

To the Graduate Council:

I am submitting here with a thesis written by Sherman Authur Matthews entitled “A Life Cycle Comparison of Light-Frame Wood and Insulated Concrete Form Building Envelopes: Energy Use and Green House Gases.” I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Civil Engineering.

We have read this thesis
And recommend its acceptance:

Chris D. Cox

Richard M. Kelso

Qiang He
Major Professor

Accepted for the Council:

Carolyn R. Hodges
Vice Provost and Dean
of the Graduate School

A Life Cycle Comparison of Light-Frame Wood and Insulated Concrete Form Building Envelopes: Energy Use and Green House Gases

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the Master of Science
Degree
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Sherman Authur Matthews
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Dedication

To my Father
Sherman Matthews

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Abstract

Given the building sector's substantial contribution to global energy use and green house gas (GHG) emissions, it is of great importance that only the most effective building envelopes are utilized. Conventional light-frame wood building envelopes are highly popular due to their ease of construction and building economy; however the life cycle performance of the building envelope is often overlooked when this selection is made. Although insulated concrete form (ICF) building envelopes generally require a substantially higher embodied energy input, it should be considered that improvements during a building's operation phase can offers significant energy returns, ultimately reducing the building's life cycle energy use and GHG intensity. Therefore, an assessment is conducted regarding the life cycle energy use and GHG intensity of the ICF building envelope, in addition to two light-frame wood building envelopes; the average light wood frame envelope (U.S. Department of Energy, 2007), and a more highly insulated wood frame envelope. The operation phase of the building envelopes proves to be of greatest significance, as it is attributed to 95- 97% of the total life cycle energy use, and 93-96% of life cycle GHG emissions, assuming a 100 year life cycle. Ultimately, the life cycle performance of the ICF building envelope is superior to the two wood frame envelopes due to its improvements in the operation phase. The ICF building envelope has a life cycle energy requirement of 11% to 14% less than the two light-frame wood envelopes, and a 10% to 12% lower life cycle GHG intensity. Although the increased thermal resistance certainly contributes to the superior life cycle performance of the ICF envelope, the improved infiltration leakage area of the envelope is key to its operational performance, and subsequently to its improved life cycle performance. End of life energy use for the demolition, recycle, and disposal of the building envelopes is nearly negligible, as it is attributed to less than 0.3% of the life cycle energy for any of the envelope scenarios.

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Chapter 1: Introduction

1.1 Relevance

Amid rising concerns regarding energy consumption and green house gas emissions in the U.S., the selection of a structure's building envelope is becoming increasingly important as it directly affects energy use. Given that roughly 20% of the world's building sector energy is consumed within the U.S., it is especially important that the highest level of efficiency is attained in the U.S. building sector. Seeing as the energy demand of the U.S. building sector is largely attributed to the conditioning of interior air, the selection of a building's enveloping materials is critical as it directly influences building energy use. As the energy use of an enclosed building is contingent on the physical properties of the building's envelope, and that the built environment is responsible for consuming 40% of the energy consumed in the U.S., the significance of the proper choice of building materials is reiterated (U.S. Department of Energy, 2011; Omer, 2007). As the residential building sector accounts for approximately 22% of U.S. building energy use, reductions in energy use within the residential building sector could be of significant benefit in reducing total building sector energy use.

1.2 Background

Throughout the last several decades, light-frame wood construction has been widely viewed as the default option for detached single family housing, particularly throughout the U.S., as it still made up the large majority of new single family housing as of 2005 (U.S. Department of Energy, 2011). Historically, it has been regarded as an obvious choice of building type considering its ease of construction, limited use of structural material, abundance of building material, and relatively low cost. However these attributes do little to influence the amount of energy used throughout the useful life of the building, as the initial cost of construction has had much greater influential on the selection of building materials than energy use. In previous years, life cycle energy use and carbon emissions have had little influence on the type of construction utilized, and still play only a modest role in the selection criteria for most building materials. As the cost of a construction type is typically reflected in the energy required to acquire and produce the materials, light-frame wood construction is an attractive option given its relatively low energy expenditures. Monolithic construction methods, such as ICF construction, typically require more material and

energy, resulting in greater initial cost. However, it should be considered that these are merely initial costs and initial energy inputs. They are representative only of the embodied energy of the building, as they are neither indicative of the total energy use, nor the cost over the life cycle of the building. Though decision analysis in the U.S. has historically been influenced primarily by cost, as awareness increases regarding the depletion of resources, air quality, and the effects on the environment, greater consideration will be allocated to the environmental implications of each decision.

1.3 Purpose

Given the potential environmental ramifications of the increasing energy demand, it is necessary to reassess current practice and explore these alternative methods and technologies to determine the most efficient solution. It is well documented in various LCA studies that the operation phase of a building often accounts for the majority of life cycle energy consumption (Ramesh, Prakash, & Shukla, 2010). Given the significance of the operational energy with regard to total energy use, it is necessary to explore the energy use and carbon emissions during the life cycle of both the light-frame wood and ICF building envelopes. As the operational energy of a building is affected by the energy embodied in the building envelope, there is a complementary relationship between the two energy forms. To attain a desired level of operational efficiency for the building envelope, a particular amount of embodied energy is necessary.

1.4 Goal and Procedure

The goal of the current investigation is to compare the life cycle energy performance of the insulated concrete form (ICF) building envelope to the conventional light-frame wood building envelope, and to identify the characteristics of each envelope which most affects their performance. In analyzing each of the alternatives, a key concept considered throughout the process is sustainability. The scope of the study is cradle-to-grave, as the study accounts for all of the phases throughout the life of the building envelopes and considers the energy requirements for the extraction, processing, and manufacture for the assemblies, the resulting performance of the composite building system including the HVAC system, and the subsequent end of life processes for disposal and recycle. Regarding energy use, the selection of the building envelope is vital due not only to the amount of energy consumed during its production (embodied energy), but also for

its effect on building energy consumption during its use phase (operational energy). The hope is that this study will provide a better understanding of the energy requirements of the building envelopes and materials addressed in this study, and will shed light on their subsequent effect on the long term energy use of buildings.

This life cycle study consists of three separate phases; the production phase, the operation phase, and the end of life phase. To analyze the performance of each building envelope, a case study is performed based on an existing home located in Rockwood, Tennessee. By the use of life cycle assessment modeling software, and through an investigation of literature, an investigation of the production phase is conducted to determine the embodied energy and green house gas (GHG) intensity of the ICF and light-frame wood construction. Subsequently, using a computer modeling program for building energy use, the house is replicated with the ICF building envelope, along with two additional light-frame wood envelopes, to determine the operation phase energy and GHG intensity. Lastly, the end of life requirements are analyzed and the total life cycle performances of the envelopes are assessed.

Chapter 2: Literature Review

2.1 Energy Use and Building Envelopes in the U.S.

According to the U.S. Department of Energy, the building sector of the U.S., alone, accounted for 8% of the world's primary energy use in 2008, as building energy use has increased by nearly 50% since 1980 (U.S. Department of Energy, 2011). In terms of energy use, the U.S. is behind the performance curve of the developed OECD (Organization of Economic Cooperation and Development) nations of Europe, using 22% more energy for a population nearly half the size of the OECD European nations. The need to better manage energy use, on a global scale, is well evident; however the preceding numbers show the urgent need for improvements in managing energy, use particularly in the U.S. Regarding building energy use, Norman et. al (2006) suggests that although transportation may be the most crucial sector to reduce GHG emissions in urban areas, the building sector should be the most targeted area in terms of energy use.

As about half of U.S. building energy use is attributed to the residential sector, it is evident the impact of the building sector on world energy use is substantial. Previous work suggests that high density residential housing is the more sustainable option in terms of energy use, however single family detached housing has its place in the social order and must be optimized to reduce its environmental burden (Norman, MacLean, M.ASCE, & Kennedy, 2006). Obviously, the light-frame wood building envelope is the typical choice in the residential sector given that, as of 2005, 95% of all single family housing units was light-frame wood units, according to a survey (U.S. Department of Energy, 2011). Two percent of new construction were modular units, another 2% were panelized construction units, while the remaining 1% were unspecified. The insulated concrete form housing type most likely resides in the unspecified housing types. Ultimately, these figures reiterate the limited exploration of alternative building envelope and construction type options within the U.S.

Few studies provide relative comparisons of alternative construction types and building envelopes, particularly considering the insulated concrete (ICF) form building type. Perez-Garcia et. al (2006) conducted a study addressing the environmental performance of alternative construction types for residential structures, considering wood frame, steel frame, and concrete construction. However, of particular interest are the evaluation of the wood frame and concrete building types

located in Atlanta, Georgia. The study addresses aspects of energy use, GHG intensity, and cost throughout the life of each of the construction types. It should be noted that the concrete residence of the study is not an ICF structure, as it included wood framing material on the interior face of the concrete to house the insulation, and to support the interior finish gypsum board. Ultimately, the results of the study suggest the embodied energy of the concrete structure is considerably greater than the wood frame envelope, as they have initial embodied energies of 456 MJ and 395 MJ, respectively. The operational performance of each of the structures are determined to be an equivalent 4575 GJ for a 75 year useful life, however the analysis neglects the distinction of the envelope characteristics of each construction type, particularly their individual thermal mass, and infiltration properties. Consequently, the results do not provide a true assessment of the relative performance of the two buildings types.

Petrie et al. (2002) conducted a study considering the annual performance of the ICF structure, comparing it to conventional wood frame construction. The study did not address the entire life cycle of the construction types as it did not consider the production, or end of life ramifications of the structures. Furthermore, the study did not address the relative GHG intensities of the building types, however the study did consider both the thermal mass and air infiltration of the building envelopes. Relative to the ICF technology available, the ICF structure of this study was lightly insulated, with only 15 h-ft²-°F/BTU of thermal resistance, as the wood frame structure had thermal resistance of 10.6 h-ft²-°F/BTU. The study concluded that the ICF house required roughly 9% less energy, annually, than the conventional wood frame house.

Ultimately, no legitimate studies were found assessing the ICF building envelope relative to a conventional wood frame, over the course of their respective life cycles. However, several life cycle studies of buildings, both residential and commercial, have been conducted in recent years. Documentation of both the methods and results of several of these studies are provided in section 2.2.

2.2 Methods and Results of Prior Life Cycle Studies of Buildings

The method of analysis and the elements accounted for throughout the LCA of buildings vary from each study, and complicate efforts to form even comparison between individual studies. Some studies may measure only secondary energy totals and discount the removal phase of a

building, while others may measure primary energy and account for removal and recycling. However this does not render an observation between individual studies valueless, so long as sufficient transparency of analysis is provided to properly analyze energy use. Most building life cycle studies make an assumption on the useful life of a particular building type, with a time frame typically ranges from 50 to 100 years, however the basis of this assumption is often not articulated.

Mithraratne and Vale published a life cycle energy assessment of a small, 1010 ft² house in New Zealand which accounts for structural elements, envelope materials, finish materials, plumbing, site work, furniture, and appliances. The study analyzes the same building plan for three distinct construction types; light-frame wood, concrete, and super insulated building construction. The concrete construction type is not to be confused with 'insulated concrete form' construction which provides substantial insulation on both the interior and exterior face of the concrete. The study concludes that the super insulated house requires the most embodied energy at 468 MJ/ft², followed by concrete construction at 442 MJ/ft², as light construction had the least embodied energy total at 411 MJ/ft². However, the operation phase of the highly insulated structure was considerably more efficient than the light-frame structure, as would be expected, yet the relative operational performance of the concrete structure was not quite as predictable. The annual overall life cycle energy use, as well as the annual operational energy use, of the three construction types are reversed, as the light wood, concrete, and super insulated building types require 1580, 1508, and 1099 MJ/ft² annually, respectively (Mithraratne & Vale, 2003). The concrete construction type, although comparable in performance, required less life cycle energy than the light-frame structure, while the super insulated structure significantly outperformed the two. However, it must be noted that this study assumes a lifespan of 100 years for each of the construction types and that these results hold true only in the scenario that each of the houses have an equivalent useful lifespan. Both wood and concrete construction can have life spans of 100 years or greater given proper conditions and maintenance, however many would suggest that concrete structures have the potential for even greater life spans.

Ramesh et al. (2010) analyzed a field of 73 life cycle studies of buildings, residential and office, to analyze the group of studies in relation to one another and to better understand the range of life cycle energy use, and which building elements and methods of analysis contributes to the variation in life cycle results. The field of life cycle studies were normalized to similar metrics, and all of the studies were adjusted to account for primary energy and similar life cycles. The

study concluded, based on the field considered, that office buildings require more life cycle energy per unit area than residential buildings, requiring on average 84-184 MJ/ft² and 50-134 MJ/ft², respectively, due to the use of more energy intensive materials, higher occupancy, and more strenuous demands for comfort conditions and appliances. The investigation highlighted that a nearly linear relationship exists between life cycle energy and operational energy use, regardless of the variance in climatic conditions. This indicates a level of consistency with regard to the LCA process implemented amongst the studies, as the results demonstrate a degree of precision. The operational energy of the field of studies generally falls within 80 to 90% of the life cycle energy, as the embodied energy is with 10-20%. The study assumes that the demolition energy has a negligible effect on the total life cycle energy of a structure. Also noteworthy is the study's observation of the elevated primary energy use in developing nations due to their energy sources, as many developing nations have a less efficient energy balance more reliant on fossil fuels. The example given within the study which was representative of this was an LCA study of a Thai office building which was believed to require 284 MJ/ft² of primary energy annually, while the average annual primary energy total of the other LCA studies were 129 MJ/ft² (Kofoworala & Gheewala, 2008; Ramesh, Prakash, & Shukla, 2010). The study indicates that small increases in embodied energy can generate reductions that last throughout the operation phase of the building, to the extent of forming a zero energy building, however it is acknowledged that passive and active technologies can be introduced to the degree that the reductions allowed by the additional technology are outweighed by the embodied energy inputs that they entail. This is reflective of the relationship shared by the embodied and operational energies, as the rate of energy reduction of the operational energy decreases as the embodied energy increases, exhibiting a non-linear relationship.

The ASCE Journal of Urban Planning and Development published an article comparing energy use and CO₂ emissions of high and low residential density. The study does not simply analyze the performance of a single building unit, but rather the performance of the high density urban condition versus that of lower density suburban area. The study considers the cases of single-detached housing and larger apartment facilities, along with the required infrastructure which accompanies them, and calculates energy use and CO₂ equivalents per capita. The study concludes that in the low density suburban setting, 77% more energy is used per person than in the high density urban condition as 57165, and 32178 MJ/capita, respectively, when considering building operation and construction materials over a 50 year lifespan. The study highlights that

when considering energy use, the building sector is the area with the greatest potential of improvement, however the transportation sector should be the area of focus when considering improvements in GHG emissions (Norman, MacLean, M.ASCE, & Kennedy, 2006).

2.3 Life Cycle Assessment and Sustainability

The desire for sustainable behavior serves as the primary motivation for the practice of life cycle assessment. A common characterization for the concept of sustainability was coined by the Bruntland Commission and states that sustainability is the capacity to “meet the needs of the present without compromising the ability of future generations to meet their own needs.” Some question is raised as to what the amount of energy use is actually necessary versus the amount that is used. Nonetheless, life cycle assessment aids in efforts to find more efficient operations for energy production, as well as assist in the decrease of energy use during production processes. Sustainability does not only apply to the use of natural resources, as it encourages practices which do not jeopardize the wellbeing of other natural systems, valuable or non-valuable. Though sustainability is most commonly referred to with respect to environmental issues, the concept of sustainability involves multiple dimensions, as it accounts for both economic and social dynamics in addition.

In the forefront of the conversation of sustainability is the use and depletion of fossil fuels. In 2002 the International Energy Association estimated that 80% of energy demand was met using fossil fuels (M. Asif, 2005). This is of particular concern given the continual growth of energy demand, only decreasing the longevity of the energy sources, particularly oil. Additionally, concern over the emission of green house gases, released during fossil fuel combustion, discourages the use of the vital energy source. Ultimately, to properly understand the affect a particular production process or operation has on any given environmental concern, life cycle assessment is certainly plays a substantial role in the process.

2.4 Life Cycle Assessment Procedure and Protocol

Protocol for life cycle assessment is documented by the International Organization for Standardization (ISO) and is executed within the constructs of four principal phases; goal and scope (ISO 14041), inventory analysis (ISO 14041), impact assessment (ISO 14042), and Interpretation (ISO 14043). Defining both the goal and scope is the starting point of an LCA

study, as they determine which parameters are of greatest concern, while simultaneously defining the constraints of the study (Azapagic, Perdan, & Clift, 2004).

2.4.1 Goal & Scope of LCA

The goal and scope of an LCA study should plainly state the intentions of the work, and should include a clear description of the functional unit of the study, the various alternatives to be analyzed, and the reference flows used to characterize the performance of the system being assessed. Additionally, any assumptions made for the system are to be clearly stated, the system boundaries of the assessment are to be defined, and the allocation methods used to account for flows throughout the LCA should be acknowledged (Heijungs & Suh, 2002).

The scope of an investigation also offers an explanation on the extents of a study. If a study is defined as “cradle to grave,” this results in an examination of all the flows throughout the life cycle of an entity, from the acquisition of the raw materials used, to the disposal of the exploited final product. A “cradle to gate” LCA analyses a process from its origin only until the following stage of the products life cycle. However, a “gate to gate” LCA can be performed on any sole process, or sub-process, of a larger whole, from the end of the preceding process, to the start of the following process. (Azapagic, Perdan, & Clift, 2004)

2.4.2 LCA Inventory Analysis

After the goal and scope of the LCA are clarified, the subsequent procedure of the LCA is to assemble the life cycle inventory (LCI), referred to as inventory analysis. The LCI is an itemized list which accounts for all the resources and materials utilized to produce the product. This phase of the LCA is essentially the collection evidence on the efficiency of a particular stage of the life cycle. This may be the most critical phase of LCA given that the inventory analysis and interpretation of the LCA is based on the data provided in the LCI. There is always a level of variability and error in the data acquired throughout LCA process, however this does not compromise the objective of the investigation, as the purpose of LCA is not to determine exact quantities of each flows, but to provide an approximation of the flows that occur. In the assembly of the LCI, each material is identified and quantified along with the corresponding reference

flows associated with the production of the material. Although there is not always an output flow, each material requires at minimum a single input flow which is to be quantified by at least one standard of measure.

2.4.3 LCA Impact Assessment

Upon the completion of the inventory analysis, the impact assessment is to be performed considering all of the items listed in the LCI. The impact assessment analyzes the environmental burdens caused by each of the flows listed in the life cycle inventory, as each of the flows are assigned to one or more impact categories and are classified, normalized, and their environmental effects are evaluated. The classification of a flow identifies to which category of environmental effects the flow contributes. A few common categories for environmental impact include; green house gas emissions, non-renewable resource depletion, eutrophication, toxicity, and ozone depletion among others categories. Once all the flows are classified, the data is normalized in order to formulate one aggregate value for a particular environmental impact.

2.4.4 LCA Interpretation

The interpretation phase of the of LCA process reflects on the inventory analysis to pinpoint which properties or characteristics of an entity contribute the greatest environmental burdens, and at what stage in the life cycle the burdens occur. A sensitivity analysis can be very constructive in this stage of the LCA, both to help verify the accuracy of the data provided in the LCA, and to better identify the parameters which have the greatest effect on the environmental burdens. The interpretation phase of the LCA forms a framework for proposed improvements for or the system or material.

2.5 Life Cycle Assessment of Buildings

With regard to building energy use, it should be understood that life cycle energy is not simply the energy delivered to a building to heat, cool, and power appliances during the operation phase of a building, but it is the total amount of energy required, including the energy use preceding and superseding the building operation phase. In 1996, K. Adalberth outlined a method to estimate the energy use of a building throughout its life cycle by way of life cycle assessment. Although

Adalberth is not considered the sole originator of the life cycle energy of buildings as others, such as P. Beckker, had previously investigated the different forms of building energy use in the 1980s, Adalberth's article is an important piece of literature in regard to the LCA of buildings. His method highlights that a building's life cycle begins well before the origination of its operation phase, and ends well afterward, as the method broke down a building's life cycle into three temporal periods, each comprised of a few different phases. The first is the 'production' period, consisting of three separate phases; the manufacturing, transportation, and erection phases. This is all of the activity that occurs before the occupation and use of the building. The 'management' period encompasses all which occurs during the occupation, and renovation phases. The 'destruction' period is made up of the demolition and removal phases. According to Adalberth, all of the energy used throughout a buildings' life cycle should be accounted for within these three periods, and building life cycle energy use can be outlined by the following equation; (Adalberth K. , 1997)

$$Q_{life\ cycle} = Q_{manuf} + Q_{transp.prod} + Q_{erect} + Q_{occup} + (Q_{manuf.renov} + Q_{transp.reno}) + Q_{deomol} + Q_{transp.remov}$$

where Q is the energy use which occurs during,

Q_{manuf} = manufacture

$Q_{transp.prod}$ = production transportation

Q_{erect} = erection

Q_{occup} = occupation

$Q_{manuf.renov}$ = manufacture for renovation

$Q_{transp.reno}$ = transportation for renovation

Q_{deomol} = demolition

$Q_{transp.remov}$ = removal transportation

$Q_{life\ cycle}$ = total life cycle

Following Adalberth's article, many others followed up on the topic of life cycle assessment of buildings. Many articles documented case studies performed according to Adalberth's method, as other articles reconsidered or detailed portions of the method which were not articulated in Adalberth's article. Fay and Treloar stressed the importance of considering primary energy totals as opposed to secondary energy (Ray, Treloar, & Iyer-Raniga, 2000). Secondary energy is solely the energy sum that is delivered to a building; the energy which would be read from the energy

use meter on a building during the operation phase. However, primary energy is the total energy use, and accounts for all of the energy used to produce and deliver energy from the source and includes energy losses. In most cases this significantly increases the energy sum, as losses during energy production and delivery can be greater than the energy actually delivered to the building (Gustavsson & Joelsson, 2009). Fay and Treloar re-expressed the previous equation by Adalberth with the following relationship;

$$LCE = EE_i + [EE_{rec} + OE] \times \text{building life} + ELE$$

where,

EE_i = initial embodied energy

EE_{rec} = recurrent embodied energy

OE = operational energy

ELE = end of life energy

LCE = life cycle energy

Fay and Treloar's article included results from their LCA case study of a brick veneer 'Green Home' home located in Melbourne, Australia. The house contains 1380 ft² of habitable space, and given its location, heating is more critical than cooling. Two separate cases were considered in the study, the first referred to as the 'base case' which was a conventional design with a typical amount of insulation, the second case had additional insulation. The study considered all of the structural and finish materials included in the home, and accounted for household appliances as well. Given in terms of energy per unit area, the embodied energy total for the base case was 1.31 GJ/ft² and with additional insulation was 1.41 GJ/ft², total embodied energy use was 1803 GJ and 1946 GJ, respectively. The article indicates that these figures are significantly larger than previous LCA studies do to the inclusion of primary energy in the energy sum. Fay and Treloar refer to an article published by S. Pullen where embodied energy was estimate to be 0.47 GJ/ft² for a project of similar construction.

2.6 Variation of Life Cycle Assessment Results

Due to the dynamic behavior of whole building systems, the assessment of a building throughout its life cycle is a complex process and results may vary substantially depending on the method of analysis. According to a study by Optis and Wild, in which a field of separate LCA studies were

analyzed regarding their relative level of integrity, the amount of energy throughout a building's life cycle attributed to embodied energy range from 2% to 51%, and the operation phase of the life cycle vary from 49% to 98% of the life cycle energy use, while the end of life phase contribute only a small portion (Optis & Wild, 2010). Optis and Wild published an article entitled "Inadequate documentation in published life cycle energy reports on buildings" intended to address the level of uncertainty typical to LCA studies of buildings, and attributes this to poor documentation and limited transparency of analysis. The article stresses that all analysis is performed as outlined in ISO 14041 and that an LCA study is to provide, at minimum, a list of included and excluded life cycle stages, a list of unit processes, a statement of the calculation procedure, and reference to all data sources utilized. Optis and Wild indicate that these elements are not always well documented in publications, and illustrate this point by providing a table detailing which of these elements were, or were not provided, in a field of 20 previously published LCA studies of buildings.

Although, discrepancies in the procedure of analysis is partly responsible for some of the variation in energy use, deviation in climate condition, infrastructure, material, and building properties heavily contribute to the discrepancy in energy use. Deviation of the results often can be attributed to the databases and resources used to assemble the life cycle inventory of an LCA, as the flows generated during a process vary given the different datasets. Some LCA studies make use of surrogate data, tailoring the flow data for a particular process for an alternative use (Scheuer, Keoleian, & Reppe, 2003). Given the potential for error and variation during life cycle assessment, uncertainty analysis has been recommended to account for discrepancies in life cycle results (Blengini & Di Carlo, 2010). Given the potential for variation in the LCA of a building, a clear description of the materials and processes considered throughout an LCA is necessary in order to comprehend the data, and to verify the validity of the results. A high level of transparency is essential to properly analyze the flows, identify the hotspots of the energy use, and to better understand where reductions in energy use can occur.

2.7 Useful Life of Buildings

Variation in the durability of distinct building materials is well documented, particularly the relative advantages and disadvantages of the most prevalent structural materials: wood, reinforced concrete, and steel. Concrete is known to be one of the more durable materials, as it is highly

resistant to weathering, offers great resistance to fire, and seemingly would increase the relative useful life of a building. However, upon a review of related literature, there seems to be little correlation between the useful life of modern North American buildings and the durability of a building's primary structural elements, particularly considering wood and concrete structures. Although durable materials such as concrete may appear to offer a greater service life, this is not reflected in the data collected for a survey study conducted throughout Minneapolis and St. Paul, Minnesota. Horst et al. (2005) investigated the lifespan of 227 total structures, 105 non-residential, consisting of wood, concrete, and steel. The study documented both the functional use of the buildings and their purpose for being removed. Of the non-residential structures, 56% of the concrete structures were removed within 26 to 50 years of construction, while 63% of the wood structures had a lifespan of greater than 50 years, the majority lasting more than 75 years. Of the 227 buildings sampled, only 8 of the structures were deemed no longer useful due to structural purposes, as the primary cause for building removal for physical purposes was a lack of maintenance to non-structural elements and finish surfaces. Other major causes for the removal of building structures were the redevelopment of the area, or that the building was no longer suitable for the given need. It should be noted that the study accounts primarily for demolished structures, and not for remaining abandoned or unused structures. Overall the study suggests that the useful life of buildings, when properly maintained, is dictated mostly by whether it remains functional for the intended purpose of the site. This notion is supported by the multitude of older wood structures still in use.

2.8 Tools for Life Cycle Assessment

Several different LCA tools in the form of computer software, are available to the open market, however the selection of the LCA tool is critical to an LCA study as it will most likely define the calculation method utilized during analysis, whether it be process based, an input-output based life cycle inventory (LCI), or process flow diagram based analysis. The most suitable tool for analysis is dependent on the type and amount of information available as well as the goals and requirements of the study. For the life assessment of buildings, LCA tools generally must be accompanied by the use of building energy modeling tools, as they are not capable of the thermal modeling required for the operation phase of the building, and are used primarily for embodied energy and end of life energy calculations. In practice, life cycle studies are generally utilized to identify the areas of greatest burden, referred to as hot-spots, to target these areas for future

improvement. However, the foci of these analyses may differ and could require varying levels of depth. Some studies may require a greater level of transparency and may only be concerned with a few materials used within a process, as other analyses may simply focus on an entire process as a whole. LCA tools have been produced for the specific application of calculating the embodied energy use of buildings, however many question the level of transparency provided by such exclusive tools (Rice, Clift, & Burns, 1997). Authors Gareth Rice, Roland Clift, and Richard Burns suggest that a less specific, generic LCA tool can provide a more transparent analysis, as all inputs are well known to the designer. Generic LCA tools also have the capability of creating new processes and flows from data collected by the user.

Chapter 3: Materials and Methods

3. 1 Building Envelopes

3.1.1 Insulated Concrete Form

The ICF wall envelope is specified according to the existing ICF house located in Rockwood, Tennessee, however the roof structure of the ICF building envelope is modeled according to the NREL Benchmark house described in section 3.1.2, similarly to the wood frame envelope. This roof specification is used in order to obtain a more genuine assessment of the relative performance of the building envelopes, as a variation in the roof envelope would cause undesirable disparity in the results. The building envelope is modeled as illustrated in figure 3-1. Properties of the building envelope are as specified in Section 5.3.

3.1.2 Light-Frame Wood

Two distinct light-frame wood envelopes are analyzed during the course of this study; a conventional wood frame envelope (figure 3-2), and a variation of the conventional wood frame envelope with increased thermal resistance (figure 3-3). The physical properties of the conventional wood frame building envelope ‘wood frame 1’ are modeled according to the U.S. Department of Energy’s Building America Research Benchmark Definition. The benchmark house was defined by the National Renewable Energy Laboratory (NREL), and is representative of typical residential light-frame wood construction in the U.S. (U.S. Department of Energy, 2007). The NREL house model provides the thermal resistance values for the walls, the infiltration rate of the envelope, as well as lighting, occupation, and electrical schedules. It should be noted that only the roof and walls of the superstructure are specified according to the NREL house, however the basement walls are modeled similarly to the basement wall of the ICF structure for a more genuine analysis. ‘Wood frame 2’ is identical to the ‘wood frame 1’ envelope, with the exception of a 2 inch thick addition of polyurethane insulation behind the vinyl cladding surface as seen in figure 3-3.

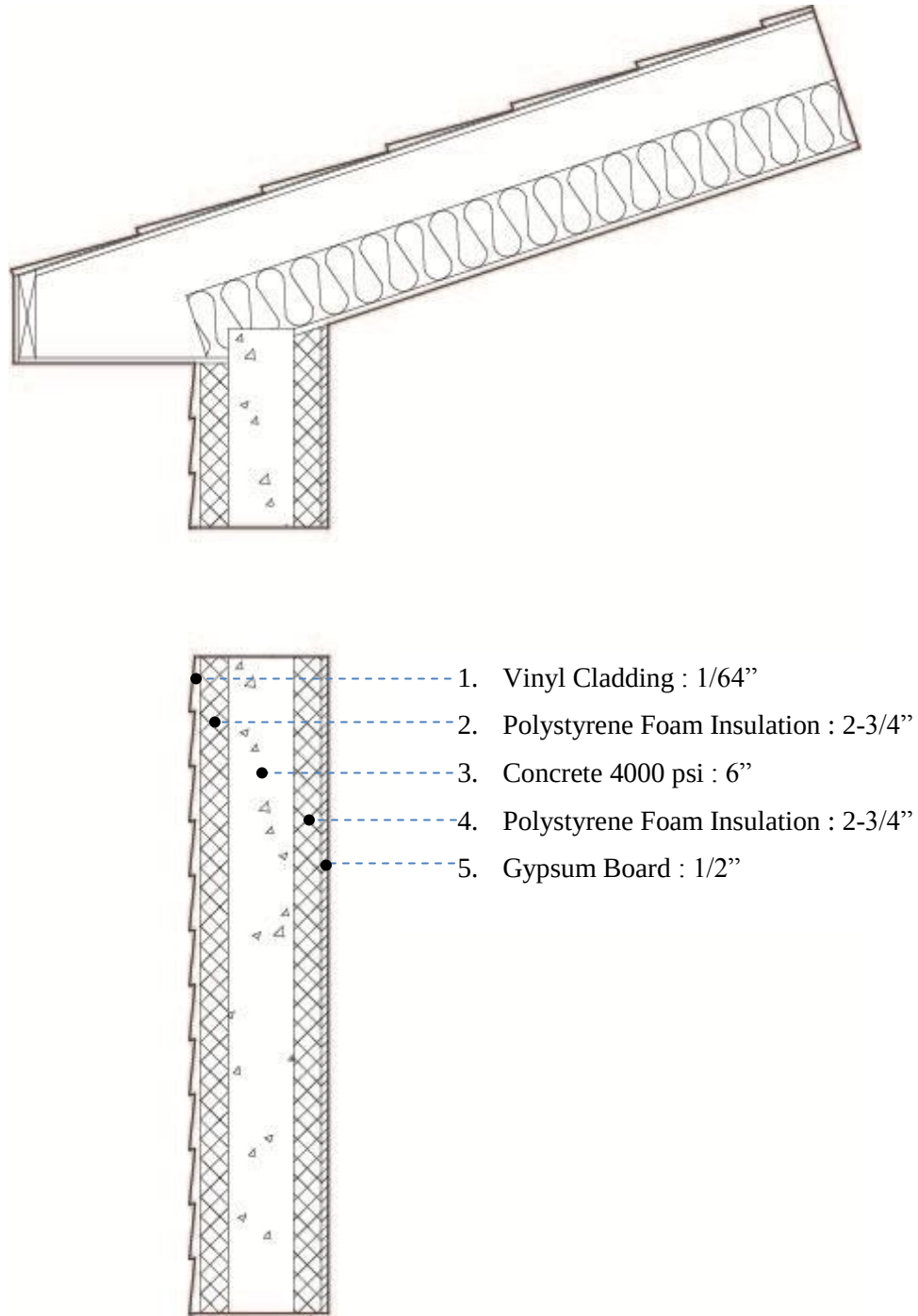


Figure 3-1: Insulated concrete form building envelope section drawing

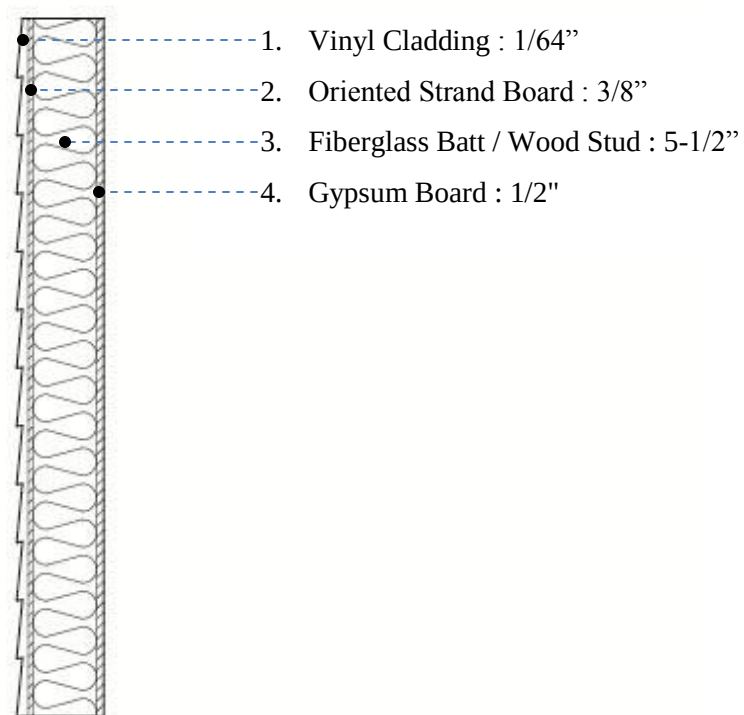
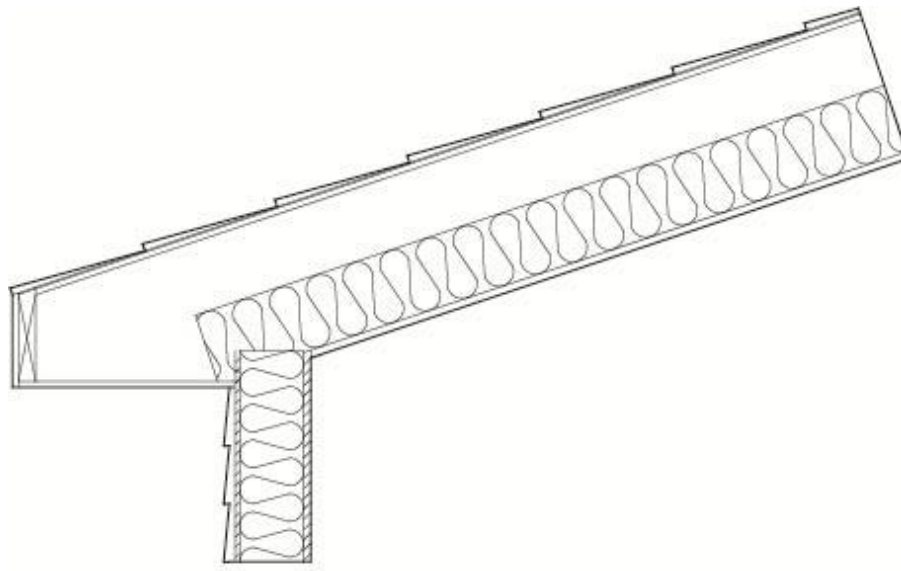


Figure 3-2: Wood frame 1 building envelope section drawing

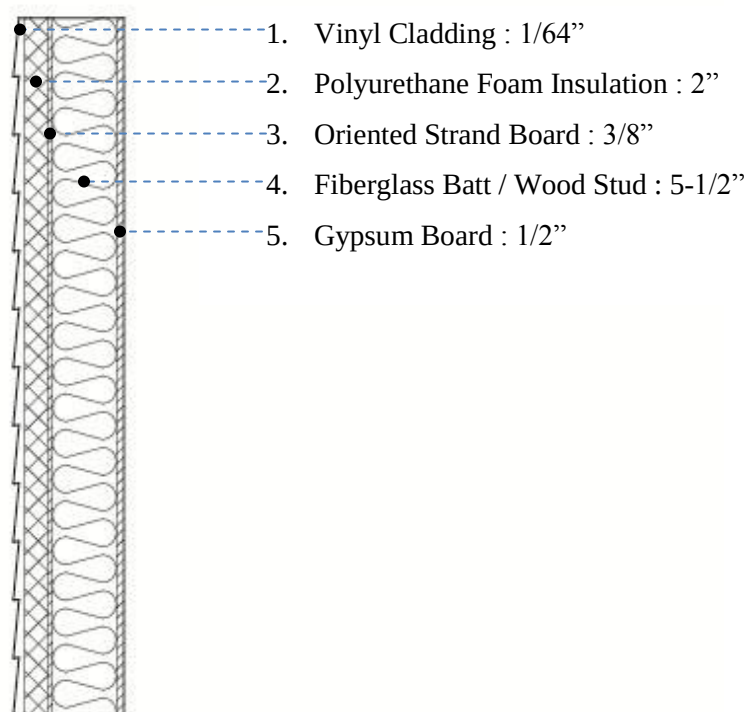
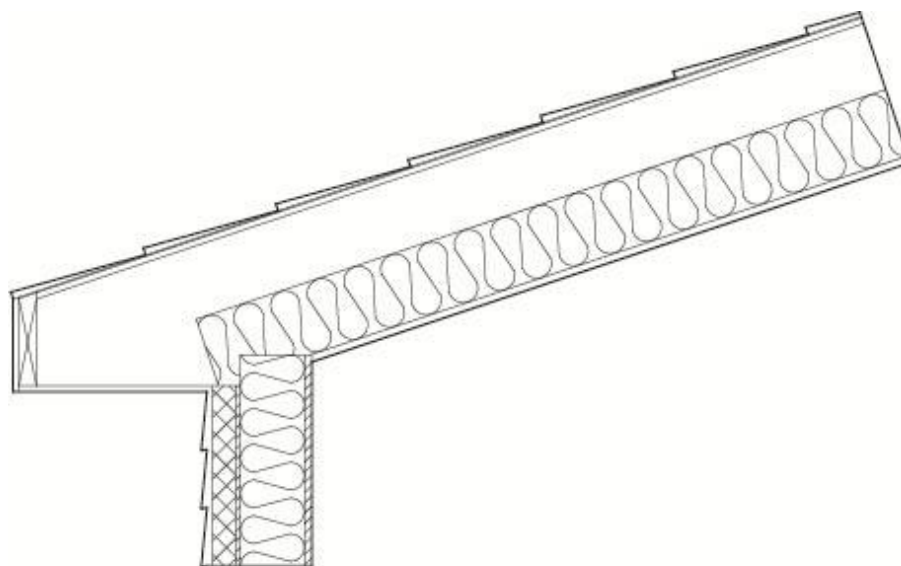


Figure 3-3: Wood frame 2 building envelope section drawing

3.2 House Design

The house is modeled according to an existing two story ICF house in Rockwood, TN, the bottom level being a partial basement space. The footprint of the house is roughly 56 ft by 40 ft, however a portion of this footprint consists of outdoor patio space. The house has approximately 2400 ft² of floor space, with approximately 27,000 ft³ of volumetric space concealed within its envelope. The house has 25 openings in the perimeter walls, 19 windows and 6 doors, with a sum of approximately 228 ft² of window glazing and 156 ft² of door enclosure area. The house is divided along its longitudinal axis into two separate areas; the private and communal areas, each with distinct ceiling heights. The private area has a partial attic with a dropped ceiling level, while the communal space is open from floor to ceiling. Floor plans and a section of the house are as seen in figures B-1, B-2, and B-3 of appendix B.

3.3 House Site

The site is located in Rockwood, Tennessee (35°52'9"N, 84°40'31"W), southwest of Oak Ridge, Tennessee, at an estimated altitude of 895 ft (U.S. Census Bureau, 2011). Rockwood is in the valley region of east Tennessee, east of a portion of the Appalachian mountain range and west of the Cumberland Mountains, an extension of the Appalachian Mountains. The site is fairly remote and potentially could require additional burdens for the transportation of materials to the site, depending on the material. Rockwood experiences a humid, subtropical climate, consistent with the temperate climate of the surrounding area. Both heating and cooling are of concern, as Rockwood averages 4183 heating degree days and 1156 cooling degree days, annually. Below grade temperatures fluctuate around an average temperature of 61°F, as the sub-surface soil conditions consist primarily of a heavy clay (ASHRAE, 2005)

3.4 Parameters and Procedure for the Life Cycle Assessment of Buildings

Generally, life cycle assessment (LCA) can be utilized to estimate any number of environmental impacts due to a given product, investigating all the processes which occur throughout its production. For the purposes of this investigation, LCA is utilized to account for the total energy inputs and green house gas (GHG) emissions due to the production and operation of the distinct building envelopes, through the course of their manufacture and useful life. The chief flows

accounted for in the life cycle study of the building envelopes are joules of energy, primarily, and CO₂ equivalents of GHGs are the secondary flow accounted for. Given that energy production is generally associated with the depletion of fossil fuels, fresh water, useable land and other natural resources, while additionally contributing to problems of eutrophication, ozone depletion, and air pollution; joules of energy use is an adequate flow to account for environmental burdens. This holds true, particularly in the U.S. southeast, in a region with an energy balance heavily reliant on coal and other fossil fuels of high GHG intensity. The LCA is to account for flows which occur during each of the following; the extraction and processing of raw materials, material manufacturing, transportation, building use and maintenance, and end of life operations.

As life cycle assessment is dependent on the limited data provided by the manufacturing industry, much of the process of life cycle assessment consists of researching and studying the data, identifying the various flows, verifying their accuracy, then subsequently modeling and quantifying the flows that each processes is responsible for. This is necessary in order to provide the appropriate level of accuracy and transparency of analysis, and to allow the areas of greatest burden to be properly identified.

An LCA study on the performance of a building envelope requires modeling of the embodied energy of the assembly, the operational energy of the building throughout its use, and the energy required to remove it at the end of its life. The embodied energy of the building envelope is the summation of all of the energy required throughout its production. It includes the energy used to extract and refine the raw materials, and to manufacture, transport, and assemble all of the components of the building envelope into its final functioning form. The building's operational energy consists of the energy required to heat and cool the space, and to power all the electrical and mechanical components of the building. The energy embodied in the building envelope directly affects the energy use during the operational phase, forming reciprocal relationship between the two phases. The end of life energy consists of the energy required to demolish and dispose of, or recycle all of the building materials after the use phase.

3.5 Modeling Procedures and Assumptions

3.5.1 Embodied Energy

In order to obtain a genuine assessment of the relative consumption and performance of each of the building envelopes, only the enveloping materials (the wall, roof, and floor assemblies) and primary structure are accounted for in the embodied energy calculation, as these are the only materials whose properties factor into the building performance throughout the use phase. Proper consideration of embodied energy use is of considerable importance and must be accounted for as its contribution to the life cycle is often underestimated (Yohanis & Norton, 1999). Therefore, GaBi LCA software is utilized to account for flows which occur during production and end of life operations of the building envelope, and contributes to a portion of the operational energy measurements (PE International, 2008). GaBi software's LCA modeling procedure is based on ISO 14040, and utilizes a hybrid method of life cycle assessment, consisting of input/output analysis and flow diagram methodology. The modeling software is accompanied by an LCA database, however this database is not the source for all of the elements and flows accounted for in this study. GaBi LCA software is instrumental in producing embodied energy estimates for the numerous phases contributing to embodied energy total, including the extraction, refining, transportation, manufacturing, and assembly phases of the life cycle. A flow diagram of the production operations, for the 4000 psi concrete modeled for this study, is illustrated in figure C-1 of appendix C. Additionally, GaBi software contributes to the end of life energy calculation, as its source data provides figures for either the disposal or recycling of certain materials.

Regarding the production phase of the LCA, it should be noted that a true embodied energy assessment is site specific and takes into account the production methods, transportation methods, and the fuel mix typical to the particular area. While the model of the energy mix for many of the production processes is relatively consistent with the geographic local of this study, transportation requirements for the materials are estimations, based on North American transit, which have been adjusted for the region.

3.5.2 Operational Energy

eQUEST building energy software is used to model the operation phase of the building envelopes, as it is a capable tool to assure that the results are within reasonable agreement of what would be expected in true application (Department of Energy). The eQUEST a modeling tool, produced in conjunction with the U.S. Department of Energy, is recognized as a qualified software for energy modeling according to the Energy Policy Act of 2005, and is within acceptable conformance with ASHRAE Standard 140. The energy modeling software accounts for the material properties of the building materials which most heavily influence the performance of a building envelope. These include surface reflectivity, thermal mass, surface roughness, and thermal conductivity or resistance. Additionally, eQUEST also accounts for the tightness of the building assembly, and calculates the building's air infiltration and exfiltration as outlined in section 3.5.3. The software estimates a building's energy use based on typical meteorological year (TMY) weather data for the given geographical coordinates. Modeling the climate for the given location, according to the TMY weather data, the software estimates the flux of heat which corresponds to the properties of the given building envelope. The program then models the response of the building's HVAC system and estimates system's energy demand based on the specified parameters of the building's mechanical components. Energy use for lighting, water heating, and other other common appliances is also accounted for within the eQUEST energy model. However, it should be noted that eQUEST is used only to determine the energy delivered to the house (secondary energy), and does not generate primary energy totals. The energy sum generated by the eQUEST model is recycled into GaBi in order to generate the total amount of primary energy used by the building. The quantity of energy used over the life cycle of the building is measured according to the following relationship;

$$LCE = EE_i + [EE_{rec} + OE] \times \text{building life} + ELE$$

where, LCE is the life cycle energy given in mega-joules, EE_i is the initial embodied energy, EE_{rec} represents the recurrent embodied energy, OE is the operational energy, ELE denotes the end of life energy, and the building life is the number of years the building is in operation. Life cycle emissions of CO₂ equivalents are determined using a similar relationship as the GHG intensity, particularly in the operation phase, is generally related to the energy use.

3.5.3 Air Infiltration and Sherman-Grimsrud Methodology

The infiltration flows during the operation phase of the houses are estimated within the eQUEST energy models using the Sherman Grimsrud Enhanced Infiltration Model. The model is intended particularly for residential structures and assumes that the structure has no internal thermal resistance as heat is free to flow. The eQUEST modeling software generates a dynamic flow model, producing results which account for the change of indoor temperature, outdoor temperature, and average wind speed over a given timeframe. It should be noted that this calculation method only accounts for infiltration flow and does not consider any effects from ventilation flow. The Sherman Grimsrud Infiltration Model is determined by the following relationships:

$$Q = Q_w + Q_s$$

$$Q_w = cC_w(sU)^{2n}$$

$$Q_s = cC_s\Delta t^n$$

where,

Q = airflow rate, cfm

Q_w = wind airflow rate, cfm

Q_s = stack airflow rate, cfm

c = flow coefficient, cfm/(in. of water)ⁿ

C_s = stack coefficient, (in. of water/°F)ⁿ

Δt = average indoor-outdoor temperature difference for given time interval, °F

C_w = wind coefficient, (in. of water/mph²)ⁿ

U = average wind speed for given time interval, mph

s = shelter factor

n = pressure exponent

In the preceding relationships, the average wind speed (U) and the Δt value both vary with time along with the infiltration flow, while the remaining values remain constant. However, the preceding relationships can be manipulated to require only the leakage area, expressed as a fraction of the floor area, which is the more common practice. Typical Meteorological Year (TMY) data is used to simulate the outdoor temperature in addition to the wind speed (ASHRAE, 2005).

3.6 Power Grid Fuel Mix

3.6.1 Energy

In order to provide a more accurate assessment of energy use and GHG emissions, a region-specific energy grid was modeled for the study, as the primary energy use is highly dependent on its energy supply (Gustavsson & Joelsson, 2009). Grid energy, produced by nearby power plants, supplies the energy demand for the operation phase of the completed residence, in addition to the production operations for several of the materials utilized in the building envelope assembly. As primary energy use is accounted for in this study, the total energy use to produce the delivered energy is considered, taking into account the subsequent energy losses. The energy mix values used to model energy consumption for this study are based on data provided for the Tennessee Valley Authority's (TVA) energy mix as of 2009. The TVA energy mix deviates considerably from the average energy mix of the U.S. grid, according to estimated values from the U.S. Department of Energy.

Table 3-1. Percent energy production by fuel source

Energy Source	TVA Energy Mix	U.S. Energy Mix
Nuclear	33	20
Hydroelectric	4	7
Natural Gas	1	23
Hard Coal	62	45
Petroleum	0	1
Other Renewables	0	4

As it is assumed that most of the materials are produced within the region of the TVA energy grid, the TVA energy mix is used as the electrical source for many of the material production operations, assuming the energy balance is reliant primarily on coal and nuclear energy. Each of the energy sources vary in efficiency regarding their conversion into electrical grid energy, as nuclear, hydroelectric, natural gas, and hard coal energies have efficiencies of 0.33, 0.90, 0.49, and 0.42, respectively (Spath & Mann, 2000; Spath, Mann, & Kerr, 1999; Darwish, Al Awadhi, & Bin Amer, 2010). The green house gas intensity of each of the energy sources varies as well. As energy losses are considered in this study, given that it considers primary energy use, the grid energy mix has some bearing on both energy use and GHG emissions. Based on the energy

source distribution provided, and for the given efficiencies for conversion to electrical energy, the TVA energy mix has a total composite efficiency of 0.427, as nearly 58% of the energy is lost during energy conversion and delivery.

3.6.2 Green House Gases

Similar to energy production, the green house gas (GHG) intensity of power generation is dependent on the fuel energy mix, as the GHG intensity of power production varies according to the power source. Coal and natural gas are by far the more carbon intensive energy sources, releasing airborne roughly 900 and 450 g CO₂ eq/kWh (250 and 125 g CO₂ eq/MJ) of energy produced by the respective fuel sources. The large majority of GHGs emitted when using these two fuels occur during the electricity production process. This is unlike hydro-electric and nuclear power production, as the majority of GHGs for these energy sources are released either upstream, or downstream of the electricity production process, and results in the release of considerably fewer GHGs. Hydroelectric and nuclear power are responsible for approximately 4 and 3 g CO₂ eq/kWh. The GHG intensities for grid energy use are based on power production processes for several developed nations and are consistent with figures used in other LCA studies (Weisser, 2007; Kofoworala & Gheewala, 2008). These GHG intensities are applied to several of the processes within this study, particularly during the operation phase of the life cycle, however some of the production phase operations have varying GHG intensities based on the energy mix of their individual production methods.

3.7 Construction Energy Use

Through the course of the study, literature was discovered with data distinguishing the variation in energy use for the different building types and sectors of construction; however the data often does not specify the deviation in energy use due to the change of materials. The deviation in energy use, within the data, appears to be related to the fuel use of the alternative construction equipment required for the different sectors. Literature and data documenting energy use during construction is sparse, particular itemized data regarding the construction energy use for distinct materials. Ultimately, an energy use value per square foot of floor area was utilized to calculate the construction energy requirements for each of the building envelopes. For the unit energy requirement, reference is made to the *Handbook of Energy Use for Building Construction*

provided by the U.S. Department of Energy (U.S. Department of Energy, 1981). Although the potential for some additional energy inputs for the ICF building envelope does exist, distinctions in the construction energy requirements for each of the building envelopes are believed not to be of great significance. Each of the building envelopes are assumed to require equivalent energy inputs, and are based on the construction energy data provided by the U.S. DOE.

3.8 End of Life Energy

For the purposes of this study, the end of life energy consists of the energy required to deconstruct and recycle, or properly disposed of, the building materials. Efforts were made to follow in accordance with the ISO 14040 series. It is assumed that the structural elements of the building envelope are the primary materials recycled, while other elements are disposed of by landfill, given the scope of this study is cradle-to-grave. This is deemed a fair assumption given the steady increase of recycle rates in recent years, and considering the building's lengthy timeline until the end of its useful life. Recycling the demolished material does not serve as benefit for the current life cycle; however, it results in energy reductions for the material's following life cycle (Gao, Ariyama, Ojima, & Meier, 2000). Cradle-to-grave analysis considers all the flows that occur until the material is ultimately disposed of, or properly processed for use for its subsequent life-cycle. Wood, concrete, and steel materials from the building envelopes are assumed as the recyclable materials. While, other elements of the building envelope could potentially be recycled or used as an energy source, such as the vinyl cladding, the energy use for landfill disposal operations for many of the remaining materials is not unlike the energy use for their recycle (Brinkley, Kirby, & Wadehra, 1996). Initially, an attempt was made to provide comprehensive documentation of the demolition energy, itemizing the recycle and disposal energy requirements of each of the materials; however, this was not possible due to insufficient data. Instead, a "per unit area" approximation of the demolition and recycle energy requirements for each of the envelopes was utilized.

3.9 Green House Gas Emissions

As carbon dioxide (CO₂) is recognized as the primary contributor to the emission of GHGs, kilograms of CO₂ equivalents serve as the metric for GHGs, as the global warming potential of all other GHGs are weighted to reflect their impact relative to the impact of CO₂. The number of

chemicals associated with global warming, green house gases (GHG), accounted for in this study are few; however, the major contributors are considered. These chemicals are: carbon dioxide (CO_2), methane gas (CH_4), and nitrous oxide (N_2O), in addition to volatile organic compounds (VOCs) and hydrocarbons. CO_2 is generally the most plentiful GHG emission; however, given the unknown contribution, and the varying amounts of the other chemicals emitted throughout the various operations accounted for in this study, it is important to account for each throughout the study. The contribution of each of these chemicals is of particular interest given the variation in their global warming potential. One gram of a hydrocarbon or non-methane VOC is equivalent to 16 grams of CO_2 . Methane gas has a global warming potential of 25 times the equivalent weight of CO_2 , and N_2O has 250 times the warming potential of CO_2 .

Calculations concerning the emissions of green house gases are aided by GaBi LCA software. The LCA modeling tool accounts for both airborne and waterborne chemical flows; however, for the purpose of the green house gas summation in the study, only airborne chemical flows are of significance. The chief chemicals which the LCA software accounts for concerning green house gases are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), volatile organic compounds (VOCs), and hydrocarbons. GaBi software sums each green house gas individually and normalizes the warming potential of each relative to the warming potential of carbon dioxide.

Chapter 4: Production Phase Energy and Green House Gases

4.1 Introduction

The assessment of the building envelopes' production phase documents all of the energy use and green house gas (GHG) emissions which occur during the production of the assembled building units. This includes; the extraction and processing of raw materials, the manufacture and transportation of each of the envelopes' components, and the assembly of the resulting building envelope and structural materials. Life cycle documentation of the production of a building envelope is unique, given that the functional unit is the building envelope, in its entirety, however to perform a proper assessment, a documentation of the life cycle for each of its individual components is required. Although, the study is conducted to be as all-encompassing as possible, the embodied energy assessment of some of the materials is more comprehensive or transparent than for others. For the most accurate assessment of a material's life cycle, every process that takes place during production should be documented. However, due to the difficulties of LCA modeling, and to limitations of transparency and accessibility of production data, some of the analyses are broken down process by process, while others may offer a single total for a group of processes. Much effort was placed in comparisons and verification of the modeling results and the source data, as they were checked according to various outlets, when possible, to assure a level accuracy.

4.2 Construction Energy

In order to estimate the, on-site, direct energy use to assemble each of the building envelopes, reference was made to *Energy Use for Building Construction*, and the U.S. Department of Energy's (DOE) *Handbook of Energy Use for Building Construction*. The references provide, per square foot, values to estimate the construction energy use for conventional single family residences. The unit value is assumed as the energy required to construct both of the light-frame wood building envelopes, and the ICF envelope. The U.S. Department of Energy et al. (1981) estimates that a conventional single family residence requires approximately 39 MJ/ft² (37 kBTU/ft²) of direct energy for building construction. Ultimately, for the 2400 ft² of floor area, each of the building envelopes is determined to require roughly 93,600 MJ of construction energy.

4.3 Concrete Production

The production of portland cement concrete was modeled in order to assess the embodied energy inputs of the two individual concrete mixtures utilized in each of the building envelopes; a 3000 psi concrete which was specified for the concrete footings of each envelope, and a 4000 psi concrete which was specified for the superstructure walls, basement walls, and slab concrete. For the production of this material, the U.S. LCI Database of the National Renewable Energy Laboratory et al. (2010) was referenced, in addition to PE International. In order to model the production of each concrete mixture, processes for sand extraction, limestone extraction, portland cement production, and the final production of the concrete were each modeled. For the two concrete mixtures varying amounts of cement, limestone gravel, sand, and water were utilized as seen in table 4-1.

Table 4-1: Kilograms of component material per cubic foot of concrete

Material	4000 psi	3000 psi
Cement	18.5	13.1
Limestone Gravel	68.2	63.0
Sand	45.1	57.9
Water	10.0	10.0

For the production of 1 ft³ of 4000 psi concrete, 57 mega joules of energy are required. Sand excavation and processing is the most energy intensive material process, which is largely due to reducing the grain size of the material. With regard to the transportation of the raw materials, a travel distance of 65 miles was assumed, however this does not consider the transportation of the materials from the concrete production plant to the construction site. The total usage of each concrete mixture for the ICF building envelope are 2400 ft³ of 4000 psi concrete, and 760 ft³ of 3000 psi concrete. The light-frame wood envelope calls for 990 ft³ of 4000 psi concrete, and 760 ft³ of 3000 psi concrete. Waste material was accounted for in the material summation of each case. A total of 161,400 MJ of energy was consumed during concrete production for the ICF building envelope, 119,600 and 41,800 MJ for the 4000 and 3000 psi concrete mixes, respectively. The light-wood frame envelope required 1410 ft³ less concrete volume, and consumed 93,200 MJ of energy; 51,480 and 41,800 MJ for the 4000 and 3000 psi concrete mixes, respectively.

Table 4-2: Energy use and GHG emissions per cubic foot of concrete production

Process	4000 psi		3000 psi	
	MJ/ft ³	kg CO ₂ equiv.	MJ/ft ³	kg CO ₂ equiv.
Transport	4	0.3	4	0.3
Sand Excavation & Processing	14	0.8	18	1.0
Limestone Excavation & Processing	3	0.2	3	0.2
Cement Production	4	7.8	3	5.5
Process at Plant (Primary Energy)	27	2.0	27	2.0
Total	52	11.1	55	9.0

The production of concrete is highly intensive in regard to green house gas (GHG) emissions. Concrete production for the ICF and light-wood frame building envelopes is responsible for emission of 32,400 and 17,830 kg of CO₂ equivalents, respectively. This study serves as an example that energy use is not always reflective of GHG intensity, as the excavation and processing of sand is the largest energy consumer. However, within concrete production, cement production is by far the most carbon intensive process, and is responsible for about 70% of the total emissions throughout the production of concrete. The high emission totals of CO₂ equivalents during cement processing is due to its large coal heat dependency, as cement is produced by the calcination of limestone.

4.4 Dimensional Lumber

An embodied energy assessment was performed considering the dimensional lumber used for the roof of the ICF building envelope, and the superstructure walls and roof of the light-frame wood envelope. For the production energy use of the material, reference was made to the Athena Sustainable Materials Institute et al. (2000), and to the LCI Database of the National Renewable Energy Laboratory et al. (2010). All of the lumber is specified as southern pine wood, with a density of 40 lb/ft³. In order to calculate the embodied energy, figures from the material extraction, manufacture, and transportation processes of the lumber were investigated. The extraction process is attributed to 622 MJ of energy use for every cubic foot of lumber, and consists of the harvesting of the trees, their transportation to the mill site, the restoration and regeneration of the site, and the maintenance of logging equipment. The manufacturing process is responsible for 1798 MJ/ft³ of dimensional lumber, the largest fraction of the energy sum, and consists of debarking of the rough lumber, kiln heat treatment, treatment of the process air and

waste materials, sawmilling, and the maintenance and repair of the sawmilling and kiln equipment. However a large portion of this energy is produced using renewable biomass energy (Wilson, 2005). Kiln heat treatment, to reduce the moisture content of the lumber, is the by far the most energy intensive operation in the production of the lumber. Transportation of the lumber after manufacturing processes contributes an additional 31 MJ/yd³ of lumber, and is attributed to the smallest portion of the 2451 MJ/yd³ lumber production energy total. Ultimately, the ICF building envelope requires 6.7 yd³ of lumber material, consuming a total of 16470 MJ of energy for the production of its roof framing material. The light-frame wood building envelope requires 26960 MJ of energy use, utilizing 11.0 yd³ of lumber for its superstructure walls and roofing material.

Green house gas (GHG) emissions, during the production of lumber, occur mostly during the manufacturing process, and are largely attributed to the lumber's kiln heat treatment. This is due to the burning of natural gas and waste wood material during treatment. Ultimately, lumber production for the ICF and light-frame wood envelopes is responsible for the emission of 1610 and 2640 kg of CO₂ equivalents, respectively.

Table 4-3: CO₂ equivalents of GHG emissions per cubic yard of lumber production

Gas	Extraction	Manufacture	
CO ₂ (kg)	45	192	
CH ₄ (g)	15	15	
Hydrocarbons (g)	73	37	Total
GHG equivalents (kg)	47	193	240

4.5 Gypsum Board

Gypsum board is used as the finish material for all of the interior wall surface area for each of the building envelopes. Reference was made to the Athena Sustainable Materials Institute et al. (1997) and to the Inventory of Carbon and Energy (ICE) of the University of Bath et al. (2011), for figures regarding production energy use and embodied carbon. The source data for energy use during the production of gypsum board is quite transparent, as energy uses throughout each of multitude of operations are provided individually. The contribution of each energy source to the total energy use was also available. Data is provided for the extraction and transportation of the gypsum, and the manufacturing of the paper, board, and stucco required to produce the ensuing

gypsum board. Well over half of the total energy required while producing the material is attributed to kiln drying during the manufacture of the board, and a significant amount of energy is used to dry the extracted gypsum before the board manufacturing, as the extracted gypsum must be calcinated. The kiln drying processes are fueled primarily by natural gas, and are reflected in the energy source distribution.

Table 4-4: Mega joules of energy use per square foot of ½” gypsum board production

	Extraction	Production Transport	Manufacturing	Market Transport		Total
By operation	0.04	0.20	3.08	0.23		3.55
By energy source	Diesel	Natural gas	Coal	Oil	Electricity	Total
	0.53	2.34	0.00	0.39	0.29	3.55

The extraction and transportation energies sum up to less than 15% percent of the total production energy, consuming a portion of the energy from diesel and oil. This is given the assumption that the materials typically travel a total distance between 400 and 550 miles by road, and requires approximately 1.72 MJ/ton-mile on diesel fuel. The electrical energy portion is consumed primarily in operations within the manufacturing plant. Ultimately, the production of gypsum board requires an energy input of roughly 3.55 MJ/ft², as each of the building envelopes call for approximately 17,860 MJ of total energy use.

Gypsum board production is not very carbon intensive, particularly given the amount of heat energy utilized in the calcinations of the gypsum and in the slow kiln drying of the resulting board. This is most likely due to the use of natural gas for kiln heating processes, as it is considerably less carbon intensive than coal or oil burning. GHG emissions due to the extraction phase are minimal, requiring 1 g CO₂ eq/ft² gypsum board production. Transportation of the board is responsible for 31 g CO₂ eq/ft², accounting for nearly 18 percent of the total GHG emissions. The manufacturing of the board is certainly the most intensive processes, as it is responsible for 153 g CO₂ eq/ft² gypsum board production. The total production process is responsible for approximately 185 g CO₂ eq/ft² of finished gypsum board, as the production of each of the building envelopes releases approximately 930 kg CO₂ equivalents for the 5030 ft² of ½” inch thick gypsum board.

4.6 Polystyrene Insulation

Rigid polystyrene insulation is utilized in both the ICF and light-frame wood building envelopes and is placed; on each face of both the basement and superstructure walls of the ICF envelope, and behind the basement walls and below the slab of the wood frame envelope. For figures concerning energy use during production operations for the material, reference was made to the Inventory of Carbon and Energy (ICE) of the University of Bath et al. (2011), and to the Athena Sustainable Materials Institute et al. (1999). Although the embodied energy assessment of this material is not incredibly transparent and does not detail the amount of energy attributed to each of the processes, the assessment includes; the energy required for the manufacturing of process chemicals, expansion of the foam, forming of the sheets, packing, transportation, and the refining of the oil, petroleum, and natural gas required throughout polystyrene production. The manufacture of polystyrene insulation relies on fossil fuels as both a component substance and a production energy source, and therefore requires the use of a substantial amount of energy potential.

The production of 1.5 lb/ft² expanded polystyrene consumes approximately 31 MJ of energy per cubic foot of insulation when neglecting feedstock energy, however this energy requirement increases to 60 MJ/ft³ when the feedstock is considered, as the feedstock energy, mostly in the form of fossil fuels, is attributed to roughly 48% of the total manufacturing energy use. The resulting energy uses of the ICF and light-frame wood building envelopes due to the production of polystyrene insulation are 65300 and 21190 MJ for polystyrene volumes of 2080 and 675 ft³, respectively. The energy uses of the two building envelopes when including the feedstock energy are 124,800 and 40,500 MJ, respectively.

The GHG intensity of polystyrene production is, by no means, modest relative to the production operations of many other envelope materials. Production operations release airborne roughly 2.24 kg CO₂ equivalents for every cubic foot of polystyrene insulation. Although polystyrene GHG intensity is relatively high, these GHG emissions appear modest when considering the amount of petroleum and fossil fuels consumed during processing. Ultimately, for the 2080 and 675 cubic feet of insulation produced for the ICF and light-frame wood building envelopes, respectively, approximately 4660 and 1510 kg of CO₂ equivalents are released airborne.

4.7 Fiberglass Batt Insulation

Fiberglass batt is present in both the ICF and light-frame wood building envelopes, serving as the insulating material for the roof structure of each envelope, and is additionally utilized as the wall insulation for the wood frame superstructure. For figures regarding energy use during the production of fiberglass batt, reference was made to the University of Bath et al. (2011) *Inventory of Carbon and Energy (ICE)*, and to the Athena Sustainable Materials Institute et al. (1999). Embodied energy figures for this material were not calculated through modeling, yet were provided through an investigation of data. There is discrepancy in the data provided by several sources regarding the energy consumption of fiberglass batt production, as some estimates anticipate a total energy use of nearly twice of that utilized in this study; however, the following figures were utilized given the limited transparency of those sources. The assessment of the fiberglass batt considers the extraction and refining of the materials, particularly quartz sand and dolomite, transportation, and manufacturing. However, accounts of energy use were not individually provided for each of these processes. For the roof of both the ICF and light-frame wood roofs, 2400 ft² of 6" thick insulation was utilized, requiring 12,300 MJ of production energy. The wood envelope required an additional 11,300 MJ of energy for the 2200 ft² of fiberglass insulation produced for the superstructure walls.

GHG emissions from fiberglass batt production are substantial relative to other materials of the building envelope. Production operations of this material release roughly 1520 g of CO₂ equivalents for every square foot of 6" thick fiberglass batt insulation produced. For the 2400 ft² of insulation produced for the ICF building envelope, and the 4600 ft² for the light frame wood envelope, 3650 and 6990 kg CO₂ equivalents were emitted, respectively.

4.8 Polyurethane Insulation

Polyurethane insulation is utilized only in the additionally insulated light-frame wood building envelope, as a 2" thick addition of insulation is placed between the wood framing and the vinyl cladding surface. For data regarding energy use and GHG emissions for rigid polyurethane insulation, reference was made to the University of Bath et al. (2011) *Inventory of Carbon and Energy*. The analysis of this material is stated to be comprehensive, as the scope of the assessment is cradle to gate, accounting for the flows through a series of operations, from the

extraction of materials to the conclusion of the material manufacturing. Regarding the clarity of the assessment, energy use for individual operations is not available, limiting the transparency of the data. The energy use of rigid polyurethane foam is substantial, as 25 MJ/ft³ is consumed during production of the material, excluding the feedstock energy. Given that fossil fuels serve as a component substance of the polymer, the feedstock energy is substantial and, when included in the energy sum, more than doubles the energy total to 69 MJ/ft³. The total energy use for the additional 2" of polyurethane insulation is 8000 MJ, neglecting the feedstock energy, and increases to 22,080 MJ when the feedstock energy is accounted for.

Green house gas emissions per unit volume of the material are considerable, however for the required thickness of the insulation, the GHG emissions per unit area of the material are meager, given the quantity of fossil fuels utilized during production. Overall, the production of polyurethane foam releases 480 g CO₂ eq./ft², and results with an emissions total of 910 kg CO₂ equivalents for the 1900 ft² of 2" thick polyurethane insulation.

4.9 Plywood

Plywood is placed below the asphalt shingles of the roof, utilized as the sheathing material for each of the building envelopes. Plywood production was modeled referencing data provided by the National Renewable Energy Laboratory et al. (2010) U.S. Life Cycle Inventory. The modeling of this material is fairly transparent, offering figures for extraction, transportation, and manufacturing. The extraction phase of plywood production includes both the harvesting and reforestation of the wood utilized. The manufacturing operations of plywood include debarking and conditioning of the lumber, in addition to drying, pressing, and trimming the resulting plywood. More than 80% of the energy is used during manufacturing operations. Nearly, all of the electric grid energy is used during manufacturing, in addition to the petroleum and portions of the diesel and natural gas. The grid energy use shown in Table 4-5 is primary energy, and is representative of all the energy used to produce and deliver the required amount of power. In the energy assessment, it is assumed that the material must be transported roughly 250 miles, requiring approximately 3 MJ/ton-mile using diesel road transportation. The production of plywood consumes roughly 4.05 MJ/ft², as the total energy utilized for roof sheathing in each of the roofs is 10,130 MJ.

Table 4-5: Mega joules of energy use per square foot of ½” plywood production

	Extraction	Transport	Manufacture	Total	
By operation	0.18	0.60	3.28	4.05	
	Diesel	Natural gas	Petroleum	Grid Energy	Total
By energy source	1.13	0.46	0.07	2.39	4.05

With regarding to carbon emissions, plywood production does not require a highly intensive series of operations relative to the production of other building materials. Although a large fraction of the energy is produced by the combustion of fossil fuels, some of the more carbon intensive fuels are supplemented by the use of natural gas, a less carbon intensive fuel. The distribution of carbon emissions is reflective of the energy use, as manufacturing operations are responsible for over 75% of the total carbon released into the atmosphere during production. The diesel fuel laden transportation energy contributes a noticeable portion of the total GHG emissions, however the emissions due to material extraction is minimal. Plywood production, for each of the building envelopes, is responsible for the emission of approximately 690 kg CO₂ equivalents, for the 2500 ft² of plywood sheathing material used.

Table 4-6: GHG emissions; grams CO₂ equivalents per square foot of ½” plywood production

Substance	Extraction	Transportation	Manufacturing	
CO ₂	5.7	45.6	208.7	
CH ₄	1.0	9.4	0.0	
N ₂ O	3.0	0.7	0.5	Total
CO ₂ eq.	9.7	55.6	209.2	274.5

4.10 Oriented Strand Board

Commonly utilized as a sheathing material, as is the case for this study, oriented strand board (OSB) is positioned behind the exterior cladding of the two wood frame envelopes, and is fixed to the wooden frame. Regarding energy use and the GHG emissions of this material, reference was made to The Athena Institute of Sustainable Materials and to the National Renewable Energy Laboratory et al. (2010) U.S. Life Cycle Inventory. The assessment separately provides figures for the extraction, manufacture, and transport of the finished material, forming a moderately transparent basis for analysis. Energy figures are provided for the manufacture of the phenolic

resin adhesive, as well as information for the subsequent production of the OSB. Production of the adhesive substance consumes 1.33 mega joules per square foot of OSB. Extraction operations require approximately 0.89 MJ/ft² of gypsum board, as much of the wood material for OSB consists of the waste material from other wood products. The manufacture of OSB relies on waste material, produced during its own manufacturing process, for fuel (hogfuel), and provides nearly 80% of the heat energy used during the manufacture of OSB. The remaining heat energy is produced by natural gas. The primary operations accounted for during OSB manufacture consists of; debarking and heat conditioning, waferizing, drying, and trimming. Overall these operations consume roughly 3.90 MJ/ft² oriented strand board production. It was assumed that the materials were transported an average distance of 250 miles, using diesel road transport, and required roughly 1.8 MJ/ton-mile, and 0.29 MJ/ft² OSB production. Overall, OSB production consumes approximately 6.40 MJ/ft², as the entire wall sheathing area required roughly 1900 ft² of the material, with the subsequent total energy consumption of 12160 MJ.

As would be expected, the board manufacturing operations, which require heat energy from the burning of hogfuel and natural gas, are responsible for the largest portion of CO₂ equivalent emissions, liable for nearly 80% of the material's total GHG emissions. Emissions during the material extraction and the transportation of the board comprise a lesser, yet ever present portion of the total emissions. Overall, OSB production is not an exceedingly carbon intensive process, emitting 0.39 kg CO₂ eq./ft² of OSB, and results in a net emission of approximately 740 kg CO₂ equivalents.

Table 4-7: GHG emissions; grams CO₂ equivalents per square foot of 3/8" Oriented Strand Board Production

Chemical	Extraction	Board Manufacture	Adhesive Manufacture	Transportation	
CO ₂	58	277	23	15	
CH ₄	0	1	0	6	
VOC	1	2	0	5	Total
Total	60	280	23	26	388

4.11 Vinyl Cladding

Used for both the wood frame and ICF building envelopes, polyvinyl chloride (vinyl) serves as the exterior cladding material. Energy use and carbon emissions for this material were modeled

with reference to the Athena Institute of Sustainable Materials et al. (1999), and to U.S. Department of Energy et al. (2011) Building Energy Data Book. Regarding the energy use and carbon emissions data, transparency is limited for this material. Figures are provided for the extraction and manufacturing of the material, in addition to material transport. A total of 400 miles is assumed as the transportation distance, requiring 1.8 MJ/ton-mile, and characteristic of diesel road transportation, ultimately consuming 0.06 MJ/ft² vinyl cladding. Extraction and manufacture operations consume the remaining 1.32 MJ of the total 1.38 MJ/ft² vinyl cladding production energy. Manufacturing operations include; the production of vinyl chloride monomer (VCM) gas, the subsequent liquification of the VCM, the polymerization of the monomer, and the extrusion of the resulting vinyl cladding, however the energy requirement for these individual operations is not provided. It should be noted that the preceding values consider only the energy required to power the production processes. While neglecting the feedstock energy, production energy requirements are particularly modest; however inclusion of the material's feedstock energy would multiply the manufacturing energy sum, as the production of PVC relies on gasoline and natural gas as component substances for the material. Though, the feedstock energy contribution is uncertain due to the limited transparency of the study, according to a study in the Inventory of Carbon and Energy regarding PVC pipe, feedstock energy is estimated to increase total energy use to the equivalent of 5.33 MJ/ft² based on European operations. Neglecting the feedstock energy, the total energy use for the 2300 ft² of cladding surface area is 3170 MJ. If feedstock energy is included, the embodied energy could increase to roughly 12260 MJ.

Reflective of the low production energy use, GHG emissions due to the manufacture of vinyl cladding are modest. Although, plenty of fossil fuel is consumed during PVC production, as much of the fuels utilized are not combusted during manufacture operations, the total GHG potential is not airborne. Extraction and manufacturing operations are responsible for 202 grams CO₂ eq/ft² vinyl cladding production, as transportation is attributed to only 5 g CO₂ eq/ft². Given the emission of roughly 0.21 kg CO₂ eq./ft² of vinyl material, production operations for each of the completed building envelopes emit roughly 480 kg CO₂ equivalents.

4.12 Windows

Present in each of the window openings of the building envelopes are double pane, argon filled, glass windows. Separate models were constructed for the glass and window frame materials to

assess the production energy use and embodied carbon of the window assemblies. In modeling the flows during window production, reference was made to the Athena Institute of Sustainable Materials et al. (1999), and the University of Bath et al. (2011) Inventory of Carbon and Energy. The assessment is not fully transparent, as flow values are not offered for each individual processes, yet values for the production energy use, and carbon emissions are given for the extraction and manufacture of the glass material, the frame material, and the required transport. A distance of 400 miles is specified as the average transportation distance of the assemblies, requiring 1.8 MJ/ton-mile of transport, as 1.84 MJ/ft² of window surface is consumed during transport. Production operations for the glass material include the extraction and processing the sand, dolomite, and limestone material, and the subsequent production of soda-lime float glass. It should be noted that approximately 15% of the glass, by mass, is recycled material, reducing the energy required for virgin material. Float glass production is highly energy intensive per unit area as it consumes 57.6 MJ/ft² of window assembly, as it calls for high heat from both natural gas and oil firing, and electrical energy inputs of roughly 6.14 MJ/ft² of delivered electrical energy. Flows due to electrical energy use are modeled according to the energy mix estimates provided in section 3.6.

Window framing material is largely composed of aluminum, and is attributed to only a portion of the total energy use. Operations for aluminum frame production included; the extraction and processing of bauxite, limestone, and salt; the manufacture of alumina, lime, coke, and sodium hydroxide; and the ensuing aluminum smelting and sheet manufacture. For the given window area, extraction and manufacture operations for the aluminum window frame consume 3.4 MJ/ft² of window surface. The energy use value for the production of the frame is accurate only for the window perimeter to area ratio of this study as the flows were initially calculated per unit length of window frame. Overall, the total energy use per unit area of window assembly is relatively high, as approximately 61 MJ/ft² is consumed during production. Although there is only 225 ft² of glazing area, a towering 13700 MJ were consumed during window assembly production.

A large portion of the GHG emission, during the production of window assemblies, occurs during the floating of the glass, and is due to the firing of natural gas and oil for heat energy. Transport and window frame manufacture have visible affect on the GHG emissions total, however are not comparable to emissions released airborne during glass manufacturing. Reflective of window production energy use, the GHG intensity per unit area of window assembly is relatively high, as

the production of the assemblies releases approximately 4.4 kg CO₂ eq./ft². Overall, window production is responsible for the emission of roughly 1000 kg CO₂ equivalents.

Table 4-8: GHG emissions- grams CO₂ equivalents per square foot of window area production

Chemical	Glass Extract & Manufacture	Frame Extract & Manufacture	Transport	
CO ₂	3930	180	95	
CH ₄	145	6	38	
VOC	0	1	31	Total
Total	4075	187	164	4426

4.13 Glass Fiber Shingle

Glass fiber shingles are specified as the roofing material for each of the building envelopes. Figures for energy use and carbon equivalent emissions during the production of the shingles were determined with reference to the Athena Institute of Sustainable Materials et al. (2000). The reference data was adjusted to better reflect operations within the U.S. southeast, particularly figures concerning transportation. The assessment is moderately transparent, as it provides itemized fuel use data for the extraction and manufacturing energy, in addition to the transportation energy use. Materials for the glass fiber shingle are assumed to travel a total of approximately 400 miles, primarily by road, requiring roughly 1.8 MJ/ton-mile with diesel as the fuel source. This results in 0.85 MJ/ft² glass fiber shingle production for transportation purposes. Extraction and manufacture operations for glass fiber shingles require 1.88 MJ/ft², and consist of the production and compilation of fiberglass mat, asphalt binder, along with ground limestone, talc, and sand. The production of each square foot of glass fiber roofing requires an energy input of 2.73 MJ, however this figure neglects the feedstock energy of the materials. Inclusion of the feedstock energy more than triples the embodied energy total to 11.13 MJ/ft² glass fiber shingle. The required energy use of throughout the production of the shingles, including and excluding the feedstock energy, is 6830 and 27825 MJ, respectively.

Table 4-9: Mega Joules of energy use per square foot of glass fiber shingle production

Energy Source	Oil & Gas	Natural Gas	Diesel	Electric (Primary)	Petroleum	Total
Quantity	0.40	1.16	0.85	0.31	0.01	2.73

The production of asphalt shingles is not a rigorous process regarding the emission of green house gases. Although ample fossil fuels are utilized during the their manufacturing, the whole of these fossil fuels are not burned during operations, as much of the fuel becomes an inherent portion of the glass mat and the asphalt binder. In total, the production of the shingle releases approximately 0.22 kg CO₂ equivalents for each square foot of roofing area, resulting in the emission of roughly 550 kg CO₂ equivalent for the 2500 ft² of roofing area.

Table 4-10: GHG emissions- grams CO₂ equivalents per square foot of glass fiber shingle production

Chemical	Extraction & Manufacture	Transportation	
CO2	98	43	
CH4	3	18	
VOC	44	14	Total
	145	75	220

4.14 Reinforcing Steel

Reinforcing steel is required for both the basement and above grade walls of the ICF envelope, and only for the basement walls of the light-frame wood envelopes. In both basement, and above grade walls, horizontal reinforcing bars are placed at 16 inches on center, while vertical bars are placed at 18 inches on center. All reinforcing is of #4 bar size, with a cross-sectional area of 0.2 in². During the assessment of steel production, reference was made to the Athena Institute of Sustainable Materials et al. (2002). The fuel source of the energy uses are clearly stated, offering considerable transparency with regard to the consumption of resources, however a detailing of the energy use attributions of the individual processes is lacking introducing a level of ambiguity to the data. A large portion of the steel produced is recycled scrap material, significantly reducing the production energy requirement by roughly 40%, as virgin steel production is considerably more energy intensive than the recycling steel. Natural gas contributes the largest portion of the energy total during production operations, at nearly 52%, followed by electricity and coal. The overall energy use per unit volume of steel production is 321 MJ/100 ft of rebar, however this figure would be extensively greater without the use of recycling, as the use of scrap material allows an energy saving of 219 MJ/ft of rebar production. Production of reinforcing steel for the light-frame wood envelope consumes 4980 MJ, for the 1550 ft of #4 size rebar. The ICF wall

envelope requires considerably more steel, consuming 12,330 MJ during production of the 3840 ft of reinforcement.

Table 4-11: Mega joules of energy use per 100 feet of #4 size rebar

Source	Coal	Natural Gas	Gasoline & Oil	Diesel	Electricity	Oxygen & Chemical Heat	Total
Quantity	63	167	3	6	76	7	321

Due to heat requirements during the production of steel reinforcement, and the subsequent use of natural gas and coal energy, unit GHG emissions from rebar production are sizeable relative to other materials, consisting primarily of CO₂. Total production operations release approximately 67 kg CO₂ eq./100 ft of 0.2 inch diameter steel reinforcing, however, given the limited steel volume requirement, total releases of GHGs due to rebar are not overwhelming. For the 2.15 ft³ of reinforcing required for the light-frame wood envelope, 1040 kg CO₂ equivalents were release airborne, as the ICF envelope required considerably more steel, releasing 2570 kg CO₂ equivalents.

4.15 Results and Discussion

4.15.1 Embodied Energy Comparison

In order to compare the available envelope options, the embodied energy and green house gas (GHG) intensity of the materials must be known, however to perform a true assessment of the building materials, values for energy use and GHG emissions during the production phase cannot stand alone, as an understanding of the materials' performance during the operation phase is often more critical. As would be expected, the ICF structure has the greatest embodied energy of the building envelopes, requiring a total production energy use of roughly 422 GJ. The standard wood frame envelope has an embodied energy of 331 GJ, while the addition of 2" of polyurethane insulation to the above grade walls increases the embodied energy by only 8 GJ, to 339 GJ. Energy use for the ICF superstructure wall envelope was more than double than that required for the 'wood frame 1' wall and nearly double than the required energy for the 'wood frame 2' wall, as seen in table 4-14. Amongst each of the building envelopes, the differentials in embodied energy were primarily due to variation in the amounts of the following materials; structural wood and concrete, fiberglass batt and polystyrene insulation, and reinforcing steel.

Regarding GHG emissions, the primary sources of the variation are concrete and reinforcing steel. Concrete production was by far the most energy intensive process, due to the amount of concrete material necessary to meet the structural requirements. For the ICF and light-frame wood envelopes, 57% and 32% of total GHG emissions, respectively, are attributed to the production of structural concrete. Overall, the variation in GHG emission amongst the building envelopes is reflective of their respective energy uses, as the production of the ICF structure has a 37% higher GHG intensity, relative to the wood frame building envelope. Overall, production of ICF superstructure wall envelope emitted more than twice the amount of green house gases than both of the wood frame superstructure walls as seen in table 4-14.

4.15.2 Insulated Concrete Form Building Envelope

The material attributed to the greatest portion of the energy consumed during the production of the ICF building envelope was, by far, concrete, as its production was responsible for roughly 40% of the energy consumption for the entire building envelope. The use of concrete walls, solely as structural elements for typical residential design loads, would be remarkably inefficient given the wood frame's capability to satisfy these loads while requiring nearly 85% less embodied energy (61.8 GJ), 90% less material volume, and 97% less material weight for the above grade walls of the house. However, it is understood that the concrete wall serves more than structural purposes, as it is expected to offer energy returns during the operation phase due to its air-tightness and thermal mass.

Overall, 15 % of the total ICF envelope production energy is attributed to the 5.5" thick polystyrene insulation forms used for the walls. Use of the insulation forms, as opposed to the 5.5" of fiberglass batt of the wood frame envelope, results in a 33 GJ increase in embodied energy, however due to the increased thermal resistance of the polystyrene, energy returns are anticipated.

4.15.3 Light-Frame Wood Envelopes

Although, the above grade structural elements of the wood frame envelopes consist of southern pine lumber, the largest portion of energy emissions for the building envelope is attributed to concrete production, for footings and basement walls, due to the materials large production energy requirements. Nonetheless, relative to the ICF building envelope, the use of wood frame

walls reduces the embodied energy consumption by more than 25%. For structural purposes, southern pine dimensional lumber is highly efficient regarding embodied energy use, requiring only 10.5 GJ for above grade wall framing; however, the wood frame envelope also utilizes oriented strand board (OSB) sheathing as a supplemental structural material requiring an additional 12 GJ.

Table 4-12: Insulated concrete form envelope material inventory- energy use & GHG emissions

Material	Quantity	Unit	Production Energy (MJ)	% energy use	CO ₂ equivalents (kg)
Superstructure Concrete (4000 psi)	2,400	ft ²	124,800	30	26,640
Footing Concrete (3000 psi)	760	ft ²	41,800	10	6,840
Southern Pine Dimensional Lumber	6.72	yd ³	16,470	4	1,610
Fiberglass Shingle Roofing	2,500	ft ²	6,830	2	550
Plywood (1/2" Roof Sheathing)	2,500	ft ²	10,130	2	690
Vinyl Cladding	2,300	ft ²	7,130	2	740
Gypsum Board (1/2")	5,030	ft ²	17,860	4	930
Fiberglass Batt (6" Roof Insulation)	2,400	ft ²	12,330	3	3,650
Polystyrene Insulation	2,080	ft ³	65,300	15	4,660
Windows	225	ft ²	13,700	3	1,000
Reinforcing Steel (#4 bar)	3,840	ft	12,330	3	2,580
Construction Energy Use	2,400	ft ²	93,600	22	
Totals			422,280	100	49,890

Table 4-13: Light-frame wood envelope material inventory- energy use & GHG emissions

Material	Quantity	Unit	Production Energy (MJ)	% energy use	CO ₂ equivalents (kg)
Polyurethane Insulation (wood frame 2 only)	1900	ft ²	8000	--	910
Basement Wall Concrete (4000 psi)	990	ft ²	51,480	16	10,990
Footing Concrete (3000 psi)	760	ft ²	41,800	13	6,840
Dimensional Lumber (Southern Pine)	11	yd ³	26,960	8	2,640
Fiberglass Shingle Roofing	2,500	ft ²	6,830	2	550
Plywood (1/2" Roof Sheathing)	2,500	ft ²	10,130	3	690
Oriented Strand Board (3/8" Wall Sheathing)	1,900	ft ²	12,160	4	740
Vinyl Cladding	2,300	ft ²	7,130	2	740
Gypsum Board (1/2")	5,030	ft ²	17,860	5	930
Fiberglass Batt (6" Wall & Roof Insulation)	4,600	ft ²	23,640	7	1,510
Polystyrene Insulation	675	ft ³	21,190	6	6,990
Windows	225	ft ²	13,700	4	1,000
Reinforcing Steel (#4 bar)	1,550	ft	4,980	2	1,040
Construction Energy Use	2,400	ft ²	93,600	28	
Totals			331,460	100	34,660

Table 4-14: Energy use and GHG intensity per square foot of wall envelope

Wall Envelope	MJ/ft ²	kg GHG eq./ft ²
ICF	45.2	6.96
Wood Frame 1	22.0	2.79
Wood Frame 2	26.1	3.27

Figure 4-1: Insulated concrete form building envelope production energy distribution

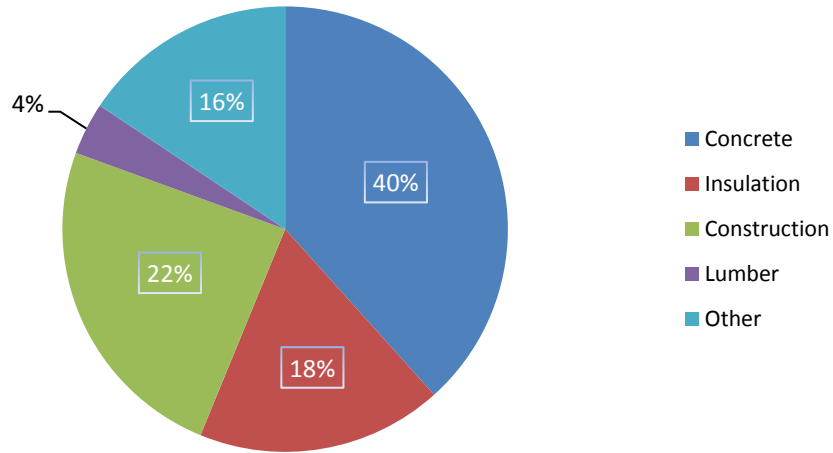
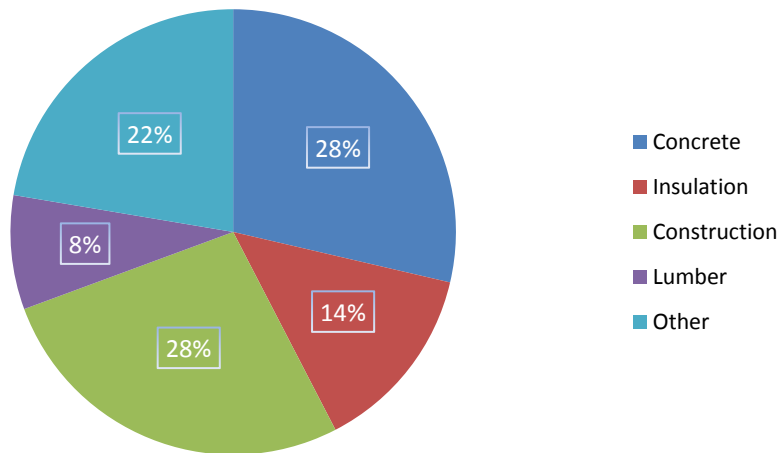


Figure 4-2: Light-frame wood building envelope production energy distribution



Chapter 5: Operation Phase Energy and Green House Gases

5.1 Introduction

A proper accounting of the operational energy of each of the building envelopes is crucial for the accuracy of the study as the operation phase of a building is generally responsible for the largest portion of the life cycle energy use, given both its duration and intensity. Energy use during the building's operation phase is modeled using the Department of Energy's eQUEST energy modeling program, as the program calculates the annual energy use of the building, and as stated in the methods section, the annual energy use is extrapolated throughout the useful life building to determine the total operation phase energy use.

A parametric analysis is conducted for the operation phase of the building envelopes in order to better understand the relative influence some their primary characteristics have on the overall performance of the envelope. The characteristic of interest for the building envelope are; infiltration, thermal mass, and thermal resistance. Additionally, the building envelopes were modeled with both; ground source heat pump (GSHP), and air heat pump (AHP) mechanical air conditioning systems. This is to provide better understanding of the relative influence that, both, the building envelope and mechanical system have on the annual energy performance of the building. Additionally, it will allow an observation of the relative level of energy performance for each of the envelopes when utilizing air conditioning systems of greater and lesser efficiency; the air heat pump being the system of lesser efficiency.

To assure a level of accuracy for the results, the ICF energy model was constructed with similar properties and parameters to the existing ICF house, and was compared according to their annual energy performance. Relative to the annual performance of the existing house, the results of the ICF model has an error of less than 1%. It is important to note that the performance was not calibrated according to the existing house, however it was simply modeled with parameters similar to those of the house. The ICF model is deemed to have a level of agreement with the actual behavior of the existing house, as this level of error is within an acceptable range for the modeling of building energy use. Variation in the behavior of the model and the existing house is inevitable given the difficulties of modeling the performance of such a complex system. Variation in energy use may be attributed to a number of different factors, however it should be noted that

the existing house has a partial basement, as opposed to the full basement characterized in the energy model, and also has some variation in material use, and roof shape.

5.2 Building and Material Useful Life

The useful lives of the ICF envelope and each of the light-wood frame building envelopes are assumed to be equivalent for the purposes of this study, as each building envelope is assessed for both a 60, and 100 year lifespan. This assumption is based on research which suggests that, although the durability of the concrete structure of the ICF envelope is greater than the wood frame durability, the useful life of a structure is primarily determined by the level of maintenance provided to finish surfaces and other non-structural elements (Horst, O'Connor, & Argeles, 2005). Generally, these elements do not include the wood framing of light-frame construction or the concrete walls of ICF construction, as these are structural elements. Literature suggests that structural deficiency is often not the cause for the removal of a structure, and that the structure will reside so long as it remains functional for the purposes of the given site. As the useful life of a residential structure in the U.S., with reasonable maintenance, will often last for 60, this seems as an appropriate lower boundary for the study. As the useful life of properly maintained wood frame houses have proven to last for 100 years, and beyond, this seems as an appropriate upward boundary for the study.

For the purposes of this study, it is assumed that the building is properly maintained during its useful life. Proper maintenance for the building envelopes entails replacement of the various building materials at the end of their respective useful life. The operation phase accounts for the additional embodied energy input due to the replacement of each of the materials at the end of their respective useful life. For each of the given building envelopes, the only materials which require replacement during the buildings useful life are the vinyl cladding, asphalt roofing material, and the windows, as they must be replaced every 35, 20, and 25 years, respectively (Athena Sustainable Materials Institute, 2002).

5.3 Building Envelope Materials and Properties

Ultimately, the physical properties of the building envelope determine the heating and cooling load imposed on the building mechanical system. The ICF building envelope and the light-frame

wood building envelope differ substantially in terms of their physical properties. The differences are most prominent with regard to the thermal mass, thermal conductivity, and infiltration flow of the two wall assemblies. As the skeletal building type of light-frame wood construction allows for light, easily managed wall enclosures, they provide minimal thermal storage given the walls' limited heat capacity. The ICF building envelope is a monolithic construction type, as the concrete both supports and forms the enclosure of a building. This results in a considerably higher thermal mass, several times greater than the light-frame wood wall assembly.

5.3.1 Thermal Resistance Parameters

The thermal resistance of each of the building assemblies differ due to the different forms of wall insulation utilized. The 5.5 inches of polystyrene insulation used in the ICF wall cross-section contributes the majority of its 32 hr-ft²-°F/BTU of thermal resistance. For each of the light-frame wood envelopes, fiberglass batt insulation is utilized within the wall cavity. For the 'wood frame 1' envelope, the batt insulation provides the majority of its 16 hr-ft²-°F/BTU of thermal resistance. The 'wood frame 2' envelope has an additional 2 inches of polyurethane insulation increasing the thermal resistance to roughly 28 hr-ft²-°F/BTU. The basement walls of the two envelopes provide equivalent resistance to the walls of the ICF structure. The surface roughness and reflectivity of the two wall assemblies are identical, given that they share the same exterior vinyl cladding material and interior gypsum board finish, however the contribution of these parameters are negligible. The two envelopes utilize identical windows and window frames, as the center pane window resistance is 2.2 hr-ft²-F°/BTU and the window frame provides 1.5 hr-ft²-F°/BTU. The roof assemblies of each of the building envelopes are identical, each offering 23 hr-ft²-°F/BTU of thermal resistance.

5.3.2 Infiltration Parameters

Infiltration flow is yet another distinguishing physical characteristic of the two building envelopes as the level of infiltration typical of an ICF envelope is considerably lower relative to light-frame construction. Infiltration flow calculations are performed according to Sherman-Grimsrud methodology, as stated in the methods section 3.5.3, utilizing a stack coefficient value (C_s) of 2.41 (in. of water/°F), correlating with a two story residence with a flue. A wind coefficient (C_w) of 2.14 (in. of water/mph²) is used in correlation with a two story residence with a slab on grade

basement and a flue. A shelter factor (s) of 0.64 is used, which is characteristic of building with obstructions within close proximity of the structure. The flow coefficients (c) of the light-wood frame and ICF building envelopes differ, and are reflected in their respective leakage area fraction values. The light-frame wood envelope has a leakage area fraction of 0.00050 of the floor area, based on Sherman-Grimsrud methodology. The ICF building envelope is regarded as a tight building enclosure, as based on a study performed by the Oak Ridge National Laboratories where the ICF envelope has a leakage area fraction of 0.00038 times the floor area according to Sherman-Grimsrud methodology (Petrie, et al., 2002).

5.3.3 Thermal Mass Parameters

The effectiveness of the additional thermal mass, of the ICF building envelope, to reduce energy use was estimated based on the annual and monthly energy use of the eQUEST building models. It was hypothesized that a building of greater thermal mass would afford a higher level of performance as, theoretically, this building envelope should maintain the indoor temperature with greater ease. The ICF wall envelope has substantial thermal mass, given its 70 lbs/ft² unit weight, mostly attributed to the 6 inch thick layer of concrete. The discrepancy in thermal mass of ICF and light-frame wood building envelopes' is significant, as the unit weight of the light-frame wood wall is an estimated 12 lbs/ft².

5.4 HVAC Systems

5.4.1 HVAC System Parameters

In order to make the analysis of the two building envelopes as true a comparison as possible, each of the mechanical systems were modeled to be as similar as possible, aside from the variance in the required size of the units. The heat flux through a given building envelope determines the amount of refrigeration capacity required of the mechanical system. The flux of heat through the building envelope is dependent on the characteristics of the building envelope, particularly the infiltration, thermal resistance, and thermal mass.

The mechanical system of the ICF house requires just over 2.25 tons (27500 BTU/hr) of refrigeration capacity at minimum. The 'wood frame 1' and 'wood frame 2' envelopes requires

3.5 and 2.75 tons (42000 and 33000 BTU/hr) of refrigeration capacity, respectively. The systems are sized to handle refrigeration loads of 1.15 times the maximum anticipated heating or cooling load. Due to the variation in cooling and heating demand of the building envelopes, their respective HVAC systems differ in refrigeration capacity and ground loop trench length, however nearly every other parameter of their each of their systems are identical. It is a ducted systems equipped with heat recover ventilators and supply a flow 10 percent non-recirculated air from the outdoors. The heating and cooling design temperatures are 72°F and 75°F, respectively. The supply fans are cyclic and operate at an efficiency of 53%, with a design flow of roughly 35 cfm per occupant, assuming two occupants. Each of the building envelopes are modeled with both, ground source heat pump and air heat pump HVAC systems.

5.4.2 Ground Source Heat Pump System

The ground source heat pump (GSHP) systems are dual function unit, used to meet both the required heating and cooling demands. The GSHPs are modeled to simulate the behavior of systems with horizontal u-tube ground loops placed at a depth of 6 feet. At this depth, the ground temperature is assumed as 61°F, as recommended by ASHRAE for clay soil types for the given geographical conditions of Rockwood, Tennessee. As GSHP systems utilize the earth as both a heat source and a heat sink, the below grade soil conditions factor into the performance of the HVAC system.

Based on recommendations from the ASHRAE Handbook, the ground source system of the ICF house is modeled to have 750 ft of pipe and a pipe diameter of 1 in (0.88 in inside diameter), required for clay soil conditions as exist in eastern Tennessee. This specification correlates with the 27500 BTU/hr load of required refrigeration capacity. The GSHP system of the light-frame wood house requires 2400 ft of pipe, of the same diameter, given the more intensive heating and cooling requirements of 42000 BTU/hr. The thermal conductivity of the soil is assumed to be 0.75 BTU/h-ft-°F and the soil diffusivity was assumed as 0.025 ft²/hr. These properties are characteristic of a heavy clay soil with a unit weight of 120 lbs/ft³ and moisture content between 5 to 15%. The thermal conductivity of the piping material is 0.2970 BTU/h-ft-°F. The ground source heat pump HVAC system is modeled to have an overall heating coefficient of performance (COP) of 3.2 and cooling energy efficiency ratio (EER) of 14. Although GSHPs are capable of

performing at more efficient levels, these performance characteristics are slightly conservative, yet are representative of a typical GSHP supported HVAC system.

5.4.3 Air Heat Pump System

The ICF house and the light-frame wood house were both modeled with an air to air heat pump (AHP) system. The AHP system is a dual function unit used to meet both the heating and cooling demands of a house. The system relies on fewer variables than the GSHP system, and is more reliant on outdoor air conditions. As the outdoor air temperature range is much greater than the subsurface temperature range, with temperatures straying much farther from the indoor design temperature, the AHP systems are less energy efficient than the GSHP systems. For the ICF envelope and for the two wood frame houses, the refrigeration capacities are 28000, 42000, and 33000 BTU/h-ft-°F, respectively, equivalent to those required for the GSHP. However, the AHP has a coefficient of performance for heating of 2.0, and a cooling energy efficiency ratio of 9. These values are representative of the true behavior of AHP systems.

5.5 Results

5.5.1 Energy Use with Ground Source Heat Pump

As anticipated, the ICF envelope offers the best annual energy performance of the three building envelopes due primarily to its high thermal resistance and low rate of infiltration, relative to the two light-frame wood envelopes. The ICF structure has an annual energy demand of 16% less than the conventional wood frame envelope, as the annual energy requirements for the two building envelopes are approximately 43 GJ and 51 GJ, respectively (Table 5-1). In comparison with the heavily insulated wood frame envelope, which requires 49 GJ of energy use annually, the ICF envelope requires 12% less annual energy use.

5.5.2 Energy Use with Air Heat Pump

Inevitably, each of the building envelopes consumed more energy, annually, when modeled with the AHP, as opposed to the GSHP. However, the purpose for modeling each envelope with the AHP, in addition to the GSHP, is to compare the performance of the building envelopes relative

to one another, using mechanical systems of varying efficiency. As shown in table 5-1, the relative deviation in the annual energy use when using the AHP, is similar to the GSHP, as the ICF envelope consumes 53 GJ, 16% and 13% less energy than the 63 and 61 GJ of annual energy use for the wood frame 1 and wood frame 2 envelopes, respectively. Modeled with the GSHP, the ICF envelope required 16% and 12% less energy than the two wood frame building envelopes.

Table 5.1: Gigajoules of monthly operational energy use - delivered energy

Month	Ground Source Heat Pump			Air Heat Pump		
	ICF Model	Wood Frame 1	Wood Frame 2	ICF Model	Wood Frame 1	Wood Frame 2
January	5.15	6.26	5.98	8.06	9.68	9.32
February	4.32	5.33	5.08	6.19	8.17	7.88
March	3.78	4.68	4.54	4.79	6.37	6.08
April	2.63	3.24	3.17	3.02	3.46	3.35
May	2.52	2.92	2.84	3.10	3.28	3.20
June	3.38	3.64	3.64	3.71	3.60	3.60
July	4.10	4.50	4.46	3.92	4.03	4.00
August	4.14	4.54	4.46	3.96	4.07	4.03
September	2.92	3.06	3.06	3.46	3.28	3.24
October	2.41	2.84	2.70	3.13	3.60	3.46
November	3.49	4.39	4.03	4.03	5.54	5.33
December	4.32	5.40	5.18	5.72	7.78	7.45
Total	43.2	50.8	49.1	53.1	62.9	60.9

5.5.3 Green House Gas Emissions

Unlike the processes of the production phase, operation phase green house gas emissions for a given system are proportional to their respective energy use, as power generation parameters do not vary according to the envelope, yet only according to the fuel mix. Based on the fuel energy mix of the local grid, 157 grams CO₂ eq/MJ of electrical energy is emitted during power generation. Of the three building assemblies, the ICF envelope has the smallest GHG intensity, releasing 7.48 tons CO₂ equivalents annually while utilizing a ground source heat pump (GSHP). This total increases to 9.20 tons CO₂ equivalents when utilizing an air heat pump (AHP). Overall, the use of the ICF building envelope in place of the conventional wood frame 1 building envelope results in a 15% reduction in annual operation phase GHG emissions as the wood frame 1 envelope is attributed to 8.80 and 10.90 tons CO₂ eq./yr for the GSHP and AHP, respectively.

The wood frame 2 building envelope is responsible for 8.51 and 10.55 tons CO₂ equivalent emissions annually for the GSHP and AHP, respectively.

Figure 5-1: Building envelope monthly energy use when utilizing a ground source heat pump – Gigajoules

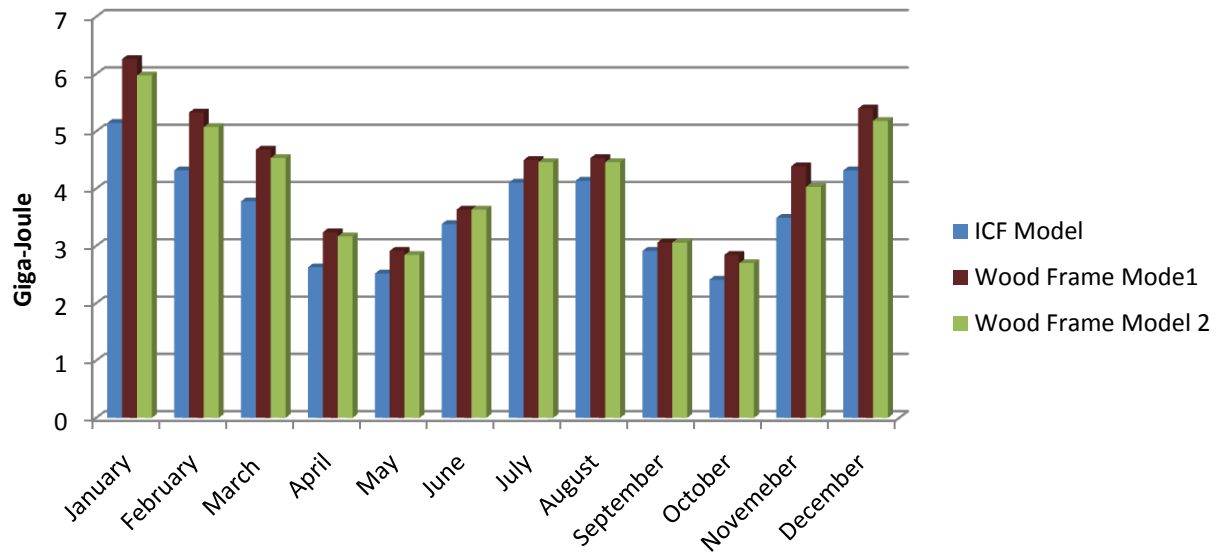
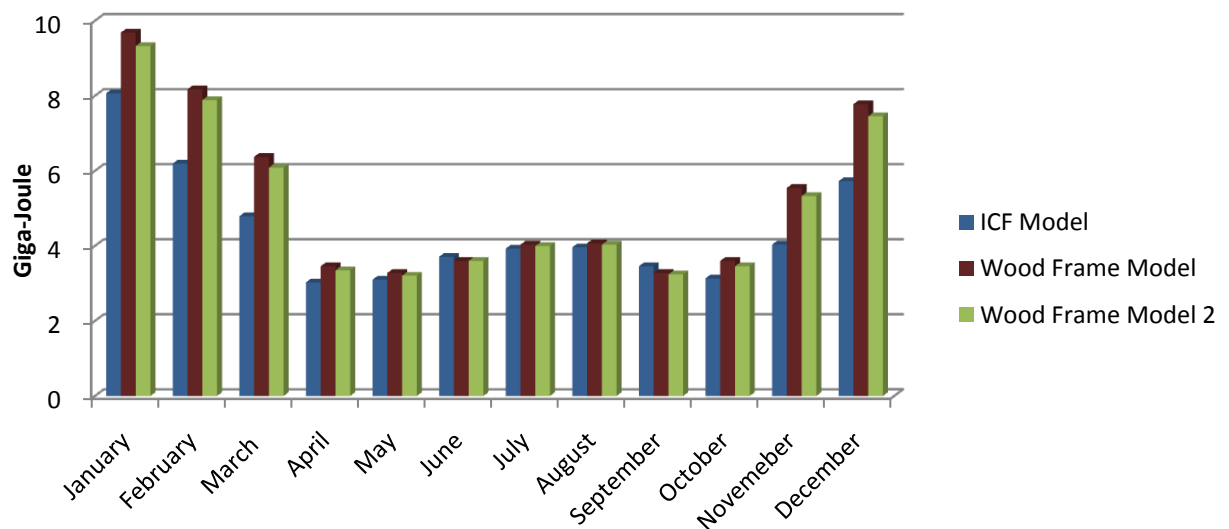


Figure 5-2: Building envelope monthly energy use when utilizing an air source heat pump – Gigajoules



5.6 Discussion

5.6.1 Performance of the Envelopes

Variation in the energy performance of the three building envelopes is fairly significant, even more so if the values were extrapolated throughout a portion of the life cycle. Ultimately, the annual energy use of the ICF, wood frame 1, and wood frame 2 building envelopes are 43.2, 50.8, and 49.1 GJ, respectively. For each of the building envelopes the greatest energy demands occur during the winter months, requiring nearly twice the amount of energy, regardless of the type of heat pump utilized, as the extreme winter temperatures deviate further from the indoor design temperatures than the extreme summer temperatures. Given the behavior of heat pumps in sub-tropical climates, the further the outdoor air temperatures stray from indoor comfort temperatures, the more work required of the refrigeration cycle of the air conditioning system. Using the GSHP, as opposed to the AHP, reduces the annual energy demand 22 to 24 percent for the three building envelopes. However, these reductions occur primarily during the winter months, as the energy use of the envelopes during the summer months, using AHPs, is either equivalent or slightly lower.

5.6.2 Infiltration Contribution

To gauge the influence of the infiltration, a check was done on the Sherman-Grimsrud infiltration parameter of the ICF envelope, increasing the leakage area from $0.0038 \text{ ft}^2/\text{ft}^2$ to the equivalent of the light-frame wood envelope, $0.0005 \text{ ft}/\text{ft}$. This resulted in an increase in annual energy use of 3.8% for the ICF envelope using a ground source heat pump. Conversely, reducing the infiltration parameter from $0.0005 \text{ ft}^2/\text{ft}^2$ to $0.00038 \text{ ft}^2/\text{ft}^2$, the respective values of the light-frame wood and ICF envelopes, reduces the annual energy use of the wood frame envelope by 3.5%.

A parametric analysis shows that the Sherman-Grimsrud infiltration leakage fraction has a nearly linear effect on the energy use of the building envelope as seen in figure 5-3. As the infiltration leakage area increases the momentary energy demand increases, potentially calling for a larger size unit and requiring even more energy use.

5.6.3 Thermal Resistance Contribution

The thermal resistance of the walls has considerable effect on the performance of the envelope, however according to the building energy model, as the thermal resistance value (R-value) of the building envelope increases; reductions in energy use slowly decrease as shown in figure 5-4. This is partly because the window openings have a constant flux of heat, given their constant 2.1 R-value, allowing decreases in energy use only to a certain extent. As the thermal resistance varies from low to high, energy use decreases in a nearly linear fashion until it surpasses a threshold at roughly 22 h-ft²-°F/BTU, as the behavior then becomes curvilinear.

Figure 5-3: Annual energy use (GJ) vs. infiltration leak fraction (ft²/ft²) utilizing ground source heat pump

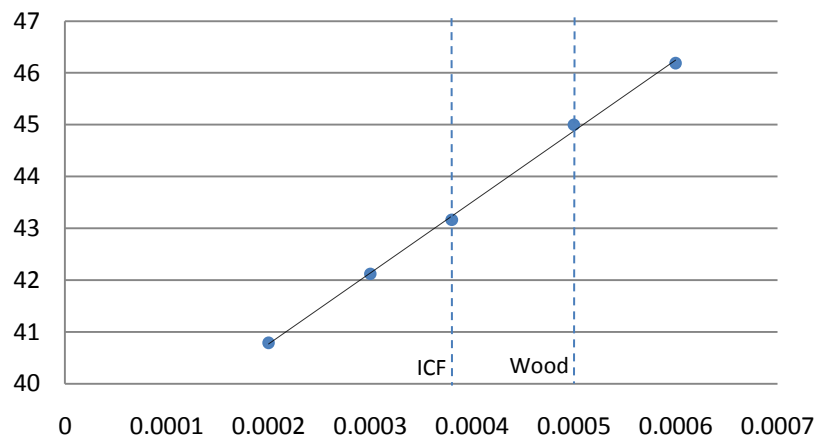
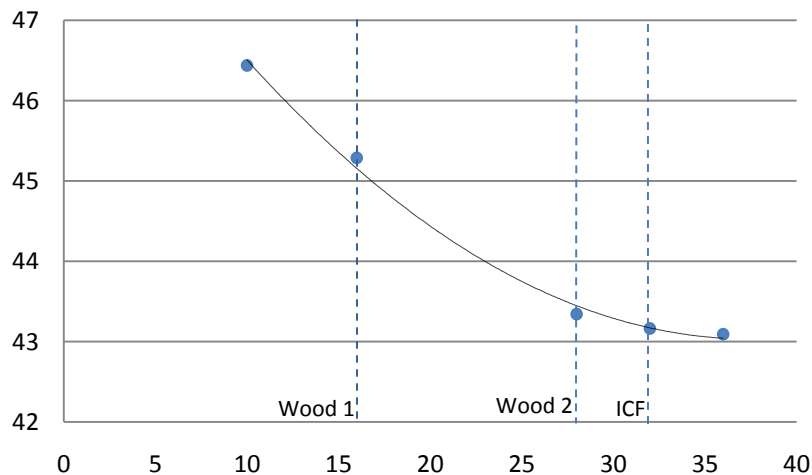


Figure 5-4: Annual energy use (GJ) vs. thermal resistance (h-ft²-°F/BTU) utilizing ground source heat pump



5.6.4 Thermal Mass Contribution

According to the behavior of the energy model, the contribution of thermal mass to the performance of the ICF building envelope is minimal. A wall was modeled with properties identical to the ICF wall, with the exception of thermal mass which was modeled to have the thermal mass of the light-frame wood wall, and performed similarly to the ICF wall. This resulted with an increase in energy use of only 0.33% of the previous value. The small amount of benefit came mostly during the temperate periods of the spring and fall months. The Thermal mass was less beneficial in the extreme winter and proved to be detrimental during the hot season. It is believed that the meager effect of the thermal mass of the ICF building envelope may be due to the level of thermal resistance afforded on both faces of the of the concrete in the ICF wall (15 h-ft²-°F/BTU). Ultimately, as the thermal resistance of the confining material of the wall mass increases, the opportunity for heat to be absorbed into the mass decreases, minimizing the influence of the thermal mass.

5.7 Conclusions

Although the change in thermal resistance is greatly responsible for deviations in energy use, the infiltration properties of the ICF envelope offer benefits unavailable to the light-frame wood envelopes, as its reduced infiltration fractional leakage area of the ICF is key for its energy reductions relative to the light frame wood envelopes. This is particularly true in regard to the variation in energy demand between the ICF envelope and the more heavily insulated ‘wood frame 2’ envelope. This is illustrated by the relationship of thermal resistance and energy use, as shown in figure 5-4, as the increased thermal resistance the wood-frame envelope converges on the thermal resistance of the ICF envelope, the ICF envelope maintains its relatively superior energy performance.

Chapter 6: End of Life Phase

6.1 Introduction

The end of life phase of the building envelopes includes the demolition and recycle of the building materials. For data regarding the demolition and recycle operations for both the wood and concrete structures, reference was made to the Athena Institute of Sustainable Materials. The data was initially derived from demolition operations performed on office buildings; however the data was generated to reflect more general deconstruction and recycle operations. According to the evaluation, demolition and recycling processes for wood structures is slightly more intensive than for concrete structures, particularly during recycling, due to the more delicate, labor intensive processes required for the separation of materials during disassembly. For each of the structures, it is assumed that the exterior cladding and interior finish materials are removed from the building, as the structural materials are the primary recyclables.

6.2 Light-Frame Wood Demolition and Recycle

The wood structure demolition and recycle data accounts for the deconstruction of wood frame walls with plywood sheathing, in addition to floor and roof plywood sheathing, glue-laminated beams and columns, and engineered wood joists. The light-frame wood building envelopes of this study are composed of both wood and concrete elements, given the basement structure consists mostly of concrete. However, this is accounted for in the wood structure demolition and recycle total. It is assumed that both the above and below grade demolition is conducted using excavators which are equipped with various grapple and demolition attachments. The wood material is disassembled and subsequently chipped into smaller material on-site for ease of transportation. The below grade concrete material is excavated, broken into rubble, and transported off-site. Overall, operations for the demolition and recycle of wood structures are estimated to require roughly 11.0 MJ/ft² of floor area.

6.3 Insulated Concrete Form Demolition and Recycle

The concrete structure demolition and recycle data accounts for the deconstruction of reinforced, cast in place shear walls, columns, floor slabs, and roof slabs. Typically, recycle concrete from

demolished structures is broken into rubble, shipped from the site, and subsequently crushed and used as feedstock material for products such as concrete masonry units and new concrete. Reinforcing steel is cut and separated from the concrete as the material is broken into rubble. Concrete structures are estimated to require roughly 9.6 MJ/ft² of floor area, however given that operations for wood disassembly and recycle are estimated to be more energy intensive, a slightly increased value of the concrete demolition energy is utilized to account for the recycle of the wood frame roof structure of the ICF envelope. The demolition and recycle energy of the ICF envelope is estimated to require roughly 10 MJ/ft² of floor area.

6.4 Results and Discussion

Overall, the end of life energy of the building envelopes is not very significant relative to the other stages of the life cycle. The end of life energy would, most likely, be reduced assuming that all materials were disposed of by landfill, however the wood, concrete, and steel materials of the building envelopes are recycled. The energy uses for demolition and recycle of the three building envelopes are nearly equivalent, as for the roughly 2400 ft² of total floor area of the structure, the ICF building envelope required 24.0 GJ of energy for demolition, disposal, and recycle. The light-frame wood envelopes require 26.4 GJ of energy throughout end of life operations. It should be reiterated that these values are representative of the energy required to prepare the salvageable material from the demolition waste to serve as feedstock material for the subsequent life cycle.

Green house gas emissions were not calculated for end of life operations due to insufficiency of data. The GHG intensity per unit of energy use during the end of life operations would be expected to be relatively high given that nearly all of the power would most likely be generated on-site by the combustion of fossil fuels. However, given that energy use is somewhat reflective of GHG emissions, and based on the limited energy requirement of the end of life phase, it is believed that end of life operations have only a limited impact on life cycle GHG emissions.

Chapter 7: Life Cycle Assessment Results

7.1 Results

Ultimately, there is substantial deviation amongst the various life cycle energy sums. Considering delivered energy, the variance in energy use amongst the building systems is evident, yet somewhat modest; however, when primary energy is considered, the variance becomes even more defined, and only increases as the useful life of the building increases (Figures 7-1, 7-2). When considering only the delivered energy, while utilizing a ground source heat pump, the life cycle energy use for the ICF, wood frame 1, and wood frame 2 building envelopes are 3090, 3462, and 3368 GJ, respectively, for a 60 year life cycle (Table 7-1). For a 100 year life cycle, the values increase to 4865, 5543, and 5382 GJ, respectively, as the relative proportion of the operation phase increases (Table 7-2). However, these figures are not representative of the entire ‘life cycle’ energy use, as they do not consider energy losses during the production and delivery of the energy, and only represent a portion of the life cycle energy use. The power generation efficiency for the operation phase of the life cycle is determined to be 0.427 based on the fuel mix of the energy grid. For the given efficiency, the life cycle energy use (primary energy) for the ICF, wood frame 1, and wood frame 2 envelopes are 6561, 7548, and 7319 GJ for a 60 year useful life, and 10649, 12354, 11967 for a 100 year useful life, respectively.

Given that green house gas (GHG) emissions during the operation phase of the building envelopes are proportional to energy use, and the predominance of operational energy use within the life cycle energy sum, the large majority of green house gas emissions occur during the operation phase, as displayed in figure 7-3. Although the ICF building envelope has the highest production phase GHG intensity of the three envelopes, it has the lowest life cycle GHG intensity, releasing 505 tons of CO₂ equivalents airborne during its production and operation phases given a 60 year useful life, and 812 tons assuming a 100 year lifespan, both while utilizing a ground source heat pump. Although end of life GHG emission are not accounted for in this energy sum, due to the nearly negligible energy use of the end of life phase of the life cycle, it is believed that the summation of GHGs emissions presented is representative of the life cycle life cycle emissions of the envelopes.

Figure 7-1: Life cycle delivered and primary energy use of building envelopes for 60 year useful life – gigajoules

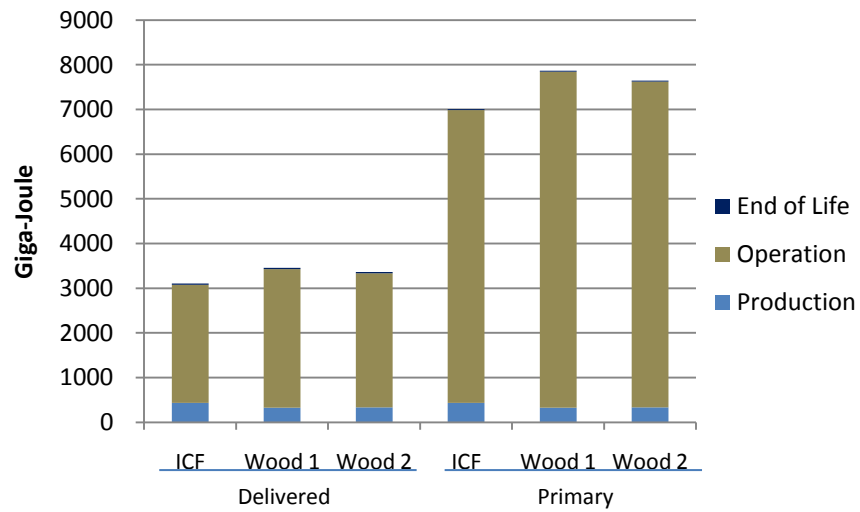


Figure 7-2: Life cycle delivered and primary energy use for 100 year useful life – gigajoules

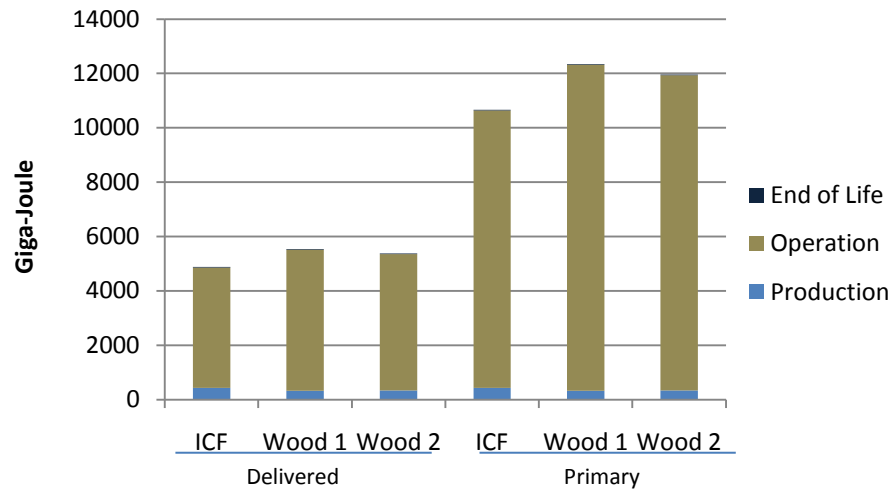


Figure 7-3: Life cycle green house gas emissions – Tons CO₂ equivalents

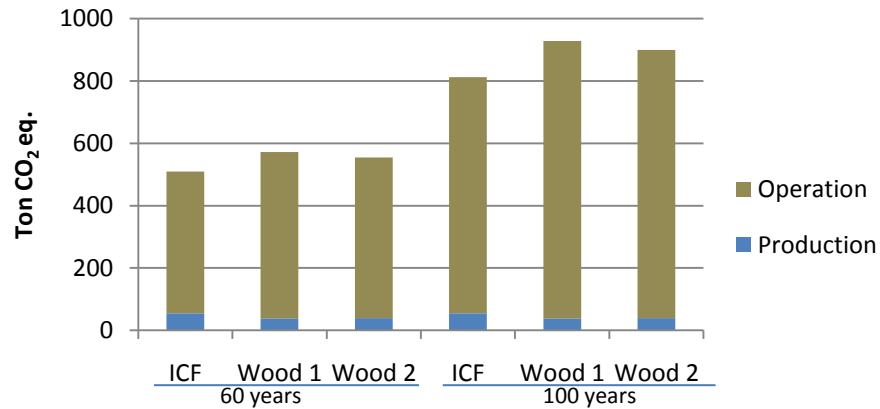


Table 7-1: Life cycle delivered and primary energy use of building envelopes for 60 year useful life – Gigajoules

Case	Ground Source Heat Pump						Air Heat Pump					
	ICF Delivered	ICF Primary	Wood Frame 1 Delivered	Wood Frame 1 Primary	Wood Frame 2 Delivered	Wood Frame 2 Primary	ICF Delivered	ICF Primary	Wood Frame 1 Delivered	Wood Frame 1 Primary	Wood Frame 2 Delivered	Wood Frame 2 Primary
Production	422	422	331	331	339	339	422	422	331	331	339	339
Operational	2644	6115	3105	7191	3003	6954	3240	7510	3826	8875	3712	8612
End of Life	24	24	26	26	26	26	24	24	26	26	26	26
Total	3090	6561	3462	7548	3368	7319	3686	7956	4183	9232	4077	8977

Table 7-2: Life cycle delivered and primary energy use of building envelopes for 100 year useful life – Gigajoules

Case	Ground Source Heat Pump						Air Heat Pump					
	ICF Delivered	ICF Primary	Wood Frame 1 Delivered	Wood Frame 1 Primary	Wood Frame 2 Delivered	Wood Frame 2 Primary	ICF Delivered	ICF Primary	Wood Frame 1 Delivered	Wood Frame 1 Primary	Wood Frame 2 Delivered	Wood Frame 2 Primary
Production	422	422	331	331	339	339	422	422	331	331	339	339
Operational	4419	10203	5186	11997	5017	11602	5413	12528	6385	14803	6198	14365
End of Life	24	24	26	26	26	26	24	24	26	26	26	26
Total	4865	10649	5543	12354	5382	11967	5859	12974	6742	15160	6563	14730

Table 7-3: Life cycle green house gas emissions – Tons CO₂ equivalents

Case	60 Year Useful life			100 Year Useful Life		
	ICF	Wood Frame 1	Wood Frame 2	ICF	Wood Frame 1	Wood Frame 2
Production	55	38	39	55	38	39
Operational	454	534	516	757	890	861
Total	509	572	555	812	928	900

7.2 Discussion

Regarding total life cycle energy use and GHG emissions, the ICF building envelope outperforms the two wood frame envelopes for both the 60 and 100 year useful lives, according to the life cycle data presented. Although, the ICF structure has a roughly 28% greater embodied energy relative to the wood frame envelope, the total energy use of ICF envelope breaks even with the two light frame wood envelopes after a relatively small portion of their life cycles. This occurs only 6 years into the life cycle relative to the ‘wood frame 1’ envelope, and after roughly 7 years for the more thermal resistant ‘wood frame 2’ envelope (Figure 7-4). Assuming a 60 year life cycle, the ICF envelope uses roughly 10% to 13% less energy than the ‘wood frame 2’ and ‘wood frame 1’ envelopes, and 11% and 14% throughout a useful life of 100 years.

The operation phase is by far the most energy intensive phase of the life cycle. As the annual operational energy use is extrapolated annually, the initial embodied energy seemingly becomes of less significance regarding total energy use, as observed in Figure 7-5. The y-intercept of each of the energy functions represents the initial embodied energy of the building envelope, as the slope of the functions represent the annual energy use. The slope of each of the energies is not completely continuous, as there are periodic increases in energy use due to scheduled maintenance and replacement of materials as specified in section 5.2. Assuming a 100 year useful life for the ICF, wood frame 1, and wood frame 2 envelopes and utilizing a ground source heat pump, the operation phases of each of their life cycle is attributed to 95%, 97%, and 97%, respectively. For a shorter life cycle of 60 years, the operational energy percentage reduces only to 93%, 95%, and 95%.

Although the operation phase is the most by far the most critical phase of the life cycle, the embodied energies from the production phase of the envelopes’ life cycles are not completely insignificant. The embodied energy of the ‘wood frame 1 envelope, is equivalent to nearly 3 years of primary operational energy, and for the more efficient ICF envelope, is equal to roughly 4.5 years of operation. Overall, when considering total, primary, energy use, the embodied energies constitute between 2.7% and 4.0% of the total life cycle primary energy assuming a 100 year useful life, and between 4.4% and 6.4% assuming a 60 year lifespan. As seen in figures 7-1 and 7-2, the end of life phase is insignificant in comparison to the rest of the life cycle of the building

assemblies. The end of life energy for demolition, disposal, and recycle makes up less than 0.3% of the life cycle energy for any of the scenarios.

Figure 7-4: Break even analysis - Primary energy use (GJ) vs. time (years) utilizing ground source heat pump

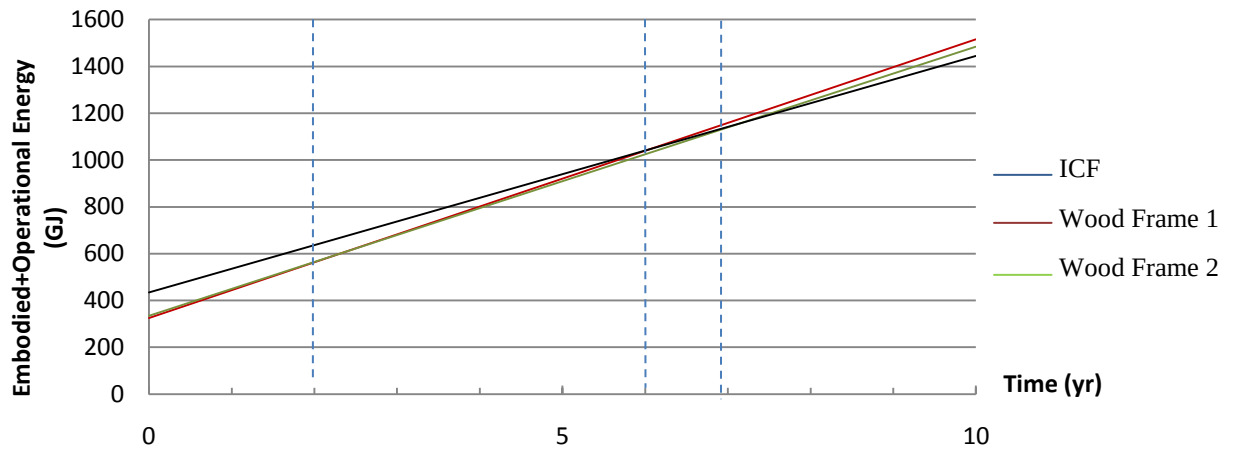


Figure 7-5: Primary energy use (GJ) vs. time (years) utilizing ground source heat pump

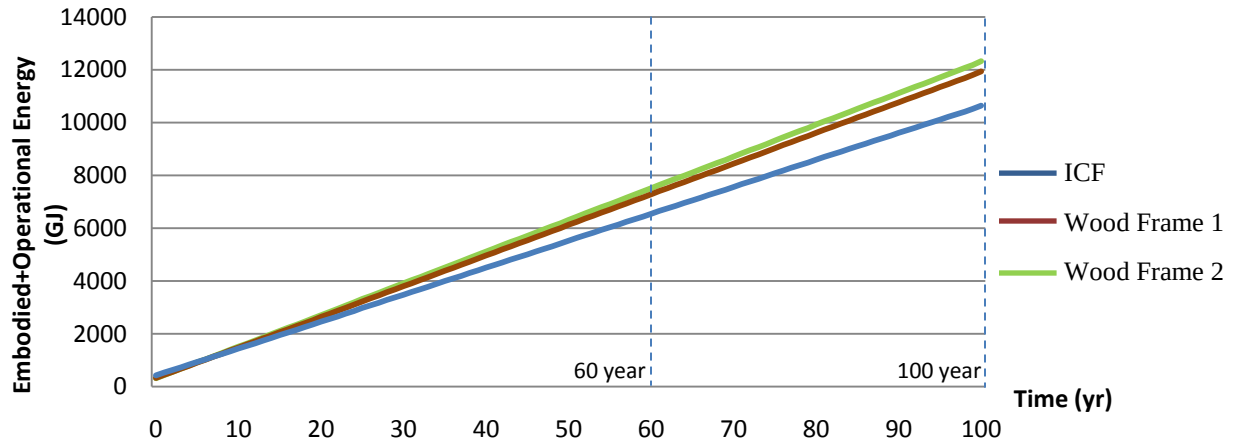
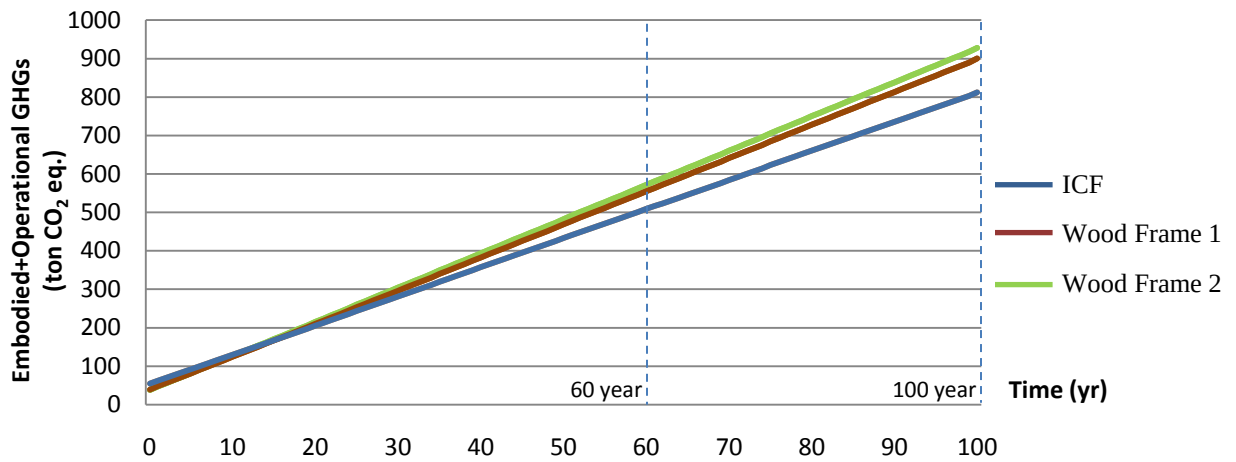


Figure 7-6: Green house gas emissions (Tons CO₂ equivalent) vs. time (years) utilizing ground source heat pump



7.3 Conclusions

As illustrated by the performance of the insulated concrete form (ICF) building envelope, few concessions should be made regarding reductions in either embodied energy, or end of life energy when improvements can be made for the operation phase. According to this study, the additions in embodied energy for the ICF envelope are more than recovered by the reductions in the operational energy use. Regarding light-frame wood construction, the conventional wood frame envelope's alternate building insulation may be utilized for higher thermal resistance for increased performance, however it should be noted that a continuous addition of insulation will not result in continual improvements in the operation phase, as displayed in figure 5-4. As the thermal resistance of a wall increases past a certain extent, increases in thermal resistance of the wall assembly alone become less significant as most of the remaining heat flow occurs at window and door openings. It should be noted that continuous reductions in infiltration leakage area provide continuous reduction in energy use and carbon emissions, as shown in figure 5-3. Therefore, air infiltration should be an area of emphasis when considering the efficiency of a building envelope. This is one of the primary benefits of insulated concrete form construction. Although the performance of the envelope is of great importance regarding energy use, the selection of HVAC system is equally important, given the relative energy performances of the envelopes using the ground source heat pump and the less efficient air heat pump.

Assuming that the infiltration data provided by the Oak Ridge National Laboratories is correct, ICF technology offers reductions in infiltration, relative to conventional wood frame envelopes, and offer increased life cycle energy performance, and life cycle reductions in green house gas emissions. However, it should be noted that alternative wood construction technologies exist, such as structurally insulated panels (SIPS), which offer some reduction in infiltration leakage as well, and should be considered as a potential alternative.

7.4 Future Work

The thermal resistance characteristics of the various building envelope materials are well documented, however the infiltration parameters of these envelopes are not documented to the same standard. In this study, a value for the infiltration leakage area from a very different ICF technology, with half the thermal resistance, was utilized as an infiltration parameter. There is

potential that the infiltration parameter of the ICF technology utilized in this study could be an improved value relative to the value used. As the tightness of a building envelope is of great influence on the thermal performance of an envelope, it would be of great benefit if further research more carefully considered these infiltration parameters.

Regarding the exploration of alternative building envelope options, of particular interest would be structurally insulated panel (SIP) building technology. Prior research has been conducted regarding the operational performance of such structures, and further investigation into the life cycle ramifications of alternative technologies, such as SIPs, would be of benefit.

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Appendices

Appendix A

Table A-1: Life Cycle Material Inventory - Energy use & GHG emissions per unit

Material	Unit	Megajoules	kg CO ₂ equivalents	Resource
Concrete (4000 psi)	ft ³	52	11.1	U.S. LCI
Concrete (3000 psi)	ft ³	55	9.0	U.S. LCI
Southern Pine Dimensional Lumber	ft ³	91	8.9	Athena/ U.S. LCI
Fiberglass Shingle Roofing	ft ²	2.7	0.2	Athena
Plywood Sheathing (1/2")	ft ²	4.1	0.3	U.S. LCI
Oriented Strand Board (3/8")	ft ²	6.4	0.4	Athena/ U.S. LCI
Vinyl Cladding	ft ²	1.4	0.2	Athena/BEDB
Gypsum Board (1/2")	ft ²	3.6	0.2	Athena/ICE
Fiberglass Batt (6")	ft ²	5.1	1.5	Athena/ICE
Polystyrene Insulation	ft ³	31	2.2	Athena/ICE
Polyurethane Insulation	ft ³	25	2.9	ICE
Windows	ft ²	61	4.4	Athena
Reinforcing Steel (#4 bar)	Ft	3.2	0.7	Athena
Construction Energy	ft ²	39		Construction Handbook

U.S. LCI – NREL *U.S. Life Cycle Inventory*

Athena – Athena Sustainable Materials Institute

ICE – University of Bath *Inventory of Carbon and Energy*

Construction Handbook – Department of Energy *Handbook of Energy Use for Building Construction*

BEDB- Department of Energy *Building Energy Data Book*

Appendix B

DOORS		
Men	Size (WxH)	Type
1	3'-0"x8'-0"	Interior
2	3'-0"x8'-0"	Interior
3	3'-0"x8'-0"	Closet
4	3'-0"x8'-0"	Interior
5	3'-0"x8'-0"	Interior
6	3'-0"x8'-0"	Closet
7	3'-0"x8'-0"	Interior (Pocket)
8	3'-0"x8'-0"	Interior (Pocket)
9	3'-0"x8'-0"	Closet
10	3'-0"x8'-0"	Interior
11	6'-0"x8'-0"	Exterior
12	6'-0"x8'-0"	Exterior (Sliding)
13	6'-0"x8'-0"	Exterior (Sliding)
14	3'-0"x8'-0"	Exterior
15	3'-0"x8'-0"	Interior (Pocket)
16	3'-0"x8'-0"	Interior (Pocket)
17	3'-0"x8'-0"	Interior (Pocket)
18	6'-0"x8'-0"	Exterior (Sliding)
19	3'-0"x8'-0"	Interior

WINDOWS		
Men	Size (WxH)	
1	6'-0"x1'-4"	
2	6'-0"x1'-4"	
3	6'-0"x1'-4"	
4	10'-0"x8'-0"	
5	3'-0"x8'-0"	
6	6'-0"x4'-0" (D)	
7	6'-0"x4'-0" (D)	
8	2'-0"x8'-0"	
9	2'-0"x8'-0"	
10	2'-0"x8'-0"	
11	2'-0"x8'-0"	
12	2'-0"x8'-0"	
13	2'-0"x8'-0"	
14	(6) 3'-0"x1'-4"	

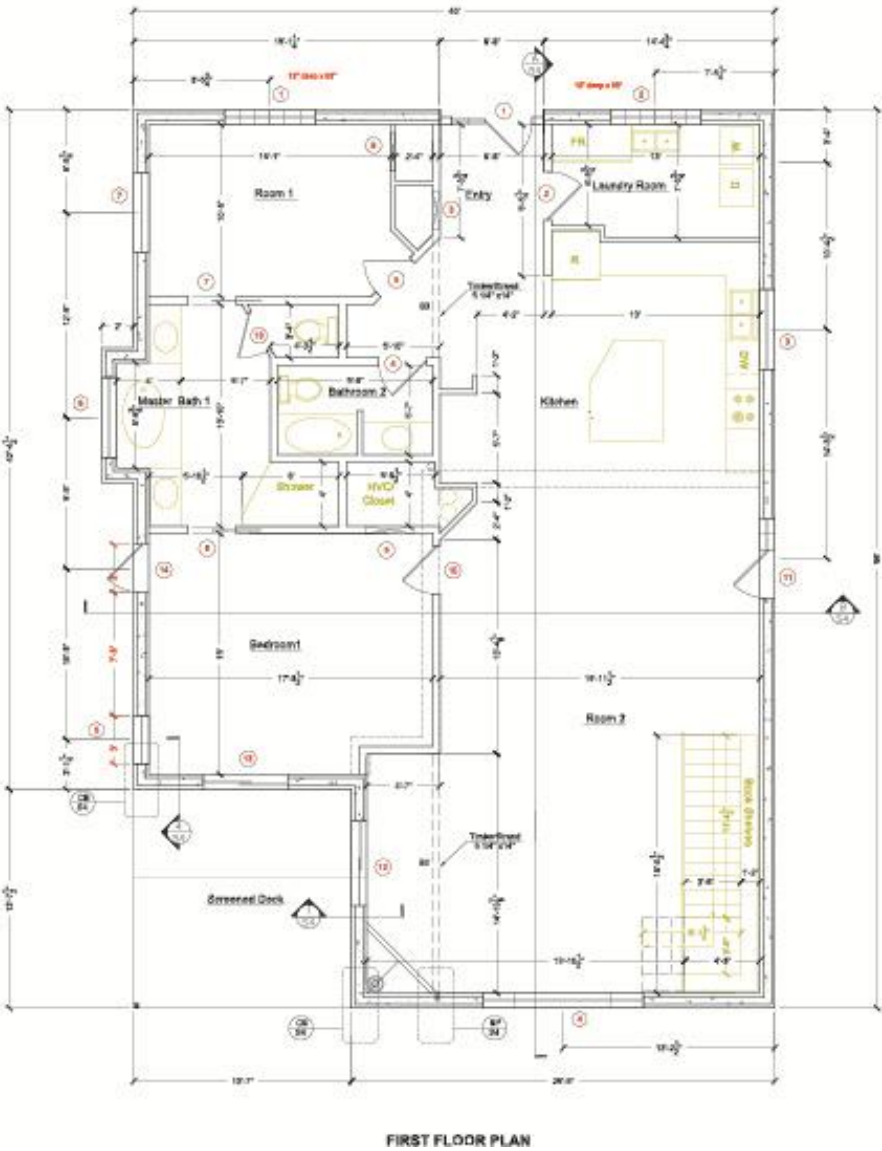


Figure B-1: Entry level floor plan of the case study house

FIRST FLOOR		
ID		Area (sqft)
1	Room 1	117.8
2	Room 2	711.2
3	Kitchen	248.8
4	Entry	188.5
5	Laundry	89.2
6	Bedroom 1	230.8
7	Bedroom 1	191.7
8	Bedroom 2	56.8
9	Screened Deck	185.1
TOTAL:		2,510.8

BASEMENT		
ID		Area (sqft)
1	Basement	994.4
2	Patio	135.1
TOTAL:		999.5

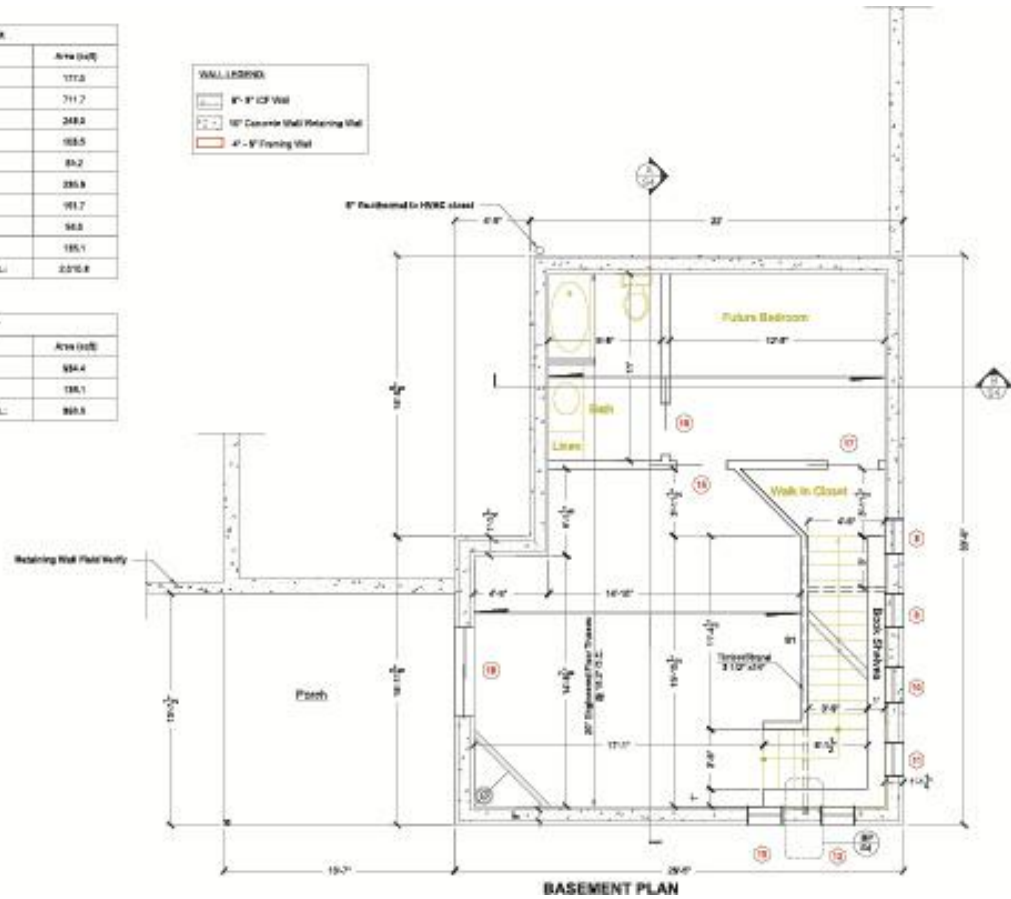


Figure B-2: Basement level floor plan of the case study house

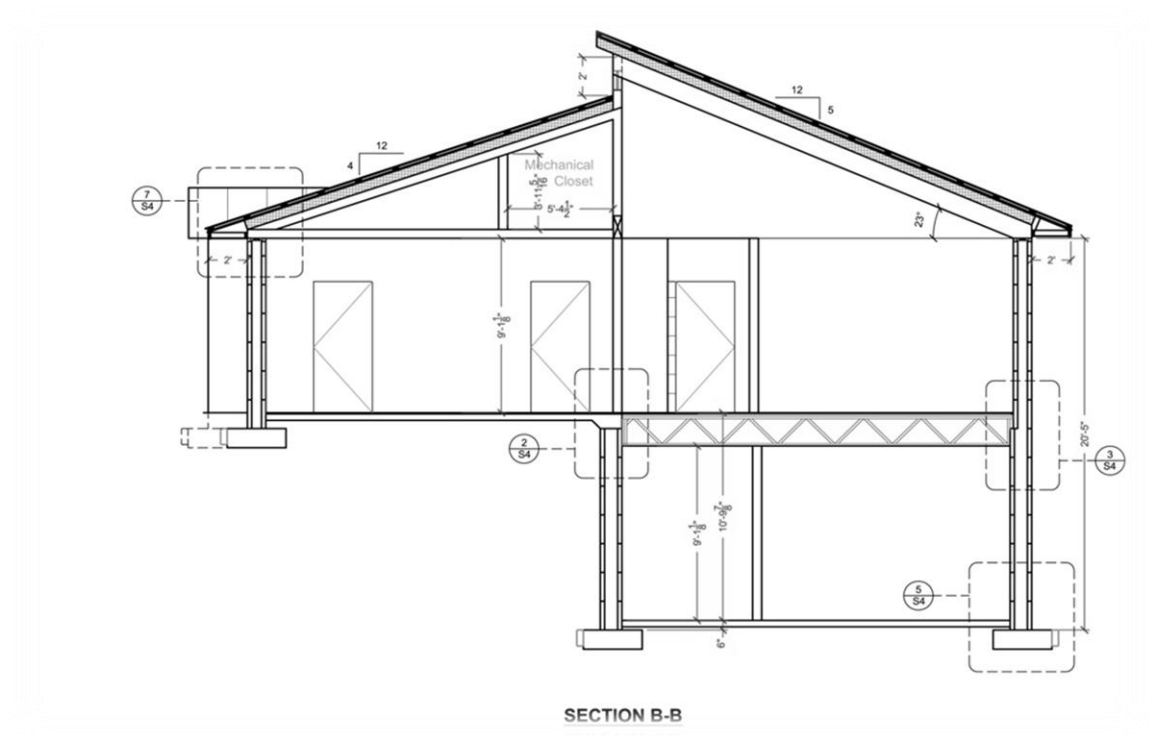


Figure B-3: Transverse Section of the case study house

Appendix C

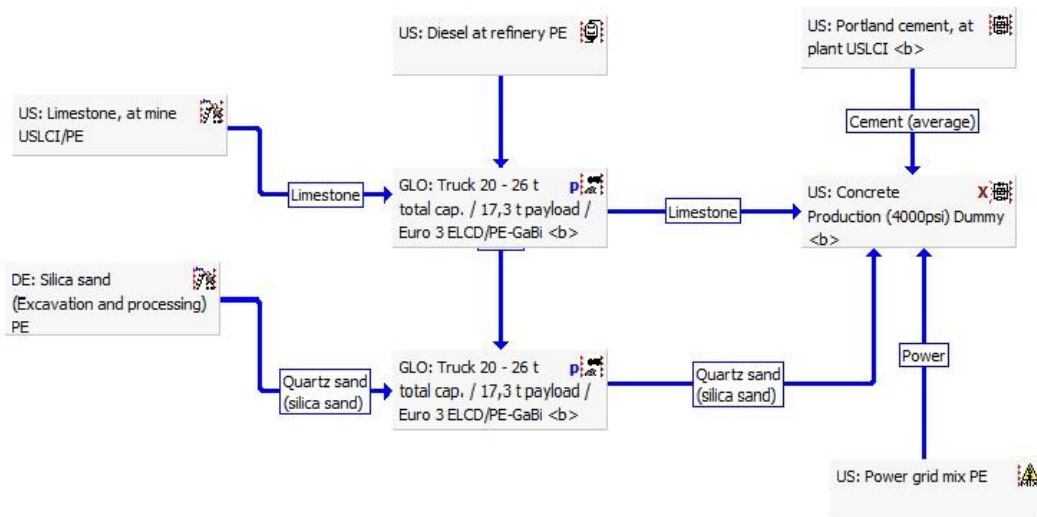


Figure C-1: Example flow diagram from GaBi LCA Software – Concrete production

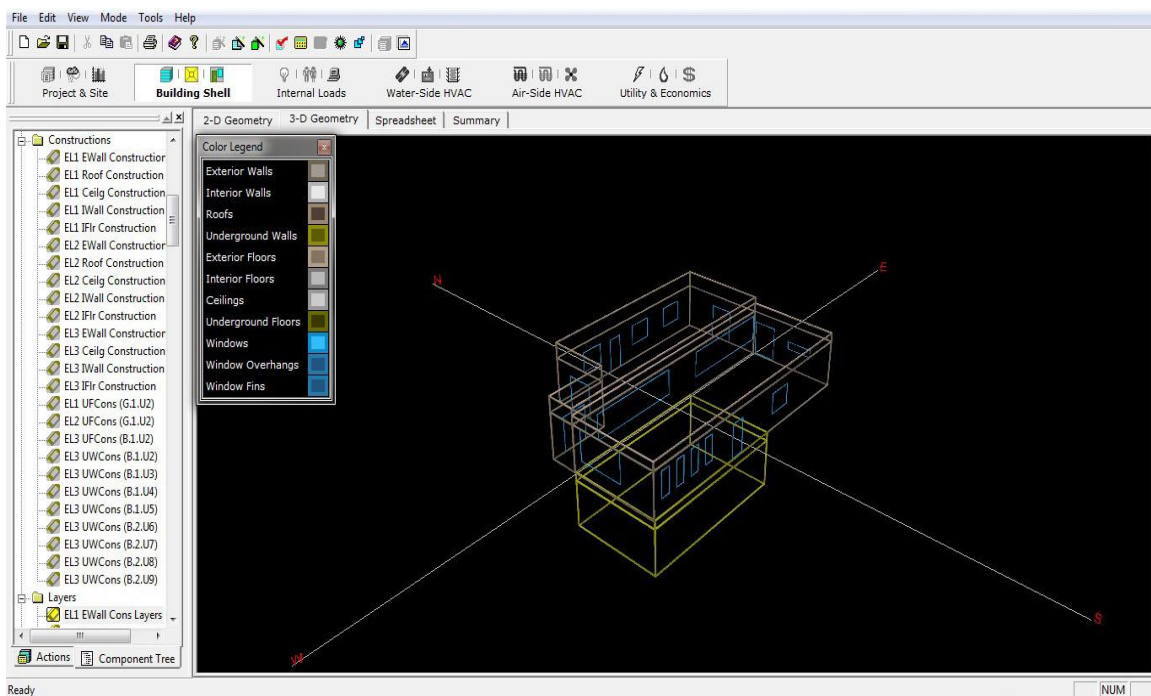


Figure C-2: eQUEST energy model of case study house

Vita

Sherman Authur Matthews was born on August 18th, 1985 in the city of Knoxville, Tennessee. He graduated from Knoxville West High School in May of 2003. He was then enrolled by the College of Architecture at the University of Tennessee. In August of 2004, he began coursework for a second major in Civil Engineering. In May of 2008, he earned a Bachelor of Architecture and later earned a Bachelor of Science in Civil Engineering in May, 2009. In January, 2010, he was enrolled as a Master of Science student by the Department of Civil and Environmental Engineering at the University of Tennessee. Through one and a half years research and study, he completed the requirements for his Master of Science degree in Civil Engineering (structural concentration) in August of 2010.