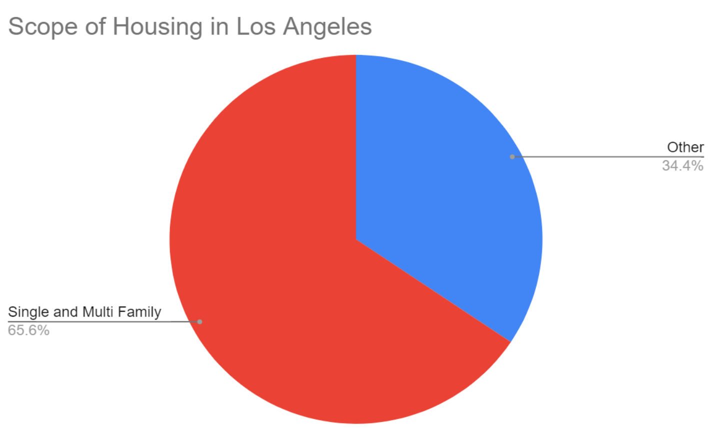


Table 1: Number of Homes Per Decade Per Category (In Thousands)[30]

Minneapolis, MN			Los Angeles, CA		
Year	**Single Family**	**Multi-Family**	**Year**	**Single Family**	**Multi-Family**
< 1939	130.7	23.7	< 1939	312.7	116.9
1940-1949	48.3	S*	1940-1949	242.4	36.1
1950-1959	137.6	S	1950-1959	545.7	49.4
1960-1969	92.5	S	1960-1969	318.7	109.6
1970-1979	127.1	16.1	1970-1979	250.2	117.4
1980-1989	119.8	38.1	1980-1989	215.3	138.9
1990-1999	121	33.7	1990-1999	137.3	82.3
2000-2009	107.8	34.2	2000-2009	138.8	33
2010-2019	66.7	9.9	2010-2019	32.5	S
2020-2022	S	0	2020-2022	S	S

*S indicates that the estimates did not meet publication standards or were withheld to avoid disclosure

In summary, 43% of all single family homes and 12.7% of all multi-family homes in Minneapolis were constructed in 1970 or before while 57% of single family and 70.8% of all multi-family homes were constructed between 1970 and 2021. The sub-100% total of multi-family homes is due to several decades having data that did not meet the US Census' statistical publishing requirements and thus that data being omitted.

On the contrast, 63.8% of all single family homes and 41.1% of all multi-family homes in Los Angeles were constructed in 1970 or before while 35.2% of single family and 49% of all multi-family homes were constructed between 1970 and 2021 meaning Los Angeles statistically

[30] "American Housing Survey (AHS) - AHS Table Creator," accessed December 10, 2022, https://www.census.gov/programs-surveys/ahs/data/interactive/ahstablecreator.html?s_areas=33460&s_year=2021&s_tablename=TABLE1&s_bygroup1=4&s_bygroup2=3&s_filtergroup1=1&s_filtergroup2=1.

has older and less energy efficient, presumably leakier/less up to code, homes. Data was also left out of the Los Angeles numbers for not meeting the US Census' standards.

This shows that a larger percent of housing in Los Angeles is older homes and thus the city would require more retrofitting practices than Minneapolis. Minneapolis can focus less on retrofitting older homes and bringing them up to code and more on designing new-builds centered around new-zero design. These design strategies can also be integrated individually for retrofitting purposes in addition to habitual changes.

2.6 Development and Methods of Net Zero Residential Development

2.6.1 Net Zero Energy Buildings

In this paper net zero energy buildings (NZEBs) are defined as buildings that generate at least as much energy as they consume on an annual basis when tracked at the building site. [31] With an established understanding of the historical contexts of residential buildings and energy crises, we look to learn from current examples of net zero projects in the United States. Analyzing methods of current net zero residential construction aids in understanding the various paths designers and developers take when creating these hyper-modern homes. Looking at a variety of existing examples of current net-zero residential construction aids in understanding the various paths designers and developers can take when creating these hyper-modern homes.

[31] Igor Sartori, Assunta Napolitano, and Karsten Voss, "Net Zero Energy Buildings: A Consistent Definition Framework," *Energy and Buildings* 48 (May 1, 2012): 220–32, https://doi.org/10.1016/j.enbuild.2012.01.032.zer

2.6.2 Case Studies

2.6.2.1 Hope Landing Lot 2

Hope Landing Lot 2 is a residential project developed by the Manatee County Habitat for Humanity organization. Manatee County Habitat for Humanity's mission is to build simple, low-cost homes for forming working partnerships with low-income families in need of decent housing.[32] For this new development, the developer committed to design a 1,143 square foot duplex to take on the USDE Challenge Home Program. Significant takeaways from this development include the switch from a 2x4' wood-stud exterior wall frame to insulated concrete form (ICF) construction. ICF walls provide an R-23 insulation value, a complete thermal break around the home's exterior, and provide the thermal mass benefits of a concrete wall. Further, energy efficiency upgrades include the implementation of solar water heating, double-pane and argon-filled low-e windows, as well as PV panels providing 2.5 kW to the homes energy star certified home appliances. The implementation of PV panels cuts grid reliance to half, resulting in over $427 in annual utility savings Overall, the strength and benefits of the wall structure and components as well as the efficiency of mechanical systems within the home make this a perfect example of how residential green buildings can be maximized on a budget.

[32] "DOE Zero Energy Ready Home Case Study: Manatee County Habitat for Humanity, Ellenton, FL, Affordable," Energy.gov, accessed December 1, 2022, https://www.energy.gov/eere/buildings/downloads/doe-zero-energy-ready-home-case-study-manatee-county-habitat-humanity.

Figure 10: Hope Landing Lot 2 by Manatee County Habitat for Humanity

2.6.2.2 Built Green Home at Suncadia

The Built Green Home at Suncadia is a green home demonstration in Roslyn, Washington where there was not an established green home building program at the time.[33] The home's building envelope utilizes insulated concrete forms (ICF) with spray foam insulation. The use of ICF exterior walls makes the home energy efficient, while improving indoor air quality and using locally sourced materials.The spray foam insulation provides sufficient energy efficiency but degrades the air quality potential and is not biodegradable.

[33] "King County, Washington - King County," accessed December 1, 2022, https://kingcounty.gov/.

The home's interior systems include the implementation of a geothermal heat pump which distributes thermal supply needs through radiant floor heating. Further heating needs are supported by an energy star furnace and gas fireplace, while these increase energy use, they can serve as a backup if the geothermal hydronic pump has any failures. Although the cost premiums from utilizing ICF construction and geothermal heat pumps were higher, these options were chosen for their proven long-term savings. The use of spray foam insulation costs more than conventional fiberglass batts but it has superior performance for heating and cooling.

Overall, the implementation of green building products have comparable costs to premium building materials, and the added environmental benefits set a precedent. By specifying and installing green building solutions, the market for environmentally preferable and energy efficient products is increased. While ICF utilizes traditional concrete materials, it is worth pondering how an alternative concrete mixture with less environmental and financial impact could fare in an ICF wall assembly.

Figure 11: Built Green Home at Suncadia

2.6.2.3 Oak Haven Modular House

The Oak Haven Modular House[34] located in Ojai, California, utilizes a factory-build process which allows energy-efficient construction characteristics to be built at a lower cost, with less intensive labor methods and on site construction time. A modular home is the general name for a factory-built house, which can be pre-assembled at a factory either as a panelized system or as a whole module. Historically this housing production model became popular in northern europe around the early 20th century. One of the reasons for this construction method's popularity in Northern Europe is the cold climate, where rapid construction time is valuable, a remarkably fast erecting home is favorable.

[34] Edward Dean, *Zero Net Energy Case Study Homes*, Volume 1 (Southern California Edison, 2018).

In the United States, only 2%-3% of all housing built has been factory-built in recent years. In this project, the developer sources a factory in Phoenix, Arizona and a construction company in California to build the foundation and assemble the house components on site. Construction methods included using thicker than standard wall modules and a roof space with 12" of blown cellulose insulation which created R-28 and R-42 values respectively. A plywood roof sheathing with low-emissivity foil facing the interstitial space creates a radiant barrier and suppresses internal heat gain. As required by California's title-24 energy code, double glazed windows with additional features such as argon gas within the glass unit increases the overall R-value of the window by 33%. A low-e coating on the glazing also reduced the thermal transmission via radiation, further improving performance. The heating, ventilating and cooling systems are made up of an Energy Star air source heat pump with a SEER rating of 13. In addition, a 90-cfm whole house fan can be utilized to pre-cool the house at night when the temperatures are low enough to be effective. This reduced the cooling load during the following day. Domestic hot water is supplied via a gas-fired water heater, the home is pre-plumbed to add solar-thermal water heater at a later date. All electrical appliances meet the Energy Star standard, providing energy-efficiency guarantees for the internal equipment loads.

Renewable energy sources include an on-site solar PV system with a total power rating of 2.0kW(DC). While not enough to make the average occupancy zero net energy, the home was ready to adopt more solar panels and the mentioned solar-thermal water heater. A post occupancy report showed that the addition of 2.5kW(DC) of solar panels would provide enough energy to render the home net positive. The controlled environment of the factory, plus the routine methods of quality assurance in the factory setting, makes the air-tightness a noteworthy advantage.

Overall, modular construction techniques allow for reduction in material transportation and on site energy and material waste. Contrastingly, evidence from the modular industry shows that many factories are in large warehouses with little, if any, insulation.[35] As these facilities themselves must be temperature controlled throughout the year for worker comfort, a significant amount of energy is wasted here. Thus, while the modular design and implementation of homes appears to be more environmentally friendly to the building site itself, it is still unclear how much energy is being offset by producing residential homes in this way.

Figure 12: Oak Haven Modular House

2.6.2.4 Harvard Center for Green Buildings and Cities "HouseZero"

At the Harvard Graduate School of Design, the Center for Green Buildings and Cities has retrofitted one its headquarter building into a data driven living lab named HouseZero[36]. While many projects declare themselves net zero, this residential home outfitted for office work and research is delving into the next generation of net zero design approaches. Targeting a set of

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[35] John Quale et al., "Construction Matters: Comparing Environmental Impacts of Building Modular and Conventional Homes in the United States," *Journal of Industrial Ecology* 16, no. 2 (2012): 243–53, https://doi.org/10.1111/j.1530-9290.2011.00424.x.

[36] "CGBC Headquarters: HouseZero | Harvard Center for Green Buildings and Cities," accessed October 12, 2022, https://harvardcgbc.org/research/housezero/.

rigorous efficiency standards, HouseZero utilizes passive features such as 100% natural ventilation, daylight autonomy, and produces zero carbon emissions, with the goal of offsetting embodied energy in materials. Utilizing AI technology and coding, the building's 285 sensors collect 17 millions data points each day to prepare its energy needs and calculate self-adjusted responses to internal and external variables like outdoor air temperature, rain, and indoor factors like CO2 levels and air temperature.

While the architecture firm Snøhetta claims the home utilizes "No HVAC" systems, it does have two geothermal heat pumps in different configurations (zig-zag and looped) to test and study their efficiency differences.[37] This geothermal system works as a two in one HVAC system and becomes more effective and efficient overtime as thermal storage cycles continue. This geothermal energy is distributed through radiant flooring, using a series of pipes underneath the floors which circulate hot or cold water to heat the floors directly. Concrete flooring produced with slag which requires less energy to produce than traditional concrete. The concrete flooring also dissipates energy slowly thus allowing for a consistent thermal storage.

All buildings need to be decarbonized with an emphasis on strategies that deliver for overburdened and underserved residential communities. In the residential sector households with an annual income below $60,000 account for nearly 50% of all household energy consumption, further establishing the need for practical and attainable building solutions.[38] While HouseZero is a remarkable design with notable net zero solutions, the implementation of all design measures the home has is not practical for a majority of residential homes. Fully automated windows and hundreds of sensors to implement autonomous home energy management is not a financial option for most. Being mindful of proposing financially attainable solutions for the majority of

[37] "Harvard HouseZero," accessed October 31, 2022, https://snohetta.com/projects/413-harvard-housezero.

[38] John Kerry, "The Long-Term Strategy of the United States, Pathways to Net-Zero Greenhouse Gas Emissions by 2050," n.d., 65.

homeowners is a goal that needs to be met if net-zero homes are going to become the standard.Utilizing existing technology and tools residents can access to gain similar results to HouseZero's could help in this effort. Analyzing these advanced design strategies provides us with options that can be refined and rethough to implement into more practical future residential developments.

Figure 13: House Zero

2.7 Conclusion

Understanding the U.S. relationship with environmental consciousness and how energy usage has evolved allows us to predict the direction current policies and efforts will take residential development in the future. For typical homeowners, coping with the consequences of energy insecurity comes with its own negative consequences, such as loss of social networks, institutional ties, and living in unhealthy or unsafe conditions. Other factors including physical home improvement needs and economic expenditures are paramount in supporting residents with high energy insecurities. The best method of increasing home energy efficiency may just stem from comprehensive education on home energy analysis and existing improvement options. This way, homeowners can make more informed decisions and be more confident with improvements they choose to make.

If people wish to start a new home development or retrofitting project, how can they utilize current design tools and materials to produce resilient residential infrastructure? Furthermore, how can we further educate and promote the use of green strategies and systems to develop resilient net-zero residential infrastructure in the United States? The team will evaluate and recommend strategies to develop functional building energy models to improve building functions that adhere to global climate goals. Whether it be a new construction or retrofitting solutions, the team wishes to show that implementing the use of contemporary technologies can result in a process that is safe to build and easy to adopt for future generations.

3 Methodology

3.1 Introduction

The goal of this project was to analyze the feasibility of implementing a new generation of renewable energy sources, habitual practices, and building construction in residential buildings. This project employs a number of methods to obtain information on the effects of passive and active design strategies possible in green residential buildings. Developing alternative models to compare and explore the effects of various sustainability improvements will help in making findings applicable in a variety of residential climates. The following sections expand upon these methods adopted to achieve the goal.

3.2 Ecological Approaches

When designing a net zero energy building (NZEBs), the largest focus is on lowering energy usage and creating a more energy efficient system. Several other factors such as embodied energy, material selection and cost shouldn't be forgotten however. Embodied energy of materials is the energy consumed by all of the processes associated with the production of the material. Cost allows NZEBs to be more readily accessible to the typical homeowner. Environmentally friendly and ecological approaches can help to greatly reduce the carbon footprint of your new build. Our main ecological approaches involve selecting more eco-friendly materials and alternatives to current standard materials.

Spray foam insulation is offered in two forms; open cell and closed cell. Both are created by a chemical interaction that causes it to expand and fill its insulative region. A much more ecological approach to insulation is an environmentally friendly material known as Wood Fiber

Insulation. Wood fiber insulation has a comparable insulation value of R-3.75 per inch. It is hydrophobic and vapor open, meaning it is moisture permeable so as not to trap moisture and lead to mold. Wood fiber boards come in sizes ranging from 1" to 9.25" thick with insulation values of R-3.6 to R-34 respectively. As opposed to spray foam insulation, wood fiber insulation is recyclable, sustainable, meets fire code and releases no harmful chemicals in these fire tests, and arrives on site with a negative carbon footprint.

Other materials that could be considered in the future but are too relatively new at this point in time with not enough long term research conducted on them are Timbercrete and Ferrock. Timbercrete is a brick made by mixing sawdust and concrete waste products together. Its load bearing capacity is comparable to concrete at 15 Mpa - concrete testing at 17 Mpa. The insulation value is substantially higher at R-2.5 per inch as opposed to concrete achieving only R-0.9 per inch. Timbercrete has a high fire resistance and due to it being less porous than concrete, it withstands erosion longer.[39] Also a considered future concrete material is Ferrock. Approximately 95% of Ferrock is made from recycled products and byproducts of other construction processes. It is carbon negative by trapping carbon in during its formation process. It is created by mixing excess steel dust with silica from ground up glass waste. When it is poured into the mold and it reacts with air and carbon dioxide, iron carbonate is formed, giving it its signature rusty appearance. Despite this, Ferrock is chemically inactive and does not leach into soil or water sources. The strength of Ferrock ranges between 35 Mpa and 48 Mpa and has a greater flexibility than traditional concrete. Ferrock bears more compression load caused by seismic forces when compared with concrete and would thus be great for our location of Los

[39] "Timbercrete: Components, Advantages, and Applications," The Constructor, July 13, 2022, https://theconstructor.org/building/timbercrete-components-advantages-applications/565251/.

Angeles, California. It is approved to be utilized in slabs, bricks, sidewalks, paves, breakwaters, and walls.[40]

Other ecological approaches worth mentioning are windows and artificial lighting. Traditional glass windows are already eco-friendly and more easily recyclable than its alternatives such as fiberglass or laminated glass windows. Laminated glass windows could be considered more eco-friendly however if you factor in that a window only needs to be recycled once broken and laminated windows have a significantly higher durability than traditional glass windows. Laminated glass windows are also more energy efficient due to the air gap between the two layers of glass preventing air leakage and reducing heat-loss. Additionally laminated glass is created using PVB, which has been touted as an environmentally friendly alternative to vinyl chloride due to its minimal toxic properties and ability to resist degradation by sunlight.[41] Utilizing windows and natural light is also largely an ecological approach in that it will help to use less energy overall on artificial lighting. When artificial lighting cannot be avoided, making a switch from incandescent light bulbs to LEDs is sure to lower a building's energy use as well. 5% of the average household electric bill goes to lighting and with 95% of energy from an incandescent being lost to heat and only 5% to light, this is easy to see how. LEDs last longer, give off more light and less heat, and cost less on an annual usage basis even though they have a higher upfront purchase price.

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[40] "What Is Ferrock in Construction?," The Constructor, July 25, 2022, https://theconstructor.org/concrete/ferrock-characteristics-applications/565525/.

[41] "Is Laminated Glass Eco Friendly? (Explained)," UpHomely, August 16, 2021, https://uphomely.com/is-laminated-glass-eco-friendly.

Table 2: Incandescent vs LED Light Bulbs[42]

	Incandescent	LED
Brightness	16 lumens per watt	89 lumens per watt
Energy Efficiency	60 watts of power to reach 700 lumens	8 watts of power to reach 700 lumens
Lifespan	750-1,200 hours	25,000 hours
Costs	At 10 watts of power it costs $3 a year	At 10 watts of power it costs $1.30 a year
Heat Emission	90%+ of energy is lost as heat	Give off hardly any heat
Environmental Impact	Being so energy-inefficient it gives off the most greenhouse gasses during energy generation	Most environmentally-friendly because it uses the least amount of energy

The implementation of ICF wall sections can reduce HVAC energy consumption by 25 to 50 percent. While the initial construction costs of ICF are higher than conventional wood construction, the thermal wall efficiency is able to downsize HVAC capacity needs by as much as 50 percent compared to wood frame. The downsize in HVAC system requirements and long term energy savings can make up for the higher construction costs of ICF. Although an ICF wall section can cost 5-10 percent more than a traditional wood stud construction, the development of improved designs and more efficient assembly procedures has allowed ICF construction prices to fall.[43] The U.S. Department of Housing and Urban Development (USDHUD) publication concludes that ICF construction is most appealing when considered as a "package deal" with an emphasis on structural performance and energy efficiency.[44] Based on quantitative data from the USDHUD relative performance characteristics of concrete ICF exceed wood-frame construction

[42] lpwpadmin, "CFL vs. LED vs. Incandescent Light Bulbs," *Ideas & Advice | Lamps Plus* (blog), December 16, 2020, https://www.lampsplus.com/ideas-and-advice/cfl-vs-led-vs-incandescent-light-bulbs/.

[43] Neethi Rajagopalan, Melissa M. Bilec, and Amy E. Landis, "Comparative Life Cycle Assessment of Insulating Concrete Forms with Traditional Residential Wall Sections," in *2009 IEEE International Symposium on Sustainable Systems and Technology*, 2009, 1–5, https://doi.org/10.1109/ISSST.2009.5156717.

[44] "Costs and Benefits of Insulating Concrete Forms: For Residential Construction," n.d., 30.

in every category. Mitigating the upfront cost of ICF even more, most insurance providers provide a premium reduction for high fire or wind resistance ranging from $40-$100 in annual savings.

In response to the need for improved concrete practice and the existing societal goal of creating sustainable building materials, the use of fly ash in concrete is an effective way to reduce emissions and embodied energy. Fly ash is the divided residue that results from the combustion of pulverized coal and moves from the combustion chamber through exhaust gasses. This combustion by-product (CBP) is declining as more coal-fired power plants are retired, yet, 40.8 million tons of fly ash by-products was collected from CBP production in 2019.[45] The use of CBP's in offsite solutions means that captured by-product can be embedded into new material without environmental contamination. Fly ash in high volumes between 60-70% can be used successfully in residential walls and slab-on-grade construction in quantitative terms of placing, finishing, and compressive strength.[46]

3.3 Habitual Changes and Their Corrective Technologies

Switching to more eco-friendly materials or ecological approaches to energy use can significantly help reduce a system's energy usage, but often simple changes in habit from the user can cut just as much energy use and cost a lot less. Several habits that could be easy to switch are shutting off lights when not in use, unplugging electronics/appliances when not in use, giving heating/cooling systems a break, lowering water temperatures, opting for energy efficient appliances, and becoming more conscious about using high energy load appliances.

[45] "U.S. Electric Power Industry Produces Less and Recycles More Combustion by-Product," accessed November 27, 2022, https://www.eia.gov/todayinenergy/detail.php?id=47336.

[46] Moore, "Sustainable Concretes for Insulated Concrete Form (ICF) Construction."

3.4.2 Limiting Use of Artificial Lights

The easiest way to limit use of artificial lighting in a building is to make a habit of shutting off lights when leaving a room. A technology that could be implemented to assist with this would be timer based or motion activated lights in areas not used as frequently such as a basement, attic, or store room.

3.3.1 Unplugging Electronics/Appliances

There are tons of electronics and appliances drawing energy from the building's system even while they are not being used. These are known as phantom loads. Phone chargers, computers and chargers, TVs on standby, kitchen appliances like blenders or coffee makers, etc are all phantom loads that even when not being run, still draw power from being plugged in. Making a habit of unplugging these appliances when not in use will reduce the amount of kilowatt hours accumulated. The U.S. Department of Energy says on average, 75 percent of the electricity used to power home electronics and appliances is consumed while the products are turned off.[47]

Several technological approaches to this problem exist. First, outlets can be connected to a switch by the lightswitch to control the flow of power to the outlets or not. The downside to this is if you wanted to move an appliance in your kitchen to a different outlet, then you'd have to remember to unplug it or if not, one would still have to remember to shut off the switch when

[47] "Do Appliances Use Electricity When Plugged in but Turned Off?," Take Control & Save, accessed December 10, 2022, https://www.takecontrolandsave.coop/welcome-to-our-blog/posts/2020/october/phantom-energy-load/.

done. Additionally an issue here is if you wanted the outlets controlled separately, i.e. phone charger on overnight but desktop computer off and vise versa during the day. A second technology that could solve these issues and the originally presented problem is smart outlet adaptors that plug into the outlet and then the electronic / appliance plugs into that. Take for example a phone charger; when the phone is not plugged in drawing power at a higher rate, then the adapter would shut off power flow to the charger and thus eliminate energy waste. This means individual outlets are independent of each other and can run on different schedules without owner interaction.

3.3.2 Letting Heating/Cooling Systems Rest

Heating and Cooling Systems are one of the largest contributors to energy use in a home. In the winter and summer months especially, occupants like to create an artificial environment where the temperatures inside are drastically different from those outside. In the winter, one could make a habit of putting on another layer of clothes before adjusting the thermostat to a desired comfort range. Whereas, in summer, one could open windows to create a cool draft through the space before adjusting the thermostat.

One technology many are already familiar with and implementing is smart thermostats like a google nest. With smart thermostats the user can set a schedule for more efficient heating. For instance, if the occupant works a typical work day hours of 9-5 then the house could lower the temperature at 9am, in winter, and slowly raise the temperature back up to comfort level by 5pm. Similarly, the temperature can be lowered overnight and slowly heat back up by the time one has their wake-up time set in the morning. This way the house is being optimized to only use copious amounts of energy to heat the home to a desired comfort temperature when it is occupied and not when one is out for the day or asleep. In the summer the opposite can be done, cooling rather than heating.

3.3.3 Lowering Water Temperatures

Every minute of a hot shower takes energy to heat up the water. Even an average family consistently taking ten minute showers can rack up energy usage. Making a habit of taking a shorter shower at the same heat or the same length of showers but at lower temperatures can help to lower the overall energy usage.

Alternatively, one technological approach that could be taken could be to optimize your water heater by insulating hot water pipes or the hot water heater itself while also opting for an energy star energy efficient heater. Another option could be to set a timer on the water heater so it shuts off the hot water after a certain point and thus limits one's energy use per shower.

3.3.4 Opting for Energy Efficient Appliances

Energy Star is a program that promotes energy efficiency, funded by the EPA (Environmental Protection Agency) and DOE (Department of Energy).[48] Switching to certified energy efficient appliances that typically draw a lot of power like stoves, ovens, fridges, TVs, etc can help to lower a building's energy usage. This can also be achieved by switching to more energy efficient light bulbs like LEDs that use less energy and last longer as well as lightbulbs that can be dimmed to the proper amount of light needed, and/or sensor-controlled or timer-controlled switches in less used zones of the house likely to get light left on.

[48] "ENERGY STAR," accessed December 10, 2022, https://www.energystar.gov/home.

3.3.5 Mindfully Using High Energy Load Appliances

The high load energy appliances responsible for driving up a house's energy usage are dishwashers, laundry machines, and clothes dryers, the latter being the biggest culprit. The easiest change in habit is to be more conscious of running loads of clothes or dishes and only running when the machine is full. It is also helpful to make a habit of running these loads overnight during the off-peak hours when electric rates are cheapest from the power company. The most energy-inefficient appliance in a home is the dryer; not only because it takes a ton of energy to heat up and tumble the clothes, but also because it emits heat out the back and heats up a room that may need to work harder to be cooled down in warmer months. Changing habits to air dry one's clothes instead of using the dryer can eliminate this energy load-intensive appliance

The easiest approach technologically is to invest in energy star certified appliances as mentioned above.

3.4 Solar Panels

3.4.1 Overview

The active design strategy with the greatest impact on achieving Net-Zero is the implementation of solar panels. To calculate the system size and its corresponding energy output per location, we used PV Watts, powered by the National Renewable Energy Laboratory.[49] Four tests were run for the Single and Multi-Family roofs in our two sites. For Los Angeles, CA the

[49] "PVWatts Calculator," accessed December 10, 2022, https://pvwatts.nrel.gov/pvwatts.php.

address of 3851 S Cochran Ave, Los Angeles, CA 90008 was used. For Minneapolis, MN the address of 2317 West 53rd St Minneapolis, MN 55419.

3.4.2 Sizing

PV Watts provides the following equation for finding the DC System Size your roof can support: Size (kW) = Array Area (m^2) × 1 kW/m^2 × Module Efficiency (%). Using our Design Builder Single Family base model, the south facing roof size was found to be 530.13 ft^2 (49.25m^2). Using a module efficiency of 20%, the single family size outputs 9.85 kW system size potential for the south face of the roof alone. The Design Builder Multi-Family base model's south facing roof size was found to be 828.82 ft^2 (77m^2). At 20% module efficiency, the multi-family size outputs 15.4 kW system size potential for the south face of the roof alone. This accounts for the entire roof. The size for one singular unit would be 5.13 kW.

3.4.3 Setup

While automated solar trackers could solve the problem of solar panel orientation by monitoring the position of the sun in the sky, for most homeowners this is not an economical option. By utilizing the National Oceanic and Atmospheric Administration's (NOAA) Solar Calculator, we were able to input site specific coordinates and timeframes to find optimal tilt angles. The Azimuth and elevation are angular coordinate system measures used for locating positions in the sky. Conclusively, we used a standard, fixed array panel with the default setting of 14.08% system losses. For the south facing system, 180º Azimuth orientation was used at a 34º tilt for Los Angeles and a 45º tilt for Minneapolis. For north facing systems, the Azimuth should be 0º and the tilt degree remains the same. There are also advanced parameters that can be edited but were left with the default settings for the purpose of this project.[50]

3.4.4 Results

Table 3: Solar Generation Results[51]

	South Facing Roof	North Facing Roof	Total Solar Generation
MN - Single Family	13,881 kWh	4,784 kWh	18,665 kWh
MN - Multi-Family	21,703 kWh	7,461 kWh	29,164 kWh
CA - Single Family	16,826 kWh	8,627 kWh	25,453 kWh
CA - Multi-Family	26,307 kWh	13,480 kWh	39,787 kWh

3.4.5 Analysis

Los Angeles receives more sun and thus generates an average of 36% more solar energy than Minneapolis. Due to this advantage and a more moderate climate in Los Angeles, it would be possible to only need solar panels on the south facing roof whereas in Minneapolis it is necessary to install solar panels on both the south and north facing roofs.

[50] NOAA US Department of Commerce, "ESRL Global Monitoring Laboratory - Global Radiation and Aerosols," accessed December 19, 2022, https://gml.noaa.gov/grad/solcalc/.ese

[51] "PVWatts Calculator."

3.5 Wall Design Strategies

According to the National Association of Home Builders (NAHB) analysis on the United States 2021 Census, 92% of new homes constructed were wood-framed.[52] Using a common wood-framed stud wall, we designed wall characteristics suitable for each location. A single 2x6 wood frame was created for Los Angeles, CA and a two section 2x4 wood stud wall for Minneapolis, MN. This design discrepancy creates appropriate insulation measures for the dissimilar climates and can also be applicable for many other climates in the US. One approach taken for the Minneapolis site is a double-wood stud framing made up of two layers of 2x4 stud-framed walls set up to form an extra thick wall cavity that can be filled with insulation. Due to the insulation separating the interior and exterior framing, thermal bridging is reduced. This approach allows for high R-value walls and are relatively inexpensive to construct. Using a double-stud wall with outside framing and insulation is preferable in a climate zone like Minneapolis 6A, translating to cold and humid. This approach frees up more floor space compared to a traditional double-stud wall and the gap provides several inches for insulation.

A similar approach for the Los Angeles site location is a 2x6 wood frame stud wall. Because the nominal R-value of the insulation is limited by the depth of the stud space, R-values are lower based on insulation thickness and thermal bridging through the studs is anticipated. For a climate zone like Los Angeles 3C, translating to warm marine climate, this particular wall design is time-proven, practical, and cost effective.

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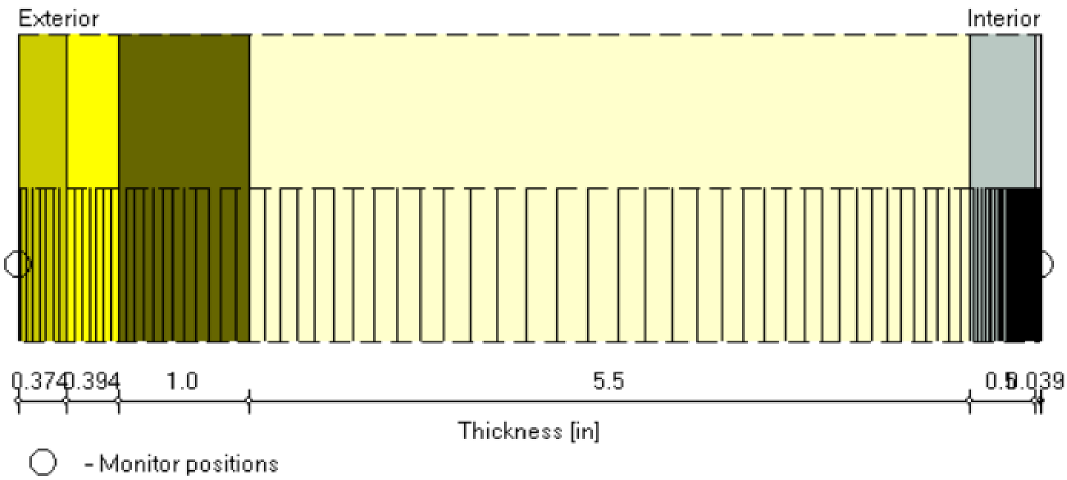
[52] "The Share of Wood-Framed Homes Increased in 2021 | Eye On Housing," July 22, 2022, https://eyeonhousing.org/2022/07/the-share-of-wood-framed-homes-increased-in-2021/.

Figure 13: *Section view of WUFI Los Angeles wood-stud wall with cellulose insulation*



Materials:

- LP SmartSide Siding	0.374 in
- XPS Surface Skin (heat cond.: 0,03 W/mK)	0.394 in
- Fiberboard	1.0 in
- Woodfiber AIR	5.5 in
- Gypsum Board (USA)	0.5 in
- Vinyl Wallpaper	0.039 in

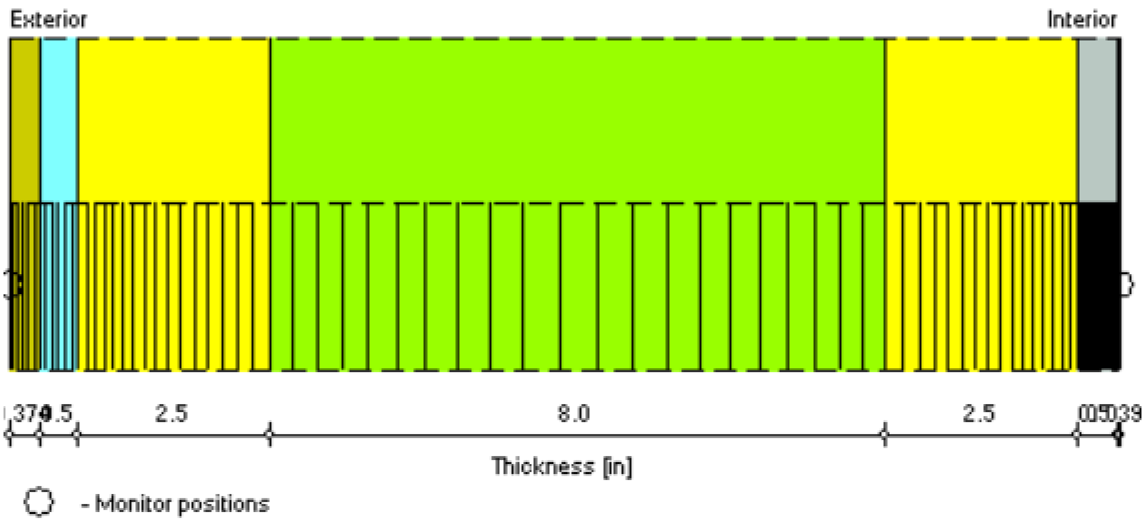
Total Thickness: 7.807 in
R-Value: 26.71 h ft² °F/Btu
U-Value: 0.036 Btu/h ft²°F

Cellulose insulation is a popular option, commonly made from recycled newsprint; it can provide a better thermal performance than an identically sized sample of fiberglass insulation. A more sustainable option includes wood fiber insulation, this option is made of a variety of renewable resources and can provide thermal and acoustic insulation when produced as a panel like assembly. The benefits of wood fiber are also greater than cellulose when it comes to vapor openness that won't trap moisture in the wall assembly. While the performance is comparable, this solution is praised as a more ecologically and economical choice. Interior vapor retarders are not necessary in Los Angeles zone 3C but are required for Minneapolis zone 6A the IRC requires Class I or Class II vapor retarders on the interior side of most above-grade frame walls in Climate Zone 6.

Another improving method for residential wall design that is cost effective and attains R-values that exceed minimum code requirements include insulated concrete forms (ICF's). ICF results in cast-in-place concrete walls that are sandwiched between two layers of insulation material. Typical insulation boards in the forms of expanded polystyrene (EPS) foam insulation and less commonly wood fiber board were tested to understand and compare the effectiveness of the insulation materials compared to less comparable wood frame construction. According to a University of Calgary report, houses with ICF exterior walls can require an estimated 44% less energy to heat and 32% less energy to cool than comparable insulating wood-frame houses.[53] This performance is attributed to the consistency of the EPS insulation on both sides reducing energy loss. The ICF walls provide a complete thermal break around a home's exterior and provide the thermal mass benefits of a concrete wall. Having no studs extending through the wall to provide thermal bridging from the interior to the exterior the concrete is able to heat up slowly during the day and release this heat flowy at night.

[53] Lindsay Moore, "Sustainable Concretes for Insulated Concrete Form (ICF) Construction" (master thesis, University of Calgary, 2006), https://doi.org/10.11575/PRISM/703.

Figure 14: *Section view of WUFI Los Angeles ICF wall with EPS insulation*



Materials:

- LP Smart Side Siding	0.374 in
- Air Layer 25 mm	0.5 in
- EPS (heat cond.: 0.04 W/mK - density: 30kg/m³)	2.5 in
- Aerated Concrete	8.0 in
- EPS (heat cond.: 0.04 W/mK - density: 30kg/m³)	2.5 in
- Gypsum Board (USA)	0.5 in
- Vinyl Wallpaper	0.039 in

Total Thickness: 14.413 in
R-Value: 29.07 h ft² °F/Btu
U-Value: 0.033 Btu/h ft²°F

The standard governing ICF's in the USA is ASTM E2634, standards on flat ICF wall systems as well as common industry standards for ICF assemblies. In the United States, ASTM code requires a concrete core with a 8 inch thickness for walls over 14' in height. The vapor barrier from the wood-stud design was removed on the exterior wall layer as the ICF's insulation on the exterior and interior of the walls separated by a thermal mass of concrete acts together as a sufficient vapor retardant. The vapor retarder required by the code for the Minneapolis climate zone was kept in place to avoid any conflict with codes in the site.

3.6 THERM Simulation

3.6.1 Introduction

THERM is a computer program used to simulate heat transfer through building components and wall assemblies. This program analyzes the building components from the perspective of a two-dimensional cross section. For the purposes of this report, we will be utilizing the version of THERM 7.8. While the majority of the materials were already existent in the material library, several materials had to be added with custom thermal properties such as thermal conductivity and emissivity.

Two tests were run with the Wood-Stud Wall and ICF wall assemblies. Each had boundary conditions set that correlated more with our more harsh climate: Minneapolis, MN - Climate Zone 6. The purpose of this simulation was to understand how effectively these wall designs would hold up to heat transfer in a colder climate as well as prove the applicability of our proposed wall assemblies and their newer materials.

3.6.2 THERM Design Considerations

The wall designs for each site include two load bearing material options. In all, two distinct wall type simulations for each site were conducted. The wood-stud wall was analyzed with wood fiber insulation. The ICF wall was also run with wood fiber insulation board.

3.6.3 Model Setup - Wood-Stud Wall

Table 4: Wood-Stud Wall Assembly

Material	Thickness (in)	Thermal Conductivity (BTU / hr * ft^2 * F)
Polyvinyl Chloride (PVC) / VInyl - Rigid	.25	.098
Frame Cavity Slightly Ventilated NFRC 100*	1	
Furring Strips - Particleboard, Plywood (Low Density)*	1	.058
Insulation Fiberboard	.5	.029
2x4 studs (16" OC) - Douglas Fir*	3.5	.064
Wood Fiber Insulation*	3.5	.022
Particleboard, Plywood (Low Density)	.5	.058
2x4 studs (16" OC) - Douglas Fir*	3.5	.064
Wood Fiber Insulation*	3.5	.022
Drywall	.5	.058

*In parallel (with material above and below)

Boundary Condition	Temperature (F)	Film Coefficient (BTU / hr * ft^2 * F)	Radiation -> Black Body -> View Factor
Outside Boundary	69.998	8	.5
Inside Boundary	32	25	.5

3.6.4 Model Setup - ICF Wall

Table 5: ICF Wall Assembly

Material	Thickness (in)	Thermal Conductivity (BTU / hr * ft^2 * F)
Polyvinyl Chloride (PVC) / VInyl - Rigid	.374	.098
Frame Cavity Slightly Ventilated NFRC 100	.5	
Wood Fiber Insulation	2.5	.022
Aerated Concrete	8	.037
Wood Fiber Insulation	2.5	.022
Drywall	.5	.058

Boundary Condition	Temperature (F)	Film Coefficient (BTU / hr * ft^2 * F)	Radiation -> Black Body -> View Factor
Outside Boundary	69.998	8	.5
Inside Boundary	32	25	.5

3.6.5 Results

For both the Wood-Stud Wall, as seen in Appendix A, and ICF Wall tests, as seen in Appendix B, all data and results came back consistent with expectations. These Isotherm and

Infrared graphs show that the two wall assemblies are fairly comparable in their thermal properties.

3.6.6 Conclusion

In all, the wall envelope of residential homes is essential in mitigating heat transfer and maintaining a comfortable interior temperature for occupants. The data results from the THERM simulations show that both wall assemblies can achieve this. Due to the studs in the wood-stud wall, there is opportunity for thermal bridging to occur. Thermal bridging is caused by an area that has a higher thermal conductivity than the surrounding materials and thus creates a path of least resistance for thermal heat transfer. Looking at our wood-stud wall design, the thermal bridging in the wood stud sections has minimal impact on the heat transfer through the wall section. In terms of the wood fiber insulation in both the wood-stud wall and the ICF wall, its thermal properties and how it holds up to heat transfer in the harsh Minneapolis Climate, shows us it would be a suitable option when looking solely at the thermal study.

3.7 WUFI Pro Hygrothermal Simulation

3.7.1 Introduction

WUFI Pro is a program that creates a comprehensive dynamic hygrothermal analysis that can be used to assess the risk of condensation in enclosure assemblies. Hygrothermal analysis refers to the movement of heat and moisture through buildings. While WUFI has a suite of various programs that can simulate different building envelopes and energy conditions, out of all the variants WUFI Pro is the easiest to use. Performing one-dimensional hygrothermal calculations on building component cross sections, the software takes into account built-in moisture, driving rain, solar radiation, long-wave radiation, capillary transport, and summer condensation. For the purposes of this report, we will be utilizing the WUFI Pro 6.6. The materials discussed and implemented are all available on the WUFI material databases provided with the software and have properties that may vary compared to other databases.

Through a 10-year simulation period, a variation in external wall components including load bearing and insulation materials were tested to compare how each wall type would fare in their respective climates. Overall, the goal of this hygrothermal simulation was to understand how effectively these wall designs would be able to prevent internal moisture level and moisture content fluctuation internally while also providing analysis on thermal performance of various insulation materials.

3.7.2 WUFI Design Considerations

The wall designs for each site include two load bearing material options along with two variations of insulation for each load bearing material. In all, four distinct wall type simulations for each site were conducted. The wood-stud wall variations included one with cellulose insulation and one with wood fiber insulation, both loose fill. The ICF wall variations included one with wood fiber board insulation and one with EPS insulation. The ICF wall utilized different insulation materials than the wood-stud wall because the ICF wall required a solid board insulation type rather than a loose fill insulation.

3.7.3 Los Angeles Wood-Stud Wall

Data was rendered from the 10-year WUFI simulation period for the Los Angeles site with wood-stud walls and analyzed using 1D film data, as seen in Appendix C. For the wood fiber insulation wall type, the greatest total moisture content accumulated on the outside layer of LP smartside siding fluctuated from 8.5% to 16%. Critical layers such as the wood fiber insulation reached between 10.5%-14% moisture content.

Completing the same simulation for the cellulose insulation wall type, the maximum total moisture content was accumulated on the outside layer of LP smartside siding ranging from 8.5% to 16%. Critical layers such as the cellulose fiber insulation fluctuated between 10.5%-14% moisture content.

Overall, the simulated models, shown in Figure 13 and Appendix D, illustrate nearly identical results between the wood fiber insulation and the cellulose fiber insulation in a wood frame assembly. The overall temperature of both variations is stabilized through the wood framed insulation and works well in keeping the interior temperature between 68-72 degrees fahrenheit. The moisture content figures for both options are acceptable as the thermal performance of insulation is decreased when moisture levels reach above 18% leading to possible decay of wood framing and fungi growth, potentially rotting the wall space.

3.7.4 Los Angeles ICF Wall

For the wood fiberboard insulation, as seen in Appendix E, the greatest total moisture content accumulated on the outside layer of LP smartside siding ranged from 8.5% to 16%. Critical layers such as the interior wood fiberboard insulation reached between 6%-7% moisture content. The exterior wood fiberboard insulation stayed under 12% moisture content which is important in showing the beneficial evaporation effect of the air layer. The moisture content of the gypsum board was below 0.5%, satisfying a safe moisture content.

For the EPS wall type, as seen in Figure 14, the greatest total moisture content accumulated on the outside layer of LP smartside siding ranged from 8.5% to 16%. Critical layers such as the interior EPS insulation stayed at a moisture content of 3%. The exterior EPS insulation stayed under 7% moisture content which is important in showing the beneficial evaporation effect of the air layer. The moisture content of the gypsum board remained below 0.5%, satisfying a safe moisture content.

Overall, the EPS insulation performed better than the wood fiberboard and reduced the moisture level reaching the interior sections of the wall. The WUFI 1D film data, as shown in Appendix F, showed a clear increase in water content into the first layer of wood fiberboard insulation signifying a potential problem in not adding an external vapor barrier. Despite this increase, the overall relative humidity was kept between 55 and 65% for both EPS and wood fiberboard insulation types. The interior temperature was kept at a consistent 68-72 degrees fahrenheit in both variations of the ICF wall.

3.7.5 Minneapolis Wood-Stud Wall

For the wood fiber insulation wall type, as seen in Appendix G, the greatest total moisture content accumulated on the outside layer of LP smartside siding ranged from 8% to 25%. Critical layers such as the wood fiber insulation fluctuated between 8%-16% moisture content. The interior wood fiber insulation had a moisture content fluctuating between 5%-13%.

Completing the same simulation for the cellulose insulation wall type, as seen in Appendix H, the maximum total moisture content was accumulated on the outside layer of LP smartside siding ranging from 8% to 25%. Critical layers such as the interior cellulose fiber insulation reached between 5%-11% moisture content.

Overall, the data, as shown in Appendix I, shows near identical results between the wood fiber insulation and the cellulose fiber insulation in a wood frame assembly. The overall temperature of both variations is stabilized through the wood framed insulations and works well in keeping the interior temperature between 68-72 degrees fahrenheit. The moisture content figures for both options are acceptable as the thermal performance of insulation is decreased when moisture levels reach above 18% leading to possible decay of wood framing and fungi growth, potentially rotting the wall space.

3.7.6 Minneapolis ICF Wall

For the wood fiberboard insulated ICF wall, as shown in Appendix J, the greatest total moisture content on the outside layer of LP smartside siding ranged from 8% to 25%. Critical layers such as the interior wood fiberboard insulation reached between 6%-7% moisture content. The exterior wood fiberboard insulation stayed under 12% moisture content which is important in showing the beneficial evaporation effect of the air layer. The moisture content of the gypsum board was below 1%, satisfying a safe moisture content.

For the EPS insulated ICF wall, as shown in Appendix K, the greatest total moisture content accumulated on the outside layer of LP smartside siding ranged from 8% to 25%. Critical layers such as the interior EPS insulation fluctuated in moisture content from 2-3%. The exterior EPS insulation stayed under 12% moisture content which is important in showing the beneficial evaporation effect of the air layer. The moisture content of the gypsum board remained below 1%, satisfying a safe moisture content.

Overall, visualizing the two insulation types, as shown in Appendix L, the EPS insulation performed better than the wood fiberboard and reduced the moisture level reaching the interior sections of the wall. The WUFI 1D film data showed a very high water content into the first layer of wood fiberboard insulation signifying a potential problem in not adding an external vapor barrier. Despite this increase, the overall relative humidity was kept between 55%-65% for both EPS and wood fiberboard insulation types. The interior temperature was kept at a consistent 68-72 degrees fahrenheit in both variations of the ICF wall.

3.7.7 Conclusion

In all, the wall envelope of residential homes are essential in creating a safe and comfortable environment for its occupants. The data results from the WUFI simulations show that all designs and variations are suitable and in compliance with building codes and recommendations. The most sustainable material for wood-stud framing is the wood fiber insulation, with identical performance of cellulose insulation but has the benefit of a sustainable, cost effective, and material with greater longevity than cellulose insulation. The ICF wall type provides the best results with EPS insulation, the moisture content brought by the Minneapolis climate simply is not suitable for the exterior wood fiber board insulation and has potential to lose structural and thermal integrity overtime.

3.8 Design Builder

3.8.1 Introduction

DesignBuilder is an energy analysis software that assists in sustainable building design. The software will be used for building energy simulation to provide data on building energy usage and energy breakdown. The version utilized will be v7.0.1.6. In DesignBuilder,there are various built-in templates for construction, lighting, openings , activity levels, and HVAC systems. When applicable, these templates will be used to apply the design strategies. If there are no templates available for a specific design strategy, DesignBuilder also allows users to customize settings to match these design strategies.

Once the general building shape has been established, the interior of the building is split into various zones. Following that, settings for building construction, activity, HVAC, and lighting will be implemented. The simulations are then run multiple times, with each iteration representing changes to specific settings. Data will be collected from these simulations to show the EUI and fuel breakdown of each design strategy.

3.8.2 DesignBuilder Design Considerations

In this work, we will create four different baseline models in DesignBuilder. Each will be created with modern-day energy codes in mind and thus be a code-compliant representation of modern-day single-family and multi-family homes. These variations will each run simulations testing the effects of optimizing lighting, unplugging electrical equipment, optimizing HVAC systems, improving building construction, and lastly a combined net-zero design.

3.8.3 Baseline Settings

For both locations, and for both single and multi-family homes, the basic setting for the code compliant model are the same. Firstly, a new file must be created and the location must be selected, either Minneapolis or Los Angles depending on the model. Once the file has been made, the next step is to create a building. The building should be set to a new proposed residential building. This will assure that the future step will have the same default data.

3.8.4 Minneapolis, MN Single-Family

The Minneapolis, MN single family home was modeled with two floors, each ten feet tall. The dimensions of the house are 30 ft x 40 ft. The floor plan of the first and second floor are shown in Figures below.

Figure 16: First Floor Plan of Single Family Home in Minneapolis, MN

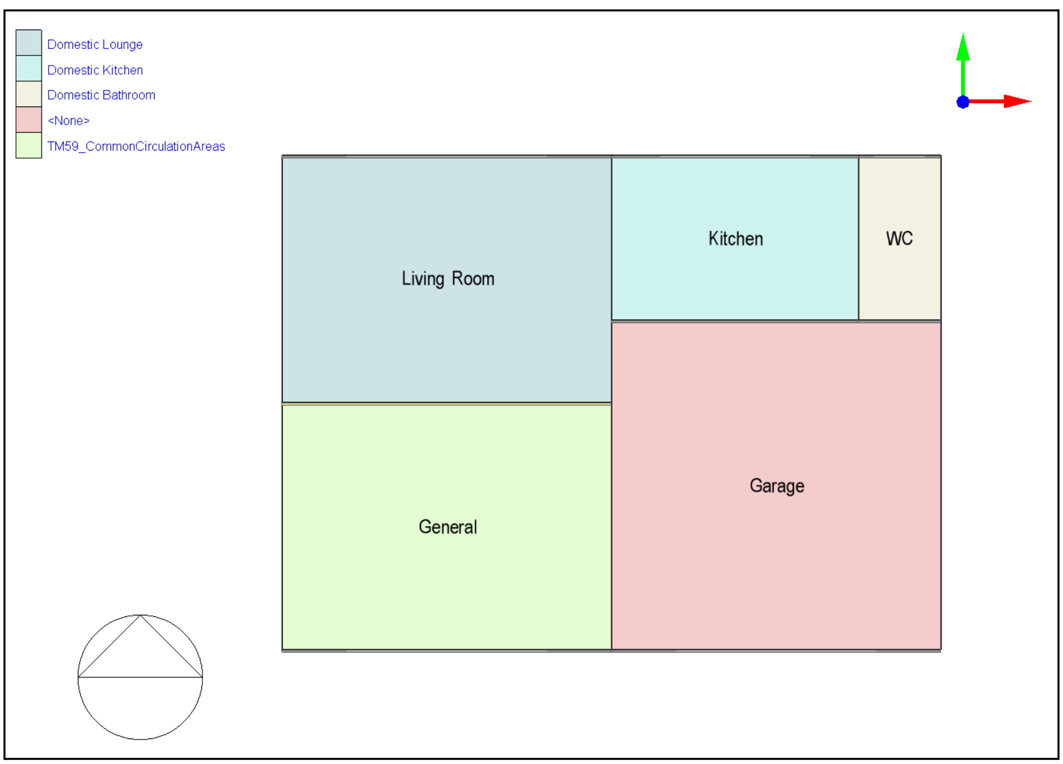
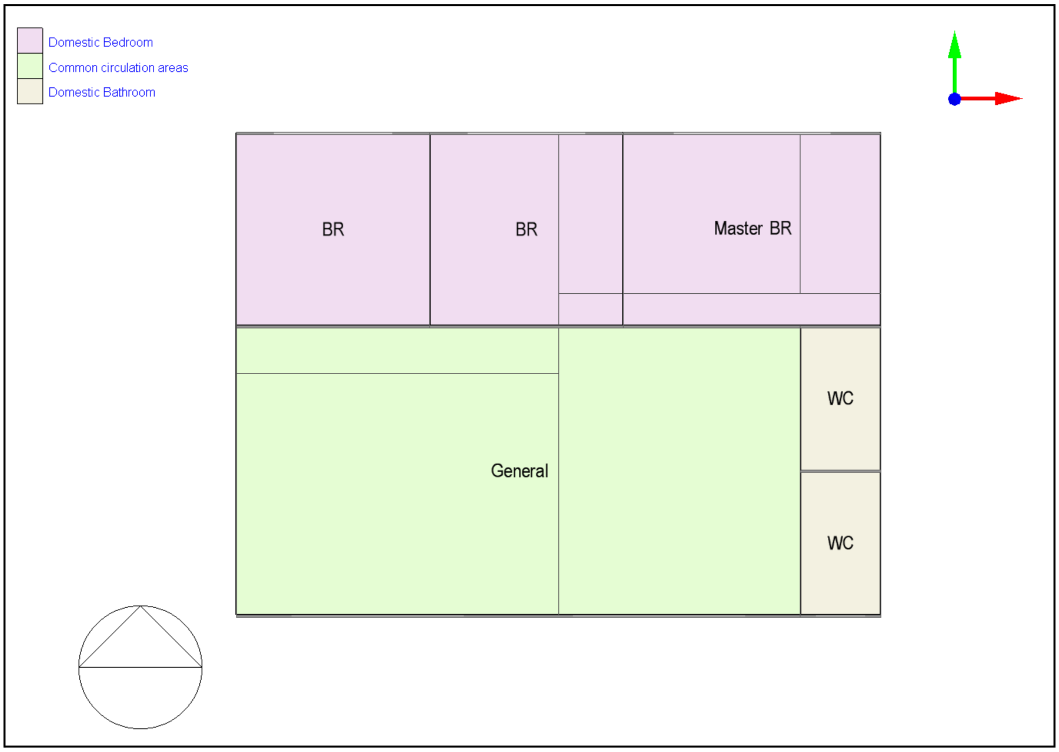


Figure 17: Second Floor Plan of Single Family Home in Minneapolis, MN



For the code compliant model, the setting were changed from the default based on what is shown in the Table 6 below. Then for each strategy the settings are changed from the code compliant model as shown in Table 6 below. Once all models have been made, simulations are run for each to collect data on the EUI and fuel usage breakdown.

Table 6: Minneapolis, MN Single-Family DesignBuilder Settings

Model Variation	Activity	Construction	Opening	Lighting	HVAC
Code Complaint	Select preset templates that reflect the use of each zone	Construction Template: CZ3 Residential Baseline Constructions	Default	Default	Natural Ventilation: On
Design Strategy #1	No Change	No Change	No Change	Power Density: 0.10 W/ft^2 Lighting Control: On	Default
Design Strategy #2	Misc or Office Power Density: 0.25 W/ft^2	No Change	No Change	No Change	No Change
Design Strategy #3	No Change	No Change	No Change	No Change	Heat Recovery: On
Design Strategy #4	No Change	Crack Template: Good External Walls: Custom Wall Assembly	No Change	No Change	No Change
Net-Zero	Misc or Office Power Density: 0.25 W/ft^2	Crack Template: Good External Walls: Custom Wall Assembly	No Change	Power Density: 0.10 W/ft^2 Lighting Control: On	Heat Recovery: On

3.8.5 Minneapolis, MN Multi-Family

The Minneapolis, MN multi-family home was modeled with two floors, each ten feet tall. The dimensions of the house are 20 ft x 25ft for each 1000 sqft unit. The floor plan of the first and second floor are shown in the Figures below.

Figure 18: First Floor Plan of Multi-Family Home in Minneapolis, MN (Single Unit)

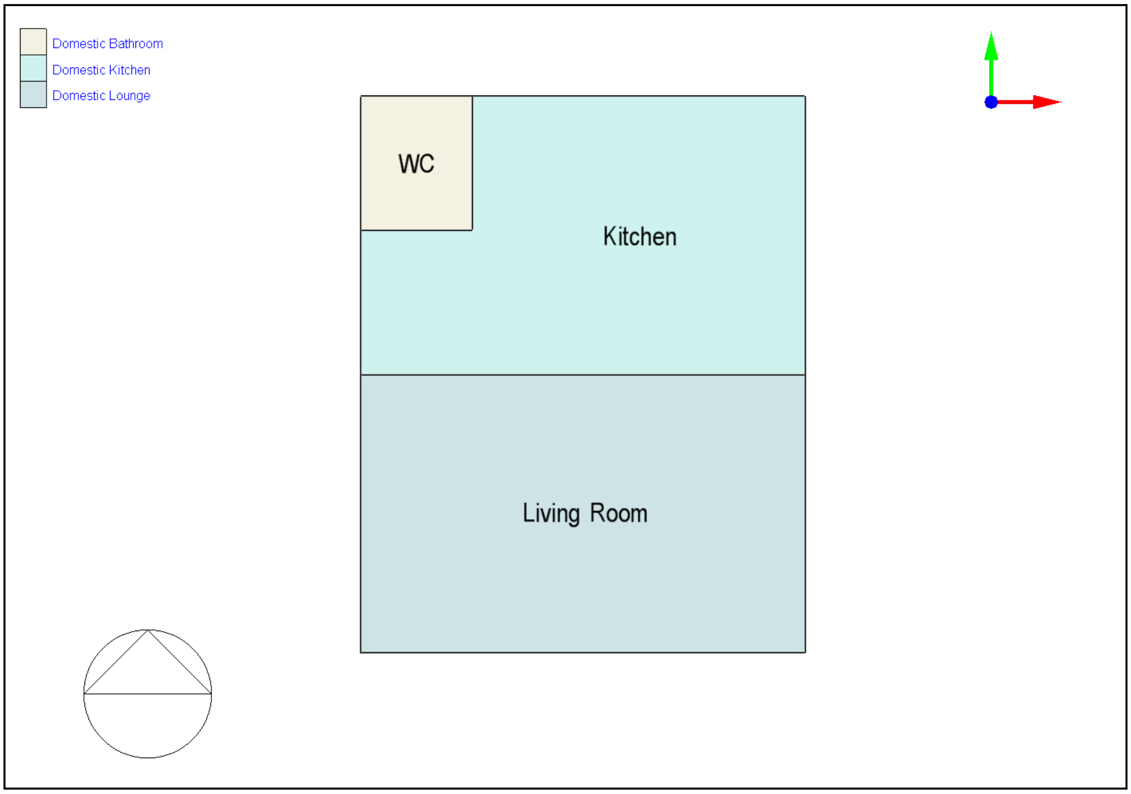
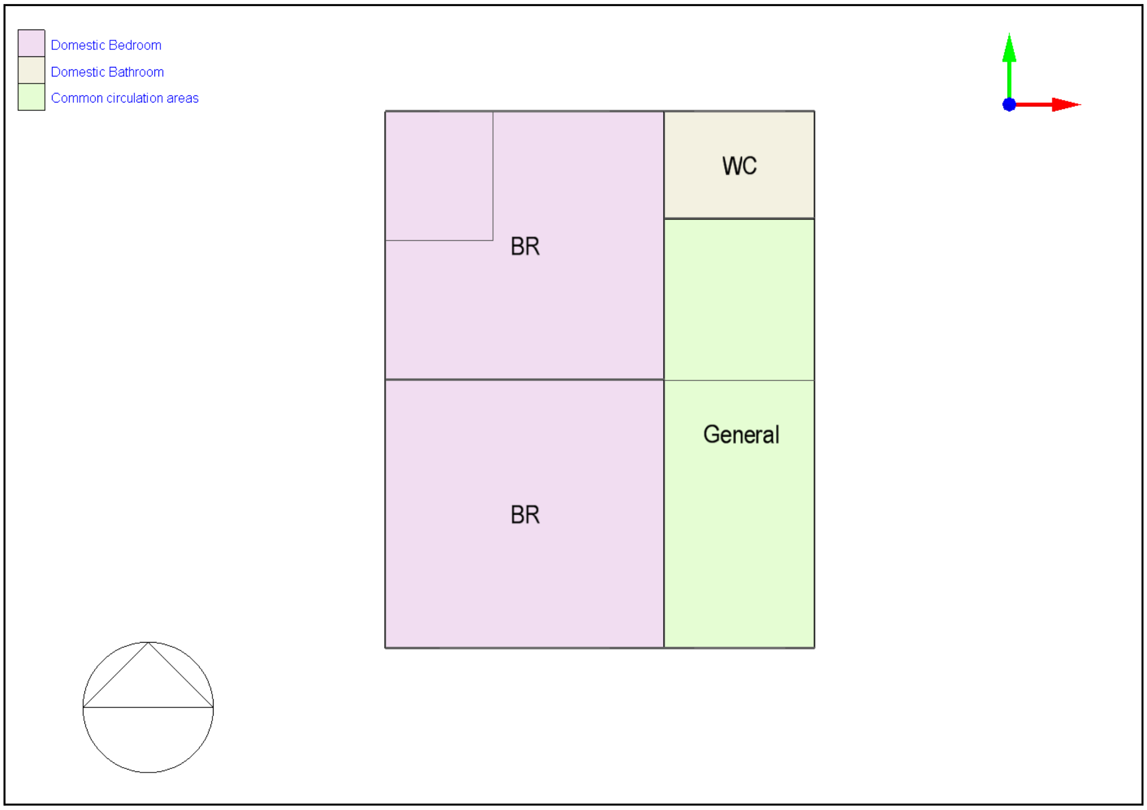


Figure 19: Second Floor Plan of Multi-Family Home in Minneapolis, MN (Single Unit)



For the code compliant model, the setting were changed from the default based on what is shown in the Table 7 below. Then for each strategy the settings are changed from the code compliant model as shown in Table 7 below. Once all models have been made, simulations are run for each to collect data on the EUI and fuel usage breakdown.

Table 7: Minneapolis, MN Multi-Family DesignBuilder Settings

Model Variation	Activity	Construction	Opening	Lighting	HVAC
Code Complaint	Select preset templates that reflect the use of each zone	Construction Template: CZ3 Residential Baseline Constructions	Default	Default	Natural Ventilation: On
Design Strategy #1	No Change	No Change	No Change	Power Density: 0.10 W/ft^2 Lighting Control: On	Default
Design Strategy #2	Misc or Office Power Density: 0.25 W/ft^2	No Change	No Change	No Change	No Change
Design Strategy #3	No Change	No Change	No Change	No Change	Heat Recovery: On
Design Strategy #4	No Change	Crack Template: Good External Walls: Custom Wall Assembly	No Change	No Change	No Change
Net-Zero	Misc or Office Power Density: 0.25 W/ft^2	Crack Template: Good External Walls: Custom Wall Assembly	No Change	Power Density: 0.10 W/ft^2 Lighting Control: On	Heat Recovery: On

3.8.6 Los Angeles, CA Single-Family

The Los Angeles, CA single family home was modeled with two floors, each ten feet tall. The dimensions of the house are 30 ft x 40 ft. The floor plan of the first and second floor are shown in the Figures below.

Figure 20: First Floor Plan of Single Family Home in Los Angeles, CA

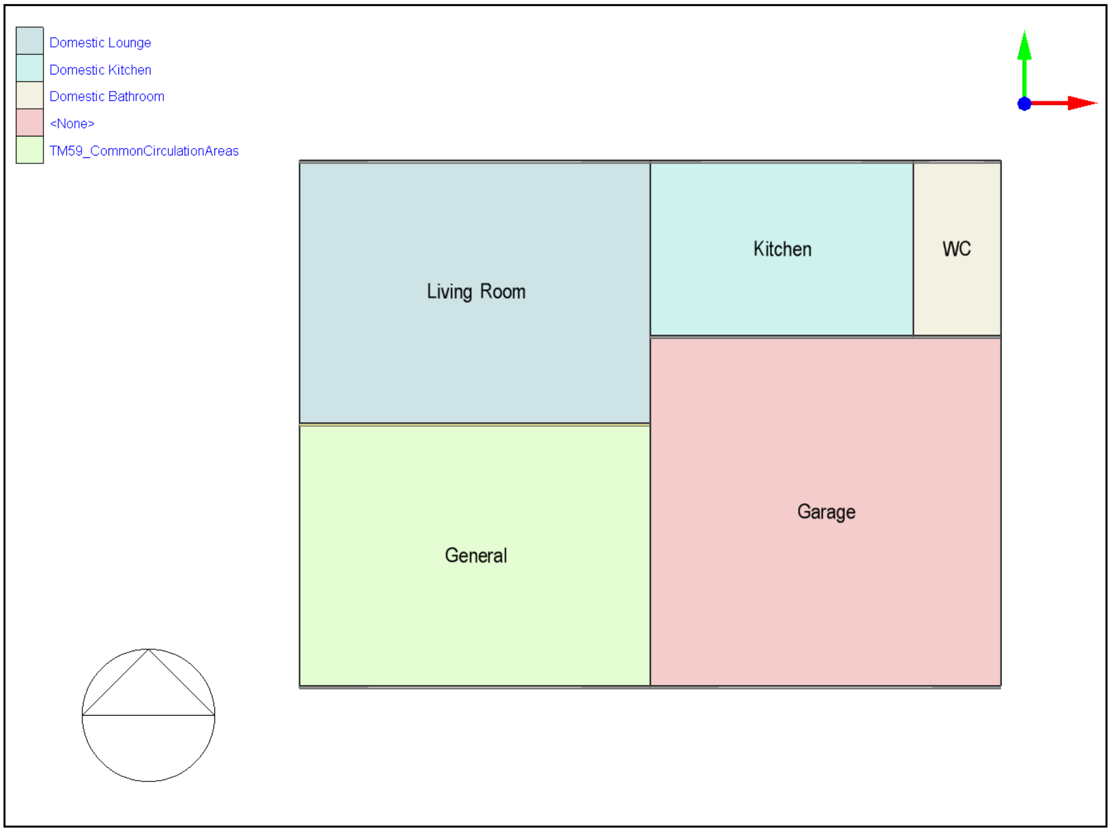
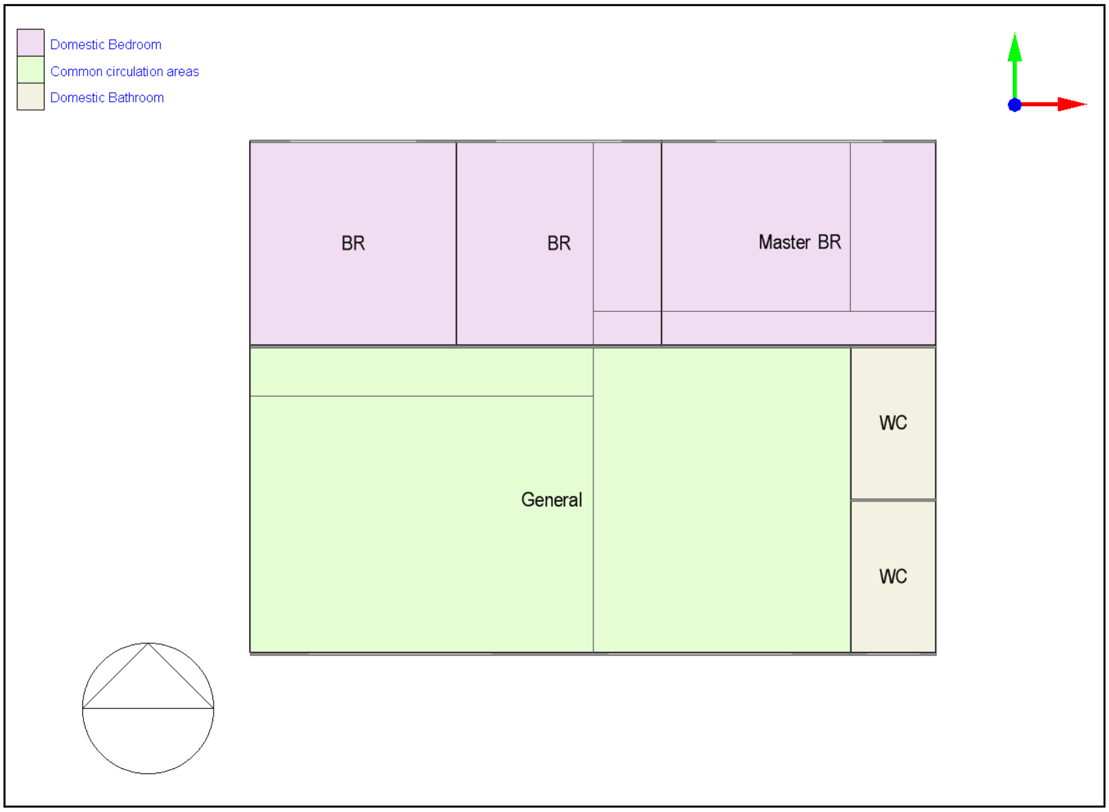


Figure 21: Second Floor Plan of Single Family Home in Los Angeles, CA



For the code compliant model, the setting were changed from the default based on what is shown in the Table 8 below. Then for each strategy the settings are changed from the code compliant model as shown in Table 8 below. Once all models have been made, simulations are run for each to collect data on the EUI and fuel usage breakdown.

Table 8: Los Angeles, CA Single-Family DesignBuilder Settings

Model Variation	Activity	Construction	Opening	Lighting	HVAC
Code Complaint	Select preset templates that reflect the use of each zone	Construction Template: CZ3 Residential Baseline Constructions	Default	Default	Natural Ventilation: On
Design Strategy #1	No Change	No Change	No Change	Power Density: 0.10 W/ft^2 Lighting Control: On	Default
Design Strategy #2	Misc or Office Power Density: 0.25 W/ft^2	No Change	No Change	No Change	No Change
Design Strategy #3	No Change	No Change	No Change	No Change	Economizer: On
Design Strategy #4	No Change	Crack Template: Medium External Walls: Custom Wall Assembly	No Change	No Change	No Change
Net-Zero	Misc or Office Power Density: 0.25 W/ft^2	Crack Template: Medium External Walls: Custom Wall Assembly	No Change	Power Density: 0.10 W/ft^2 Lighting Control: On	Economizer: On

3.8.7 Los Angeles, CA Multi-Family

The Los Angeles, CA multi-home was modeled with two floors, each ten feet tall. The dimensions of the house are 20 ft x 25ft for each 1000 sqft unit. The floor plan of the first and second floor are shown in the Figures below.

Figure 22: First Floor Plan of Multi-Family Home in Los Angeles, CA (Single Unit)

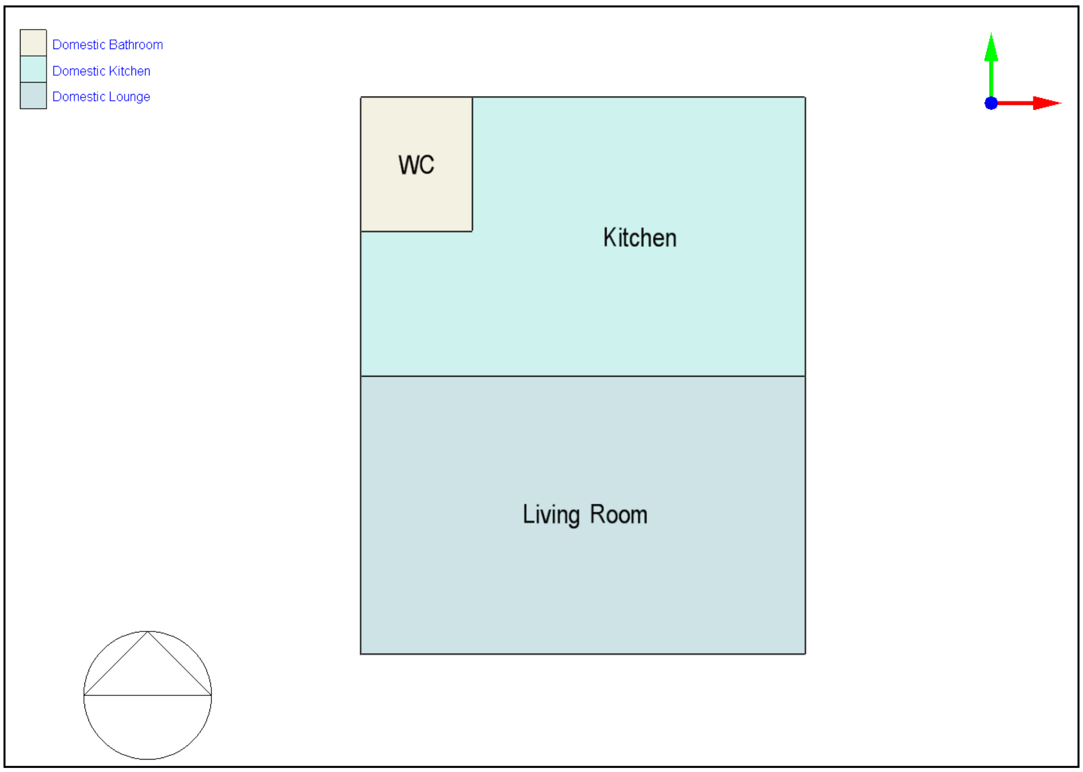
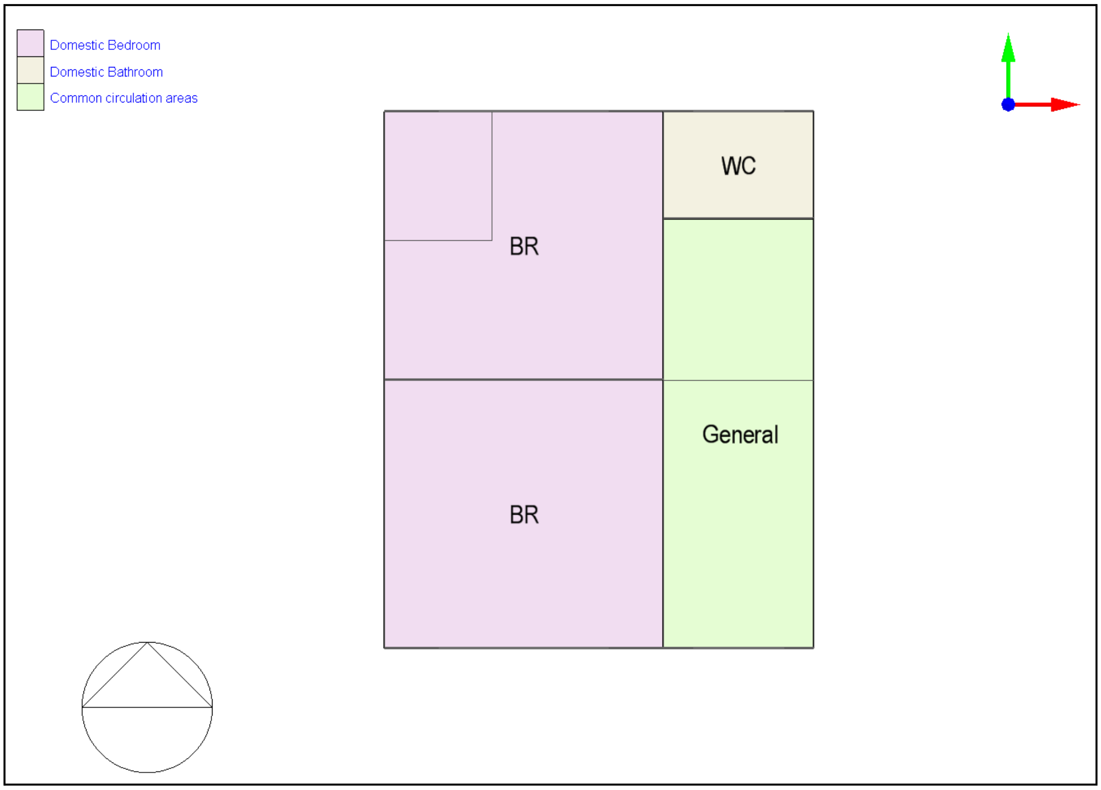


Figure 23: Second Floor Plan of Multi-Family Home in Los Angeles, CA (Single Unit)



For the code compliant model, the setting were changed from the default based on what is shown in the Table 9 below. Then for each strategy the settings are changed from the code compliant model as shown in Table 9 below. Once all models have been made, simulations are run for each to collect data on the EUI and fuel usage breakdown.

Table 9: Los Angeles, CA Multi-Family DesignBuilder Settings

Model Variation	Activity	Construction	Opening	Lighting	HVAC
Code Complaint	Select preset templates that reflect the use of each zone	Construction Template: CZ3 Residential Baseline Constructions	Default	Default	Natural Ventilation: On
Design Strategy #1	No Change	No Change	No Change	Power Density: 0.10 W/ft^2 Lighting Control: On	Default
Design Strategy #2	Misc or Office Power Density: 0.25 W/ft^2	No Change	No Change	No Change	No Change
Design Strategy #3	No Change	No Change	No Change	No Change	Economizer: On
Design Strategy #4	No Change	Crack Template: Medium External Walls: Custom Wall Assembly	No Change	No Change	No Change
Net-Zero	Misc or Office Power Density: 0.25 W/ft^2	Crack Template: Medium External Walls: Custom Wall Assembly	No Change	Power Density: 0.10 W/ft^2 Lighting Control: On	Economizer: On

3.9 Cost Estimation

Utilizing construction cost data tools can make the commonly laborious task of cost estimating easier and more manageable when implementing green building solutions. Cost estimation tool options such as RSMeans provides the user with cloud-based access to a construction cost database. A cloud based format allows for construction and technology solutions to be updated regularly and keep up with new industry standards. Budgeting a project and creating building schedules creates end savings that benefit the homeowner in making conscious financial decisions for a new construction or retrofit.

Table 10: Excel sheet of RSmeans demo calculations[54]

Site: Minneapolis				
Wall Type	Insulation	Material Cost ($)	Install Cost ($)	Total Cost ($)
Double Layer Wood-Stud	Cellulose (Non-Rigid)	7,784	13,440	21,224
	Wood Fiber (Non-Rigid)	9,240	14,000	23,240
ICF	EXP (Rigid Board)	24,000	42,196	59,612
	Wood Fiber (Rigid Board)	17,640	40,264	57,904
Site: Los Angeles				
Wall Type	Insulation	Material Cost ($)	Install Cost ($)	Total Cost ($)
Single Layer Wood-Stud	Cellulose (Non-Rigid)	4,984	7,028	12,012
	Wood Fiber (Non-Rigid)	4,200	6,468	10,668
ICF	EXP (Rigid Board)	17,136	38,976	56,112
	Wood Fiber (Rigid Board)	17,388	37,212	54,600

RSmeans allows for managed estimates to be categorized by building type, construction type; such as unit, assembly, or square foot model. Data is also able to be localized to precisely estimate potential material, labor, and equipment costs. Utilizing a free RSmeans data set from 2011, we can calculate the cost difference of the exterior wall construction with site specific pricing of a home with 2800 sq*ft of wall. Because this version of RSmeans did not have all of the material data measures we needed, such as the ICF components, the labor costs may differ if a most recent version was used. Overall, the material and labor cost estimations show that the ICF construction for both sites is not economical as the typical wood-stud construction. The overall cost of materials and labor was also found to be cheaper in Los Angeles than

[54] "RSMeans Online: Manage Estimates Default," accessed December 10, 2022, https://www.rsmeansonline.com/ManageEstimate.

Minneapolis, possibly attributed to less availability in material and skilled labor. RSmeans is a good tool for homeowners considering building materials or retrofitting options from appliances to construction costs.

3.10 Conclusions

All in all, the various models have been tested and multiple simulations have been run to obtain the necessary information for the project. The various strategies for net-zero homes have been researched and narrowed down to select those feasible for residential structures. These strategies included, renewable energy sources, habitual changes, building construction changes and also minor refinements of various aspects of the home. Once these strategies were established, THERM, WUFI, and DesignBuilder were used to determine effectiveness of each strategy. Then RSMeans and additional research was used to determine the price of the various methods. Going forward we will use collected data and information to determine the ease of implementation and accessibility of each strategy for homeowners.

4 Results & Findings

4.1 Introduction

The results collected will be objectively looked at to understand which strategies were the most effective at decreasing fuel usage for each model. Then the cost of implementation is to be compared with the savings presented by the strategy to provide a cost-to-benefit ratio that will help to show which of the provided strategies should be implemented first in case of budget limitations.

4.2 Data Collected

4.2.1 DesignBuilder Data

For DesignBuilder, the data collected showed the EUI and fuel usage breakdown of a code compliant building, then the same data after testing four different design strategies. For design strategy #1, the settings were changed to use LED lights and have habitual lighting control. For design strategy #2, the settings were changed to imitate the unplugging of unused appliances. For design strategy #3, the settings were changed to have heat recovery or economizers implemented depending on the climate zone. Lastly for design strategy #4, the settings were changed to have better construction and test a newer wall assembly.

Figure 24: Minneapolis MN, Single Family Fuel Usage Breakdown

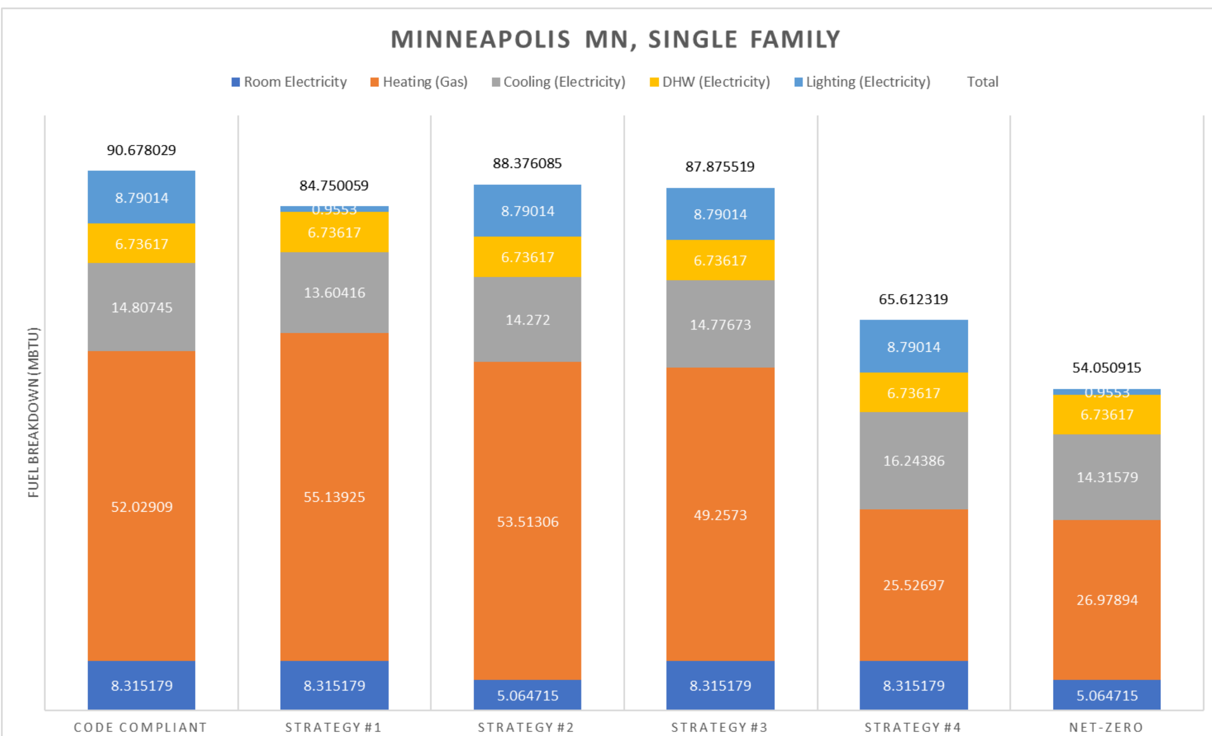


Figure 25: Minneapolis MN, Single Family EUI

Variable	EUI (kBtu/ft^2)
Code Compliant	39.07
Strategy #1	36
Strategy #2	37.83
Strategy #3	38.06
Strategy #4	30.75
Net-Zero	25.2

The data collected for the Minneapolis MN, single family home, is shown above in Figures 13 and 14. It can be seen that Strategy #1, the use of LED lights and the habitual lighting controls, decreases lighting electricity drastically while slightly increasing energy needed for heating to compensate for the lack of heat released by the lighting. Strategy #2, the unplugging of appliances when not in use, brings similar results with a decrease in room electricity instead, while still slightly increasing and decreasing heating and cooling needs respectively. For strategy #3, the change in HVAC, the only significant change is the decrease in heating due to the implementation of a heat recovery system. Strategy #4, which increases building air tightness and changes the wall construction, gives a drastic decrease in heating fuel needs while slightly increasing the cooling needs. Lastly, the net-zero solution causes a decrease in all fuel categories as it combines all four of the aforementioned strategies.

Figure 26: Minneapolis MN, Multi-Family Fuel Usage Breakdown

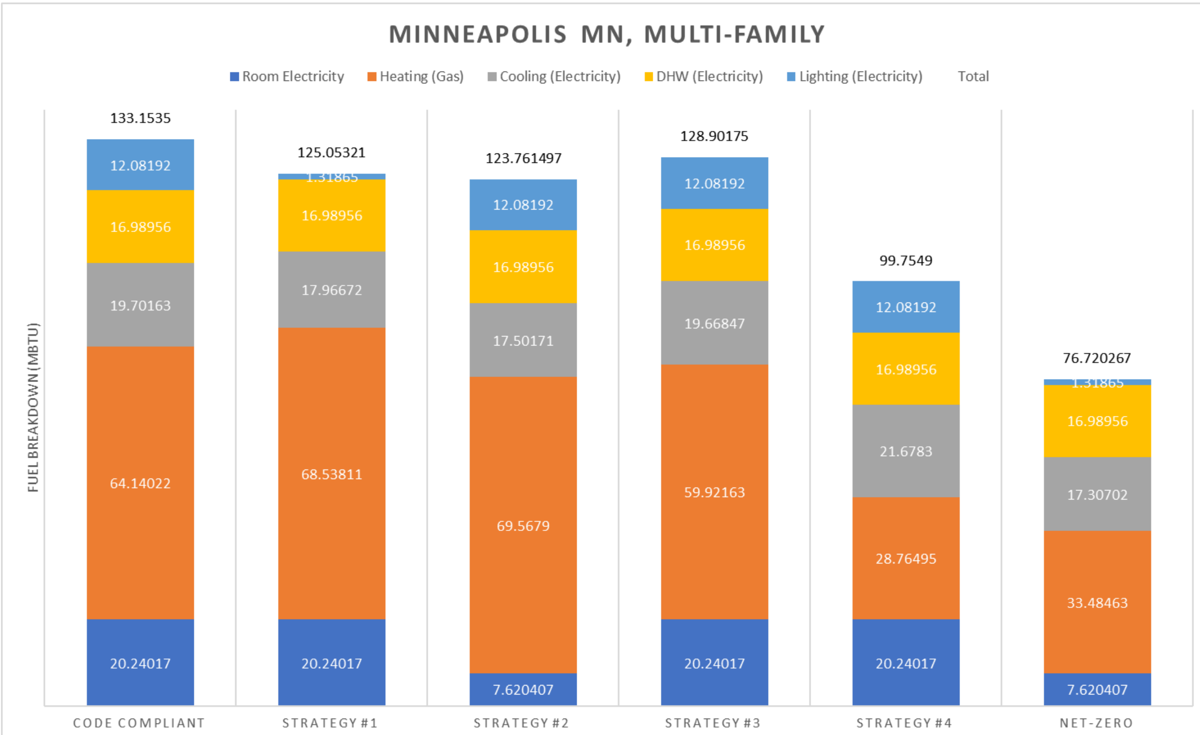


Figure 27: Minneapolis MN, Multi-Family EUI

Variable	EUI (kBtu/ft^2)
Code Compliant	28.17
Strategy #1	26.09
Strategy #2	25.71
Strategy #3	27.42
Strategy #4	22.71
Net-Zero	17.1

The data collected for the Minneapolis MN, multi-family home is quite similar, at least relatively, to the data collected for the single family home of the same location. This data is shown above in Figures 15 and 16. It can be seen that Strategy #1, the use of LED lights and the habitual lighting controls, also decreases lighting electricity drastically while slightly increasing energy needed for heating. Strategy #2, the unplugging of appliances when not in use, brings similar results with a decrease in room electricity instead, while still slightly increasing and decreasing heating and cooling needs respectively. For strategy #3, the change in HVAC, the only significant change is the decrease in heating due to the implementation of a heat recovery system. Strategy #4, which increases building air tightness and changes the wall construction, gives a drastic decrease in heating fuel needs while slightly increasing the cooling needs. Lastly, the net-zero solution causes a decrease in all fuel categories as it combines all four of the aforementioned strategies.

Figure 28: Los Angeles CA, Single Family Fuel Usage Breakdown

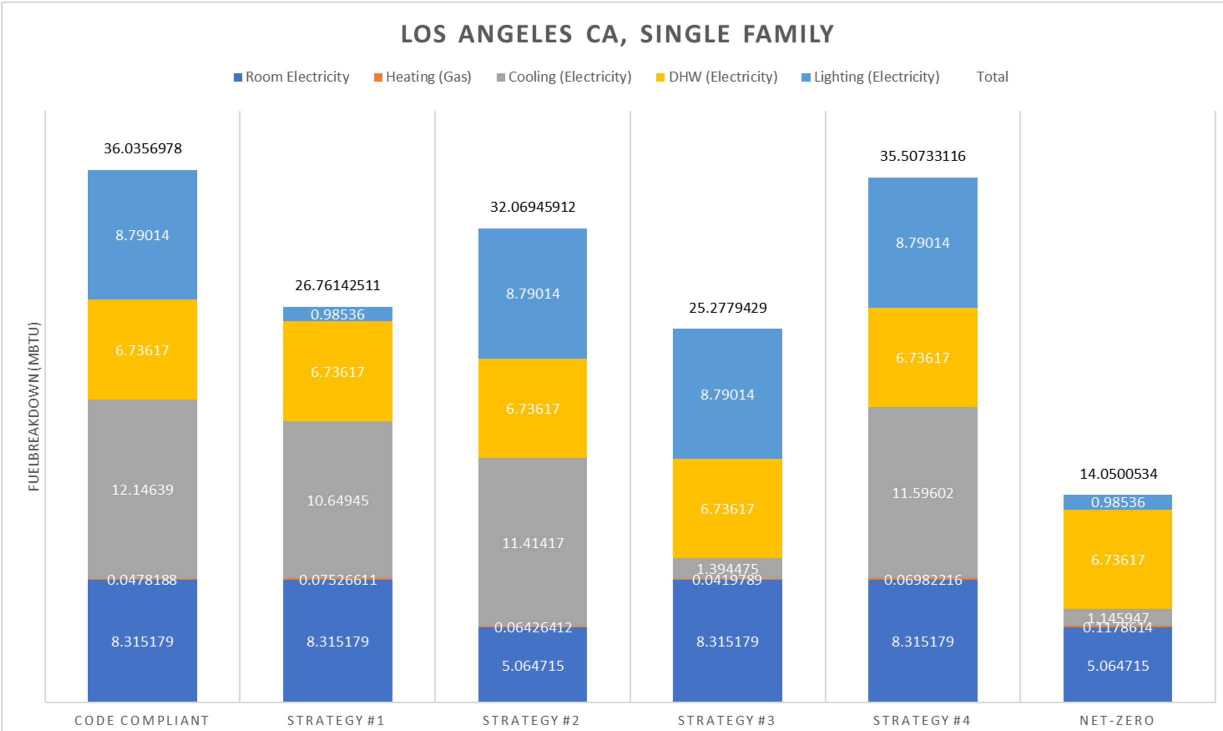


Figure 29: Los Angeles CA, Single Family EUI

Variable	EUI (kBtu/ft^2)
Code Compliant	18.65
Strategy #1	14.28
Strategy #2	16.75
Strategy #3	10.58
Strategy #4	18.24
Net-Zero	5.81

The data collected for the Los Angeles CA, single family home is shown above in Figures 17 and 18. Strategy #1, again dramatically decreases the lighting electricity usage and slightly decreases cooling energy use. Strategy #2, decreases the room electricity, while also slightly decreasing cooling energy use. For Strategy #3, an economizer was implemented and caused a drastic decrease in cooling needs. For strategy #4, the changes were minimal with a slight decrease in the cooling electric usage. Lastly, like before, the net-zero solution combines all four strategies and leads to a decrease in all fuel categories.

Figure 30: Los Angeles CA, Multi-Family Fuel Usage Breakdown

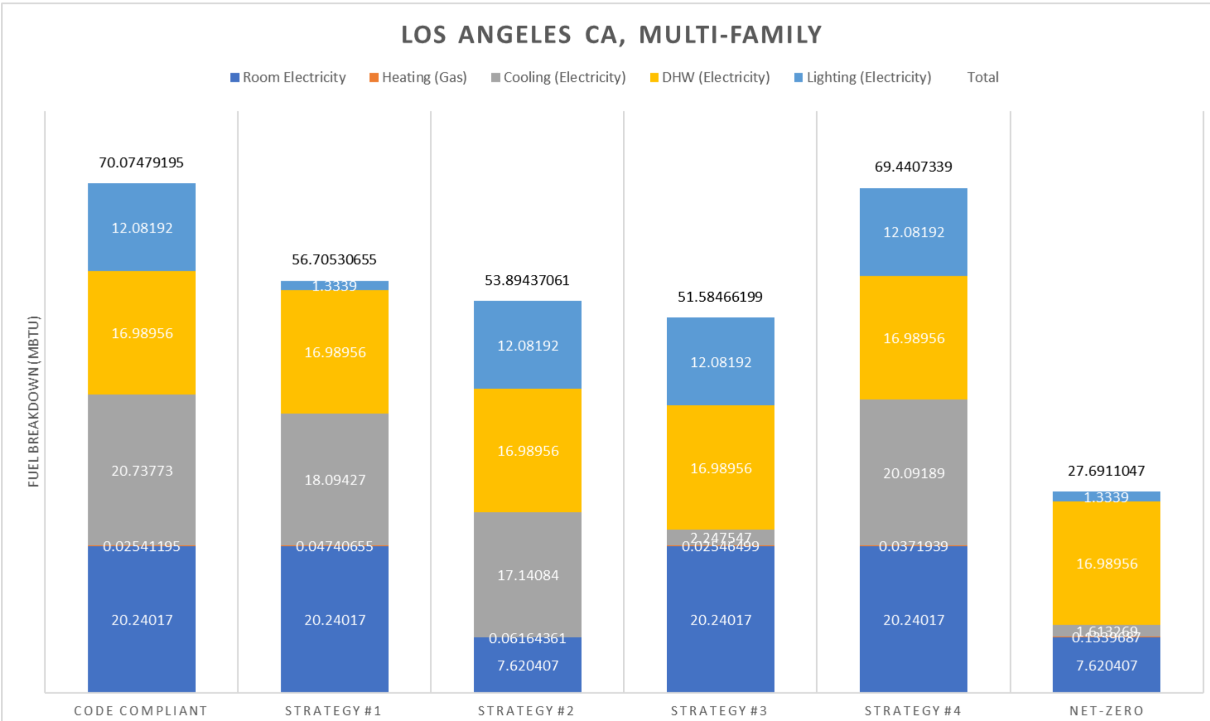


Figure 31 : Los Angeles CA, Multi-Family EUI

Variable	EUI (kBtu/ft^2)
Code Compliant	17.33
Strategy #1	14.14
Strategy #2	13.4
Strategy #3	10.47
Strategy #4	17.09
Net-Zero	5.44

The data collected for the Los Angeles CA, multi-family home is shown above in Figure 16. This data is similar to that of the single family home for the same location. Strategy #1, once again decreases the lighting electricity usage by a large amount and slightly decreases cooling energy use. Strategy #2, again decreases the room electricity, while also slightly decreasing cooling energy use. For Strategy #3, an economizer was also implemented, which again caused a drastic decrease in cooling needs. For strategy #4, the changes were even more minimal than the single family home with only the slightest decrease in the cooling electric usage. Lastly, like all others before, the net-zero solution uses all four strategies and leads to a major decrease in all fuel categories.

4.3 Cost Effectiveness

4.3.1 Strategy #1: Lighting Optimization

The use of LED light bulbs has a more expensive upfront cost but significantly lower maintenance cost due to its lifespan being five times that of similar incandescent light bulbs. Thus overall, in installation and usage alone, the LED can save homeowners significant amounts of money. The savings from decreased fuel usage are $405, $700, $560, and $1000 respectively for single-family homes in Minneapolis and in Los Angeles, and for multi-family homes in Minneapolis and in Los Angeles.

4.3.2 Strategy #2: Unplugging Appliances

For the unplugging of electrical appliances, there are no upfront nor maintenance costs. Therefore for each strategy, there exist only savings. The savings from decreased fuel usage are $405, $700, $560, and $1010 respectively for single-family homes in Minneapolis and in Los Angeles, and for multi-family homes in Minneapolis and in Los Angeles.

4.3.3 Strategy #3: HVAC Optimization

When optimizing the HVAC system, the change in cost was variable based on factors such as the HVAC system used, the CoP of the individual systems, the installation fees and maintenance fees. All in all, to keep the testing consistent, the only variables capable of being tested in DesignBuilder were the addition of a heat recovery system and the addition of an economizer for Minneapolis and Los Angeles respectively. Prices for these can range, but will be approximated to be $750 for the heat recovery system and $2000 for the economizer. With these it can then be seen that the single family and multi-family homes in Minneapolis saved $30 and $60 respectively with the heat recovery system. Thus making this strategy not feasible for Minneapolis. For Los Angeles on the other hand, the savings for single family and multi-family homes were $810 and $1390 respectively. With the payback period being less than 3 years, the economizer is a feasible strategy for Los Angeles.

4.3.4: Strategy #4: Construction

For construction, the most cost effective wall assembly was found to be wood stud with wood fiber insulation. While it is true that the price is high for construction, this is true if the normal cost of wall construction is not taken into account. Comparatively, the cost of building a wood stud wall with wood fiber insulation is not much higher than normal wall constructions. The savings from this wall construction are $290, $40, $390, and $50 respectively for single-family homes in Minneapolis and in Los Angeles, and for multi-family homes in Minneapolis and in Los Angeles. Showing that the change in wall construction is only effective in Minneapolis, while not as cost-effective in Los Angeles.

4.4 Conclusion

With both the data presented and analyzed, the cost effectiveness of each strategy was able to be determined. Overall, most of the net-zero solutions tested were able to decrease the fuel usage of each model by a significant amount. Adding on the solar energy generation from the PV panels in Minneapolis MN, which utilized both South and North-facing roofs, and in Los Angeles CA, which only used the South-facing roof due to more sun exposure and less energy use, the combined strategies were able to reach net-zero for each of the models.

5 Conclusion

This project's proposed net-zero concept will implement wood fiber wall assembly, LED lighting control, and other design strategies in addition to installing roof-mounted solar panels to generate on-site the energy needed to offset the home's reduced energy usage each year. The purpose of this project is to go above and beyond what currently exists for new-home construction and show home-owners and builders what technologies and innovative new materials exist to reduce energy usage, make more eco-conscious and sustainable decisions, and still fall within a reasonable budget.

It is important that net-zero implementation occurs now at the start of the design/build process as opposed to simply retrofitting later. Retrofitting older homes to implement more energy efficient codes or to add in design strategies such as GSHP systems and solar panels is already a system in place and a movement that has been gaining a lot of traction in recent years. However, retrofitting is a fix and not a long-term solution. So long as homes are constructed to simply meet code and not go above and beyond environmentally, then there will always be homes in need of retrofitting later. Whereas, if homes are constructed now to implement a multitude of design strategies to help reduce energy usage or work towards achieving net-zero, then they will not need to be retrofitted to the same degree in future years which will save on costs and assist in ecological conservation/impact.

For effective strategies to implement in these newly constructed homes, DesignBuilder was used to find the EUI and fuel breakdown. Models for single family and multi-family homes were created for two different locations: Minneapolis, MN and Los Angeles, CA. For each model, Four design strategies were tested individually, and their EUI and fuel breakdown was obtained. This collected data, along with cost estimation data, provided information on the savings of each strategy, allowing for proper recommendations for each model.

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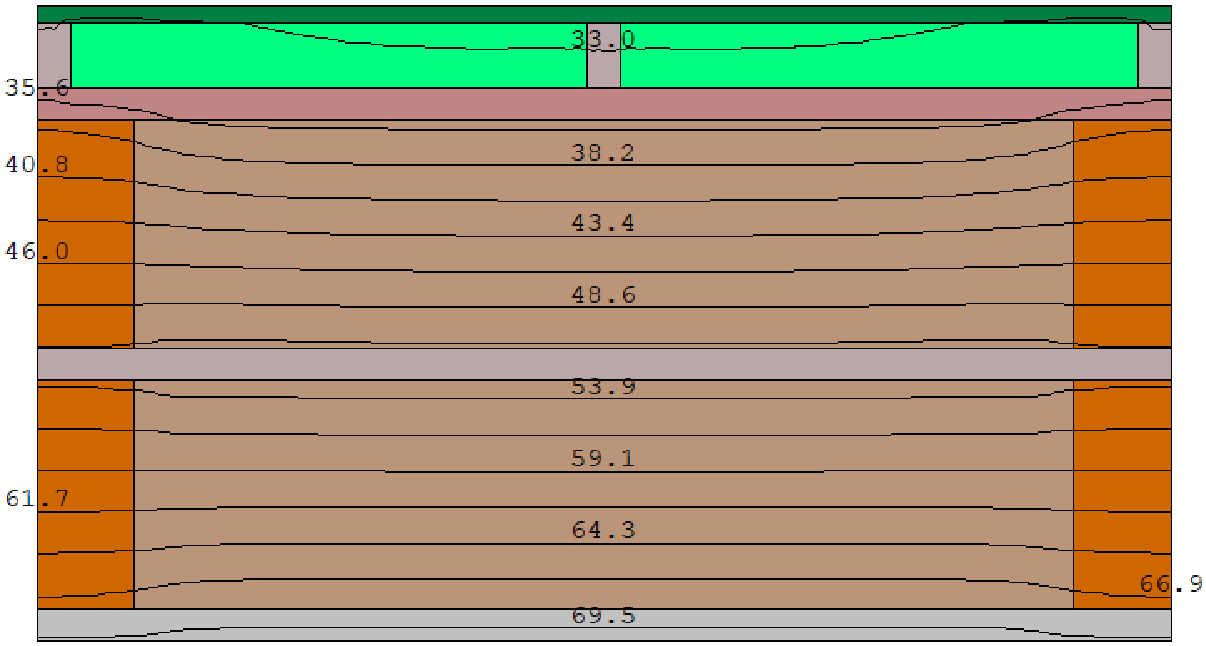
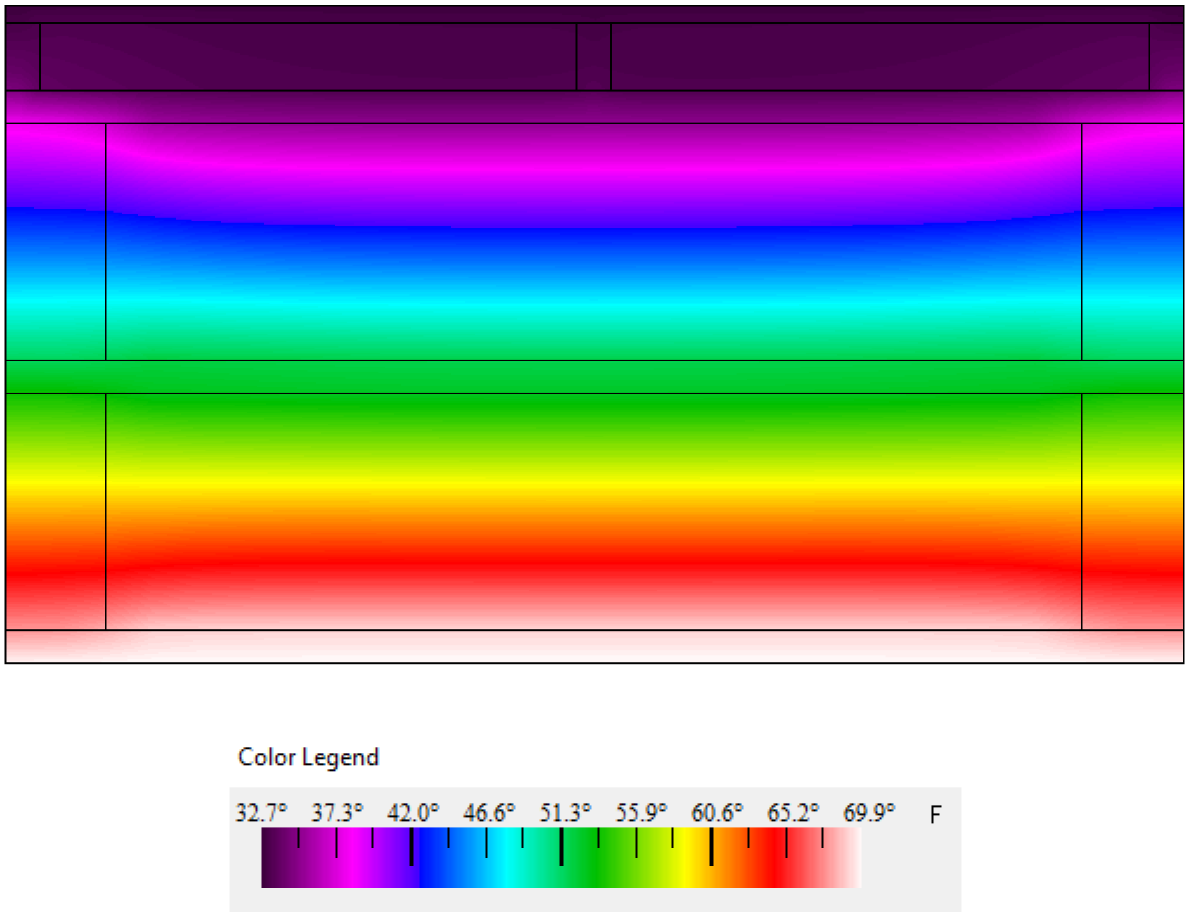
Appendices

Appendix A: THERM Wood-Stud Wall Assembly

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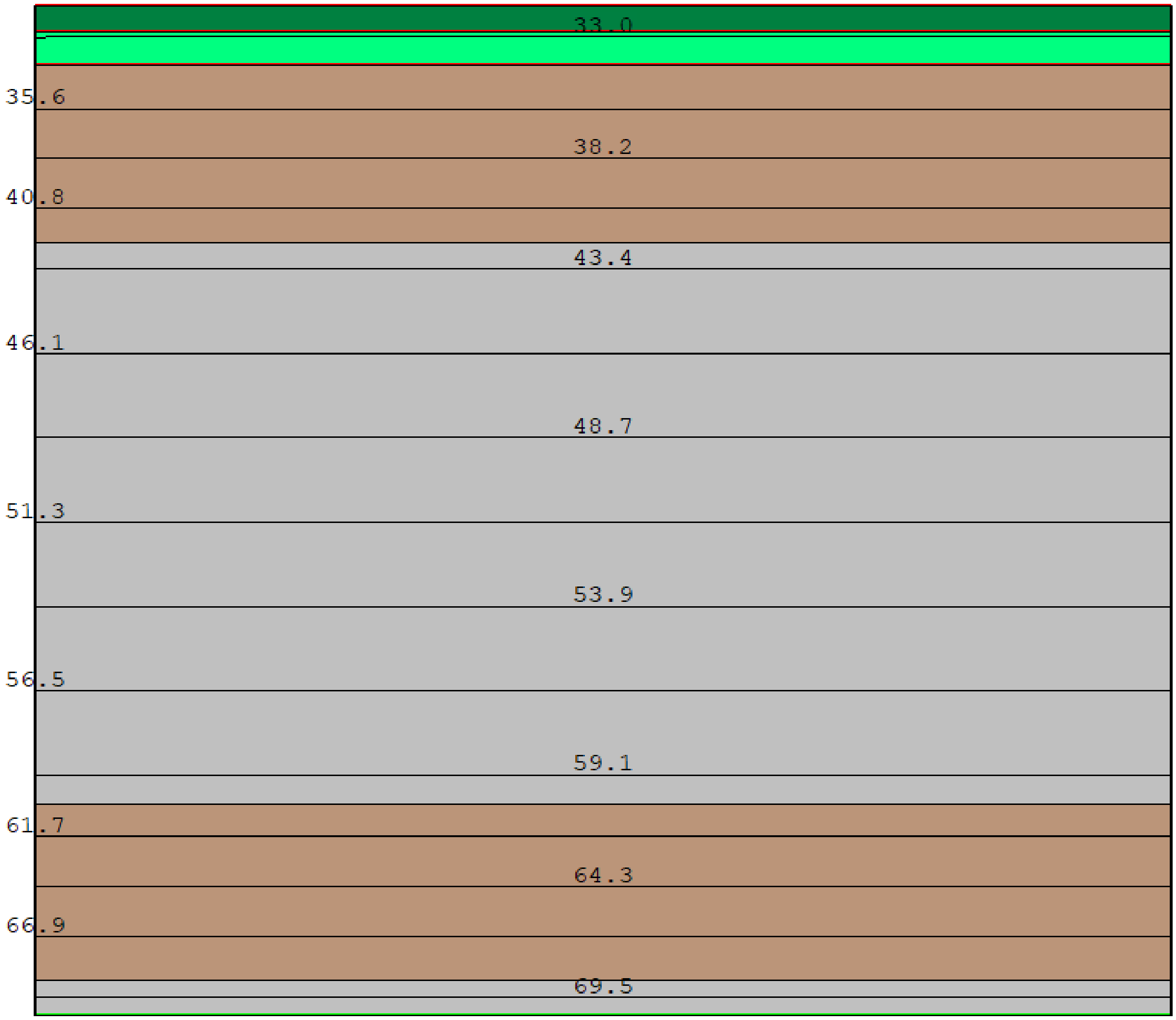
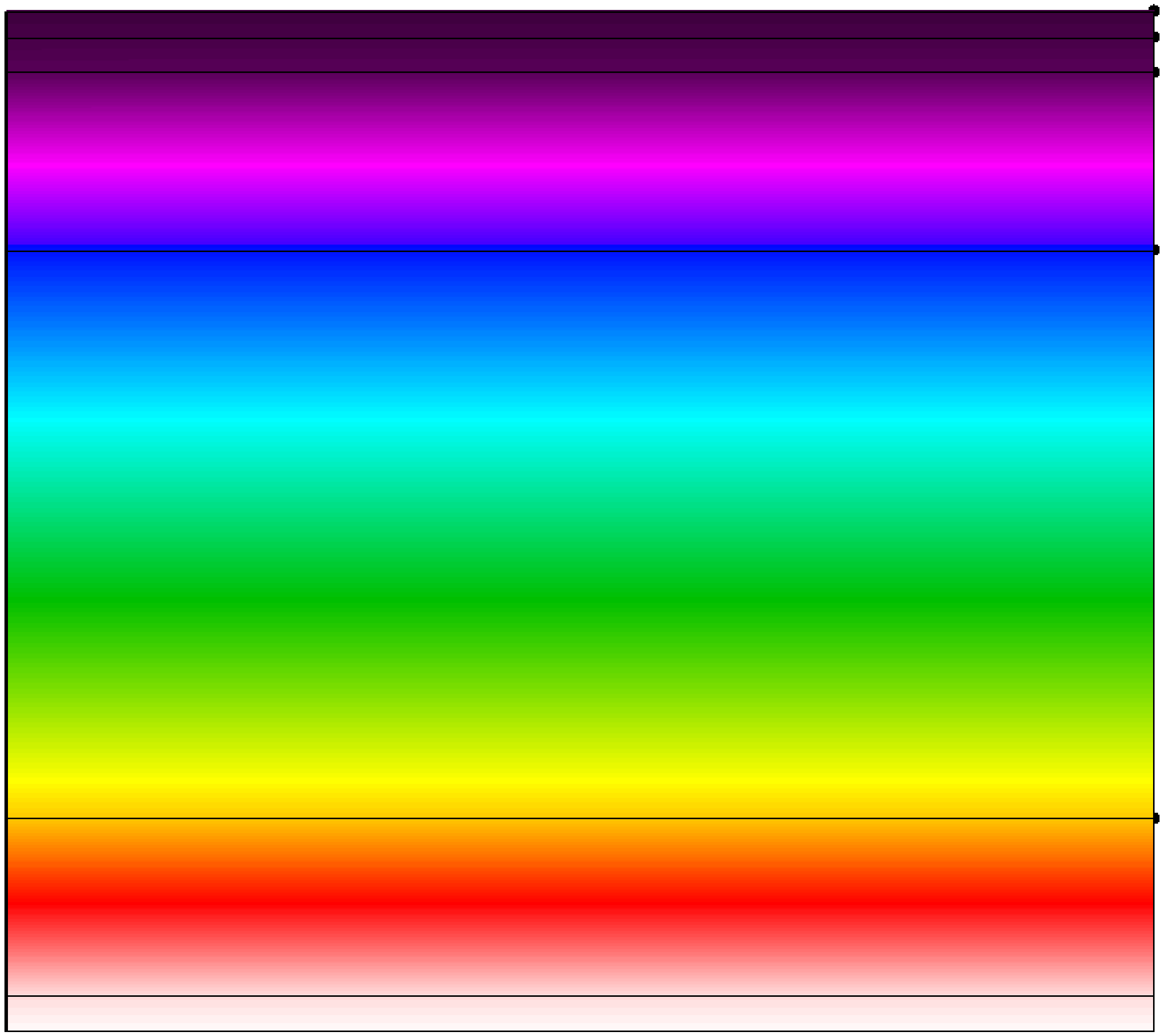
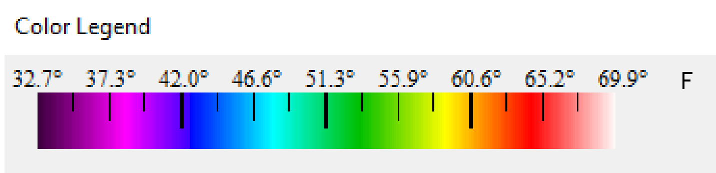
Appendix B: THERM ICF Wall Assembly



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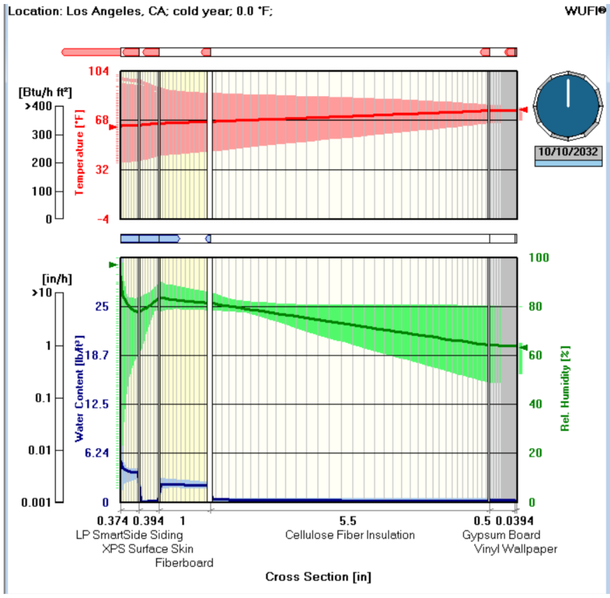
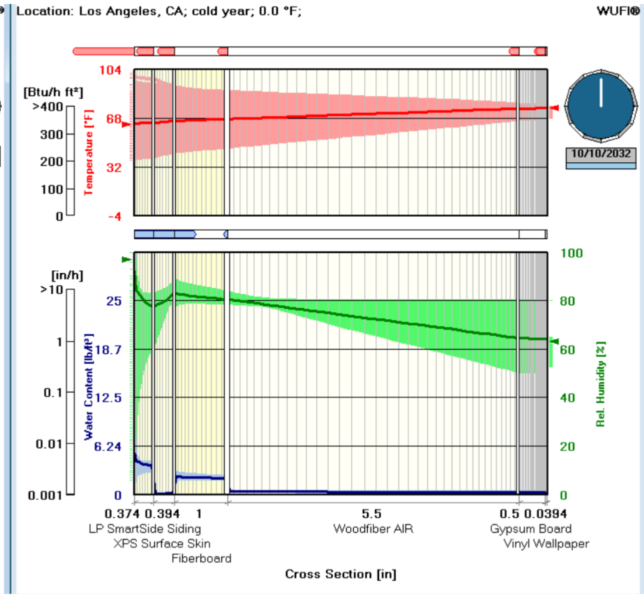
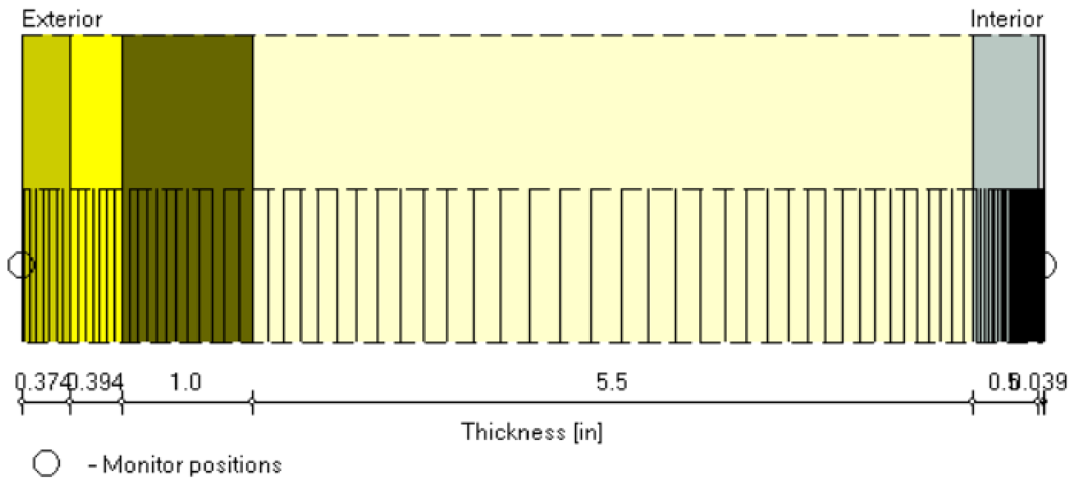
Appendix C: 10 year Film Data Simulation: Los Angeles Wood-Stud Wall





Appendix D: WUFI Los Angeles Wood-Stud Wall with Wood Fiber Insulation

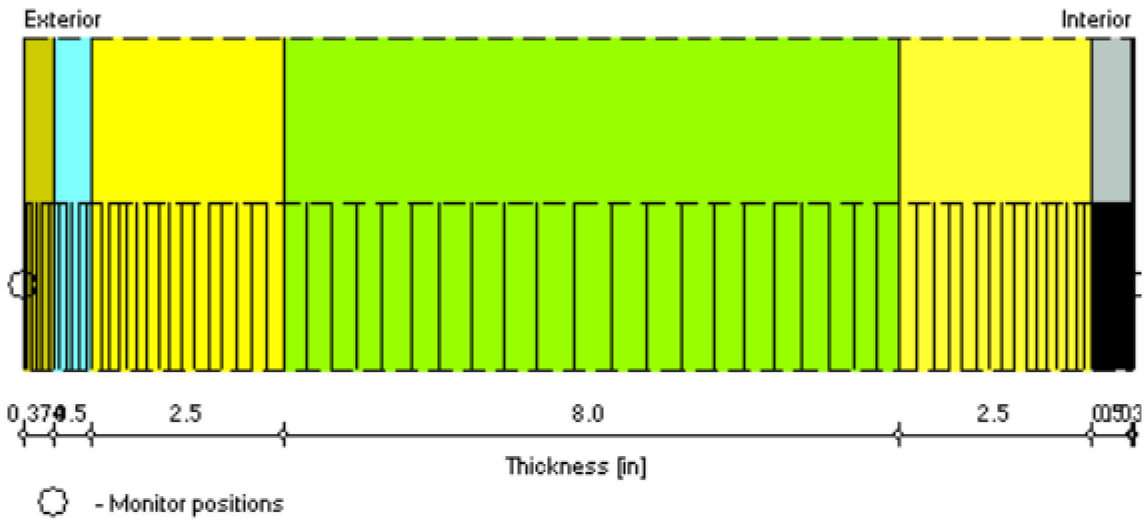


Materials:

- LP SmartSide Siding	0.374 in
- XPS Surface Skin (heat cond.: 0,03 W/mK)	0.394 in
- Fiberboard	1.0 in
- Woodfiber AIR	5.5 in
- Gypsum Board (USA)	0.5 in
- Vinyl Wallpaper	0.039 in

Total Thickness: 7.807 in
R-Value: 26.71 h ft² °F/Btu
U-Value: 0.036 Btu/h ft²°F

Appendix E: WUFI Los Angeles ICF Wall with Wood Fiber Board Insulation

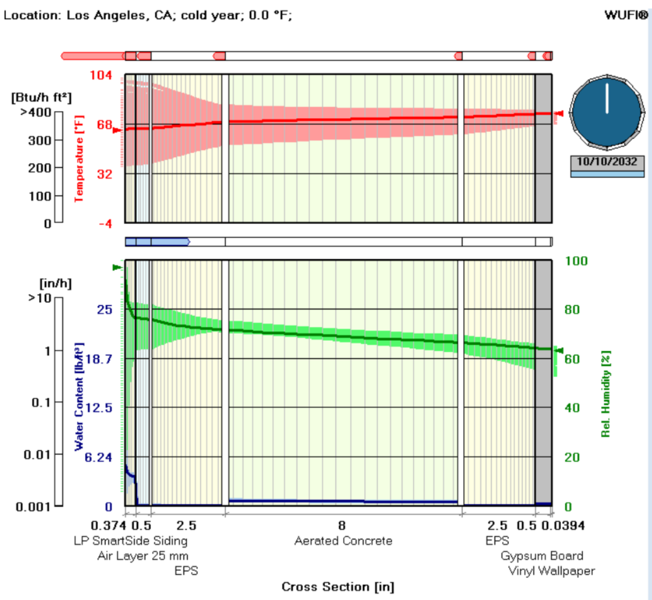


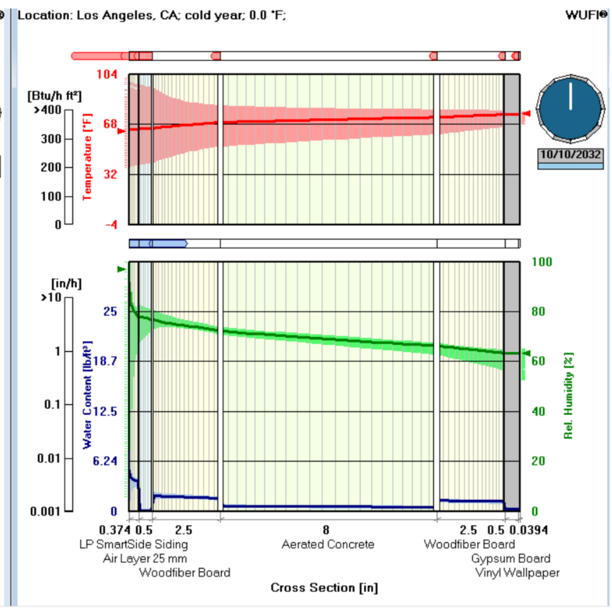
Materials:

- LP SmartSide Siding	0.374 in
- Air Layer 25 mm	0.5 in
- Woodfiber Board	2.5 in
- Aerated Concrete	8.0 in
- Woodfiber Board	2.5 in
- Gypsum Board (USA)	0.5 in
- Vinyl Wallpaper	0.039 in

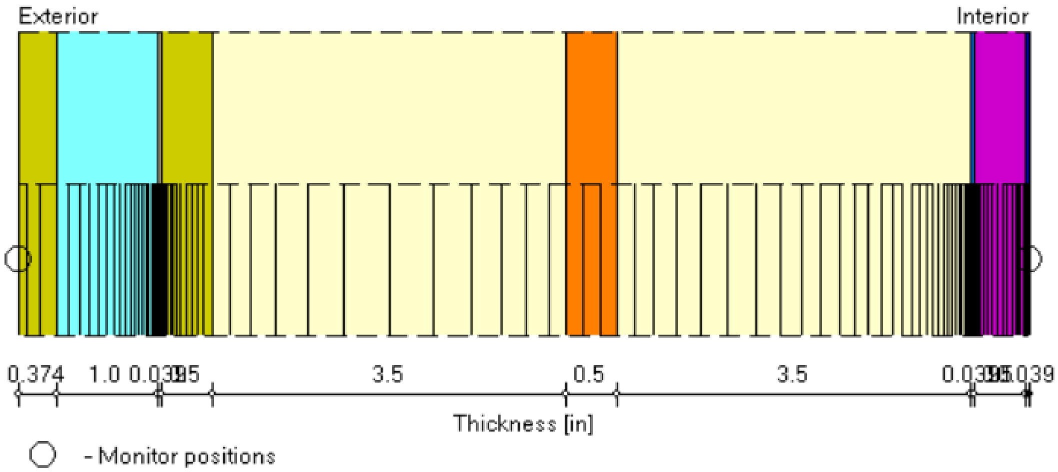
Total Thickness: 14.413 in
R-Value: 24.64 h ft² °F/Btu
U-Value: 0.039 Btu/h ft² °F

Appendix F: 10 year Film Data Simulation: Los Angeles ICF Wall





Appendix G: WUFI Minneapolis Wood-Stud Wall with Wood Fiber Insulation

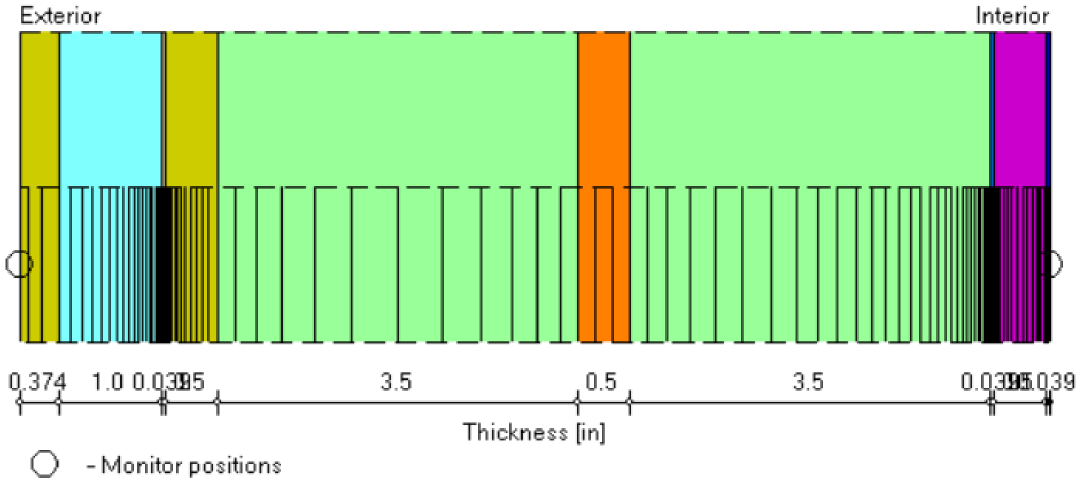


Materials:

- LP SmartSide Siding	0.374 in
- Air Layer 25 mm; without additional moisture capacity	1.0 in
- 3M™ Air and Vapor Barrier 3015	0.039 in
- Fiberboard	0.5 in
- Woodfiber AIR	3.5 in
- Plywood	0.5 in
- Woodfiber AIR	3.5 in
- vapor retarder (0.1perm)	0.039 in
- Interior Gypsum Board	0.5 in
- Vinyl Wallpaper	0.039 in

Total Thickness: 9.992 in
R-Value: 30.91 h ft² °F/Btu
U-Value: 0.031 Btu/h ft²°F

Appendix H: WUFI Minneapolis Wood-Stud Wall with Cellulose Insulation

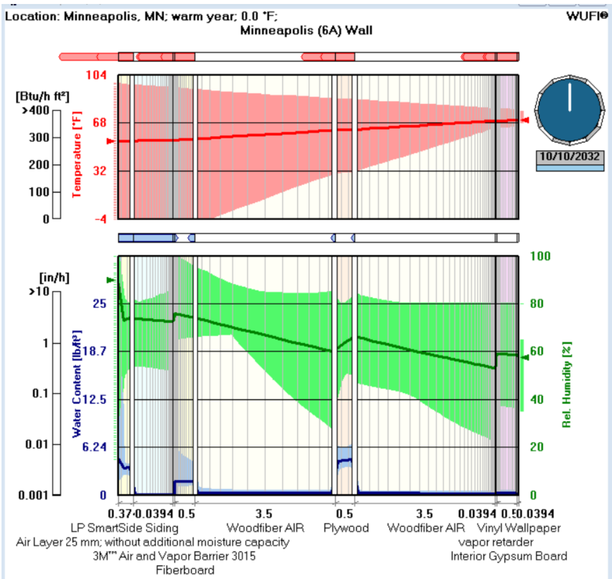


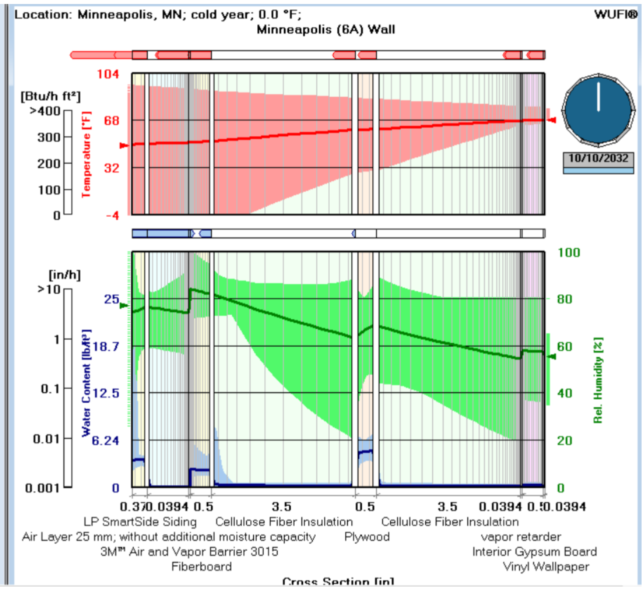
Materials:

- LP SmartSide Siding	0.374 in
- Air Layer 25 mm; without additional moisture capacity	1.0 in
- 3M™ Air and Vapor Barrier 3015	0.039 in
- Fiberboard	0.5 in
- Cellulose Fiber Insulation	3.5 in
- Plywood	0.5 in
- Cellulose Fiber Insulation	3.5 in
- vapor retarder (0.1perm)	0.039 in
- Interior Gypsum Board	0.5 in
- Vinyl Wallpaper	0.039 in

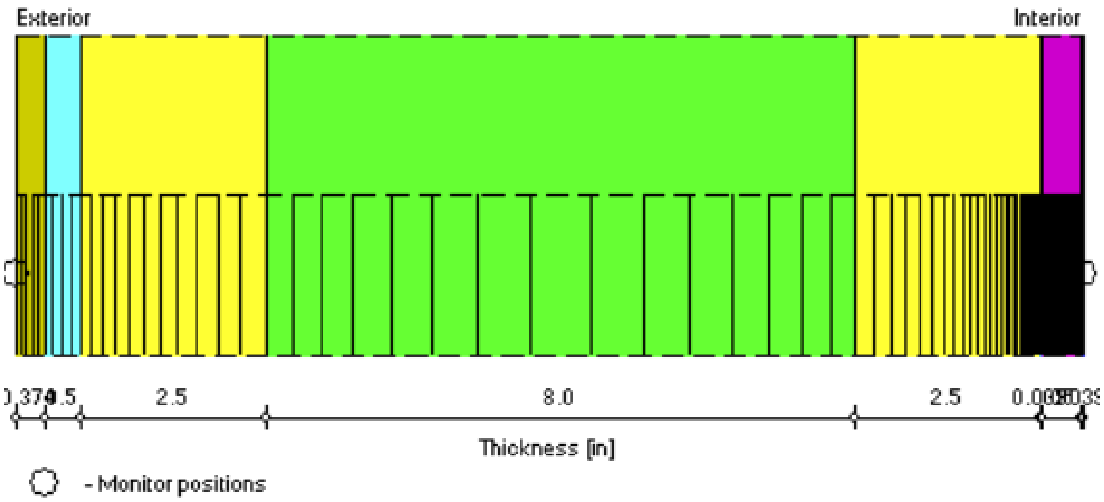
Total Thickness: 9.992 in
R-Value: 31.7 h ft² °F/Btu
U-Value: 0.031 Btu/h ft²°F

Appendix I: 10 year Film Data Simulation: Minneapolis Wood-Stud Wall





Appendix J: WUFI Minneapolis ICF Wall with Wood Fiber Board Insulation

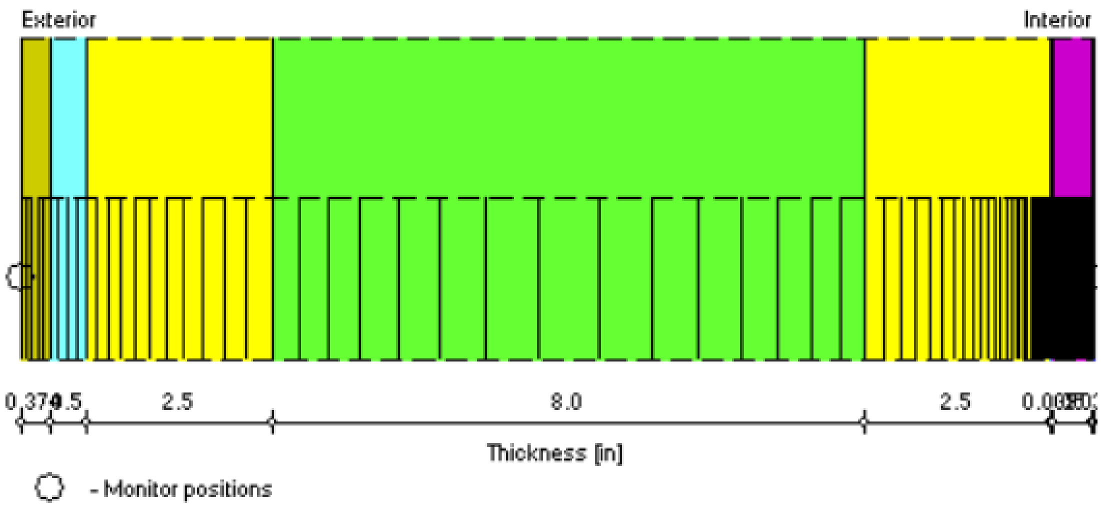


Materials:

- LP Smart Side Siding	0.374 in
- Air Layer 25 mm; without additional moisture capacity	0.5 in
- Woodfiber Board	2.5 in
- Aerated Concrete	8.0 in
- Woodfiber Board	2.5 in
- vapor retarder (0.1perm)	0.039 in
- Interior Gypsum Board	0.5 in
- Vinyl Wallpaper	0.039 in

Total Thickness: 14.453 in
R-Value: 24.67 h ft² °F/Btu
U-Value: 0.039 Btu/h ft²°F

Appendix K: WUFI Minneapolis ICF Wall with EPS Insulation



Materials:

- LP Smart Side Siding	0.374 in
- Air Layer 25 mm; without additional moisture capacity	0.5 in
- EPS (heat cond.: 0.04 W/mK - density: 30kg/m³)	2.5 in
- Aerated Concrete	8.0 in
- EPS (heat cond.: 0.04 W/mK - density: 30kg/m³)	2.5 in
- vapor retarder (0.1perm)	0.039 in
- Interior Gypsum Board	0.5 in
- Vinyl Wallpaper	0.039 in

Total Thickness: 14.453 in
R-Value: 29.1 h ft² °F/Btu
U-Value: 0.033 Btu/h ft²°F

Appendix L: 10 year Film Data Simulation: Minneapolis ICF Wall