Methods, Impacts, and Opportunities in the Concrete Building Life Cycle

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EXECUTIVE SUMMARY

Life cycle assessment (LCA) offers a comprehensive approach to evaluating and improving the environmental impacts of buildings. This research explores and advances three key areas relevant to the field of buildings LCA: methodology, benchmarking, and impact reduction opportunities. First, a general LCA methodology is put forth that describes the concepts necessary to develop and conduct a comprehensive LCA for buildings. Second, the methodology is applied to a range of buildings in order to benchmark the current emissions of concrete buildings and compare them to other construction materials. Finally, opportunities for emission reductions are identified and quantified using the LCA models.

Development of a standardized buildings LCA framework is essential in order to increase the accuracy and consistency of the LCA approach. This research supports standardization by proposing good-practice concepts for conducting any buildings LCA. Regardless of an individual project goal and scope, good practice stipulates that building LCAs use a comprehensive life cycle perspective and provide an adequate level of transparency with regards to the data, functional units, and other important LCA parameters. Drawing boundaries to include all phases of the building life cycle—materials, construction, use (including operating energy), maintenance, and end of life—allows for a representative characterization of cumulative environmental impacts over the life of a building.

The general methodology is applied to three classes of existing benchmark buildings: a 12-story, 498,590 ft^2 (46,321 m^2) commercial building; a 33,763 ft^2 (3,137 m^2) four-story multifamily building, and a two-story, 2,400 ft^2 (223 m^2) single family house. All buildings are then analyzed for two climates, Phoenix and Chicago, and for different structural materials. The commercial building is analyzed for a concrete structure and a steel frame, while the residential buildings are compared for insulated concrete form (ICF) and wood construction. The annual operating energy, determined with the EnergyPlus building energy analysis program, is projected to be constant over a 60-year analysis period. The Global Warming Potential (GWP) is quantified using CO_2-equivalent (CO_2e) for a number of purposes, including benchmarking emissions for current practices, comparing concrete with competitor materials, and understanding the relative importance of different phases of the life cycle. This analysis demonstrates that the greenhouse gas emissions due to operation energy of buildings are typically responsible for 88%-98% of life cycle emissions. Compared to wood or steel structures, concrete buildings typically have equal or higher embodied emissions, but have lower operating emissions, which can lead to similar life cycle emissions over time. For all cases considered, concrete buildings have similar emissions over 60 years as steel and wood alternatives.

Finally, a range of options for reducing life cycle emissions are considered for each concrete building type. In particular, the effects of supplementary cementitious materials (SCMs) in concrete, such as fly ash, are quantified in the context of reducing embodied emissions. Furthermore, options for reducing operating emissions are introduced and quantified within the full life cycle. For single family houses, a range of design options are considered using both life cycle assessment (LCA) and life cycle cost analysis (LCCA) to identify the most cost-effective strategies for emissions reductions. There are a number of potential emissions reduction strategies for concrete buildings, and life cycle assessment provides guidance for future environmental improvements.

KEYWORDS

Residential buildings, commercial buildings, life cycle assessment, insulated concrete forms (ICF), wood, steel, concrete, single family, mid-rise multi-family, life cycle cost analysis

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This report was initially issued on August 11, 2011 as part of the Industry Day of the Concrete Sustainability Hub at MIT. Subsequently, the structural material quantities for the commercial building were revised slightly, and an amended report was issued on August 31, 2011.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

This report presents the results of a two-year study of the greenhouse gas (GHG) emissions of residential and commercial buildings that employ concrete construction systems. It documents the process by which life-cycle emissions have been estimated, compares their estimated magnitudes with those of buildings constructed with other materials, and identifies several opportunities to improve their performance.

1.1 Problem statement

There is a strong and growing interest in the environmental performance of the construction industry worldwide. The construction and maintenance of buildings is responsible for the majority of materials consumption in the United States. The operation of buildings is currently responsible for about 40% of national annual energy usage and about 70% of national electricity consumption (EIA 2003).

In recent years, environmental concerns have come to the fore. The exponential growth of the U.S. Green Building Council over the last decade symbolizes the growing concern to reduce the environmental impacts of buildings. The steady increase of CO_2 levels in the atmosphere due to anthropogenic activity and increasing consensus among scientists of the likely relation of human emissions to changes in climate has led to consideration and implementation of policies to reduce consumption of fossil fuels and associated emission of greenhouse gases. In the U.S., experts in the government, industry and academia recognize that improved performance of buildings is financially attractive when compared with increased use of renewable, low-carbon energy sources.

Concrete is essential to the construction of buildings. It is used ubiquitously in foundations and floor slabs, is a leading option as a structural material for many types of commercial buildings and can be used in a variety of forms for the enclosure of residential and commercial buildings. As a construction material it is selected almost exclusively for its mechanical, rather than thermal, properties. However, its relatively high volumetric heat storage capacity and options for including thermal insulation in external wall systems make it worthy of further study as a dual-use material, particularly when integrated in wall assemblies or with space-conditioning systems that take best advantage of its thermal properties. Making full use of concrete is important not only for the economic bottom line of building owners but for the global environment, given the consumption of fossil fuels and production of greenhouse gases associated with its key constituent, cement.

1.2 Life Cycle Assessment

An environmental assessment of the performance of a building, a roadway, or any other object properly spans the entire life cycle. Limiting such an assessment to one phase of the life cycle can lead to conclusions and actions that are poorly informed. Products and services have impacts throughout their life, beginning with raw materials extraction and product manufacturing, continuing through construction, operation and maintenance, and finally ending with a waste management strategy. Conventional environmental assessments often overlook one or more of these phases, leading to incomplete results and inadequate conclusions. Life cycle assessment (LCA) can be used to evaluate all phases of the life cycle, providing a comprehensive analysis of the environmental burden of building construction and operation. While previous buildings LCAs have demonstrated wide variability in the results, improved transparency in methodology and data sources will increase the reliability and repeatability of LCA studies.

An LCA presents an accurate estimate of the quantities and timing of environmental impacts. It therefore provides a solid basis for identifying the benefits of changes in the construction of a building or its operation. The assessment of alternatives can yield a direction (more or less usage of a specific material or system) and order-of-magnitude estimate of the impact of a given change. Such assessments can form an unbiased comparison of alternative design strategies, and directional ideas for environmental improvements. For buildings, these strategies may include greater use of thermal insulation or location of concrete in a way that maximizes its heat-storage characteristics.

1.3 Goals

This report determines the Global Warming Potential (GWP) for a range of building types. The overarching goal of this research is to increase the ability of LCA to quantify and reduce the life cycle impacts of buildings. This is accomplished through three objectives:

1. Develop a comprehensive life cycle assessment methodology and model to quantify the GWP of buildings over the life cycle;
2. Benchmark the life cycle GWP for residential and commercial buildings of different structural materials in two locations, Chicago and Phoenix; and
3. Identify strategic opportunities for GWP reductions in concrete buildings.

Benchmarking requires careful choice and description of the buildings to be studied, the metrics to be used to characterize building performance, and the methodology to establish values for the metrics. The current study has selected representations of residential and commercial buildings that the U.S. Department of Energy and its national laboratories have prepared precisely for benchmarking studies. These representations, in the form of simulation models, constitute what national experts consider to be the geometry, layout, scale, and operation typical of different building classes in the United States. Through a detailed presentation of the processes used to establish values for the life cycle emissions of greenhouse gases, this report represents what its authors consider to be good practice for building life cycle assessment. Opportunities to extend the methodology are identified in the report. The development of an open and replicable LCA process for buildings is central to the reported research, and examples are presented of the application of the LCA methodology to evaluate residential and commercial buildings that are constructed with concrete, wood, and steel. These examples suggest ways in which the concrete industry could improve its products and their use, to the benefit of consumers and the environment and with the expectation that the market will increasingly favor a "greener" approach to building design and operation.

1.4 Outline of report

Following this introduction, Chapter 2 presents methodologies for both LCA and life cycle cost analysis (LCCA) of buildings. The chapter describes the phases of the life cycle of a building and the steps of an LCA. The tools used to estimate the life-cycle carbon emissions of buildings are defined: EnergyPlus for building energy consumption and GaBi for GWP calculations (US DOE 2010; PE International 2011). A detailed description is given of the LCA process used in this study, including goal, scope, inventory analysis, impact assessment and interpretation of results. The scope used in this study includes pre-use, use and end-of-life phases of a building. Chapter 2 emphasizes the need for transparency and identifies steps taken to allow the results in this report to be reproduced by others, including use of publicly available benchmark building models and careful documentation of inputs to and results from both building energy models and life-cycle emissions calculations. The LCCA methodology used in this study is also presented.

Chapter 3 documents an energy and emissions analysis for single- and multi-family residential buildings. A description of essential features of the design and construction of single-family houses is given for both insulated concrete form (ICF) and light-frame wood construction, followed by a discussion of the key role of air tightness in building energy use and steps taken to quantify air tightness for ICF structures. Annual fuel use at the building site is presented for the base-case model and for variations of air tightness, for ICF and light-frame wood houses located in both Chicago and Phoenix. Life-cycle emissions of both types of house construction are given, expressed in terms of CO_2-equivalents (CO_2e). The economic cost of construction and operation is quantified, as is the cost of reducing emissions for selected improvements. Energy consumption and CO_2e emissions for multi-family residential buildings are also estimated for both ICF and wood frame structures.

Chapter 4 analyzes energy usage and emissions of a benchmark large office building for both steel and concrete structures. The impact of increased thermal mass on operational energy is calculated with particular care. The building's design, construction, energy model and emissions are documented, as are the magnitudes of selected improvements. Notably, recent research has shown the benefits of embedding a radiant cooling system in concrete floor slabs; this approach takes full advantage of the thermal storage of concrete and can be applied in both new construction and, via a topping layer of concrete, in existing buildings.

Chapter 5 summarizes energy and emissions results for residential and commercial buildings and compares their performance with data from national building surveys and several other studies. Comparisons are also made with the levels of building energy use in the future that experts and advocacy groups see as an important element of national progress toward a low-carbon economy. A concluding chapter summarizes key findings and identifies future work. Key assumptions and data inputs are presented in the appendix.

2 METHODOLOGY

2.1 Introduction

This chapter describes concepts that should be considered when conducting any building LCA. Regardless of an individual project's goal and scope, good practice stipulates that a building LCA use a comprehensive life cycle perspective and provide an adequate level of transparency with regards to the data, functional units, and other important LCA parameters. Section 2.2 defines and discusses common parameters across all building LCAs and provides general recommendations regarding their consideration in a building LCA.

The methodology discussed in Section 2.3 is specific to the LCA research in this study. The concepts discussed with regards to the general building LCA methodology can be applied to all building LCAs, but project-specific objectives are necessary to provide a refined and detailed methodology. Identifying project goals allows for specific data, boundaries, functional units and other defining parameters to be determined and discussed in more detail. The project LCA discussed in Section 2.3 applies the general concepts in order to achieve a comprehensive and transparent project methodology.

The methodology discussed in Section 2.4 is specific to the Life Cycle Cost Analysis (LCCA) component of the current project. Although the LCCA work specifically focuses on single-family residential buildings, the methodology provided in Section 2.4 can be followed for other building types. The methodology describes relevant LCCA work that has been done for buildings, conceptually explains the objectives and approach for any LCCA, and provides important assumptions and considerations that must be made. The concepts discussed in Section 2.4 are further applied and discussed in the single-family residential section of this project.

2.2 General Methodology

The LCA approach to quantifying environmental burden is formalized by the International Organization for Standardization (ISO) 14040 series. Notable documents in this series are ISO 14040:2006 – Principles and Framework and ISO 14044:2006 – Requirements and Guidelines (ISO 2006a; ISO 2006b), which together outline fundamental concepts relevant to developing and conducting an LCA study. The ISO standards break the LCA framework into four stages: goal and scope definition, inventory analysis, impact assessment and interpretation. Figure 2.1 depicts these stages, their relationship and potential applications. As described by ISO, the stages include the following activities:

1. *Goal and scope definition* describes the plan for conducting an LCA. The goal defines the intended application, the reasons for conducting a study, the intended audience, and the dissemination of the final product. The scope provides the approach to meet the stated goals, including defining the functional unit(s), system boundaries, impact assessment methodology, and other relevant parameters.
2. *Inventory analysis* describes and quantifies the inputs and outputs of each process that falls within the scope. This is the key organizational step in the LCA process, where the data and process relationships are established. Within the inventory analysis, the life cycle is broken down into phases (e.g., pre-use, use, end-of-life), which are further

organized into processes (e.g., materials flows, transportation distances). On the lowest level, these processes contain data on inputs (i.e., material and energy consumption) and outputs (i.e., products, emissions and wastes). The life cycle inventory then sums up all inputs and all outputs that cross the defined system boundary. In an ideal case, the inventory contains only elementary flows (flows taken from or released into the environment without further transformation) such as resources, emissions or waste energy. Inventory analysis results can then be summed over all processes to determine the total emissions over the life cycle.

3. *Impact assessment* uses "impact categories" to quantify the environmental damages based on the inventory data. For instance, the impact category "global warming potential" characterizes carbon dioxide, methane, nitrous oxide and other greenhouse gases through their warming potential, commonly expressed in carbon dioxide equivalents, or CO_2e.
4. *Interpretation* synthesizes the results from the inventory analysis and/or impact assessment stages in order to draw defensible conclusions. This stage allows the LCA practitioner to make recommendations to decision-makers in the context of assessment uncertainties and assumptions.

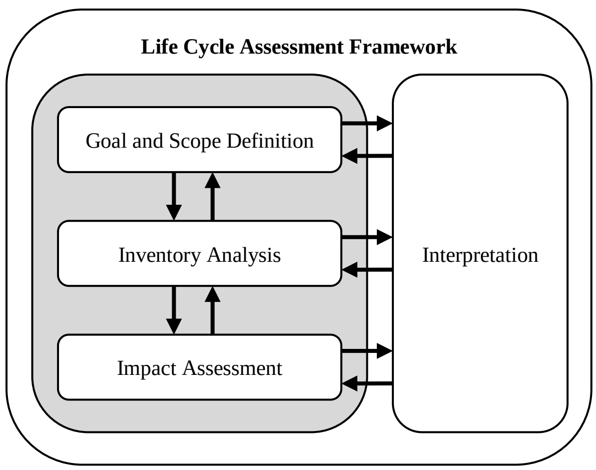

Figure 2.1 – Stages of a life cycle assessment (ISO 2006a)

2.2.1 LCA of Buildings

The life cycle assessment of buildings is now a well-established field and yet there is still no internationally agreed-upon standard for building LCAs. Many studies have focused either on the embodied energy and emissions due to building construction and disposal (the pre-use and end-of-life phases) or the operation and maintenance (the use phase) of buildings, rather than integrating the two (Borjesson and Gustavsson 2000; Kim 2008; Asif et al. 2007). The operational phase of a building, however, makes the largest contribution to the life cycle impacts of a structure and can overshadow the embodied emissions. It is important to investigate the energy use and greenhouse gas emissions of structures to determine ways that both of these impact categories could be reduced. Life cycle assessment is a valuable tool through which designers, policy-makers, and consumers can understand how to lower the environmental impact of any structure.

2.2.2 LCA Tools

LCA software packages, such as *GaBi* (PE International 2011), *SimaPro*, created by PRé Consultants (2011), and *EIO-LCA*, released by Carnegie Mellon (2011), are often used to assist in the data collection and organization processes and help provide the modeling framework. Additionally, external models, such as those describing building energy consumption, are commonly used to complement the core LCA model and provide spatial, temporal, and system-specific data. Such models are particularly useful when characterizing the operation phase of the life cycle. The energy use of a building is based on the interaction of such factors as building shape and orientation, construction materials, weather, building equipment, and the requirements of occupants. A program which incorporates all aspects of a building and the equations governing physical processes is therefore desirable for understanding the nuances involved in design decisions. There are many programs available for energy simulations of buildings, such as eQUEST, based on a calculation engine initially developed by the U.S. Department of Energy, and EnergyPlus (US DOE 2010), which can calculate annual energy use for buildings with a number of advanced features, such as the simulation of thermal mass benefits. The current study uses EnergyPlus to carry out detailed energy simulations, and GaBi to conduct the life cycle assessment. Figure 2.2 presents the project methodology used in this study, along with the software used.

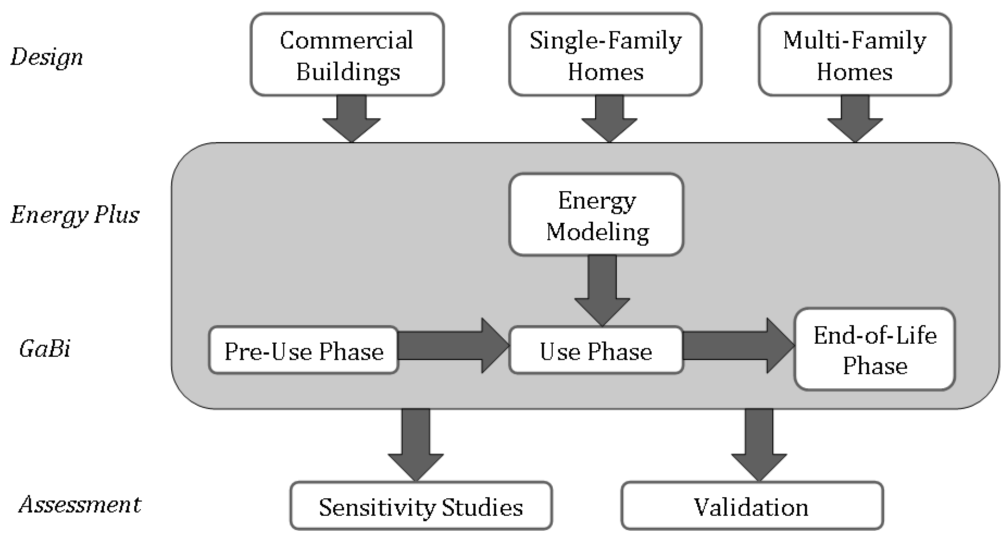

Figure 2.2 – Methodology of current project with associated software

2.3 LCA Project Methodology

While the previous section described LCA methodology in general, this section describes the methodology used to meet the objectives of the current project, which estimates the Global Warming Potential (GWP) for residential and commercial buildings.

2.3.1 Goal

This study compares different construction systems for a range of building types in order to achieve two primary goals. The first is to benchmark concrete buildings in relation to other prevalent construction systems. The second is to identify areas of improvement within concrete buildings. Understanding where the environmental impact comes from during a building's lifetime is crucial to reducing its total impact and thus working towards a more sustainable built environment. Using LCA, potential improvements to reduce the GWP of concrete buildings can be identified. Making the results available to industry allows designers and policy-makers to understand a building's impact and provides a basis from which improvements can be made.

2.3.2 Scope

The reference flow of this LCA is one building's structure and shell over a 60-year lifetime, which is a conventional analysis period of building LCAs (Athena 2011, VanGeem 2010). The functional unit is the useable area for each building type. For ease of comparison, results are also reported on a per square foot (and m^2) basis, while the total values are provided in the appendix. Annual operating impacts are also provided, to allow for extrapolation to longer or shorter analysis periods. Each building is modeled for both Phoenix and Chicago, in order to understand the role of regional variation due to climate, construction practices, and energy grid mix. All buildings are finished to the same degree with only the structural systems differing. The system boundary is defined as cradle-to-grave, with minor exceptions. For example, the excess materials and energy required for the construction of the building are neglected, as these are assumed to be outside the scope of the current study. Cole (1999) shows that average construction greenhouse gas emissions, for different structure types, would still amount to less than 1% of the total lifetime GWP for buildings, when compared to the final results of this study. Finally, at the end of life, it is assumed that much of the metal and concrete would be recycled. Interior finishes, furnishings, and other subjective occupant additions are not included in this study.

The life cycle of the buildings is broken into three phases: pre-use, use, and end-of-life (Figure 2.3). The pre-use phase is the cradle-to-site portion, from raw material extraction to manufacturing and processing and finally, transportation from the factory to the job site. As previously stated, it neglects the energy required to construct the buildings once the materials arrive at the job site. The use phase is the energy required to operate the building, such as plug loads, heating, ventilation, and cooling (HVAC) systems, and lighting. It also includes general standard maintenance throughout the building's lifetime which consists of roof and window replacements and interior and exterior re-painting. The end-of-life phase assumes total demolition of the building. The majority of the material is sent to a landfill while steel and aluminum are recycled. Additionally, half of the demolished concrete is assumed to be recycled into aggregate. The term 'embodied' refers to the emissions associated with materials and their disposal throughout the life cycle of the building. The term 'operating' refers only to the energy and emissions associated with the operation of the building throughout the use phase.

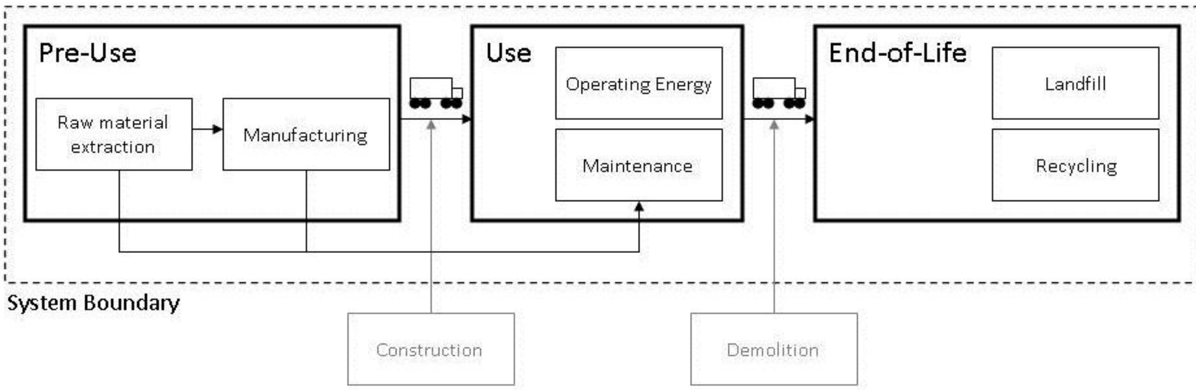

Figure 2.3 – Building LCA system boundary used in this study

Table 2.1 presents a summary of the building types being compared and the relevant structural systems addressed in this study. It also provides the number of stories in each building and the useable square footage. See the corresponding sections in the report for further building details.

It is important to note that the reference area used to determine energy and GWP is on a per square foot basis based on exterior dimensions and thus varies by climate and material. The unconditioned area is not included in this, which corresponds to conditioned floor area as defined in IECC (2009). Area-normalized energy use corresponds to the conditioned energy-use intensity used in EIA studies (Deru 2004).

Table 2.1 – Summary of buildings addressed in the scope of this study

	Structure Type	Floors	Useable Area
		No.	*ft^2 (m^2)*
Single-Family	Insulated Concrete Forms	2	2,400 (223)
	Light-frame Wood	2	2,400 (223)
Multi-Family	Insulated Concrete Forms	4	33,763 (3,137)
	Wood	4	33,763 (3,137)
Commercial	Cast-in-Place Concrete	12	498,590 (46,321)
	Steel	12	498,590 (46,321)

Data specific to North America is used whenever possible, although global or European data is substituted on occasion. In these cases, separate validation is done to check that this assumption does not significantly change results. Additionally, when issues of allocation are encountered, a mass allocation assumption is used, in which the impact is divided based on the contribution of each co-product to the total mass in accordance with ISO standards. Because the designed structures are theoretical only, material quantities are estimated based on current practice and code requirements.

2.3.3 Inventory Analysis

The inventory analysis gathers the input and output data, which is then validated and scaled to relate to the functional unit. For this project, the calculation of material quantities is the first step in data collection. The structure is designed, keeping the floor plan the same across each building type, and material weights are calculated using standard densities. The buildings are designed in accordance with applicable building codes as well as standard industry practice. ASHRAE Standards are used as a primary resource for material densities and thermal properties (ASHRAE Fundamentals 2009). The second step in data collection is the collection of inputs and outputs required for material manufacturing. Many of the required processes are available through the GaBi database, which is created in accordance with the ISO standards. Part of the available data in the models is from databases collected by PE International, while the rest comes from other sources, such as the U.S. Life Cycle Inventory database (USLCI), the Portland Cement Association (PCA), and World Steel (USLCI 2009; Marceau et al. 2007; World Steel 2011). Manufacturers were contacted when data was unavailable through these sources.

Transportation distances for the various construction materials are calculated between the center of Chicago or Phoenix and the manufacturing location, which is based on the manufacturer's available information. Manufacturers were chosen based on local producers as well as national averages, for products that typically come from one place in the country. See Appendix 8.1 for transportation distances. Distances for raw material extraction and other parts of the manufacturing process are based on national or regional averages and are already included in the overall impact calculation of each material.

A crucial step in inventory analysis is data validation, which ensures that the values used are accurate. This is done through comparisons with other published studies. Where they disagree, further research is done to determine which value is more accurate, in accordance with this project's scope and system boundary. Additionally, material CO_2e factors are provided for comparison with future studies. Separate validations are done for the cement, concrete, steel, and wood factors, as these are the most prominent structural materials being considered. Another important CO_2e factor to consider is that of the electricity mix. Regional electricity is difficult to quantify in an LCA due to the interconnectedness of the US electricity grid, since a consumed electron cannot be traced back to its specific source. Additionally, the sources of delivered electricity are constantly changing depending on which facilities are operating. The United States is divided into North America Electric Reliability Council (NERC) regions which are a best estimate breakdown of which regions share electricity sources (Weber et al. 2010). This data, available through the EPA's eGrid, details the fuel mix used as well as the grid loss factor (US EPA 2007). GaBi calculates the CO_2e emissions associated with each energy source in the fuel mixes. See Appendix 8.2 for electricity mixes.

The operating energy is obtained by modeling the energy required for lighting, plug loads, hot water, and HVAC requirements. To ensure that the buildings considered are representative of current practice, the building models are derived from benchmark buildings developed by the Department of Energy for the multi-family and residential buildings, and the Building America House Simulation Protocol (BAHSP) house for the single family residential house (US DOE

2010; Hendron and Engebrecht 2010). The commercial building is based on the DOE large office building and the multi-family building is based on the DOE midrise apartment reference building. The climate data for each city is available through the EnergyPlus website from a variety of sources. The Chicago building is modeled in ASHRAE climate zone 5A and Phoenix is in zone 2B (Briggs et al. 2003). The calculated energy demand is then used as an input into the GaBi program to determine the impacts due to building operation. The current annual operating energy predictions are assumed to hold constant for the next 60 years, although energy mixes and their carbon intensities are likely to change in the future.

2.3.4 Impact Assessment

The primary goal of this study is to determine the greenhouse gas emissions of a range of building types. As a result, the chosen impact category is global warming potential (GWP), which has units of weight of carbon dioxide equivalent emissions (CO_2e). Other assessment categories could have been used, but policy makers and practitioners are moving toward GWP as a leading metric. Discussing CO_2e emissions is an agreed-upon standard for analyzing the environmental impact of a product or system and establishes a common metric across industries and national borders to gauge relative impacts of climate change. In this case, GWP effects over a 100-year time interval was chosen, per recommendations of the International Panel on Climate Change (IPCC 1995). The CO_2e conversion factors are provided through GaBi by the Institute of Environmental Sciences (CML) at Leiden University in the Netherlands and were last updated in December 2009 (PE International 2011). The main contributors to GWP for a building are carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4); see Table 2.2 for the CO_2e conversion factors for these gases. Since GWP is a global impact category, the factors are not region specific. GaBi provides other impact categories by which to evaluate a product, such as acidification or eutrophication, but these are outside of the scope of this study.

Table 2.2 – Universal CO_2e conversion factors for greenhouse gases (IPCC 2007)

Greenhouse Gas	lbs CO_2e/ lbs kg CO_2e/kg
Carbon Dioxide, CO_2	1
Nitrous Oxide, N_20	298
Methane, CH_4	25

2.3.5 Interpretation

The final step in an LCA is the interpretation of the results. Values from the impact assessment are analyzed for robustness and sensitivity to inputs. Much of the data validation is done at this stage, when the model is compared to other published studies. This creates the iterative process of an LCA as results are discussed, data are modified, and then the system's impact is re-assessed. Material inputs can also be changed to understand their impact on the overall system.

2.3.6 Transparency

As Hsu (2010) has demonstrated, previous LCA studies of buildings have published a wide range of values and are often not repeatable due to lack of information. An additional goal of this study is to be transparent to allow others to recreate the current study and set a precedent for future building LCAs. Documentation is provided at every level of research and design. The use of DOE benchmark buildings and regional assumptions means that others could use the same design source for their own study and expect to have similar results. The models themselves are designed to be flexible and easy to change if sensitivity analysis is desired. Results have been normalized in terms of square footage for easier understanding and greater applicability. Thus, readers can gain a broad understanding of the designs and their environmental implications, and also perform similar studies of their own by following the report's methodology.

While the values used in this study are accurate given the scope, it is important to realize that other studies will have different system boundaries based on their goals. To achieve a greater level of transparency, the data provided in Table 2.4, Table 2.5, and Table 2.6 are the most important factors that would be affected by any changes in system boundary. Table 2.3 presents the sources for some of the data, the choice of which would affect conclusions.

Table 2.3 – Sources of primary data used in this study

Process	Source
Steel products	World Steel (2011)
Cement	PCA (Marceau et al. 2006)
Concrete mixes	PCA (adapted from Marceau et al. 2007)
Wood products	USLCI (data from 2009) (via PE International 2011)
Electricity grid mixes	US EPA eGrid (2007)

Table 2.4 shows the GWP associated with some of the key materials used in this study. Variation among these values can account for many of the discrepancies between similar studies.

Table 2.4 – Important CO_2e factors for materials and energy used in this study

Process	CO_2e Factor		Units	
Cement	0.928		*lb CO_2e/lb*	*kg CO_2e/kg*
Concrete Mix (5000 psi)[a]	0.144		*lb CO_2e/lb*	*kg CO_2e/kg*
Concrete Mix (3000 psi)[b]	0.105		*lb CO_2e/lb*	*kg CO_2e/kg*
Steel – Structural[c]	1.001		*lb CO_2e/lb*	*kg CO_2e/kg*
Steel – Rebar	1.241		*lb CO_2e/lb*	*kg CO_2e/kg*
Wood – Sawn Lumber (PNW/SE)[d]	0.282/0.169		*lb CO_2e/lb*	*kg CO_2e/kg*
Wood – Plywood (PNW/SE)[d]	0.286/0.255		*lb CO_2e/lb*	*kg CO_2e/kg*
Chicago Electricity	1.7842	*lb CO_2e/kWh*	0.2248	*kg CO_2e/MJ*
Phoenix Electricity	1.3087	*lb CO_2e/kWh*	0.1649	*kg CO_2e/MJ*
US Natural Gas	0.5953	*lb CO_2e/kWh*	0.0750	*kg CO_2e/MJ*

[a] Pre-use impact: 0.131 lb CO_2e/lb, end-of-life impact: 0.012 lb CO_2e/lb

[b] Pre-use impact: 0.093 lb CO_2e/lb, end-of-life impact: 0.012 lb CO_2e/lb

[c] Pre-use impact: 1.563 lb CO_2e/lb, end-of-life credit: 0.562 lb CO_2e/lb

[d] End-of-life impact: 0.020 lb CO_2e/lb

As with all LCI data, values and sources differ between studies, and the selection of the present data sources are the most up-to-date, peer-reviewed, comprehensive in scope, and geographically representative of the U.S. However, it is important to note that there is inherent uncertainty and variability in these numbers. In particular, GWP emissions from cement production tend to vary significantly based on the type of kiln and energy source. The cement CO_2e factor used here represents average U.S. emissions based on a 2006 PCA study (Marceau et al. 2006). It is expected that this will decrease over time as wet kilns are phased out and other efficiency improvements are implemented.

Calculation for the GWP of wood assumes sustainable forest management. This allows for the assumption that the amount of carbon uptake in the growth of new trees planted as a result of wood construction would be equal to the amount of carbon released at the end-of-life disposal of wood in a landfill. Though the treatment of biogenic carbon in LCAs is still debated, this follows the implicit sequestration method discussed by Johnson (2009).

Table 2.5 shows the recycling details of the materials used in this study. Assumptions of recycled content and recycling rate can have a major impact on the GWP of a material.

Table 2.5 – Metal recycled content and recycling rates used in this study

Material (Source)	Type	Recycled Content	End-of-life Recycling Rate
Steel (World Steel 2011)	Structural	60%	98%
	Rebar	70%	70%
Aluminum (EAA 2008)	All	11%	100%
Concrete (Aggregate) (Kelly 1998)	All	0%	50%

The differences between recycled content and end-of-life recycling rate for structural steel members creates a GWP credit at the end-of-life of the commercial buildings. The 60% recycled content of the initial steel members is a global average reported by the World Steel Association. Specific U.S. data was unavailable, but it is expected that the recycled content and initial manufacturing processes will change. Future research should include regional specific data based on manufacturing process (e.g. electric arc furnace versus blast furnace) and electricity mixes.

Finally, Table 2.6 details the maintenance schedule used for all buildings in the current study. Different regions and studies will use different timeline assumptions, changing the total embodied GWP of the maintenance materials.

Table 2.6 – Maintenance schedules used in life cycle assessments for exterior envelope of the single-family, multi-family and commercial buildings in this study

Material	Years before replacement
Roof	15 years
Windows	15 years
Paint	10 years

2.4 LCCA Methodology

Buildings have economic as well as environmental importance. Research shows that buildings and construction products have a significant socio-economic impact. Buildings require high initial investments, operating expenditures, long life cycles and a large amount of materials and energy (Nemry et al. 2010). Technologies that pay back for themselves quickly are desirable to consumers because there is less uncertainty with respect to forecasting into the future (Fabrycky and Blanchard 1991). Due to increasing awareness of the environmental impacts associated with buildings, there is a growing interest in increasing the energy efficiency of buildings (Kneifel 2010). In order to understand the implications of an energy saving option, it is important to understand the total cost associated with that technology.

The focus of this LCCA is to understand the economic and environmental impact of the thermal performance of different wall systems in residential construction. There has been significant research in understanding the economics of increasing the thermal performance of walls (Kosecka and Kosny 2002; Gregory et al. 2008; Pulselli et al. 2009). There is a lack of research, however, that combines the economics of thermal performance of walls with an understanding of the environmental impacts of emissions. From that standpoint, this research provides a focus on understanding the cost of reducing GWP through improved building design.

LCCA is an important tool to understand the economics of different options. LCCA takes into account the costs of a particular alternative accrued over time. This can be broken down more specifically into initial costs and future expected costs (Fabrycky and Blanchard 1991). For buildings, the initial cost includes all related activities prior to occupation (e.g. materials, labor, and construction equipment) and future expenditures after occupation (e.g. energy and maintenance requirements). LCCA can provide insight into understanding the economics of two completely different design alternatives or the economics of optimizing one alternative. To combine the initial and future expected costs, all costs must be combined to a present value.

The scope of this LCCA strictly pertains to single-family residential construction for Chicago and Phoenix. It focuses on understanding the economics of typical ICF versus typical light-frame wood construction, and the associated cost of optimizing the ICF wall. As shown in Figure 2.4, research has shown that from a base-case home, reductions in energy consumption can also reduce total cost (Christensen 2004). There reaches a point, however, where it becomes costly to add energy reduction benefits. The goal of this LCCA is to try to optimize an ICF wall by taking advantage of thermal mass (e.g., thickness of concrete) and thermal performance (e.g., increasing the amount of insulation) and understanding the relative cost to do so.

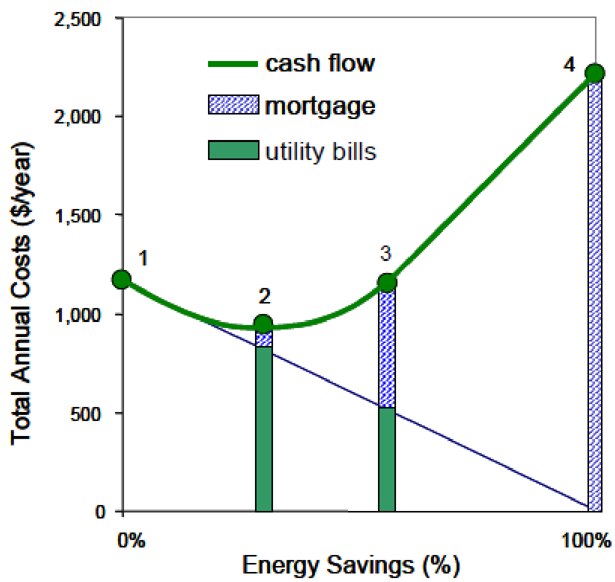

Figure 2.4 – Cost to reduce energy consumption from a base case (Christensen 2004). From a base case (point 1) there are initially cost-effective methods to reduce energy consumption, but those energy saving methods eventually become more costly (points 2, 3, and 4).

Initial costs for materials, labor, and construction are calculated using RS Means and National Construction Estimator (RS Means 2010; Ogershok 2010). These sources provide national average data for both light-frame wood and ICF construction, and allow the user to scale material and labor rates to their respective region. The initial costs include relevant materials, labor costs, and construction equipment necessary for both wall systems. The future expected costs only include the energy requirements of the walls over the lifetime. Based on the energy requirements for the wall assembly being considered, energy costs are calculated from data provided by EIA for Chicago and Phoenix (US EIA 2011a; US EIA 2011b). The annual energy costs are then turned into a present value using the appropriate discount rate and life-cycle. Future work should also consider maintenance, which is ignored due to the difficulty of quantifying the maintenance life of a wall system. The sum of the initial costs and present value energy costs represent the life cycle cost for the different design options.

Two important factors in any LCCA are the time frame of the study and the discount rate. Predicting the exact expected useful life of a building is not possible; however, a time frame of 60 years is used for the analysis, to correspond to the LCA analysis period described above. The real discount rate takes into account the time value of money. There are two important concepts to understand: the earning power and purchasing power of money (Fabrycky and Blanchard 1991). A dollar today is worth more than a dollar in the future because of the opportunity to invest that dollar earlier, yielding a return that represents the earning power of that dollar. Additionally, as inflation increases over time, the purchasing power of that same dollar decreases. Therefore, in any LCCA it is extremely important to use a real discount rate to take into account the earning power and purchasing power of money. This analysis uses a real discount rate of 2.3%, the real discount rate for 2011 provided by Circular A-94 which governs the discount rate for regulatory analysis, as the expected discount rate (Office of Management and Budget 2010). A sensitivity analysis of 0- 5% is used to estimate the variation of the results with discount rate.

Beyond understanding the economic implications of different construction systems, the goal of this research is to combine the understanding of economic and environmental implications of different types of construction to realize more sustainable solutions. Cost is an important consideration by all builders and consumers, but most previous work has focused on understanding the environmental impacts of different forms of construction. There is a lack of research, however, that integrates the two together to determine which environmental reductions are economically sound decisions.

2.5 Conclusion

This chapter has presented the general methodology for life cycle assessment, with specific application to buildings. The ISO methodology has been used to create the current LCA models of standard-practice commercial and residential buildings in two climate regions of the United States. Benchmark buildings have been chosen as a basis for the designs, because they represent an average of what exists in the built environment today. These robust models can be adjusted to accommodate other climate regions or design alternatives.

3 ENERGY AND EMISSIONS ANALYSIS OF RESIDENTIAL BUILDINGS

Despite progress in improving the energy efficiency of residential buildings, total consumption has remained approximately constant over the past 30 years at roughly 10.55 quadrillion Btu (3.09 trillion kWh) annually (US EIA 2011c). Although there have been significant reductions in space heating and cooling in homes in the United States, progress has been neutralized by a growing building stock and increasing energy consumption for appliances and electronics (US EIA 2011c). The residential sector as a whole in the United States represents 20% of all end-use energy consumption. Additionally, the residential sector annually generates approximately 18% of all global warming potential emissions in the United States (Emrath and Helen 2007).

3.1 Single-Family Residential

3.1.1 Introduction

Residential construction is responsible for a large portion of energy consumption and emissions in the United States. Single-family residential buildings account for the majority of those numbers, representing 80% of the total residential energy consumption in the United States (US EIA 2008).

The current study focuses on understanding the economic and environmental implications in Chicago and Phoenix of Insulated Concrete Form (ICF) construction consisting of concrete walls encased in expanded polystyrene (EPS) insulation, and light-frame wood construction, the latter the predominant form of single-family construction in the United States. Benchmark single-family houses, which represent typical forms of these construction methods, are designed and modeled based on the Building America House Simulation Protocol (BAHSP) as described below (Hendron and Engebrecht 2010). The total materials, energy requirements and GWP results are reported below per square foot of floor area to allow for comparison with other studies. The economics of the different wall systems are presented in terms of wall area, the typical way in practice to present the cost of wall systems. The research also considers potential improvements to reduce the emissions of typical ICF construction and the relative associated cost.

3.1.2 Design and Construction

The benchmark BAHSP house considered is a 2-story, 2,400 ft^2 (223 m^2) house with dimensions 37.5 ft x 32 ft (11.4 m x 9.8 m). Figure 3.1 presents an interior floor layout of the house. To model representative houses for the two different climate regions, the Phoenix house is supported by a slab-on-grade (SOG) and the Chicago house has a basement wall foundation. The only major difference between the light-frame wood and ICF house is the exterior walls. Table 3.1 and Table 3.2 provide a more detailed list of the different materials, size, and spacing of structural members for the ICF and light-frame wood houses in Chicago and Phoenix.

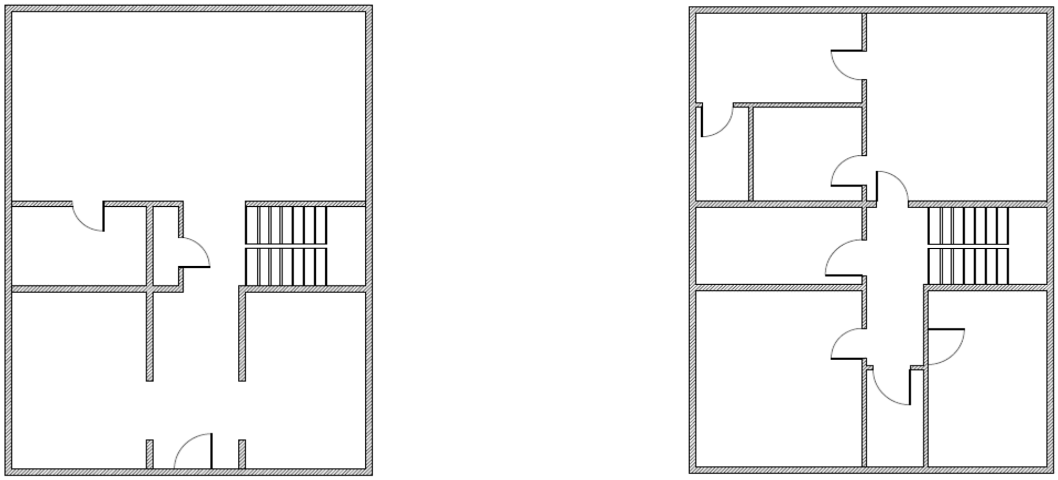

Figure 3.1 – General floor layout for the single-family home to calculate material quantities

For all single-family houses, the roof, partitions and floors are designed in the same manner. The interior wood partition walls use 2x4 (38 mm x 89 mm) lumber at 16 in (406 mm) on center. Floors of both houses are designed using 9.5 in (241 mm) engineered lumber I-joists spaced 16 in (406 mm) on center and both houses have a 6:12 pitch roof that is wood framed. Design of the exterior walls and foundations vary between the different buildings. The light-frame wood house in Chicago uses 2x6 (38 mm x 140 mm) studs at 24 in (61 cm) on center, while the Phoenix wood house uses 2x4 (38 mm x 89 mm) studs at 16 in (41 cm) on center. The ICF house consists of a 6 in (152 mm) load bearing reinforced concrete wall with 2.5 in (63.5 mm) thick expanded polystyrene (EPS) panels on each side. The exterior cladding is stucco with a metal lath for support and expansion joints. The exterior has three layers of silicate emulsion paint. Maintenance of the single family house is assumed to occur regularly over the 60-year lifetime of the building. Roof shingles, windows and window frames are replaced every 15 years and surfaces are repainted every 10 years.

Table 3.1 – Similarities among all of the single-family houses

Roof	
Pitch	6:12
Shingles	Asphalt
Sheathing	½ in (12.7 mm) Plywood
Insulation	Fiberglass-batt
Drywall	½ in (12.7 mm) thick
Rafters	2x10 (38 mm x 235 mm) @ 16 in (406 mm)
Load Bearing Partitions	
Studs	2x4 (38 mm x 89 mm) @ 16 in (406 mm)
Drywall	½ in (12.7 mm) thick
Floors	
Sheathing	5/8 in (15.9 mm) Plywood Sheathing
Joists	9-½ in (241 mm) I-Joists @ 16 in (406 mm)
Drywall	½ in (12.7 mm)

Table 3.2 – Differences in the single-family houses

	ICF – Chicago	ICF – Phoenix	Wood – Chicago	Wood - Phoenix
Exterior Walls				
ICF Wall	6 in (15.2 cm) core	6 in (15.2 cm) core	N/A	N/A
EPS Insulation	2.5 in (63.4 mm) panels	2.5 in (63.4 mm)	N/A	N/A
Studs	N/A	N/A	2x6 @ 24 in o.c. (38 mm x 140 mm @ 61 cm o.c.)	2x4 @ 16 in o.c. (38 mm x 89 mm @ 41 cm o.c.)
Sheathing	N/A	N/A	5/8 in (15.9 mm) Plywood	1/2 in (12.7 mm) Plywood
Insulation	N/A	N/A	Fiberglass	Fiberglass
Drywall	½ in (12.7 mm)	½ in (12.7 mm)	½ in (12.7 mm)	½ in (12.7 mm)
Foundation				
	ICF – Chicago	ICF – Phoenix	Wood – Chicago	Wood - Phoenix
Wall Height	8 ft (2.44 m)	1 ft (0.30 m)	8 ft (2.44 m)	1 ft (0.30 m)
Thickness	8 in (20.3 cm)	8 in (20.3 cm)	8 in (20.3 cm)	8 in (20.3 cm)
EPS Insulation	2.5 in (63.4 mm) panels	2.5 in (63.4 mm) panels	N/A	N/A
XPS Insulation	Around the perimeter of SOG	N/A	Around the perimeter of SOG	N/A
Footing	21 in (53.3 cm) width	21 in (53.3 cm) width	16 in (40.6 cm) width	16 in (40.6 cm) width
Isolated Footings	5 ft x 5 ft x 1 ft (152 x 152 x 30.5 cm)	N/A	5 ft x 5 ft x 1 ft (152 x 152 x 30.5 cm)	N/A

The foundation and foundation walls are designed to meet code requirements of ACI 332, which provides foundation requirements for residential construction (ACI 2010). Design of the ICF wall is met using the International Residential Code to meet steel reinforcement requirements (IRC 2003). The flooring, light-frame wood exterior walls and partitions are designed in consultation with local builders. Lastly, the structural design is checked with code requirements for the greater Chicago and Phoenix areas to ensure the benchmark houses are representative of the two locations. An overview of the structural designs for the single-family buildings in both Phoenix and Chicago can be seen in Figure 3.2 and Figure 3.3.

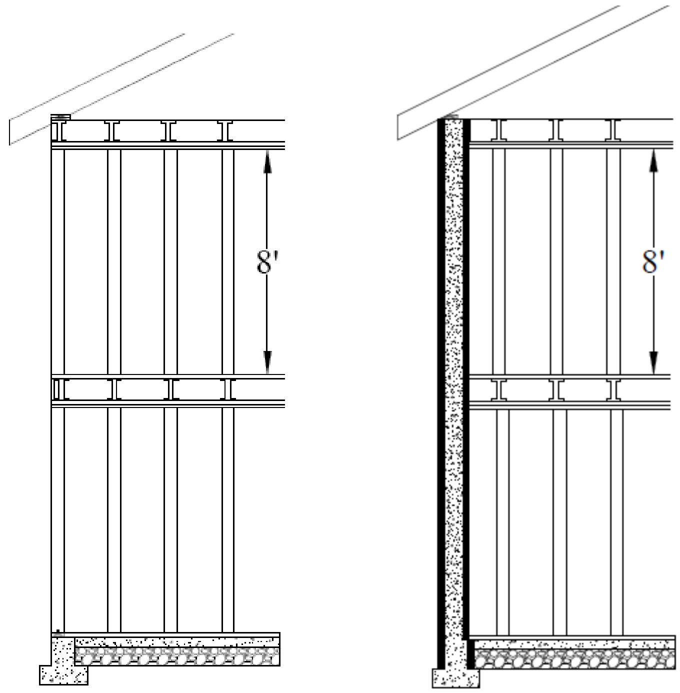

Figure 3.2 – Structural design of the light-frame wood and ICF single-family houses for Phoenix

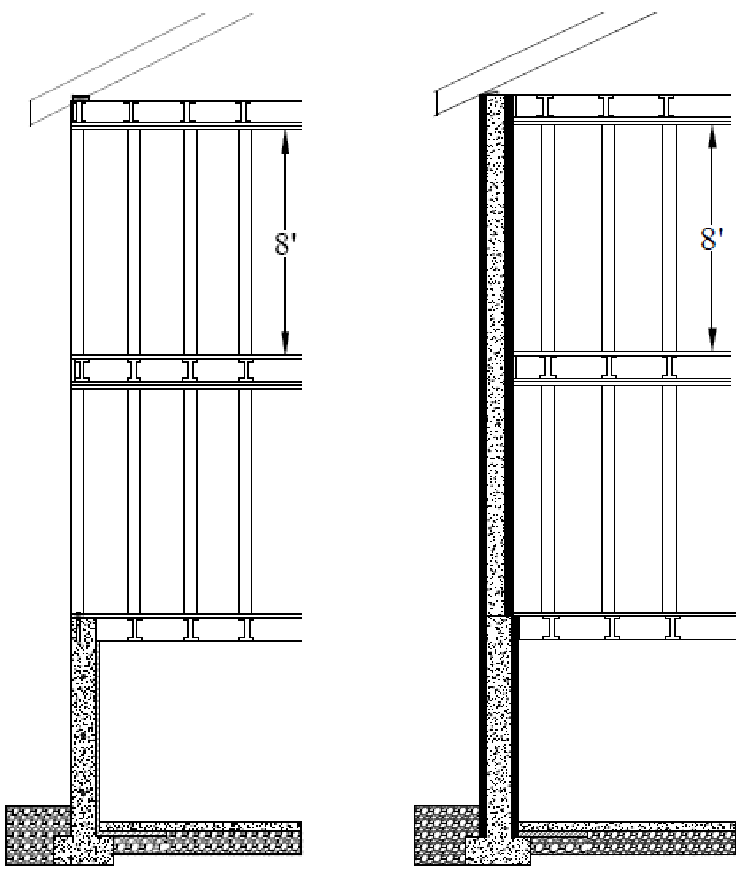

Figure 3.3 – Structural design of the light-frame wood and ICF single-family houses for Chicago

Figure 3.4 shows the contribution of different materials to the total mass of the ICF and light-frame wood houses for Chicago and Phoenix. Additionally, Appendix 8.6 provides all material masses. Concrete, the dominant material by mass for all of the cases, is much greater in Chicago than Phoenix because of the basement wall foundation. The 'other' category includes stucco for the exterior, gravel and waterproofing for the foundation, drywall, paint, and windows. The major contributor of mass for the 'other' and 'maintenance' categories are the 6 in (152 mm) underlayment of gravel and the asphalt shingles for the roof.

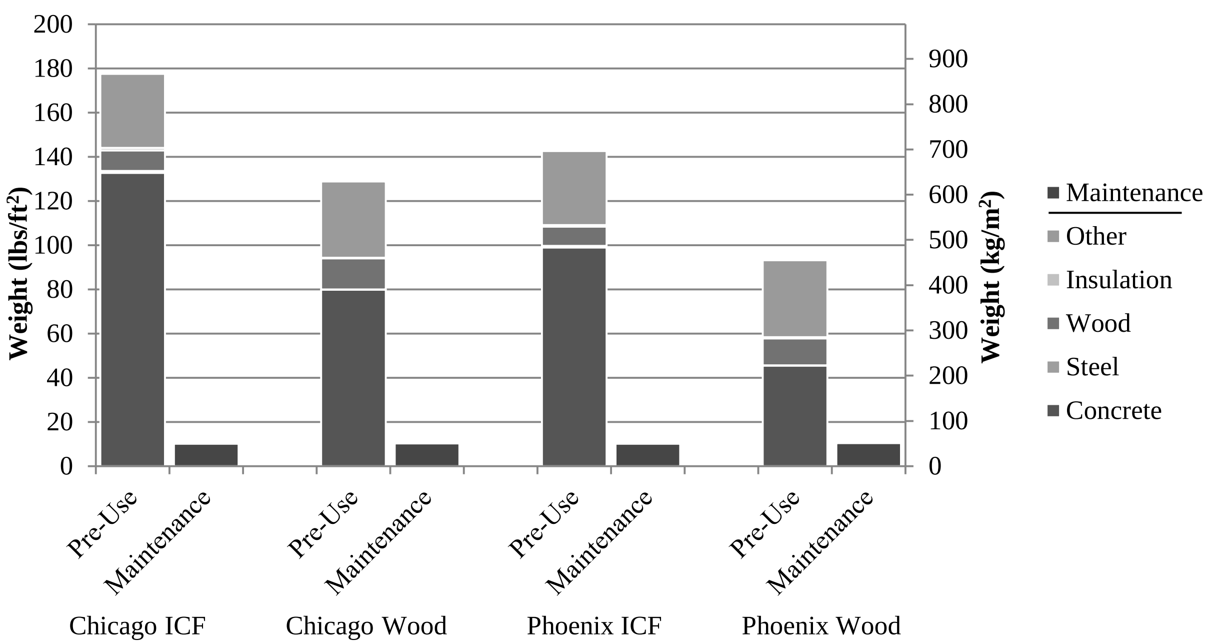

Figure 3.4 – Weight of materials normalized by gross floor area (exterior dimensions) and separated into type and phase for the single-family houses

3.1.3 Energy Modeling

3.1.3.1 Basic Specifications

As stated previously, the single-family house model employs the Building America House Simulation Protocol (BAHSP) as the reference standard. This document, created by the U.S. Department of Energy's (DOE) National Renewable Energy Laboratory (NREL), provides guidelines for analyzing home energy use in a consistent manner (Hendron and Engebrecht 2010). The document outlines a modeling methodology for residential buildings and could be considered the analog for ASHRAE Standard 90.1's Appendix G, which provides modeling methodology for commercial buildings. Unlike Appendix G that is part of a standard, the BAHSP is a guideline. The performance of a benchmark building meeting the BAHSP 2010 is equivalent to one meeting the minimum requirements of IECC 2009. For the current study, the house is modified to have both light-frame wood and ICF envelopes. Table 3.3 summarizes the properties used to model the single-family house.

Table 3.3 – Summary of the single-family house model

Input	
Reference Standard	Building America House Simulation Protocol 2010 [Performance equivalent to IECC 2009]
Conditioned Area	2400 ft^2 (223 m^2)
Unconditioned Area	1200 ft^2 (112 m^2) (Chicago only due to basement)
Number of Floors	2 + unconditioned attic
Number of Zones	3 (1 conditioned, 1 plenum, 1 unconditioned)
Building Dimensions	37.5 ft x 32 ft (11.43 m x 9.75 m)
Percent Glazing	15%

3.1.3.2 Building Envelope

The thermal resistance and thermal mass, two of the more important aspects of the single-family house for energy performance, are described in Table 3.4.

Table 3.4 – Thermal resistance requirements and values and thermal mass values of the single-family house

		R values ft^2·°F·h/Btu (m^2K/W)			Thermal mass Btu/ft^2°F (kJ/Km^2)	
		Wood Frame Requirements	Wood	ICF	Wood	ICF
Exterior Wall	Chicago	20 (3.52)	17.1 (3.01)	21.9 (3.86)	2.4 (48.5)	14.2 (290)
	Phoenix	13 (2.29)	10.6 (1.87)		2 (41.8)	
Ground Floor	Chicago	10 (1.76) for 24 in (61 cm)	13.6 (2.40)		15.7 (323)	
	Phoenix	0	9.6 (1.69)			
Attic Floor	Chicago	38 (6.69)	37.7 (6.64)		0.52 (10.6)	
	Phoenix	30 (5.28)	29.7 (5.23)		0.49 (10.0)	

Also included in Table 3.4 are the requirements for the R-value based on the relevant international energy code (IECC 2009). While the insulation requirements are being met in the models, the R-value of the entire wall assembly is different. The effective R-value of the studs and cavity is calculated using the percentage of wood framing, and then the R-values of each component of the assembly are summed. The windows are assumed to be double-paned insulated units, and the glazing properties are given in Table 3.5.

Table 3.5 – Thermal and solar properties of window glazing in the single-family house

	U value Btu/hr-ft^2-F (W/m^{2}K)	Solar Heat Gain Coefficient
Chicago	0.35 (1.99)	0.35
Phoenix	0.40 (2.27)	0.30

3.1.3.3 Internal Loads

The internal loads in the house are displayed in Table 3.6. Schedules apply to all loads and are based on the values provided by the BAHSP. The values listed here are electrical power consumption when the lighting and equipment are in use. Internal loads are a large portion of usage, and are therefore significant inputs in the energy model.

Table 3.6 – The internal loads in the single-family house based on BAHSP

Lighting	Btu/ft^2 (W/m^2) 1.04 (3.29)
Equipment	Btu (W)
Refrigerator	311 (91.1)
Cooking Range	701 (206)
Clothes Washer	74.4 (21.8)
Clothes Dryer	977 (286)
Dishwasher	198 (58.1)
Misc Electric load	1950 (571)
Misc Gas Load	38.6 (132)

3.1.3.4 Air Tightness

Air tightness is a measurement of how much air leaks in and out of a house through unplanned openings. Blower door tests are used to determine air tightness. These tests, described in Appendix 8.4, have several different outputs that can be entered into an energy model to calculate the movement of air. Some of these outputs are the values *C* and *n*, seen in Equation 3.1, where Q is the airflow through the building in m^3/s and ΔP is the difference in pressure between the building and the environment, in pascals (Pa).

$$Q = C\Delta P^n \qquad [3.1]$$

The process of calculating air tightness can be found in Appendix 8.5. Based on the literature, *n* is assumed to be 0.65 (Sherman and Chan 2004). Minimum, median and maximum values, corresponding to “loose,” “average” and “tight,” are calculated for the ICF single-family house using new data collected for the current study. Blower door tests were conducted for 40 ICF houses in different regions of the United States constructed in the last ten years. Appendix 8.5 provides this new data set for air tightness of ICF houses, demonstrating a range of air infiltration values in current construction. These values are very similar to those for light-frame wood houses based on the Lawrence Berkeley National Laboratory database of U.S. houses (Chan et al. 2003). For the energy simulations of the ICF and light-frame wood houses, the air infiltration values are assumed to be the same, and are given in Table 3.7. Additional research is necessary to better understand the air tightness of ICF and light-frame wood houses. A range of air tightness values are considered in the current study, in order to demonstrate the influence of air tightness on the cumulative LCA results.

Table 3.7 – Values of C used to calculate air tightness

Average	0.050
Tight	0.011
Loose	0.092

3.1.3.5 The HVAC system

The HVAC system delivers conditioned air to the house. The air loop includes a fan, heating coil, cooling coil, and a dehumidifier. The HVAC model does not include outside air, which is provided through infiltration. There is a whole house exhaust fan that meets the minimum ventilation requirements of ASHRAE 62.2 (2007). The most relevant numbers for the HVAC system are presented in Table 3.8.

Table 3.8 – Relevant inputs for the HVAC system in the single-family house

Input	Value
Supply airflow rate	Determined by EnergyPlus
Fan efficiency	0.389
Gas burner efficiency	0.805
COP of cooling coil	3.895
Energy factor of dehumidifier	1.1
Water heater efficiency	0.78

3.1.4 Results

This section summarizes the results of the LCA of single-family houses in both ICF and light-frame wood for a range of air infiltration values for Chicago and Phoenix. See Appendix 8.7 for tables of results.

3.1.4.1 Embodied Emissions

The embodied global warming potential (GWP) of the single-family house per square foot is shown in Figure 3.5. The first bar shows the GWP associated with the pre-use phase, separated by material. The second bar shows the emissions from maintenance over the use phase, and the third bar shows the end-of-life emissions, associated with land filling and recycling. The last bar, outlined in black, shows the total embodied GWP for each house, summed from the pre-use, maintenance, and end-of-life phases. The results show a range of total GWP between 56 and 69 lbs CO_2e/ft^2 (273 and 337 kg CO_2e/m^2) in all houses and climates. Concrete typically accounts for 10-13 lbs CO_2e/ft^2 (49-64 kg CO_2e/m^2) in the ICF houses and 4-8 lbs CO_2e/ft^2 (20-39 kg CO_2e/m^2) in the light-frame wood houses, which is about 7.8%-19% of the embodied life cycle emissions due to materials. The large material GWP in the maintenance phase is due to the asphalt roof replacement, which is assumed to occur every 15 years. The end-of-life phase is a small percentage of the embodied emissions. The total embodied GWP for ICF houses is 13% higher in Chicago and 14% higher in Phoenix than light-frame wood houses.

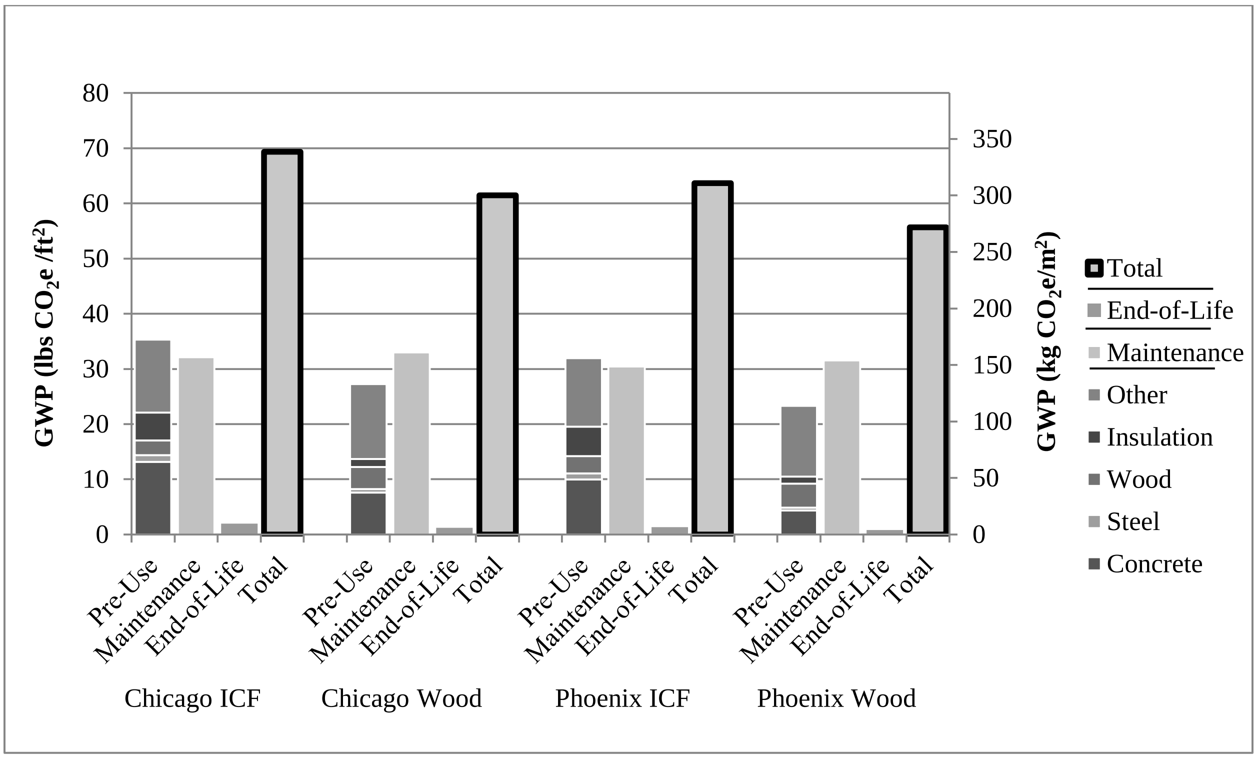

Figure 3.5 – Embodied GWP normalized by gross floor area and separated by material and phase for the single-family houses

3.1.4.2 Operating Emissions

Figure 3.6 displays the annual energy use of the single-family house in Chicago over the loose, average, and tight values of air tightness in Chicago. The lighting, equipment, and water loads stay the same among all building and climate variations, but the HVAC, pumps, and fans change based on the climate and source of energy. For Chicago, the ICF houses use 5.8%, 7.4% and 8.4% less energy than the equivalent light-frame wood house for loose, average and tight construction, respectively. The ICF houses have slightly higher R-values and greater thermal mass, which accounts for the lower energy consumption. Based on energy simulations of the single-family model, the difference in R-value is more important than the difference in thermal mass.

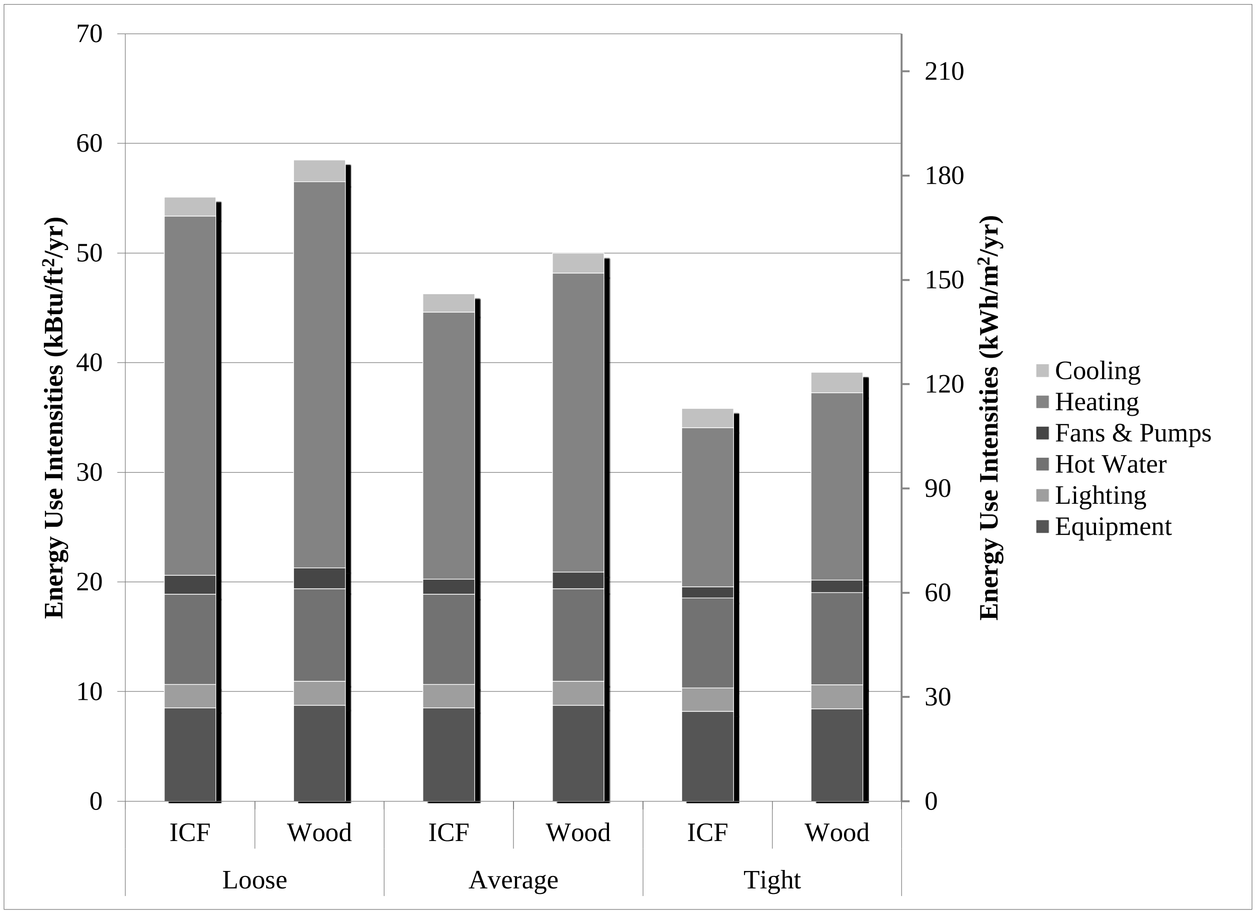

Figure 3.6 – Annual energy use intensities normalized by gross floor area for the single-family houses in Chicago, separated by air tightness and energy end-use

A similar study is performed for Phoenix. In this case, the percentage difference between ICF and wood is larger, with ICF using 11.9%, 11.6% and 11.0% less energy than wood for loose, average and tight constructions respectively. This is due to the fact that ICF walls have even higher R-values than what code requires in a mild climate (Table 3.4), and higher thermal mass than their wood counterparts. Finally, the difference between the loose, average and tight cases is smaller in Phoenix than it is in Chicago, due to the milder climate of Phoenix. Figure 3.7 displays the energy use of the single-family house in Phoenix.

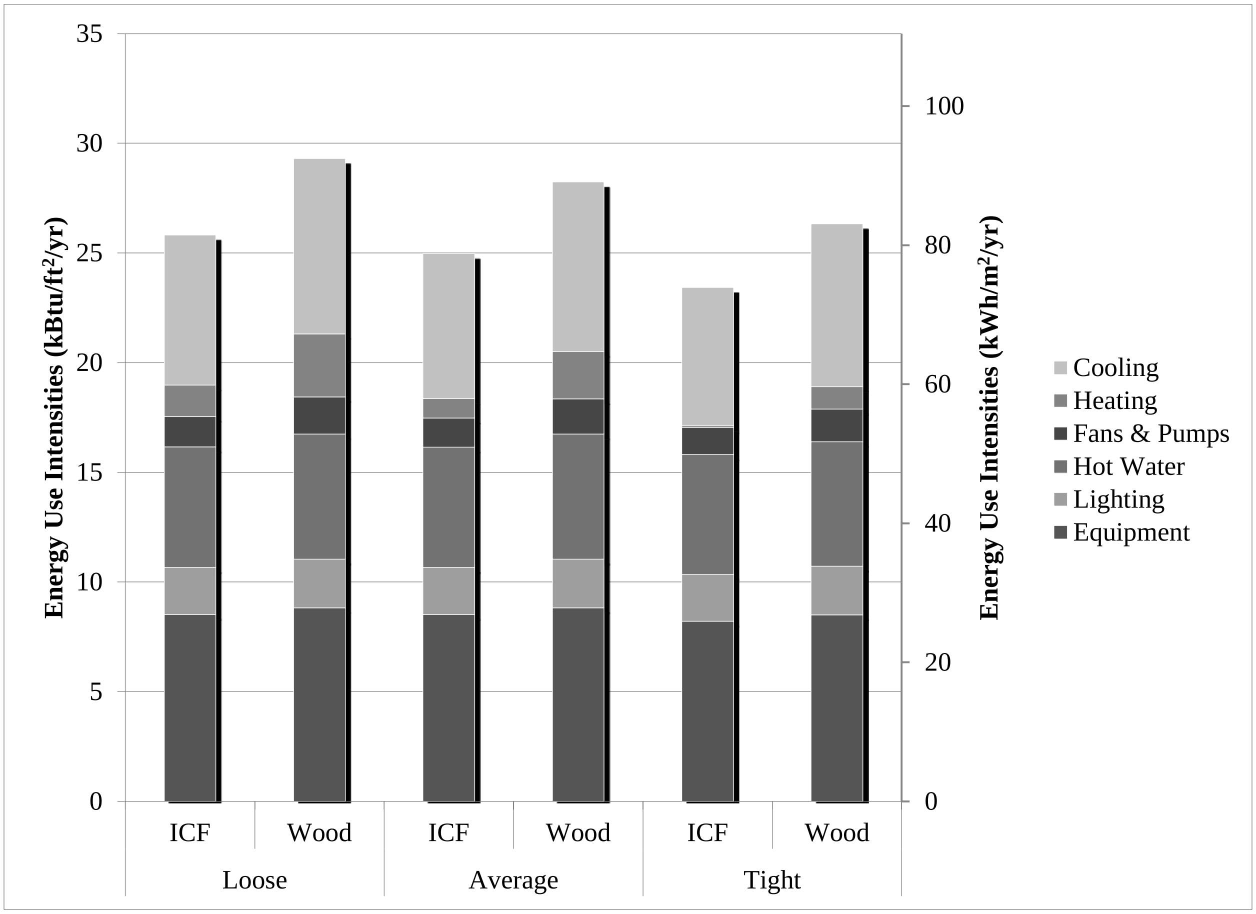

Figure 3.7 – Annual energy use intensities normalized by gross floor area for the single-family houses in Phoenix, separated by air tightness and energy end-use

The operating energy required is then converted to GWP for the single-family house, as seen in Figure 3.8 and Figure 3.9. The trends are the same in this chart as in Figure 3.6 and Figure 3.7, but the percentage differences change slightly depending on the GWP intensity of the regional fuel mix. The GWP of the ICF house in Chicago is 5.4%, 6.1% and 6.6% lower than the light-frame wood house for the loose, average and tight cases, respectively. In Phoenix the GWP of the ICF house is approximately 10% lower than the wood house across the range of air tightness cases. The ICF house of average air tightness is responsible for approximately 12.7 lbs CO_2e/ft^2 (62.2 kg CO_2e/m^2) annually, while the average light-frame wood house is responsible for approximately 13.6 lbs CO_2e/ft^2 (66.3 kg CO_2e/m^2) per year, in Chicago. In Phoenix, the ICF and light-frame wood houses of average air tightness are responsible for 8.18 lbs CO_2e/ft^2 (39.9 kg CO_2e/m^2) and 9.12 lbs CO_2e/ft^2 (44.5 kg CO_2e/m^2), respectively.

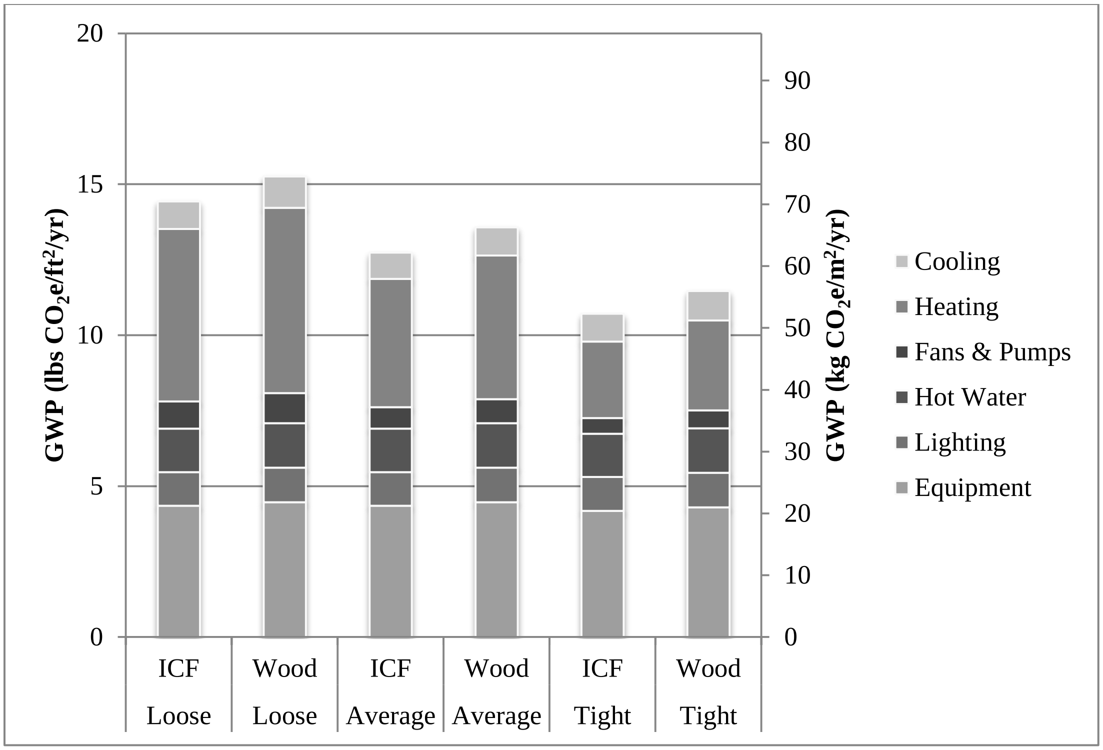

Figure 3.8 – GWP associated with annual energy use and normalized by gross floor area for the single-family houses in Chicago, separated by air tightness and energy end-use

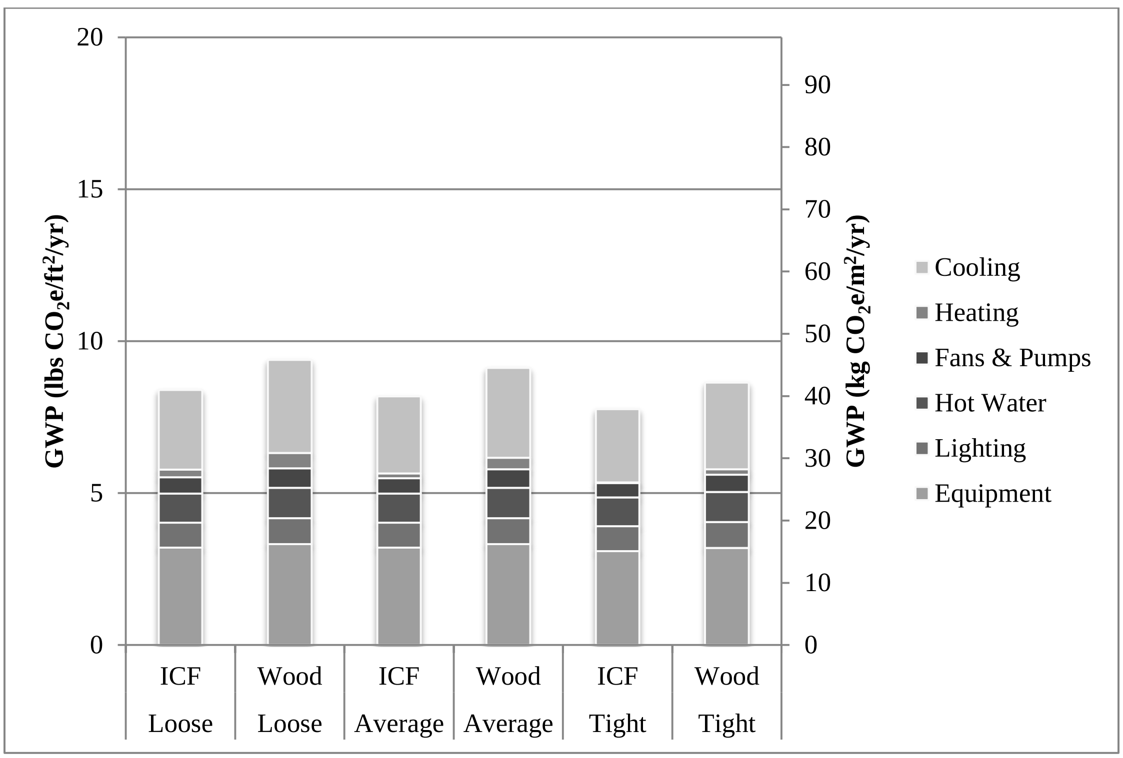

Figure 3.9 – GWP associated with annual energy use and normalized by gross floor area for the single-family houses in Phoenix, separated by air tightness and energy end-use

3.1.4.3 Life cycle results over 60-year period

When the GWP for the total life cycle is calculated, it becomes clear that the embodied emissions are a small fraction of the life cycle emissions, as shown in Figure 3.10 for a building lifetime of 60 years. The cumulative emissions of the ICF houses are 4.7% lower in Chicago and 8.0% lower in Phoenix than the equivalent light-frame wood house. The total GWP of the buildings ranges from 554 to 876 lbs CO_2e/ft^2 (2,705 to 4,277 kg/m^2) for this lifespan. If the GWP is considered for a longer lifespan of 75 years, the overall GWP increases to between 685 and 1088 lbs CO_2e/ft^2 (3,345 and 5,312 kg/m^2), with the embodied GWP making up an even smaller percentage of the total (Figure 3.11). Although the concrete houses have higher initial embodied emissions than light-frame wood construction, the lower annual operating emissions means that the emissions of concrete houses are lower over a 60-year period.

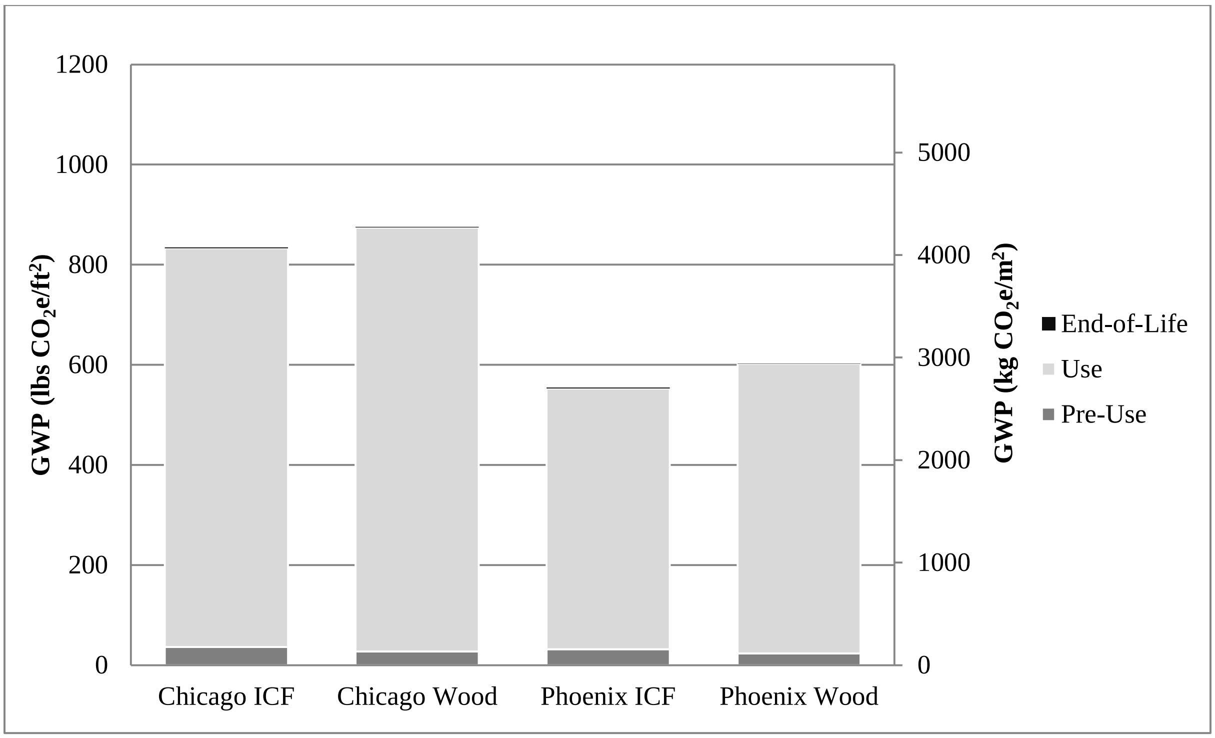

Figure 3.10 – GWP normalized by gross floor area over a 60-year lifespan for single-family houses of average air tightness separated by phase

Regional variation has a major impact on the life cycle of these single-family houses. Assuming a 60-year lifetime, a house in Phoenix has over 30% lower emissions than a house in Chicago, due to the milder climate of Phoenix. Transportation emissions for the building materials account for only a small fraction of the embodied GWP, and are almost negligible over the full life cycle.

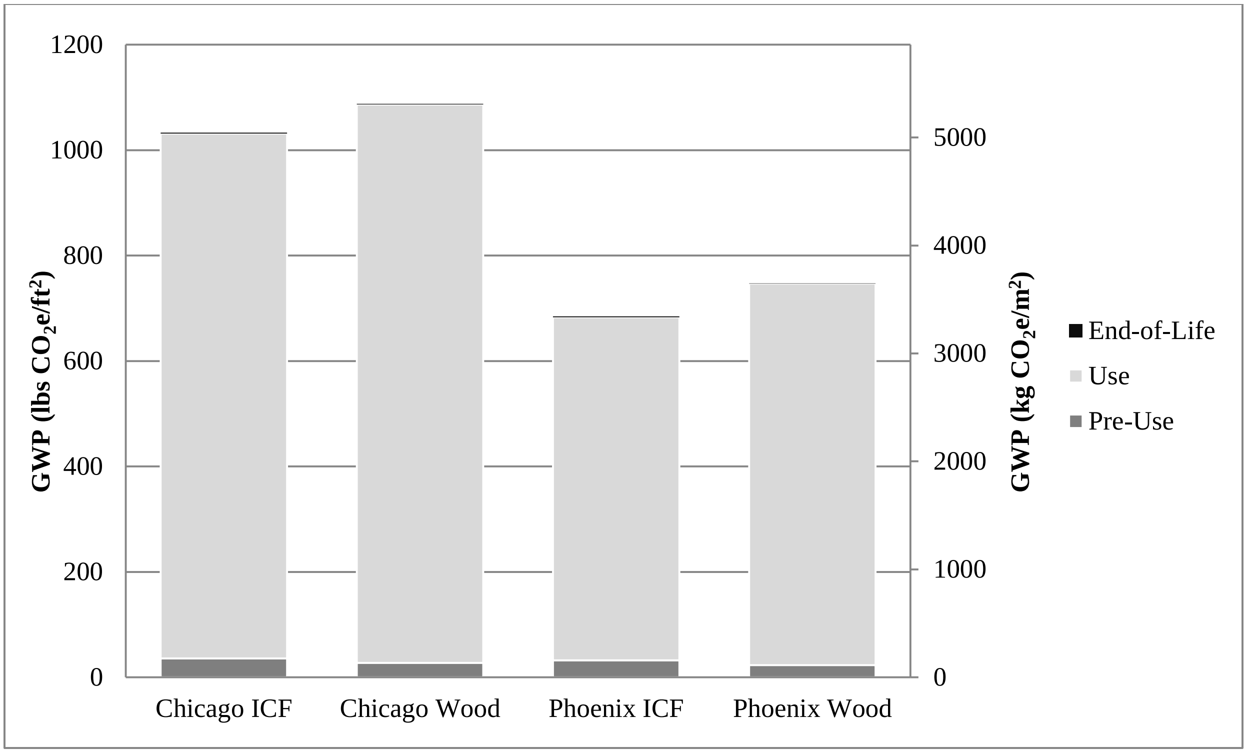

Figure 3.11 – GWP normalized by gross floor area over a 75-year lifespan for single-family houses of average air tightness separated by phase

3.1.5 Life Cycle Cost Analysis (LCCA)

3.1.5.1 Methodology of LCCA

This LCCA aims to quantify the economic cost of ICF versus light-frame wood construction, the cost of potential improvements to standard ICF construction, and the cost to reduce GWP. The analysis only considers the relevant differences between the different alternatives being explored and ignores similarities between the two designs, such as interior and exterior finishes.

The initial cost for each wall system encompasses all related expenses for materials, labor, and construction equipment. An overhead and margin of 25% is included for both sources, which includes direct overhead, indirect overhead, contingency, and profit. The future expected costs only include operational energy requirements and ignores maintenance over the lifetime of the ICF and light-frame wood wall systems. Since light-frame wood is the predominant form of single-family residential construction in the United States, energy savings for ICF are given relative to the light-frame wood wall. Table 3.9 provides a more detailed understanding of what has been included and excluded in the current LCCA.

Table 3.9 – Information included and excluded in the LCCA which only evaluates the different wall systems

		ICF	Light-Frame Wood
Included			
	Materials	ICF blocks; steel reinforcement; concrete	Lumber for framing; plywood for sheathing; weather proofing; insulation
	Labor	Bucking of openings; pumping of concrete; placing steel reinforcement; erecting leveling, and bracing ICF wall; overhead and margin	Studding of wall; labor for sheathing and insulation; labor for weather proofing and sealing the wall; framing of openings; overhead and margin
	Operating	Energy requirements	Energy requirements
Excluded			
		Interior and exterior finishes; engineering fee; shipping of ICF blocks; maintenance; HVAC equipment	Interior and exterior finishes; maintenance; HVAC equipment

Initial costs are calculated with RS Means and National Construction Estimator (RS Means 2010; Ogershok 2010). Both sources provide national average material and labor cost for ICF and light-frame wood construction. Initial costs are scaled by regional factors provided by the sources to represent expected costs for Chicago and Phoenix. Operating costs are calculated using regional residential energy prices provided by the EIA (US EIA 2011a; US EIA 2011b). The annual savings of the ICF wall system are then converted into a present value. A sensitivity analysis between 0 and 5 percent is used for the discount rate, with 2.3% representing the expected discount rate.

3.1.5.2 LCCA Results

The average initial costs for light-frame wood and ICF construction are provided in Table 3.10. While the LCA in the previous section had units of floor area, the LCCA considers the costs of the wall assemblies in units of wall area. For all cases estimated prices are higher using National Construction Estimator than RS Means. The major discrepancy between the two sources for ICF construction is the labor cost. One possible reason is that ICF construction is a relatively new form of construction and builders may lack the same level of familiarity found in traditionally practiced light-frame wood construction. Research has shown that builders become comfortable with ICF construction after having completed at least three projects (PCA 2004).

Table 3.10 – National average initial costs in 2011 U.S. dollars per square foot of wall area for ICF and light frame wood construction using RS Means and National Construction Estimator

	National Construction Estimator $/ft² ($/m²)	RS Means $/ft² ($/m²)
ICF	10.57 (114)	8.35 (90)
2 x 4	5.20 (56)	4.50 (48)
2 x 6	5.75 (62)	4.99 (54)

Table 3.11 provides costs scaled for the two respective regions using regional factors provided by the two sources. For RS Means, scaling is done using the provided factor for the specific city. For National Construction Estimator, since it provided factors more specifically by zip code, an average was taken of the rates for residential areas for the two respective cities. For Chicago, the initial cost is $4.10-4.64/ft^2 ($44.1-49.9/m^2) of wall area higher for ICF construction, and for Phoenix the initial cost is $3.31-5.22/ft^2 ($35.6-56.2/m^2) of wall area higher. The cost differences match up well to a Portland Cement Association (PCA) and National Association of Home Builders (NAHB) co-sponsored project in 2004, which found that on a national average basis ICF is around $3-4/ft^2 ($30-40/m^2) of wall area higher (PCA 2004).

Table 3.11 – Regionally scaled cost of ICF and light-frame wood construction in 2011 U.S. dollars per square foot of wall area (per square meter of wall area)

	National Construction Estimator $/ft² ($/m²)		RS Means $/ft² ($/m²)	
	Chicago	Phoenix	Chicago	Phoenix
ICF	11.88 (128)	10.47 (113)	10.18 (110)	7.18 (77)
Wood	7.24 (78)	5.25 (57)	6.09 (66)	3.87 (42)
Initial Cost	4.64 (50)	5.22 (56)	4.10 (44)	3.31 (36)

To complete the LCCA, energy requirements for the two different wall systems are considered based on the energy simulations for "average" air infiltration described in the previous section. Table 3.12 shows calculated annual energy savings for ICF construction relative to light-frame wood construction using the energy models for average air infiltration. Annual energy savings for Chicago are 2.9 cents/ft^2 (31 cents/m^2) of wall area and 5.6 cents/ft^2 (60 cents/m^2) of wall area for Phoenix. Figure 3.12 converts those energy savings into 60-year present value savings, with the solid bar representing a discount rate of 2.3% and the error bars showing the extremes of an undiscounted rate and a 5% discount rate. The range of energy savings for Chicago is $0.50 to $1.75/ft^2 ($5 to $19/m^2) of wall area and $1.00 to $3.50/ ft^2 ($11 to 36/m^2) of wall area for Phoenix.

Table 3.12 – Relative annual energy savings for ICF construction in Chicago and Phoenix using average air infiltration values in 2011 USD per square foot of wall area

	Chicago $/ft² ($/m²)	Phoenix $/ft² ($/m²)
Annual Energy Savings	0.029 (0.31)	0.056 (0.60)

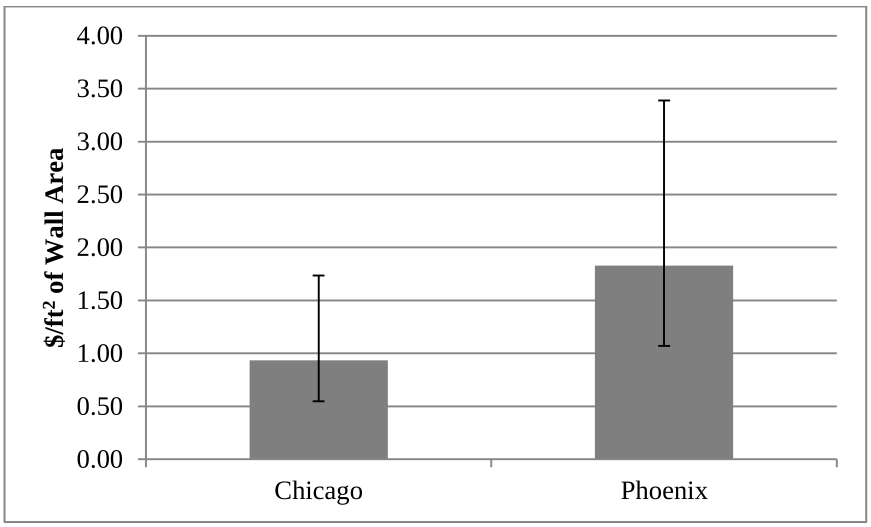

Figure 3.12 – Present value of energy savings over the 60-year lifetime of the ICF wall compared to wood construction for 2,400 ft² (223 m²) single family house

Figure 3.13 provides the total relative life cycle cost of ICF construction by combining initial costs with energy savings. The lowest cost for the bars represents the lowest initial cost with undiscounted energy savings. Conversely, the highest cost represents the highest initial cost with energy savings discounted at a 5% rate. The total life cycle cost for the ICF wall is \$2.36/ft² to \$4.09/ft² (\$25 to \$44/m²) of wall area higher in Chicago and -\$0.08/ft² to \$4.15/ft² (-\$1/m² to \$45/m²) of wall area higher for Phoenix.

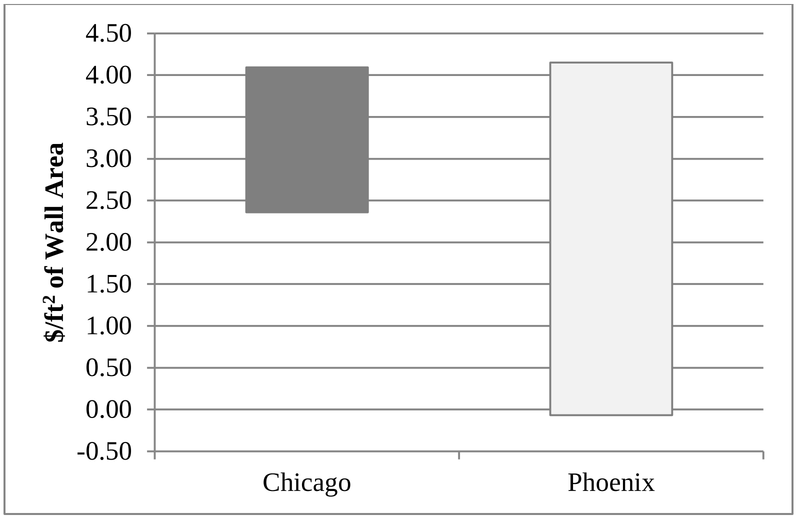

Figure 3.13 – Total life cycle cost of ICF relative to light-frame wood construction for single family house

The results of the current study indicate that standard ICF construction is more expensive than typical light-frame wood construction. Although the cost of an ICF wall is more expensive, it adds a relatively small increase to the price of new home construction.

Future work could include the savings for reducing the size of the HVAC system. ICF construction has been shown to reduce energy loads, and more specifically peak loads, which would reduce the size of the HVAC system inside a house and therefore reducing the life cycle cost of ICF construction.

3.1.6 Potential Improvements

LCCA is a useful tool not just in comparing different alternatives but also the costs associated with optimizing an existing alternative. This section considers the relative cost associated with a variety of strategies to reduce the overall emissions of ICF houses.

3.1.6.1 Reducing cementitious content

As summarized above, the total embodied GWP of a single family ICF house is approximately 64 to 70 lbs CO_2e/ft^2 (312 to 340 kg CO_2e/m^2) of floor area, of which the concrete accounts for 10-13 lbs CO_2e/ft^2 (49-64 kg CO_2e/m^2). By designing thinner ICF walls or by reducing the cement content in the concrete mix, the embodied GWP for an ICF house can be reduced.

One option to reduce the embodied emissions of an ICF house is to reduce the cement content in the concrete mix by introducing supplementary cementitious materials (SCMs), such as ground granulated blast furnace slag (GGBFS), fly ash, and silica fume. Though there are a wide range of possible mix designs using SCMs, for simplicity, only fly ash is considered here. For example, by using 50% by volume fly ash in the concrete mix design rather than the nominal 10% assumed for the base case, the embodied energy can be reduced by 4-5 lbs CO_2e/ft^2 (20-25 kg CO_2e/m^2). This represents savings in the embodied GWP of 5-10% of the pre-use phase, or 3-4 percent of the total embodied emissions when including maintenance over 60 years. Single-family residential construction presents the greatest opportunity to reach high levels of fly ash substitution due to the moderate structural requirements as compared to taller buildings. Reductions in GWP resulting from an increase in fly ash substitution of cement in the concrete mix used for single family construction are shown in Table 3.13. The details of the various concrete mix designs are presented in Table 8.7.

Table 3.13 – Possible pre-use phase embodied GWP reductions with increased fly ash replacement of cement in concrete mix used in single-family residential houses.

	Chicago ICF lbs CO_2e/ft^2 (kg CO_2e/m^2)	Chicago Wood lbs CO_2e/ft^2 (kg CO_2e/m^2)	Phoenix ICF lbs CO_2e/ft^2 (kg CO_2e/m^2)	Phoenix Wood lbs CO_2e/ft^2 (kg CO_2e/m^2)
Concrete Mix– 10% fly ash	35.3 (173)	27.3 (133)	31.9 (156)	23.3 (114)
Concrete Mix – 50% fly ash	30.4 (149)	24.4 (119)	28.2 (138)	21.7 (106)
Percent Reduction	14%	10%	12%	6.9%

The National Research Council in Canada has shown that the thermal mass benefits for increasing the thickness of the concrete core in an ICF wall may be marginal (Armstrong et al. 2011). To verify this finding, the current study modeled ICF concrete cores ranging from 4 in (101.6 mm) to 12 in (304.8 mm) thick. For the 2,400 ft^2 (223 m^2) house, the energy models predict a reduction of 1-1.5% in total energy consumption by going from a 4 in (101.6 mm) thick concrete core to a 12 in (304.8 mm) concrete core. Since thicker cores show marginal energy savings, a 4 in thick core meeting code compliance is the optimal thickness for ICF construction. Further research could explore the impact of thermal mass if the concrete is exposed on the interior of a house.

3.1.6.2 Increasing thermal resistance

Another option to reduce the energy requirements of an ICF house is to increase the thickness of the insulation panels on either side of the wall. Although this cost analysis only focuses on increasing the thickness of the foam panels, thermal resistance for ICF construction can also be increased by changing the density of the foam panels or using graphite-enhanced foams. Figure 3.14 shows the relative decrease in energy consumption from a standard ICF wall with 2.5 in (63.5 mm) thick expanded polystyrene (EPS) foam panels by increasing the panel thickness to 4 in, 5 in, or 6 in (101.6 mm, 127 mm, or 152.4 mm) on each side. The energy model shows that there are larger energy savings to be had in Chicago than in Phoenix by increasing the thermal performance of a wall, as expected. The largest incremental increase in energy savings is going from the base case to 4 in panels on each side. Figure 3.15 shows the annual economic savings relative to the 2.5 in (63.5 mm) panel base case. For Chicago, by increasing the thermal performance of the ICF wall, relative energy savings for the ICF wall increase by 5.3 – 7.0 cents per ft^2 (57-75 cents/m^2) of wall area.

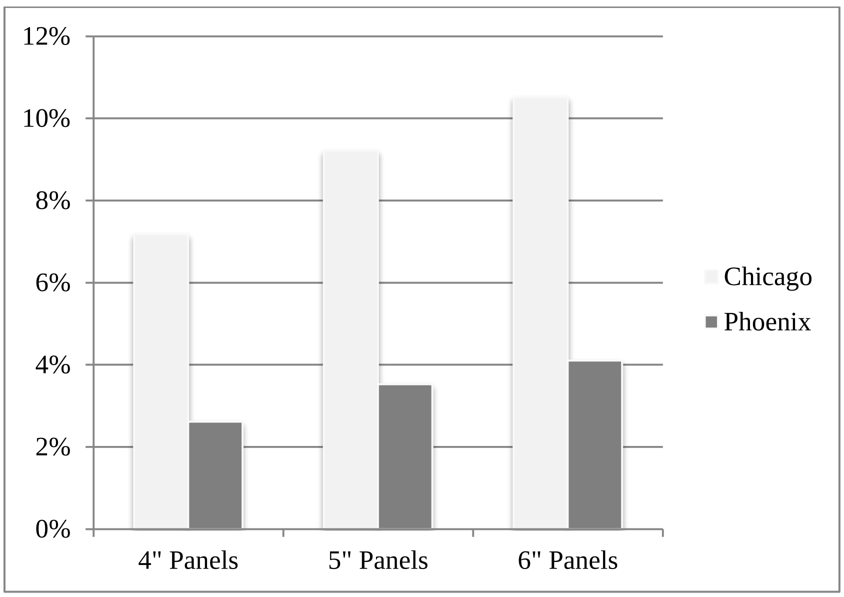

Figure 3.14 – Relative annual energy savings by increasing panel thickness from base case of 2.5 in (63.5 mm) of EPS insulation on each side

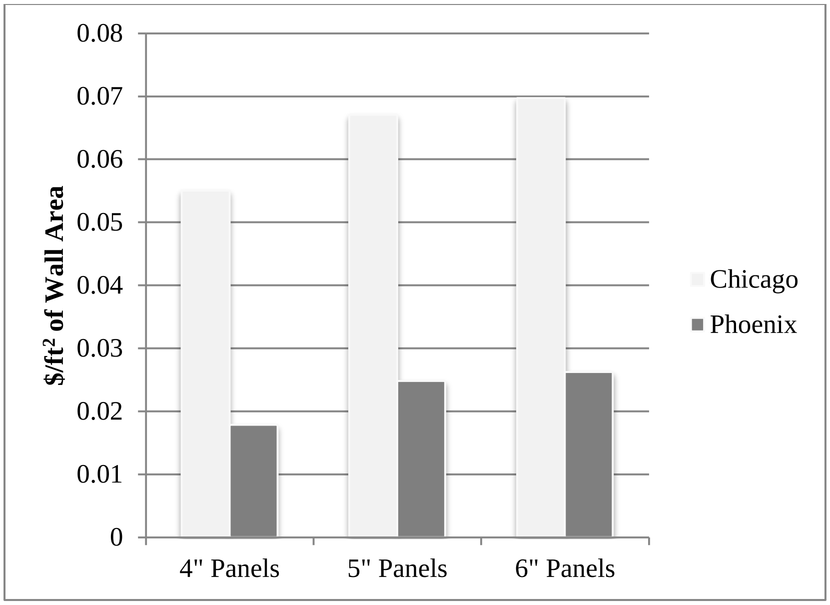

Figure 3.15 – Annual relative energy savings in U.S. dollars per square foot of wall area by increasing panel thickness from base case of 2.5 in (63.5 mm) panels on each side

Since there are so few manufacturers of ICF foam blocks with different panel thicknesses, neither RS Means nor National Construction Estimator provides cost information for varying panel thicknesses. Initial additional costs for increasing panel thickness are taken as an average between interviews with different manufacturers and distributors. Based on the average initial cost, the total present value for increasing panel thickness is calculated. Figure 3.16 shows the 60-year present value of increasing panel thickness, with the range of the bars representing a 0-5% discounted energy savings. Based on the results, increasing thermal performance of the ICF wall can be achieved for only a modest increase in the life cycle cost of a house in a cold climate.

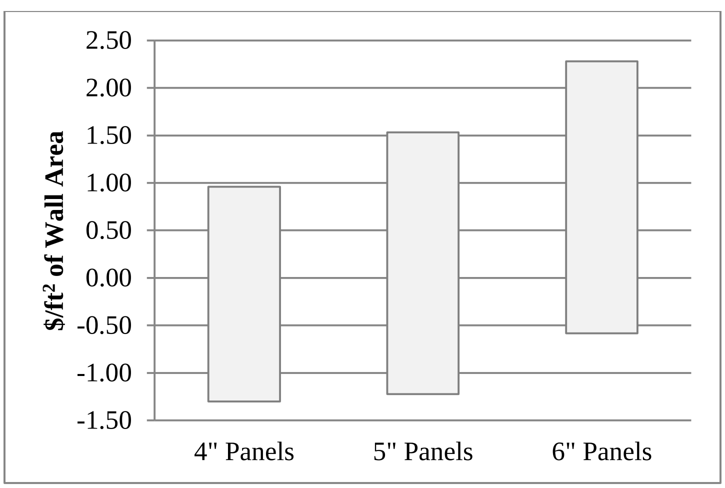

Figure 3.16 – Relative 60-year present value in dollars per square foot of wall area due to increasing panel thickness from 2.5 in (63.5 mm) on each side for Chicago, where the range of values for each bar represents a discount rate of 0-5%

3.1.6.3 Increasing Air Tightness

Increasing the tightness of an ICF wall may produce the greatest opportunity to reduce energy expenditures. As mentioned previously, ICF construction can have a range of air infiltration values that greatly impact energy consumption, although further research will help to understand what is required to reach tight air infiltration values for ICF construction, previous experimental research for other building materials has shown that some houses can meet stringent air tightness levels for a small initial cost (Newell and Newell 2011). Table 3.14 shows the annual energy savings of going from an average to tight air infiltration value for an ICF. Again, larger reductions occur for the ICF house in Chicago, the colder climate.

Table 3.14 – Relative annual energy savings by decreasing infiltration from "average" to "tight" for an ICF home in 2011 USD per square foot of wall area

	Chicago, $\$/ft^2$	Phoenix, $\$/ft^2$ ($\$/m^2$)
Annual Energy	0.152 (1.64)	0.039 (0.42)

3.1.6.4 LCCA combined with LCA

Growing awareness of climate change has made reducing emissions not just an environmental issue but also an economic one. An emerging field of interest is the economics of GWP emissions. The central issue is trying to quantify the cost of a carbon dioxide equivalent per ton. The European Union Emissions Trading Scheme (EUETS) is right now the largest such trading scheme of carbon emissions. As of 2011, the price of carbon for EUETS is 18 USD per short ton (20 USD per metric ton) of carbon (Point Carbon 2011). This price has been predicted to rise to over 50 USD per short ton (55 USD per metric ton) of carbon by the year 2016 (Point Carbon 2010). The Stern Review on the Economics of Climate Change, commissioned by the British Government in 2006, reports that the social cost of carbon is 77 USD per short ton (85 USD per metric ton) of carbon (Stern 2006). This price of carbon is generally higher than in other literature largely because the review treats risk explicitly. It is also possible that carbon emissions could be taxed in the United States in the future. Australia recently instituted a carbon tax of $25 (AUS) per metric ton of carbon emissions (Gillard et al. 2011). There are a range of values for the cost of carbon emissions, but it is clear from the literature that $18 - $23 per short ton ($20 - $25 per metric ton) is a reasonable estimate of the price of carbon emissions. Combining the LCA with the LCCA gives insight into the cost to reduce emissions of single-family ICF construction, and it allows for transparency to see if they are price competitive with potential carbon tax pricing mechanisms.

Table 3.15 provides information on the calculated present value cost, embodied emissions, operating emissions, and total emissions for each potential improvement. Moving to a 4 in (10.2 cm) concrete core from the 6 in (15.2 cm) standard core reduces life cycle costs and total emissions of the ICF wall. Since thermal mass shows negligible energy savings by adding concrete to the core, reducing the amount of concrete in the wall reduces the embodied impact with negligible impact on the operating emissions. Increasing the insulation panel thickness slightly increases the embodied emissions while substantially reducing operating emissions. By moving from standard 2.5 in (63.5 mm) to thicker 4 in (101.6 mm) insulation panels, carbon emissions pay back for themselves in 0.5 year in Chicago and 2.5 years in Phoenix.

Figure 3.17 shows the calculated cost per ton reduction of CO_2e. The graph presents costs in terms of average initial cost and energy savings with a discount rate of 2.3%. Based on the results for Chicago, using panels that are 4 in (101.6 mm) thick can reduce carbon emissions at a cost of less than $10 per metric ton reduction of CO_2e. This compares very favorably with other carbon reduction strategies, such as photovoltaic panels or other renewable energy sources.

Table 3.15 – Relative cost, embodied emissions, operating emissions, and total emissions by changing the ICF wall from the 6 in concrete core, 2.5 in EPS panel base case

	Average Cost $/ft^2 ($/m^2)	Location	Embodied lbs CO_2e (kg CO_2e)	Annual Operating lbs CO_2e (kg CO_2e)	60-year Operating lbs CO_2e (kg CO_2e)	Total lbs CO_2e (kg CO_2e)
4 in Core	-0.75 (-8.07)	Chicago	-5340 (-2427)	81 (37)	4860 (2210)	-478 (-217)
	-0.71 (-7.64)	Phoenix	-5340 (-2427)	40 (18)	2390 (1090)	-2950 (-1340)
4 in Panel	0.22 (2.37)	Chicago	1190 (541)	-2270 (-1259)	-136000 (-61800)	-135000 (-61600)
	1.42 (15.28)	Phoenix	1190 (541)	-498 (-226)	-29900 (-13600)	-28700 (-13000)
5 in Panel	0.63 (6.78)	Chicago	1980 (900)	-2790 (-1268)	-167100 (-76000)	-165000 (-75000)
	2.00 (21.53)	Phoenix	1980 (900)	-500 (-223)	-29900 (-13600)	-27900 (-12700)
6 in Panel	1.34 (14.42)	Chicago	2770 (1259)	-3115 (-1416)	-186900 (-85000)	-184000 (-83600)
	2.75 (29.90)	Phoenix	2770 (1259)	-500 (-223)	-29900 (-13600)	-27100 (-12300)

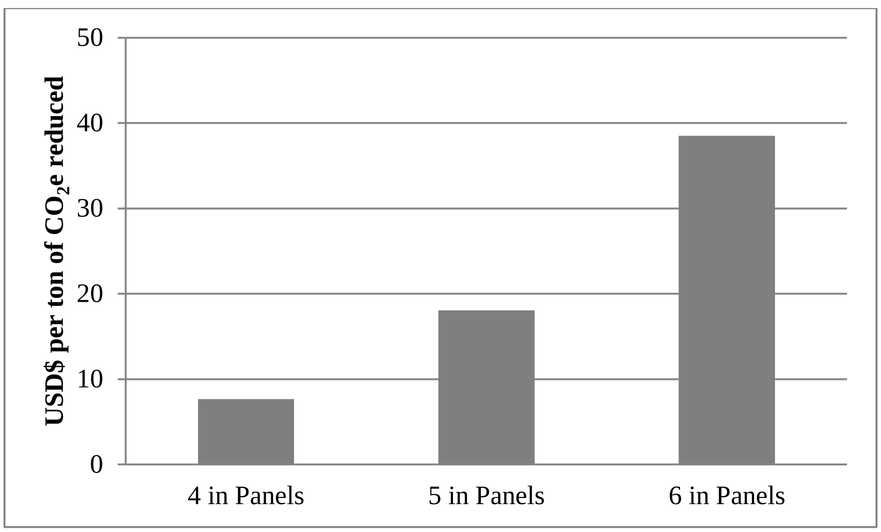

Figure 3.17 – Life cycle cost per ton of CO_2e reduction by increasing panel thickness for Chicago

3.1.7 Conclusions

This chapter analyzed the single-family house with both light-frame wood and ICF systems based on a benchmark building from the BAHSP. It also offered possible methods of improvement for the ICF house, and completed a cost analysis of these improvements. The GWP of the single-family houses considered in this chapter is summarized in Table 3.16.

Table 3.16 – Summary of the single-family house for the entire 60-year life cycle

City	Building Type	Pre-Use Materials lbs/ft^2 (kg/m^2)	Pre-Use GWP lbs CO_2e/ft^2 (kg CO_2e/m^2)	Maintenance GWP lbs CO_2e/ft^2 (kg CO_2e/m^2)	Operational GWP/year lbs CO_2e/ft^2 (kg CO_2e/m^2)	End-of-Life GWP lbs CO_2e/ft^2 (kg CO_2e/m^2)	Total for 60 years lbs CO_2e/ft^2 (kg CO_2e/m^2)
Chicago	ICF	177 (866)	35.3 (172)	32.1 (157)	12.7 (62.2)	1.96 (9.57)	834 (4074)
	Wood	129 (631)	27.3 (133)	33.0 (161)	13.6 (66.3)	1.20 (5.86)	876 (4276)
Phoenix	ICF	142 (693)	31.9 (156)	30.4 (148)	8.18 (39.9)	1.33 (6.49)	554 (2707)
	Wood	93.2 (455)	23.3 (114)	31.5 (154)	9.12 (44.5)	0.79 (3.86)	603 (2943)

The following conclusions can be drawn:

- The total embodied GWP of ICF houses is 64-69 lbs CO_2e/ft^2 (312-337 kg CO_2e/m^2) and for light-frame wood houses is 56-61 lbs CO_2e/ft^2 (273-298 kg CO_2e/m^2).
- In general, the total embodied GWP of ICF houses is around 8 lbs CO_2e/ft^2 (39 kg CO_2e/m^2) higher than light-frame wood construction.
- A significant contributor to the embodied GWP for all houses is the maintenance, and in particular the replacement of the roof and windows can equal the pre-use emissions over the life cycle.
- For the 60-year period of the study, ICF houses have 5%-8% lower GWP than light-frame wood houses, due to greater thermal mass and higher R-values.
- For a cold climate, such as Chicago, the energy savings of an ICF house built from average to tight levels of air infiltration saves 23% of total operating energy. Future work will need to quantify the additional costs to reach tight air tightness values.
- ICF construction is a more expensive construction alternative than light-frame wood construction but gives lower energy costs in the use phase. Accounting for a range of construction costs and discount rates, the relative life cycle costs for ICF construction compared to light-frame wood is \$2.36-\$4.09/ft^2 (\$25-44/m^2) of wall area higher in Chicago and -\$0.08 to \$4.15/ft^2 (-\$1 to \$45/m^2) of wall area in Phoenix. Over the total life cycle cost, however, ICF construction increases the price of a house by less than 5%.
- Moving from a 6 in (15.2 cm) to a 4 in (10.2 cm) core is both cost effective and reduces emissions over the lifetime of the wall assembly, and it should be considered in regions of the country where a 4 in (10.2 cm) core meets structural requirements.
- By producing ICF insulation blocks with different panel thicknesses, increasing the tightness of houses, and making a thinner ICF wall, greenhouse gas emissions can be reduced at prices lower than the current market pricing of carbon.
- Increasing SCM substitution from 10% to 50% in the ICF house reduces the pre-use GWP by 12% to 14%.

3.2 Multi-Family Residential

3.2.1 Introduction

This study discusses two types of multi-family buildings, one made of insulated concrete forms (ICF) with interior wood framing and one made entirely of wood. The use of the DOE midrise apartment benchmark building provides accurate estimates of energy usage and allows for a design starting point. Little research has been done previously on the life cycle carbon emissions of multi-family structures, promoting its inclusion in this study. Suzuki et al. (1995) discuss two reinforced concrete multi-family structures, but the energy and CO_2 emissions are assessed for construction requirements only, not the entire life cycle.

3.2.2 Design and Construction

The dimensions of the multi-family building are based on the DOE's midrise apartment reference building (US DOE 2004). It is four stories with a footprint of 153 ft x 56 ft (47 m x 17 m) dimensions and a total available square footage of 33,763 ft^2 (3,137 m^2). There are eight apartment units per floor that are 25 ft x 38 ft (7.6 m x 11.6 m), and a central hallway that runs the length of the building and is 5 ½ ft (1.7 m) wide. There are two sets of stairs, one at each end of the building, and a concrete elevator core. Renderings of the multi-family building model are shown in Figure 3.18.

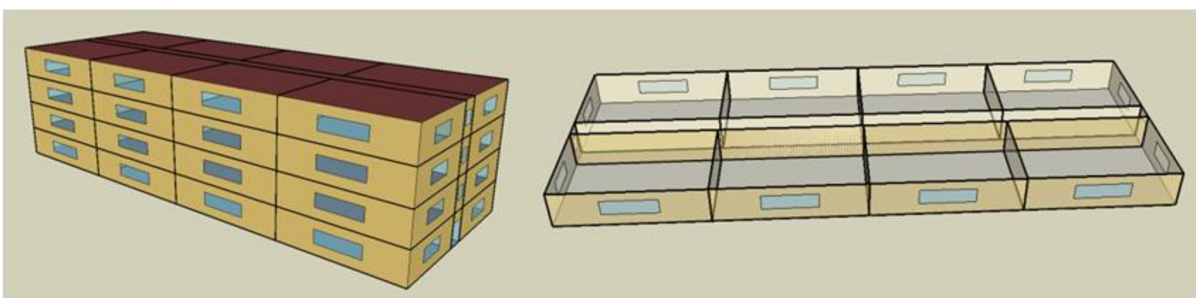

Figure 3.18 – DOE midrise apartment building, exterior and plan views, that provides the basis for the multi-family building (DOE 2004).

The structure is designed in accordance with the relevant building codes for Chicago and Phoenix and is based on standard industry practice. The ICF structure consists of 8 in (20.3 cm) load-bearing concrete walls with 2.5 in (6.4 cm) of expanded polystyrene (EPS) insulation on either side as the formwork. The two layers of EPS are connected by plastic ties. The interior of the building is framed with wood. There are load bearing-partition walls of 2x4 (38 mm x 89 mm) construction along the hallway, and 2x6 (38 mm x 140 mm) construction between the individual units. There are columns at the mid-span of the apartment areas, as well as between connecting partitions. The floors and roof consist of glue-laminated timber beams, 3 1/8 in x 12 in (79 mm x 305 mm) at 13 ft (4.0 m) on center and 3 1/8 in x 10 ½ in (79 mm x 267 mm) at 12 ft 6 in (3.8 m), respectively, in addition to floor and roof joists 2x10 (38 mm x 235 mm) spaced 16 in (41 cm) on center, and are designed to resist required live and dead loads according to the International Building Code (IBC 2009). See Table 8.7 in Appendix 8.6 for the concrete mix used.

The wood multi-family buildings are designed using typical wood-frame construction in addition to satisfying the local building codes in each region investigated. Structural design specifications for the wood multi-family buildings are in accordance with National Design Specification (NDS) for Wood Construction (2005). The exterior walls use 2x4 (38 mm x 89 mm) studs at 16 in (41 cm) on center, except for the first two levels of the 56 ft (17 m) sides which have 3x4 (64 mm x 89 mm) studs at 16 in (41 cm) on center. Table 3.17 describes the structural similarities between the buildings, while Table 3.18 describes the structural differences.

Table 3.17 – Similarities in the multi-family buildings

Roof	
Built-up	Asphalt plies
Sheathing	1/2 in (12.7 mm) Plywood
Insulation	Fiberglass
Drywall	1/2 in (12.7 mm) thick
Beams	3 1/8 in x 10 1/2 in (7.9 cm x 26.7 cm) @ 13 ft (3.8 m) o.c.
Joists	2 x 10 (38 mm x 235 mm) @ 16 in (41 cm) o.c.
Load Bearing Partitions	
Studs	2x4 (38 mm x 89 mm) @ 16 in (41 cm) o.c. (hallways)
	2x6 (38 mm x 140 mm) @ 16 in (41 cm) o.c. (apartments)
Drywall	1/2 in (12.7 mm) thick
Floors	
Sheathing	3/4 in (19.1 mm) Plywood Sheathing
Beams	3 1/8 in x 12 in (7.9 cm x 30.5 cm) @ 13 ft (4 m) o.c.
Joists	2 x 10 (38 mm x 235 mm) @ 16 in (41 cm) o.c.

Table 3.18 – Differences in the multi-family buildings

Exterior Walls	ICF – Chicago	ICF – Phoenix	Wood – Chicago	Wood - Phoenix
ICF Wall	8 in (20.3 cm) concrete core	8 in (20.3 cm) concrete core	N/A	N/A
EPS Insulation	2.5 in (6.4 cm) panels	2.5 in (6.4 cm) panels	N/A	N/A
Studs	N/A	N/A	2 x 4 (38 mm x 89 mm) @ 16 in (41 cm) o.c. 3x4 (64 mm x 89 mm) @ 16 in (41 cm) o.c. (bottom two floors, 56’ side)	2 x 4 (38 mm x 89 mm) @ 16 in (41 cm) o.c. 3x4 (64 mm x 89 mm) @ 16 in (41 cm) o.c. (bottom two floors, 56’ side)
Sheathing	N/A	N/A	1/2 in (15.9 mm) Plywood	1/2 in (12.7 mm) Plywood
Insulation	N/A	N/A	Batt and XPS	Batt
Drywall	1/2 in (12.7 mm)	1/2 in (12.7 mm)	1/2 in (12.7 mm)	1/2 in (12.7 mm)
Foundation	ICF – Chicago	ICF – Phoenix	Wood – Chicago	Wood - Phoenix
Wall Depth	42 in (1.07 m)	12 in (0.3 m)	42 in (1.07 m)	12 in (0.3 m)
Thickness	8 in (20.3 cm)	8 in (20.3 cm)	8 in (20.3 cm)	8 in (20.3 cm)
EPS Insulation	2.5 in (6.4 cm) thick panels	2.5 in (6.4 cm) thick panels	N/A	N/A
XPS Insulation	Around the perimeter of slab-on-grade	N/A	Around the perimeter of slab-on-grade	N/A
Footing	4 ft (1.22 m) width	4 ft (1.23 m) width	16 in (0.41 m) width	16 in (0.41 m) width
Isolated Footings	5 ft x 5 ft x 1 ft (1.5 x 1.5 x 0.3m)	5 ft x 5 ft x 1 ft (1.5 x 1.5 x 0.3m)	5 ft x 5 ft x 1 ft (1.5 x 1.5 x 0.3m)	5 ft x 5 ft x 1 ft (1.5 x 1.5 x 0.3m)

All buildings have a 4 in (10.2 cm) concrete slab-on-grade (SOG) with a plastic vapor barrier, a 4 in (10.2 cm) layer of gravel, and a 2 in (5.1 cm) layer of sand. Additionally, there is a continuous perimeter footing and 5 ft x 5 ft (1.5 m x 1.5 m) isolated footings for each column. Each building has a built-up-roof that incorporates a parapet, layers of asphalt/felt ply, gravel ballast, and galvanized steel flashing around the perimeter. The interior finish is 1/2 in (12.7 mm) drywall with three layers of paint on all walls and ceilings. The exterior cladding is stucco that utilizes a metal lath for support and expansion joints. The exterior also has three layers of silicate emulsion paint that is best for masonry-type purposes. Maintenance is assumed to occur regularly over the 60-year lifetime of the building. Roof asphalt, windows and window frames are replaced every 15 years and surfaces are repainted every 10 years. An overview of the structural design of the multi-family buildings is shown in Figure 3.19.

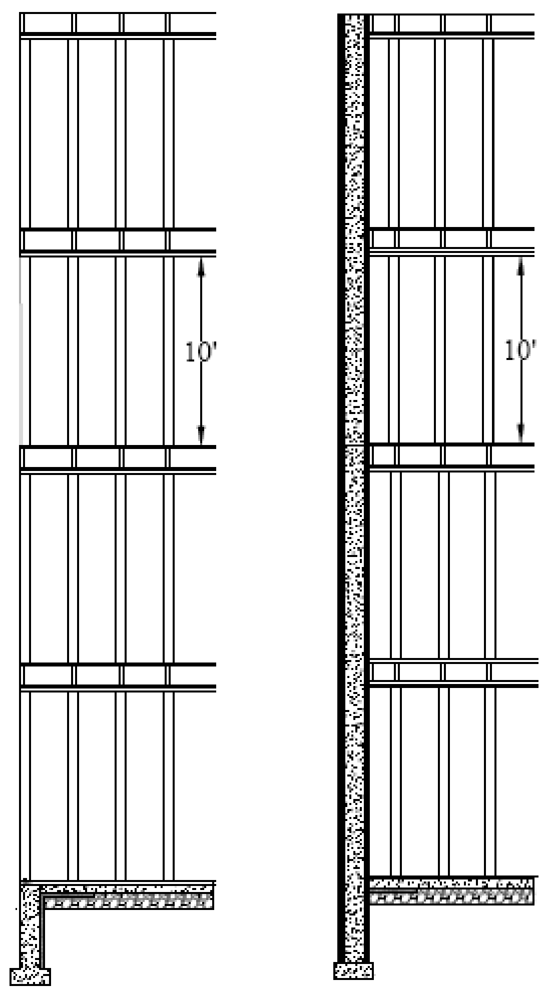

Figure 3.19 – Structural design for wood (left) and ICF (right) multi-family buildings

The total weight of materials for each building is shown in Figure 3.20. Appendix 8.6 provides all material masses. Concrete is the most dominant single material by weight and is slightly greater in Chicago than in Phoenix due to the increased foundation depths required. The ‘other’ category includes paint, windows, stucco, drywall, gravel, sand, waterproofing, and other miscellaneous materials.

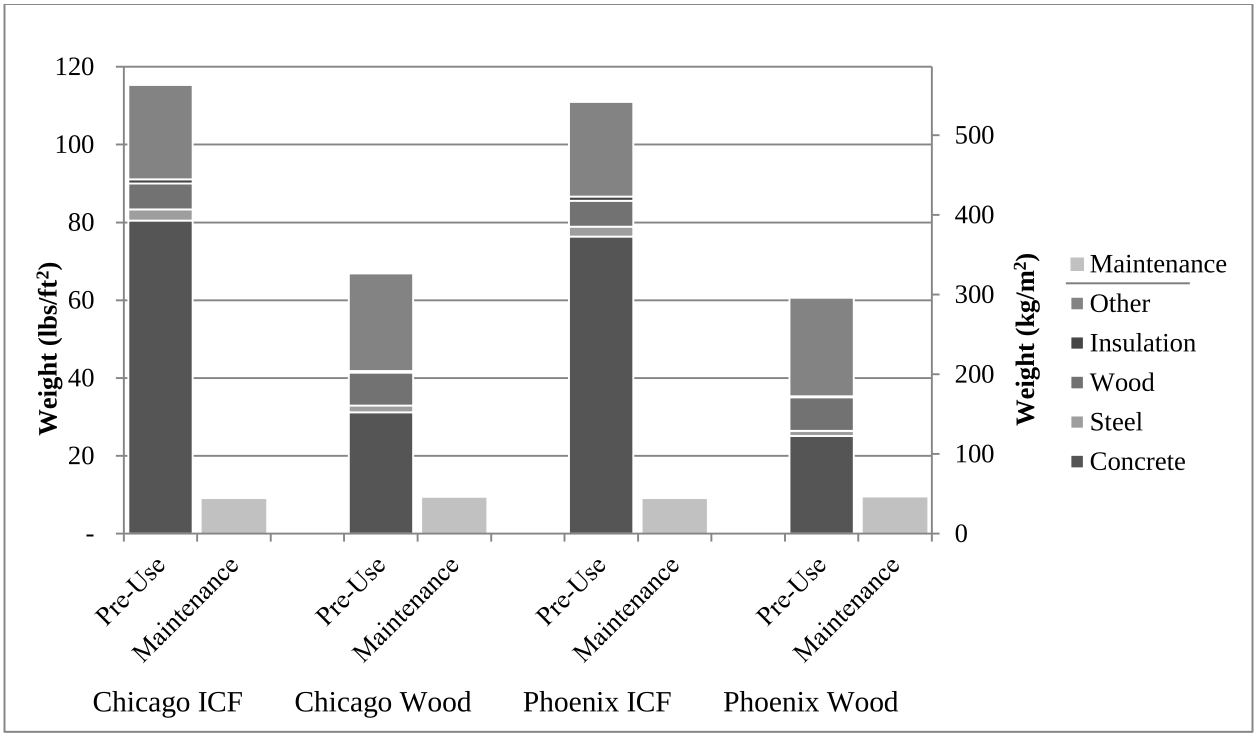

Figure 3.20 – Weight of materials normalized by gross floor area and separated into type and phase for the multi-family buildings

3.2.3 Energy Model

3.2.3.1 Basic Specifications

To determine the annual energy consumption of each building type, some changes are made to the DOE benchmark building file to create wood-frame and ICF buildings and to update it to ASHRAE 90.1 (2007) standards. First, the materials and construction were modified to create the new envelopes. In addition, the envelopes, heating coils, hot water heater, cooling coil, and lighting power density are examined to ensure compliance with ASHRAE 90.1 (2007). Since air infiltration values of multi-family homes are not well documented in the literature, the same values introduced for single-family houses in Section 3.1 are used again for multifamily construction, and will be described in more detail below. Table 3.19 summarizes the basic parameters for the multi-family building considered in this study.

Table 3.19 – Summary of the multi-family residential building

Input	
Reference Standard	DOE Benchmark Building, ASHRAE 90.1-2007
Conditioned Area	33745 ft^2 (3135 m^2)
Unconditioned Area	0 ft^2 – the entire building is conditioned
Number of Floors	4
Number of Zones	32 (8 apartments per floor, 1 corridor per floor)
Building Dimensions	55.5 ft x 152 ft (16.92 m x 46.33 m)
Percent Glazing	15%

3.2.3.2 Building Envelope

The thermal resistance and thermal mass, two of the more important aspects of the multi-family residential building for the purposes of this study, are presented in Table 3.20. Also included are the requirements for the R-value, based on the relevant energy code (ASHRAE 90.1 2007). Note that the requirement value listed is for the insulation only. As such, the values listed in Table 3.20 (which are the wall assemblies) are in some cases lower than the required values listed. See Appendix 8.3 for an example calculation.

Table 3.20 – Thermal resistance requirements and values and thermal mass values of the multi-family building

<table>
<tr><th></th><th></th><th colspan="3">R values ft^2·°F·h/Btu (m^{2}K/W)</th><th colspan="2">Thermal mass Btu/ft^2°F (kJ/Km^2)</th></tr>
<tr><th></th><th></th><th>Wood Frame Requirements</th><th>Wood</th><th>ICF</th><th>Wood</th><th>ICF</th></tr>
<tr><td rowspan="2">Exterior Wall</td><td>Chicago</td><td>13 (2.29) + 7.5 (1.32) c.i.</td><td>17.6 (3.16)</td><td rowspan="2">22.2 (3.91)</td><td>3.16 (64.8)</td><td rowspan="2">21.3 (437)</td></tr>
<tr><td>Phoenix</td><td>13 (2.29)</td><td>9.93 (1.79)</td><td>3.06 (62.7)</td></tr>
<tr><td rowspan="2">Ground Floor</td><td>Chicago</td><td>10 (1.76) for 24 in (61 cm)</td><td colspan="2">12.4 (2.18)</td><td colspan="2">22.5 (461)</td></tr>
<tr><td>Phoenix</td><td>0</td><td colspan="2">2.1 (0.37)</td><td colspan="2">22.4 (459)</td></tr>
<tr><td rowspan="2">Roof</td><td>Chicago</td><td>38 (6.69)</td><td colspan="2" rowspan="2">36.3 (6.39)</td><td colspan="2" rowspan="2">4.2 (85.2)</td></tr>
<tr><td>Phoenix</td><td>38 (6.69)</td></tr>
</table>

The walls of the ICF buildings use only the EPS form for insulation; the wood buildings use fiberglass batt insulation between the studs and Chicago also requires a 1 3/8 in (34.9 mm) layer of continuous insulation on the exterior. The slab-on-grade (SOG) has extruded polystyrene (XPS) insulation (Chicago only) around the perimeter, while the interior partitions and roof use fiberglass batt insulation. The glazing properties are given in Table 3.21.

Table 3.21 – Thermal and solar properties of window glazing in the multi-family residential building

	U value Btu/h °F ft² (W/m^2K)	Solar Heat Gain Coefficient
Chicago	0.55 (3.12)	0.40
Phoenix	0.75 (4.26)	0.25

The primary differences between Chicago and Phoenix building codes have to do with insulation requirements and foundation depths. In Chicago, insulation is required on the slab-on-grade and foundation within 2 ft (61 cm) of the building perimeter and foundation, and the footings must extend at least 42 in (110 cm) down. In Phoenix, the footings must only reach 12 in (30.5 cm), and no insulation is required for the foundation and slab-on-grade. Additionally, Chicago requires a layer of continuous rigid insulation on the exterior walls.

3.2.3.3 Internal Loads

The internal loads in the house are displayed in Table 3.22. Schedules apply to all loads and are based on the values provided by the DOE mid-rise apartment building (US DOE 2010). The values listed here are electrical power consumption when the lighting and equipment are in use. Internal loads are a large portion of usage, and are therefore significant inputs in the energy model.

Table 3.22 – The internal loads in the multi-family residential building

Number of people (per zone)	2.5
Lighting - Btu/ft^2 (W/m^2)	2.39 (7.53)
Equipment	
Office - Btu/ft^2 (W/m^2)	4.09 (12.9)
Elevator - Btu (W)	5478 (1606)
Apartments - Btu/ft^2 (W/m^2)	1.7 (5.4)

3.2.3.4 Air Tightness

Although the data that determined air tightness for ICF houses was specifically from single-family house tests, the same results are used to specify the leakiness of the multi-family residential building, but are modified. Some papers on air tightness have mentioned examining multi-family buildings, but state that these tests are difficult and few have been done (Emmerich et al. 2005; Sherman and Chan 2004). Therefore, the same values of normalized leakage are used but scaled for the dimensions of the multi-family building.

Unlike the single-family model, the multi-family building model requires effective leakage area, or the total area of "holes" in the outer wall. First, the values of normalized leakage for wood and ICF, found in Appendix 8.5, are used to create total leakage area of the entire building. Then, a weighted average of the surface area is used to find the leakage area in each zone. This accounts for the fact that the upper apartments have more leakage than the lower ones, as opposed to the result if only floor area had been used.

3.2.3.5 HVAC System

The air loop includes an outdoor air mixer, fan, heating coil, cooling coil and return path for each apartment. They are unitary units. The corridors only use unit heaters. The most relevant numbers are in Table 3.23, and are used to meet ASHRAE 90.1 (2007) standards. The electric heater is assumed to have an efficiency of 1.0 because energy not used in the creation of the heat directly is given off as heat generally.

Table 3.23 – Relevant inputs for the HVAC system in the multi-family residential building

Input	Value
Supply airflow rate	Determined by EnergyPlus
Fan efficiency	0.536
Gas burner efficiency	0.8
Electric unit heater efficiency	1.0
COP of cooling coil	3.809
Water heater Efficiency	0.8

3.2.4 Results

This section summarizes the results of the life cycle assessment of multi-family buildings for ICF and wood for Chicago and Phoenix. See Appendix 8.7 for tables of results.

3.2.4.1 Embodied Emissions

The embodied GWP of the multi-family building per square foot is shown in Figure 3.21. The first bar shows the GWP associated with the pre-use phase, separated according to material. The second bar shows the emissions from maintenance over the use phase, and the third bar shows the end-of-life emissions associated with landfilling and recycling. The last bar, outlined in black, shows the total embodied GWP for each building. The results show a range of GWP between 27 and 36 lbs CO_2e/ft^2 (132 and 176 kg CO_2e/m^2) in all buildings and climates. Concrete accounts for approximately 7 lbs CO_2e/ft^2 (34 kg CO_2e/m^2) in the ICF buildings and 3 lbs CO_2e/ft^2 (15 kg CO_2e/m^2) in the wood buildings, which is about 9%-21% of total embodied GWP. The ICF buildings have 27% and 31% higher embodied GWP than the wood alternatives in Chicago and Phoenix, respectively.

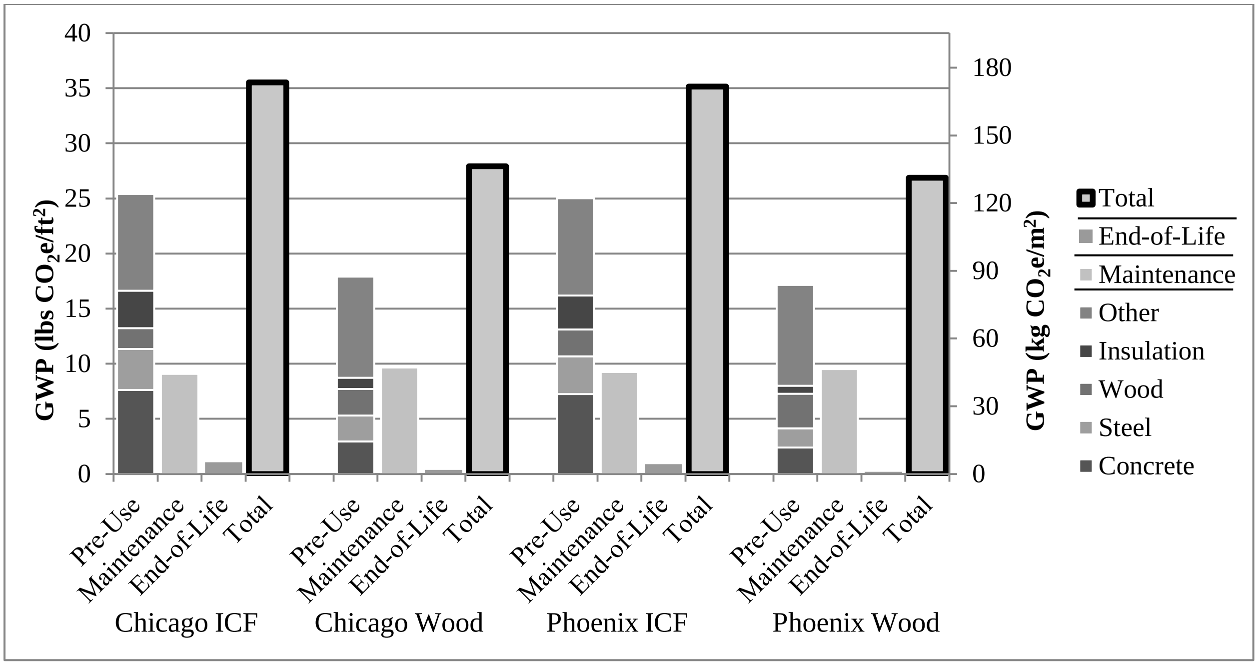

Figure 3.21 – Embodied GWP normalized by gross floor area and separated by material and phase for the multi-family buildings

3.2.4.2 Operating Emissions

Figure 3.22 displays the energy use of the multi-family building in Chicago for the loose, average and tight air tightness in Chicago. The lighting, equipment, and water loads stay the same among all building and climate variations, but the HVAC, pumps, and fans change based on the climate and source of energy. For Chicago, the ICF building uses 5% less energy than the equivalent tightness wood building for the loose, average and tight houses. The ICF building has greater thermal mass and a higher R-value, which accounts for the lower energy consumption.

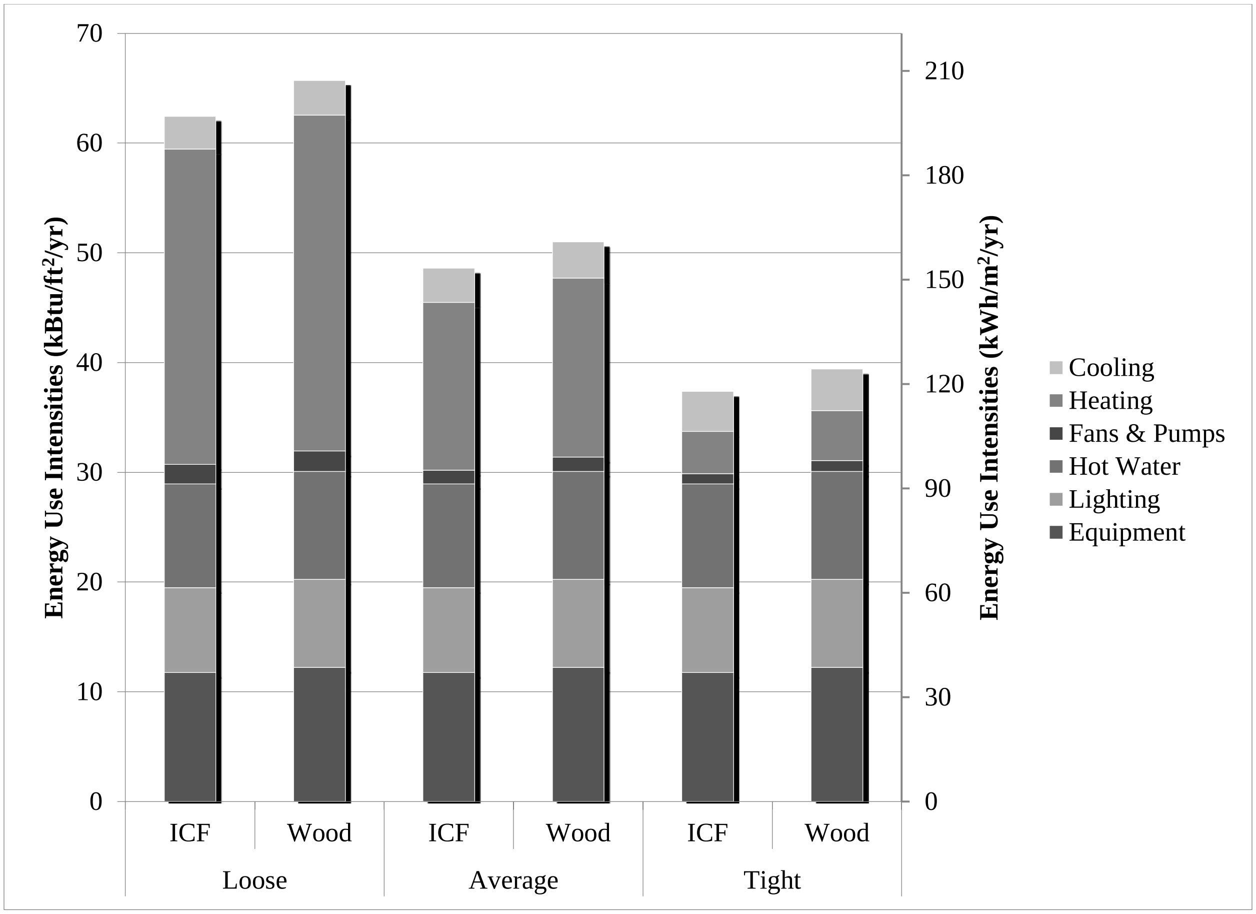

Figure 3.22 – Annual energy use intensities normalized by gross floor area for the multi-family houses in Chicago, separated by air tightness and energy end-use

A similar analysis was performed for Phoenix and the resulting chart can be seen in Figure 3.23. In this case, the percentage difference between ICF and wood was larger, with ICF using 7.7%, 6.2% and 5.7% less energy for the loose, average and tight cases, respectively. This is due to the fact that ICF walls have even higher R-values than what code requires in a mild climate (Table 3.4), and higher thermal mass than their wood counterparts. Finally, the difference between the loose, average and tight cases is smaller in Phoenix than it is in Chicago due to the milder climate in Phoenix.

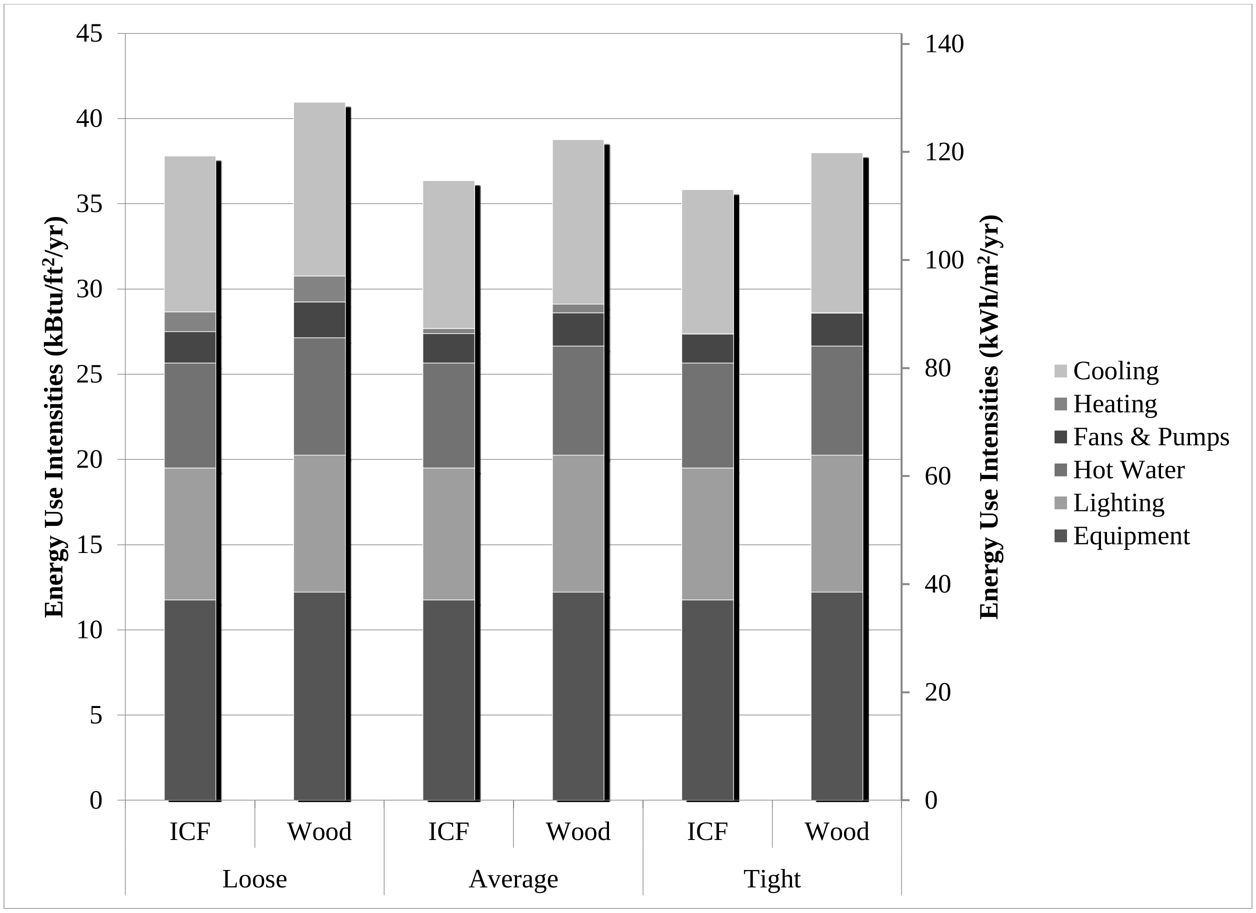

Figure 3.23 – Annual energy use intensities normalized by gross floor area for the multi-family houses in Phoenix, separated by air tightness and energy end-use.

The required operating energy is then converted to GWP for the multi-family building, as seen in Figure 3.24 and Figure 3.25. The trends in these charts are the same, but the percentage differences change slightly depending on the GWP intensity of the regional electricity and natural gas mixes. The ICF building GWP in Chicago is 4.6%, 4.4% and 4.4% lower than the wood house for the loose, average and tight cases, respectively. In Phoenix it is approximately 6.4% across the cases. The ICF building of average tightness, in Chicago, is responsible for 16.8 lbs CO_2e/ft^2 (82.0 kg CO_2e/m^2) annually, while the average wood house is responsible for 17.6 lbs CO_2e/ft^2 (85.9 kg CO_2e/m^2) annually. In Phoenix, the ICF house of average air tightness is responsible for 12.6 lbs CO_2e/ft^2 (61.5 kg CO_2e/m^2) annually, while the average wood house is responsible for 13.4 lbs CO_2e/ft^2 (65.4 kg CO_2e/m^2) annually.

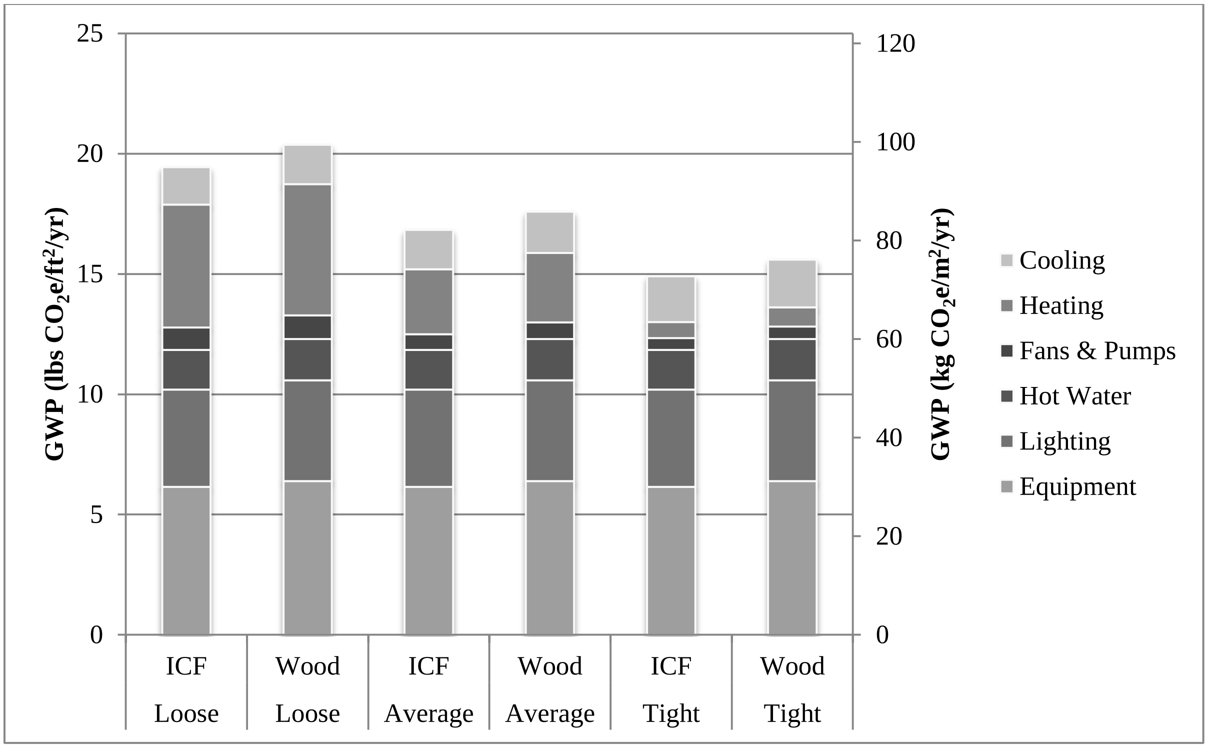

Figure 3.24 – GWP associated with annual energy use and normalized by gross floor area for the multi-family buildings in Chicago, separated by air tightness and energy end-use

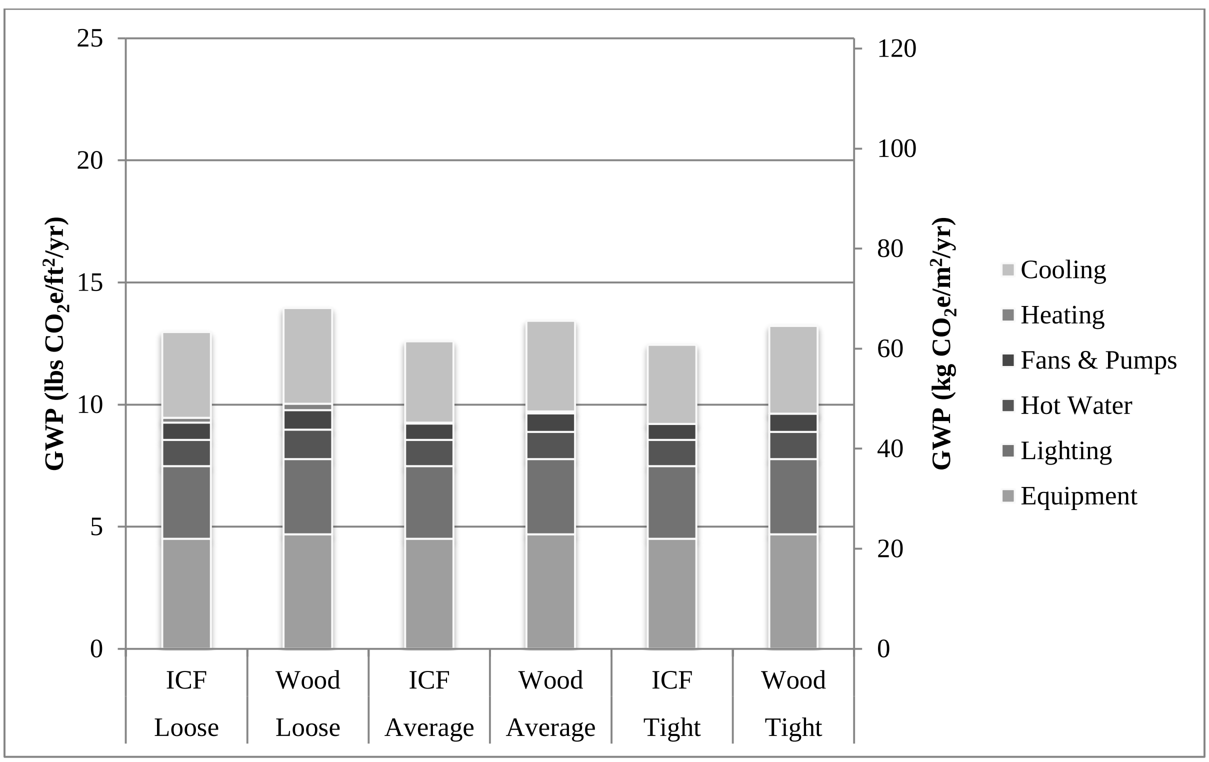

Figure 3.25 – GWP associated with annual energy use and normalized by gross floor area for the multi-family buildings in Phoenix, separated by air tightness and energy end-use

3.2.4.3 Life cycle results over 60-year period

When the GWP for the total life cycle is calculated, it becomes clear that the embodied emissions composes only a small fraction of the life cycle emissions, as shown in Figure 3.26 for a typical building lifetime of 60 years. The cumulative emissions of the concrete buildings are 2.8% lower in Chicago and 5.0% lower in Phoenix than the equivalent wood framed building. The total GWP of the buildings ranges from 791 to 1075 lbs CO_2e/ft^2 (3,862 to 5,249 kg CO_2e/m^2) for this lifespan. If the GWP is considered for a longer lifespan of 75 years, the overall GWP increases to between 982 and 1339 lbs CO_2e/ft^2 (4,795 and 6,538 kg CO_2e/m^2), with the embodied GWP making up a smaller percentage of the total (Figure 3.27). Although the ICF buildings have higher initial embodied emissions than wood-frame buildings, their lower annual operating emissions means that the emissions of concrete buildings are lower over the 60-year period.

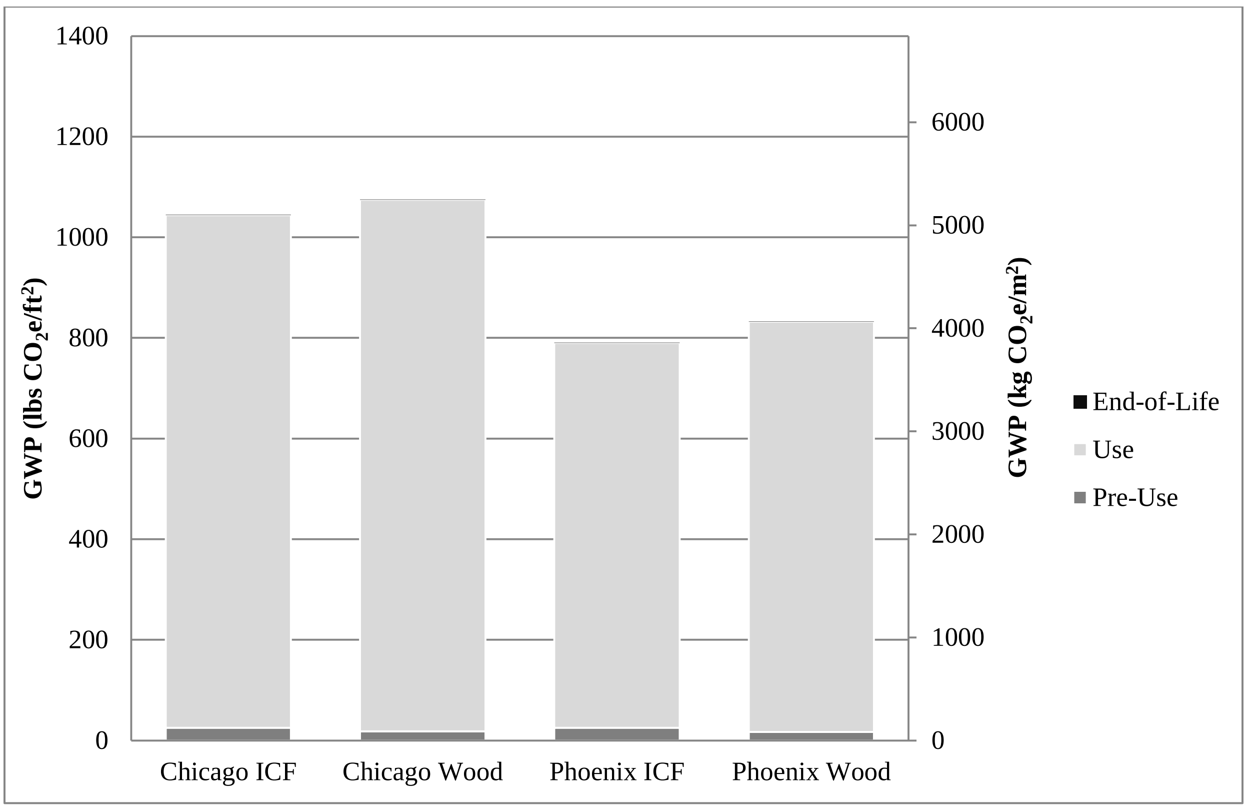

Figure 3.26 – GWP normalized by gross floor area over a 60-year lifespan for multi-family buildings of average air tightness separated by phase

Regional variation has a major impact on the life cycle of these multi-family buildings. Because of the warmer climate, a building in Phoenix has approximately 24% lower emissions than a building in Chicago. Transportation distances of the building materials account for only a small fraction of the embodied GWP, and are almost negligible over the full life cycle.

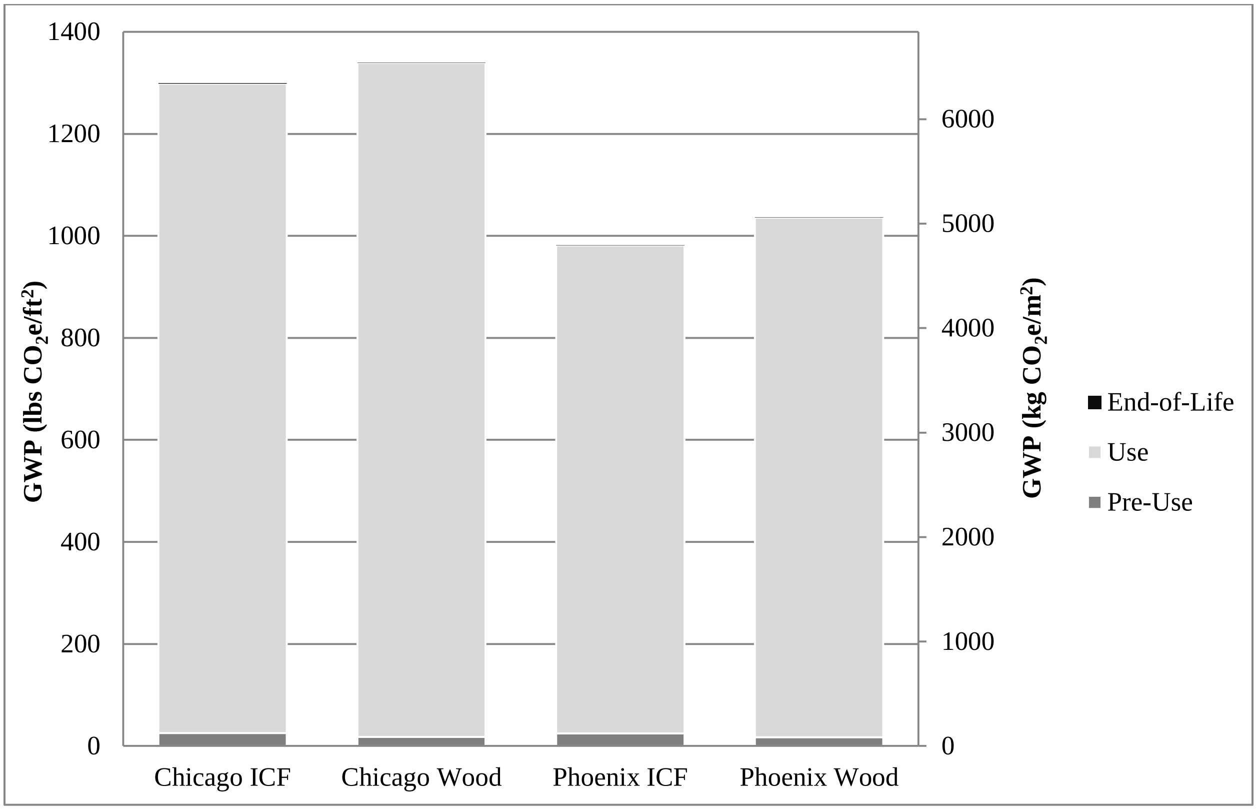

Figure 3.27 – GWP normalized by gross floor area over a 75-year lifespan for multi-family buildings of average air tightness separated by phase

3.2.5 Potential Improvements

Past work has shown that energy performance improvements for multi-family buildings display very similar results to what was discussed in Section 3.1.5 for the single-family house. Therefore, only fly ash substitution, which reduces embodied emissions, was studied as a potential improvement. Future work for mid-rise buildings could explore the potential operating energy reductions for ICF homes in more depth.

The use of supplementary cementitious materials (SCM) is a growing option for reducing the environmental impact of concrete. Because cement has the largest impact of all the ingredients of concrete, reducing its footprint subsequently reduces that of concrete. There are a wide range of possible mix designs using a variety of SCMs, such as ground granulated blast furnace slag (GGBFS), fly ash, and silica fume. For simplicity, only fly ash is considered here.

Table 3.24 presents the same multi-family buildings but with a different fly ash content in the concrete. The original mix design uses 10% while the low-cement mix assumes 50% fly ash substitution. It reduces the GWP of the ICF buildings by about 3 lbs CO_2e/ft^2 (15 kg CO_2e/m^2), or 11% of the pre-use embodied emissions. The wood buildings' GWP reduces about 1 lb CO_2e/ft^2 (5 kg CO_2e/m^2), or 5%, due to the concrete in the foundation. Changing the mix design of concrete to incorporate industrial by-products like fly ash, slag, and silica fume, is an important step in reducing the embodied environmental impact of concrete buildings.

Table 3.24 – Possible pre-use phase embodied GWP reductions with increased fly ash replacement of cement in concrete mix used in multi-family residential buildings

	Chicago ICF lbs CO_2e/ft^2 (kg CO_2e/m^2)	Chicago Wood lbs CO_2e/ft^2 (kg CO_2e/m^2)	Phoenix ICF lbs CO_2e/ft^2 (kg CO_2e/m^2)	Phoenix Wood lbs CO_2e/ft^2 (kg CO_2e/m^2)
Concrete – 10% fly	25.4 (124)	17.9 (88)	25.0 (122)	17.2 (84)
Concrete – 50% fly	22.5 (110)	16.8 (82)	22.3 (109)	16.3 (80)
Percent Reduction	11%	6.2%	11%	5.2%

3.2.6 Conclusions

This chapter analyzes the multi-family mid-rise apartment building from the DOE benchmark for both wood and ICF structural systems. It also offers a potential improvement for the ICF structure. The results of the multi-family building global warming potential study are summarized in Table 3.25.

Table 3.25 – Summary of the multi-family buildings for the entire 60-year life cycle

City	Building Type	Pre-Use Materials lbs/ft2 (kg/m2)	Pre-Use GWP lbs CO_2e/ft^2 (kg CO_2e/m^2)	Maintenance GWP lbs CO_2e/ft^2 (kg CO_2e/m^2)	Operational GWP/year lbs CO_2e/ft^2 (kg CO_2e/m^2)	End-of-Life total GWP lbs CO_2e/ft^2 (kg CO_2e/m^2)	Total for 60 years lbs CO_2e/ft^2 (kg CO_2e/m^2)
Chicago	ICF	115 (562)	25.4 (124)	9.07 (44.3)	16.8 (82.0)	1.06 (5.18)	1045 (5102)
	Wood	66.9	17.9 (87.4)	9.65 (47.1)	17.6 (85.9)	0.37 (1.81)	1075 (5249)
Phoenix	ICF	111 (542)	25.0 (122)	9.26 (45.2)	12.6 (61.5)	0.88 (4.30)	790.7 (3860)
	Wood	60.6	17.2 (84.0)	9.52 (46.5)	13.4 (65.4)	0.19 (0.93)	832.1 (4063)

The following conclusions can be drawn:

- Embodied GWP, including pre-use, maintenance and end-of-life, are 35-36 lbs CO_2e/ft^2 (171-177 kg CO_2e/m^2) for the ICF buildings and 27-28 lbs CO_2e/ft^2 (132-137 kg CO_2e/m^2). The embodied emissions are dominated by the pre-use phase, although maintenance adds to them significantly.
- Operating emissions for ICF buildings are 4.4% lower than for wood construction in Chicago, in both cases with average air tightness, and 6.2% lower than wood construction

in Phoenix. Over the lifetime of the building, the lower operating emissions associated with concrete construction outweigh the increased embodied emissions.

- The cumulative life cycle emissions over a 60-year period are 2.8% lower for the ICF building in Chicago and 5.0% lower in Phoenix.
- Increasing SCM substitution (such as fly ash) in the ICF building from 10% to 50% can decrease the pre-use GWP by 11%.

4 ENERGY AND EMISSIONS ANALYSIS OF COMMERCIAL BUILDINGS

4.1 Introduction

There are approximately 5 million office buildings in the United States (US EIA 2003). Over $60 billion was spent on the construction of new office buildings in both 2009 and 2010 (US Census Bureau 2010). Most are constructed of reinforced concrete, structural steel, or a combination of both, and are clad with many different materials such as brick, glass, and aluminum. While annual construction and maintenance of commercial buildings has a large environmental impact, their operational energy is much greater, and accounts for approximately 35% of the total electricity consumption in the United States (DOE/EIA-0384 2007).

There is no standard design for a North American office building, although building codes provide minimum performance standards. Performing an LCA of a single building chosen from the real world would reveal little about the environmental impact of such buildings as a whole. Many life cycle studies have been performed on commercial buildings, but their results vary widely (Hsu 2010). Some studies look at embodied energy or GWP without considering the building's occupancy, and others look only at operational energy. Operational energy studies show that concrete buildings can provide energy reductions ranging from 5-30% compared to steel construction (Marceau and VanGeem 2007; Gorgolewski 2007; Jacobs 2007).

This study makes use of a DOE benchmark building to create typical office building designs and incorporate energy model results into the LCA. The energy use and GWP are reported by square foot, and the GWP is separated into the emissions derived from the embodied and operational phases, so that the relative impacts of each phase can be better understood. Two structural frames, one of cast-in-place reinforced concrete and the other of structural steel, are compared with the same shell for consistency. Potential improvements to the concrete structure, which would reduce the embodied or operational GWP over the building's lifetime, are examined after the results of the initial LCA are reported.

4.2 Design and construction

This study considers the "Large Office Building" benchmark from the DOE Buildings Database (US DOE 2004). Each building has a gross area of 511,758 ft^2 (47,454 m^2), comprised of twelve 13-foot-high stories and a basement. The façade is 40% glazing and 60% aluminum rainscreen panels, as shown in Figure 4.1. As stated in the methodology description, the interior of the building, which has a usable square footage of 498,590 ft^2 (46,321 m^2), is unfinished in the LCA model and is devoid of items such as furniture and partitions that would be put up by the occupant rather than the contractor. However, these interior finishes are included in the energy model to accurately represent the internal massing for HVAC purposes. Each floor is divided into five zones, as seen in Figure 4.2, which sums to 61 zones in the building if the basement is considered to be a single zone.

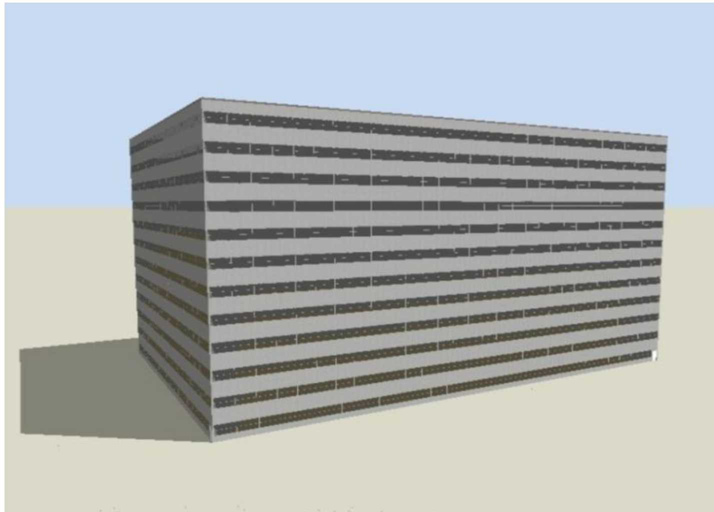

Figure 4.1 – Rendering of the twelve-story commercial building exterior, with 40% glazing and 60% aluminum rainscreen panel cladding, which displays the massing of the building

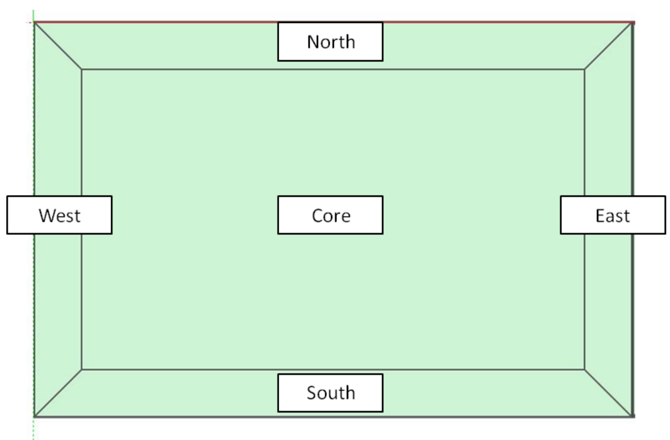

Figure 4.2 – Energy model zoning within the commercial building on each floor (excluding single-zone basement), which displays the distribution of the five zones on each level

The structural systems are designed using the *AISC Steel Construction Manual*, *13th Edition* and *Basic Steel Design with LRFD* for Grade 50 steel design with a 2 hour fire rating (AISC 2005; Galambos, Lin & Johnston 1996); *ACI 318-08* for 5000 psi normal weight concrete design (ACI 2008); and façade and floor system details from standard practice (Allen and Iano 1995; Ching 2008). A 50 psf live load and 30 psf dead load is assumed for both buildings. No interior finishes beyond paint and drywall have been included in the material quantities that go into the LCA model. Both buildings have 27 ft x 27 ft (8.2 x 8.2 m) bays and a 243 ft x 162 ft (74.0 m x 49.3 m) total footprint in plan. The structures are composed of moment frame systems, as shown in Figure 4.3, with two elevator shear-wall cores to provide lateral stability. The basement has concrete walls, and the foundation is composed of a slab with concrete footings in both buildings. Table 4.1 shows the dimensions of the structural members in each building.

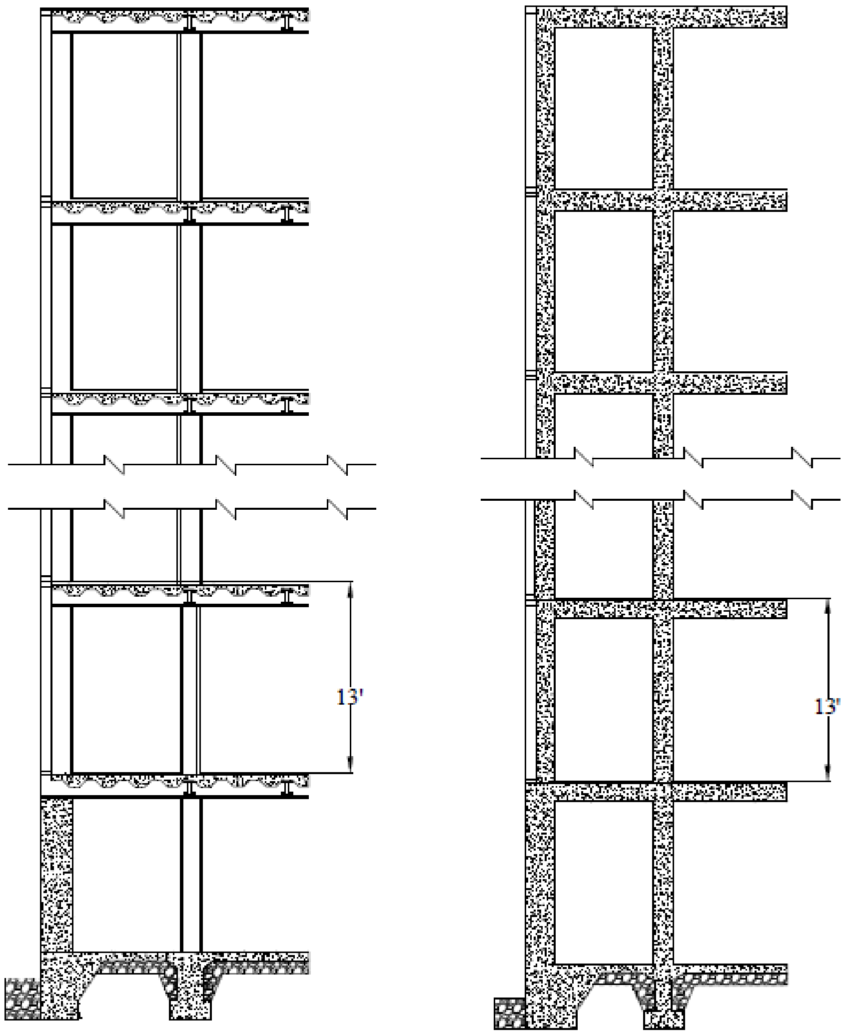

Figure 4.3 – Structural design of the steel (left) and concrete (right) commercial buildings

Table 4.1 – Structural design details of large commercial buildings

	Steel	Concrete
Slab	2 in (6.35 cm) steel decking with 5 in (12.7 cm) slab	10 in (30.5 cm) two-way slab
Columns	W14x159 (floors B-2) W14x120 (3-6) W14x90 (7-9) W14x61 (10-12)	24 in x 24 in (70.0 cm x 70.0 cm) floors B-2 20 in x 20 in (50.8 cm x 50.8 cm) floors 3-6 16 in x 16 in (40.6 cm x 40.6 cm) floors 7-9 12 in x 12 in (30.5 cm x 30.5 cm) floors 10-12
Beams	W16x26 @ 9 ft (2.74 m) o.c.	N/A
Girders	W21x44 @ 27 ft (8.23 m) o.c.	N/A

Figure 4.4 shows the mass of materials per square foot of building area, demonstrating that the mass of the concrete building is about 1.5 times higher than that of the steel building. Maintenance consists of paint replacement every 10 years, and window and roof replacement every 15 years, over a 60-year lifespan. As discussed in the project methodology, energy due to construction processes is not included. The mass of all materials comprising the structure and shell are calculated and entered into GaBi to determine the associated environmental impacts. Calculation tables for these masses are collected in Appendix 8.6.

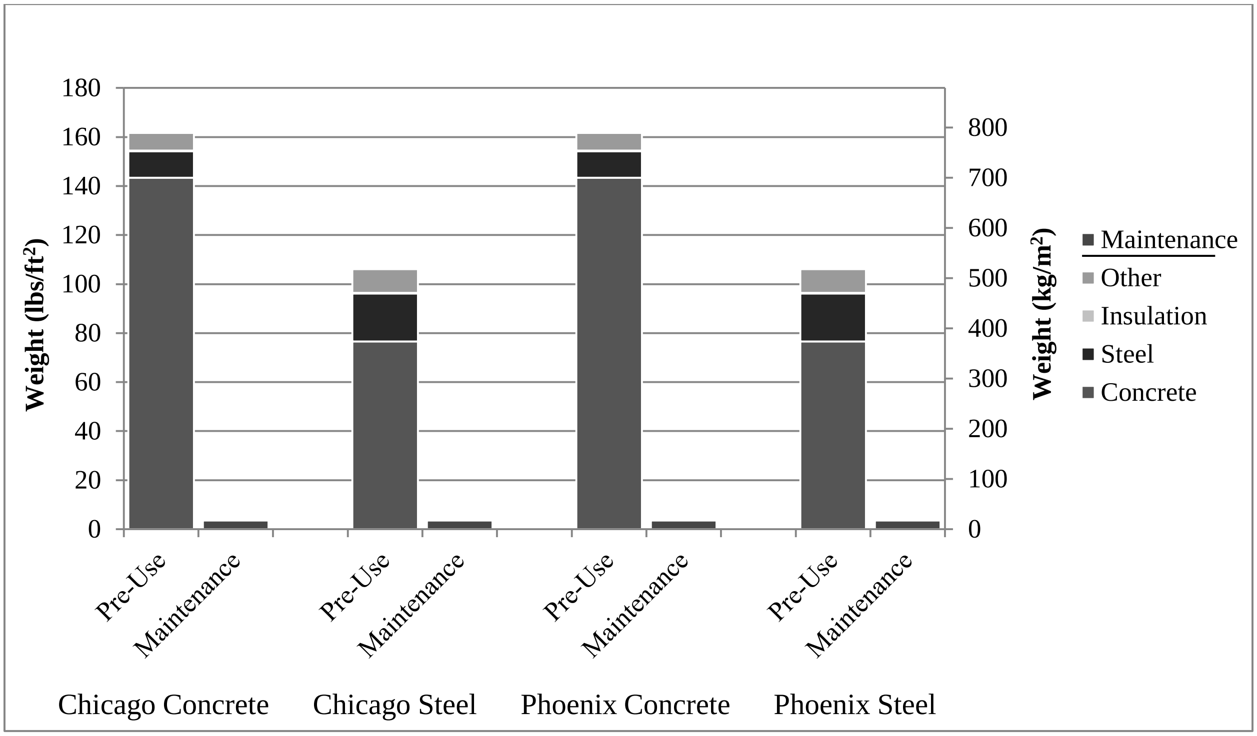

Figure 4.4 – Weight of materials normalized by gross floor area and separated into type and phase for the commercial buildings

4.3 Energy Models

4.3.1 Basic Specifications

As with the residential buildings, the commercial buildings are modeled using EnergyPlus to estimate their annual energy use. The DOE large office benchmark building is used and updated based on current codes and standards. In addition, steel and two concrete structural systems are created, while keeping the building envelope consistently composed of extruded polystyrene insulation, aluminum studs, and gypsum board. The exterior aluminum and the interior walls are painted. Of the two concrete structural systems, one has “finishes,” meaning carpet and a drop ceiling. This results in different roof systems: steel decking with a drop ceiling, concrete decking with a drop ceiling, and an exposed concrete deck with no ceiling, but the insulation and roofing material are assumed to be the same for all cases. Similarly, the internal floors are modeled in one of three ways: 1) as a composite metal deck and steel slab system with carpeting and a drop ceiling; 2) as a concrete deck with carpeting and a drop ceiling; and 3) as an exposed concrete deck with no floor or ceiling finish. Modeling all three buildings (one with steel and two with concrete) reveals the differences in energy use due to the structural material choice. Table 4.2 summarizes the commercial building.

Table 4.2 – Summary of the commercial building

Input	
Reference Standard	DOE Benchmark Buildings, and others.
Conditioned Area	498,584 ft^2 (46,320 m^2)
Unconditioned Area	13,174 ft^2 (1,223.9 m^2)
Number of Floors	12 + basement
Number of Zones	61 (5 zones per floor, 1 basement zone)
Building Dimensions	165.8 ft x 248.8 ft (50.5 m x 75.8 m)
Percent Glazing	40%

4.3.2 Building Envelope

The thermal resistance and thermal mass, two of the more prominent aspects of the commercial building for the purposes of this study, are presented in Table 4.3 below. Also included are the requirements for the R-value, based on the relevant energy code (ASHRAE 90.1 2007). Only the concrete without finishes is included in this table, as the roof insulation is assumed to be the same for both finished and unfinished, and the values for the internal floors are not listed.

Table 4.3 – Thermal resistance requirements and values and thermal mass values of the commercial building

		R values $ft^2\cdot°F\cdot h/Btu$ (m^2K/W)			Thermal mass $Btu/ft^2°F$ (kJ/Km^2)	
		Steel Frame Requirements	Steel	Concrete	Steel	Concrete
Exterior Wall	Chicago	13 (2.29) + 7.5 (1.32) c.i.	15.3 (2.26)		1.98 (40.6)	
	Phoenix	13 (2.29)	6.8 (1.20)		1.87 (38.3)	
Ground Floor	Chicago	NR	0		17.7 (363)	
	Phoenix	NR				
Roof	Chicago	20 (3.52) above deck	20 (3.52)		7.08 (145)	
	Phoenix	20 (3.52) above deck				

The windows used are selected to satisfy ASHRAE 90.1 2007 minimum standards, and are assumed to be double-glazed with an aluminum frame. The glazing properties are given in Table 4.4.

Table 4.4 – Thermal and solar properties of window glazing in the commercial building

	U value Btu/h °F ft² (W/m^2K)	Solar Heat Gain Coefficient
Chicago	0.55 (3.12)	0.40
Phoenix	0.75 (4.26)	0.25

4.3.3 Internal Loads

The internal loads in the building are displayed in Table 4.5. Schedules, which apply to all loads, are from the DOE benchmark large office building. The values listed here are electrical power consumption when the lighting and equipment are in use. Internal loads are a large portion of usage, and are therefore significant inputs in the energy model.

Table 4.5 – The internal loads assumed for the commercial building energy model

Zone Name	People ft^2/person (m^2/person)	Equipment Btu/ft^2 (W/m^2)	Lights Btu/ft^2 (W/m^2)
Floors 1-12	200 (18.58)	2.56 (8.07)	3.41 (10.76)
Basement	400 (18.58)	1.53 (4.84)	3.41 (10.76)

4.3.4 Air Tightness

The air tightness of the commercial building has a small effect on the energy use, because building energy consumption is very core-dominated. Therefore, only one number, the ASHRAE value of 0.05 gal/s per ft^2 (2 L/s per m^2) of above-grade envelope area at 1.57 lbs/ft^2 (75 Pa), was used (Deru et al. 2011). The top floor was modified based on surface area because it has more exposure and therefore more infiltration. The energy model input is Air Changes per Hour (ACH). For 1.0 ACH, all of the air in the building is replaced by outside air every hour. Air changes per hour is based on air leakage area, discussed above, and the weather. The values of ACH used in the model are presented in Table 4.6.

Table 4.6 – Values of air changes per hour in the commercial building

Zone Name	Infiltration
Floor 12, Core	0
Floor 12, Long	0.65
Floor 12, Short	0.66
Floors 1-11, Core	0
Floors 1-11, Long	0.25
Floors 1-11, Short	0.26
Basement	0

4.3.5 HVAC System

A multi-zone variable-air-volume (VAV) system with a natural gas boiler and a water-cooled chiller was determined in the CBECS survey to be the most common HVAC system in large office buildings, and is therefore implemented in the DOE Benchmark Building. The building is served by both natural gas, the fuel for the domestic hot water and the heating system boiler, and grid electricity, serving the chiller and other energy using systems. As required by ASHRAE 90.1-2007, the cooling system has a differential dry-bulb economizer, which utilizes outside air for cooling when the outside air temperature is below the building's return air temperature. The system is designed to meet the minimum ventilation requirements of ASHRAE 62.1 2007 (ASHRAE 62.2 2007). System sizes and flow rates are determined by the EnergyPlus software during simulation. The most relevant efficiencies in the HVAC system can be found in Table 4.7.

Table 4.7 – Relevant inputs for the HVAC system in the commercial building

	Efficiency
Cooling System Chiller (COP)	5.5
Heating System Boiler	0.8
Domestic Hot Water System Boiler	0.8
Floor 12 VAV Fan Efficiency	0.605
Floors 2-11 VAV Fan Efficiency	0.618
Floor 1 VAV Fan Efficiency	0.605
Basement VAV Fan Efficiency	0.592

4.4 Results

This section summarizes the results of the life cycle assessment of commercial buildings in both concrete and steel. See Appendix 8.7 for tables of results.

4.4.1 Embodied Emissions

The embodied global warming potential (GWP) of the building materials per square foot is shown in Figure 4.5. The first bar shows the GWP associated with the pre-use phase, split up by material. The second bar shows the emissions from maintenance over the use phase, and the third bar shows the end-of-life emissions, associated with landfilling and recycling. The last bar, outlined in black, shows the total embodied GWP for each building. The concrete buildings have a total embodied emissions of approximately 42 lbs CO_2e/ft^2 (205 kg CO_2e/m^2), while the steel buildings have a total embodied emissions of approximately 40 lbs CO_2e/ft^2 (195 kg CO_2e/m^2). Steel dominates the GWP of the steel building, and concrete has a larger role in the concrete building. Interior finishes are not included. The concrete building has a 5% higher embodied GWP than the alternative steel design.

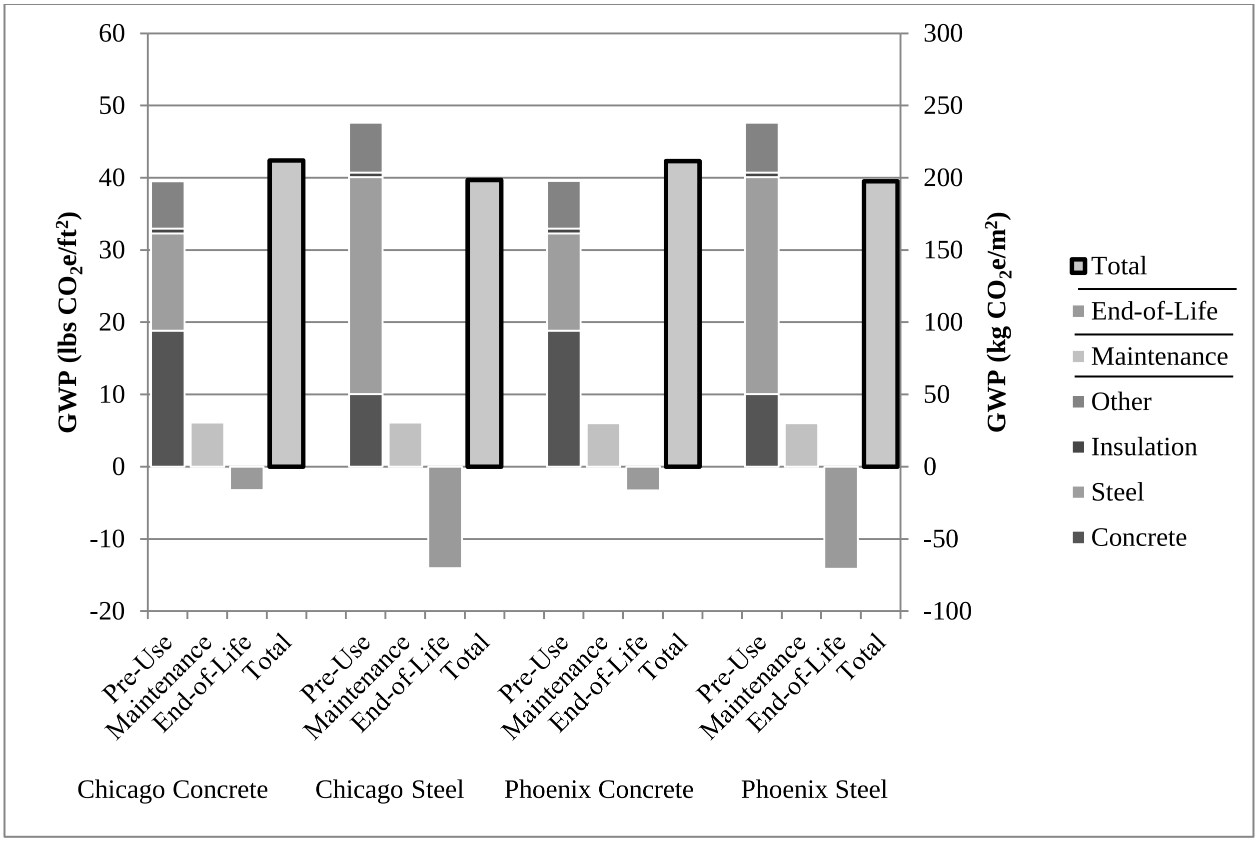

Figure 4.5 – Embodied GWP normalized by gross floor area and separated by material and phase for the commercial buildings

It is important to note that because the structural steel has a 60% recycled content, and 98% of the structural steel salvaged from the building is assumed to be recycled at the end of life, that difference in percentages adds a credit to the overall life cycle accounting, creating a negative end-of-life GWP in the steel building. The end-of-life GWP in the concrete building is also negative, due to the recycling of reinforcement, concrete, and aluminum.

4.4.2 Operating Emissions

Figure 4.6 displays the energy use of the commercial building in Chicago and Phoenix. The lighting, equipment, and water loads stay the same among all building and climate variations, but the energy used through HVAC, pumps, and fans change based on the climate and source of energy. In the climates of Chicago and Phoenix, a savings in HVAC energy of approximately 7% and 9% respectively can be seen when the exposed concrete building is compared with the steel building, which can be attributed to the higher thermal mass of the concrete building. However, when the whole building energy results are viewed, the savings are diminished to 3% in both Chicago and Phoenix. Having finishes in the building decreases this savings to roughly 2% for both cities because the thermal mass is no longer exposed in this case.

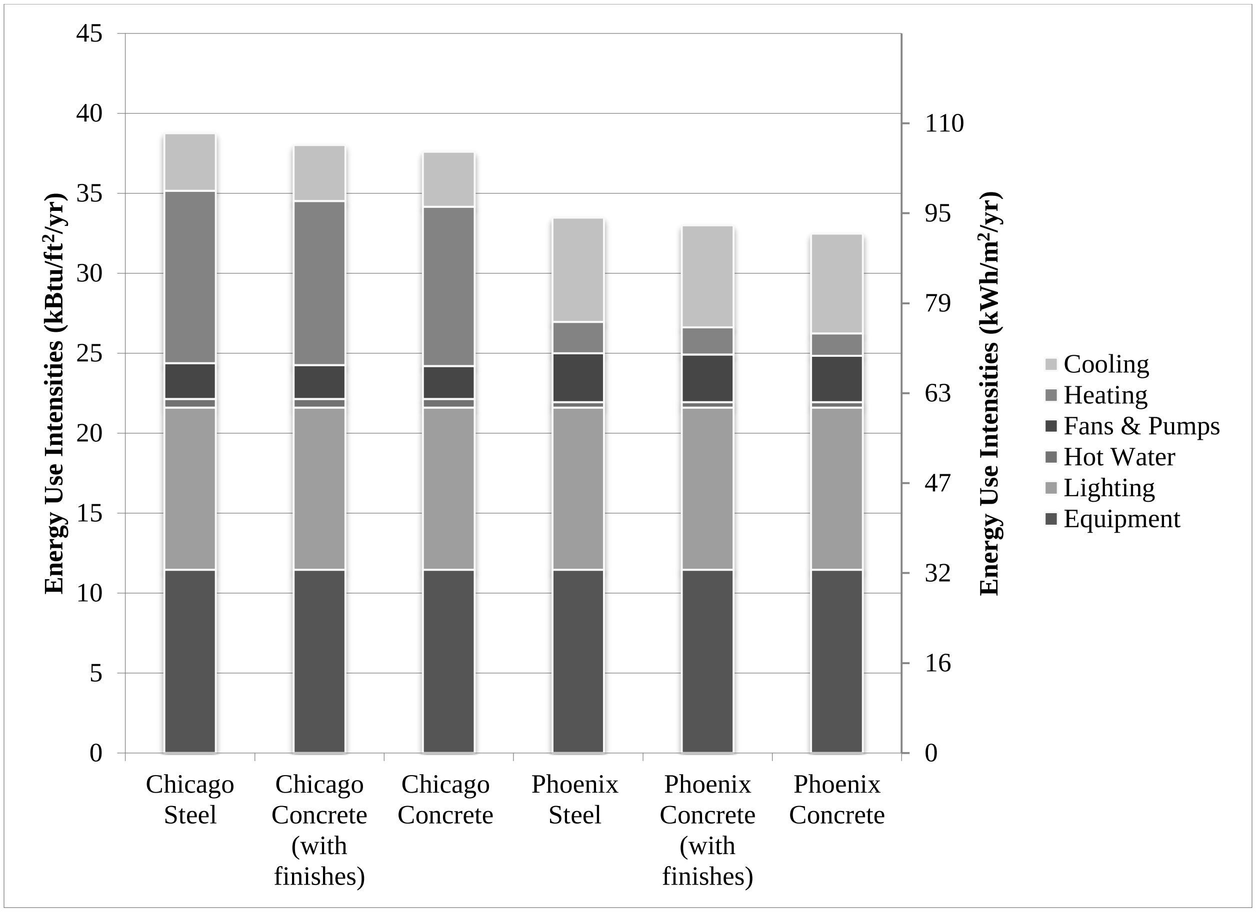

Figure 4.6 – Annual energy use intensities normalized by gross floor area for the commercial buildings in Chicago and Phoenix, separated by frame type and energy end-use

Because much of the energy reduction is seen in the heating load, which is provided by natural gas, the carbon-equivalent emission savings of concrete over steel structures are 1-2% in both climates, shown in Figure 4.7. The finishes in the concrete building are shown to have a dampening effect on the thermal storage capacity of the structure, but the results with and without interior finishes show a small savings for the concrete superstructure compared to the steel.

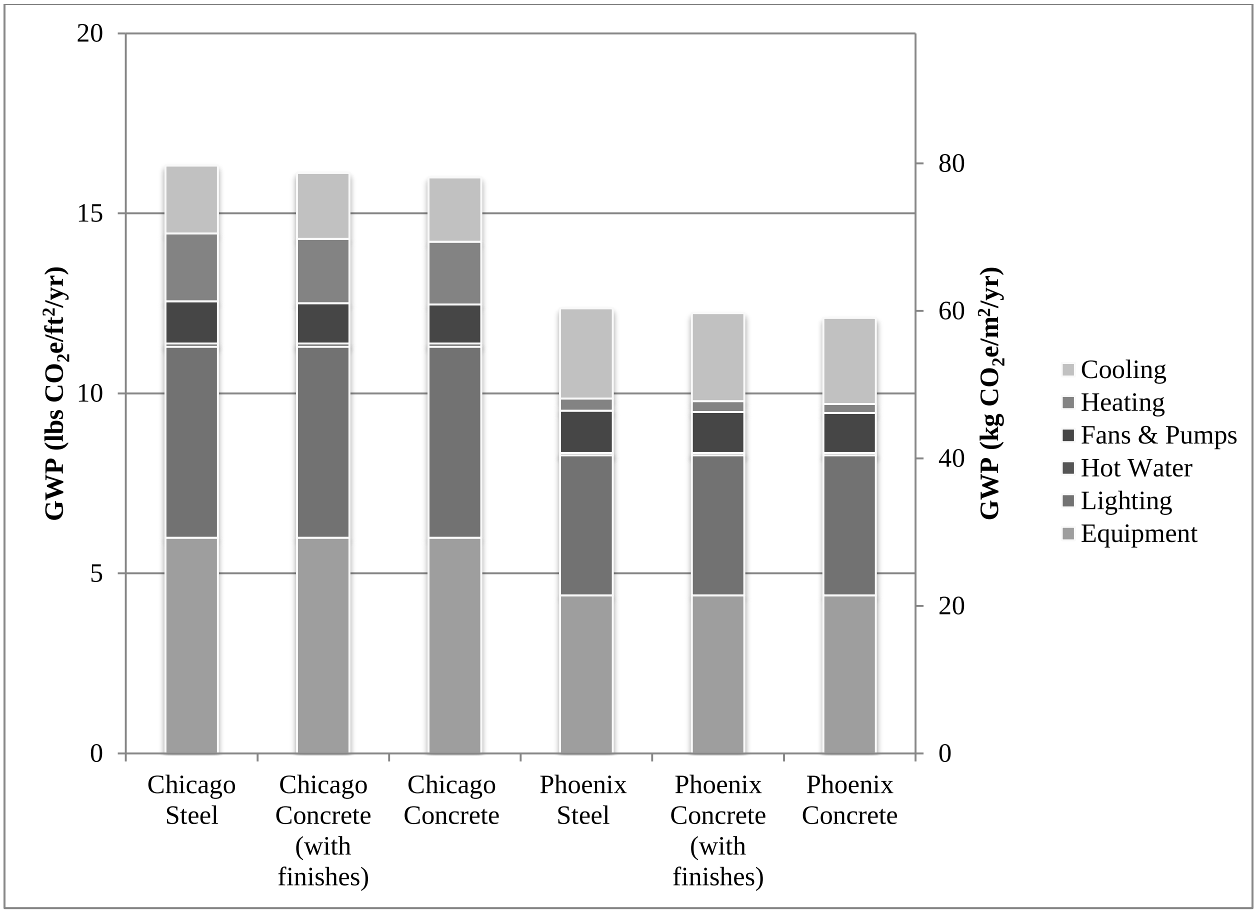

Figure 4.7 – GWP associated with annual energy use and normalized by gross floor area for the commercial buildings in Chicago and Phoenix, separated by frame type and energy end-use

4.4.3 Life cycle results over a 60-year period

When the GWP for the total life cycle is put together, it becomes clear that the embodied energy composes only a small fraction of the life cycle GWP, as shown in Figure 4.8 for a typical building lifetime of 60 years. The concrete energy model without finishes was used to calculate total life cycle GWP. Though the steel energy model includes finishes, the embodied portion of the LCA model does not. The two buildings have a difference in GWP of 1.7% in both Chicago and Phoenix. If finishes are included in the concrete building, the life cycle GWP is nearly identical to the steel building with finishes. The total GWP of the buildings ranges from 768 to 1019 lbs CO_2e/ft^2 (3,750 to 4,975 kg CO_2e/m^2) for this lifespan. If the GWP is considered for a longer lifespan of 75 years, the overall GWP increases to between 949 and 1266 lbs CO_2e/ft^2 (4,633 to 6,181 kg CO_2e/m^2), with the embodied GWP making up a smaller percentage of the total, as shown in Figure 4.9. In all cases, the embodied emissions make up 3-6% of the total emissions over the full life cycle, and the choice of structural material does not dramatically influence the total emissions.

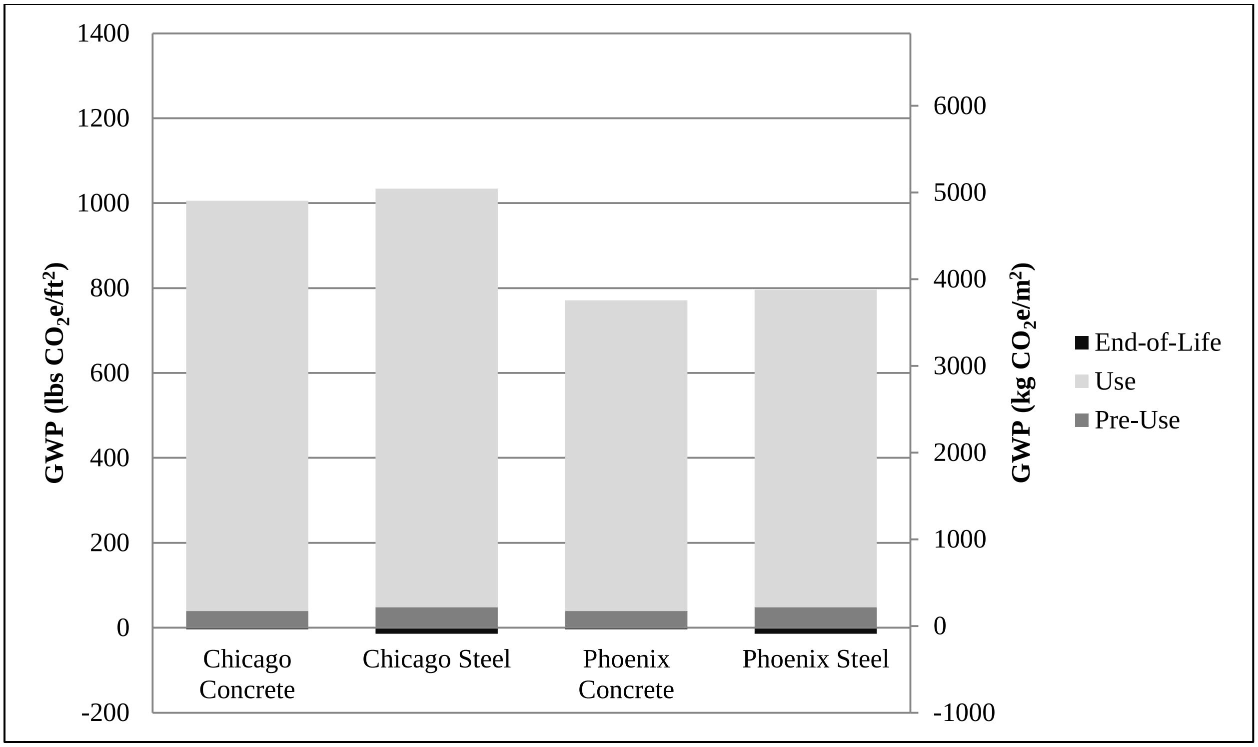

Figure 4.8 – GWP normalized by gross floor area over a 60-year lifespan for commercial buildings separated by phase

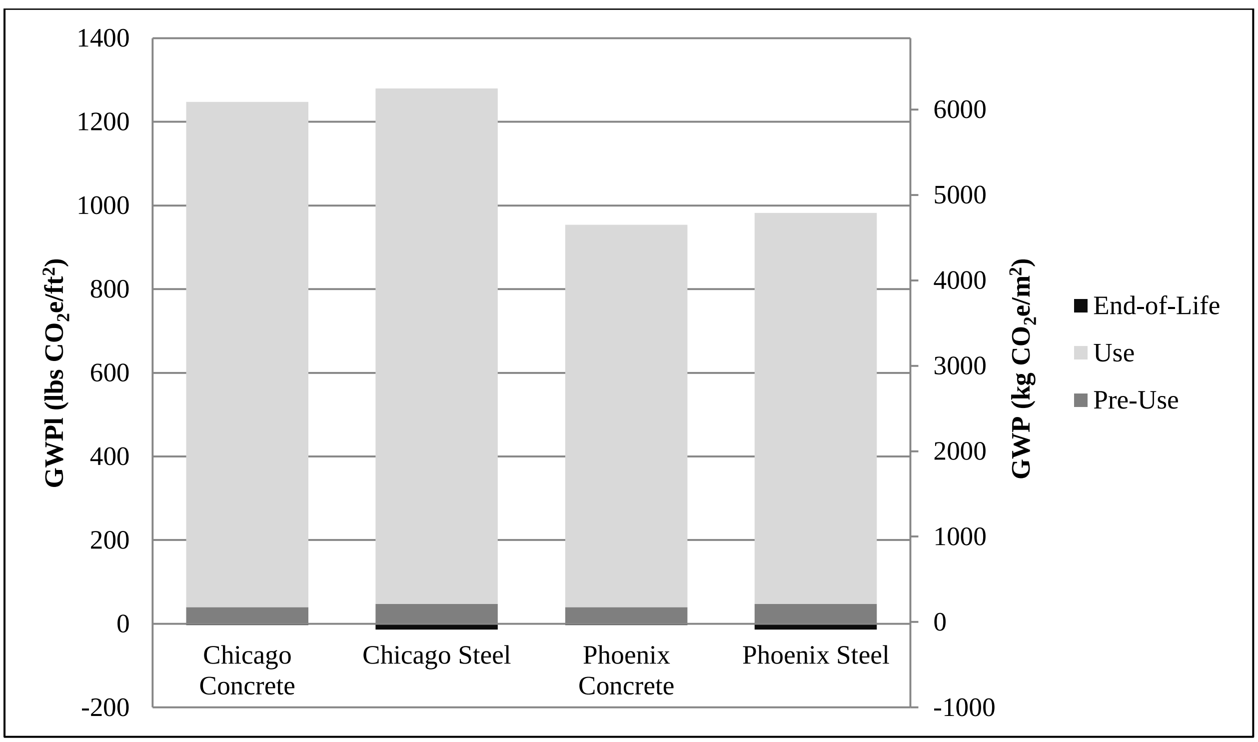

Figure 4.9 – GWP normalized by gross floor area over a 75-year lifespan for commercial buildings separated by phase

Regional variation has an impact on the life cycle of these commercial buildings. Assuming a 60-year lifetime, the difference in CO_2e between Chicago and Phoenix is approximately 23% due to the milder climate of Phoenix. This percentage decreases slightly as the lifetime of the building is increased because the pre-use embodied materials remain constant, but it is still significant. Transportation distances are negligible over the total life cycle. HVAC needs that may change among regions have less than a 15% impact in the operational energy use.

4.5 Potential Improvements

4.5.1 Fly Ash Substitution

As stated in Section 4.4.2, the embodied GWP of the concrete commercial building is approximately 42 lbs CO_2e/ft^2 (205 kg CO_2e/m^2), and the operating GWP is 12-16 lbs CO_2e/ft^2 (58-78 kg CO_2e/m^2) annually based on region. Improvements to the structural design and concrete mix would reduce the embodied GWP and the overall life cycle impact of the building.

It is important to remember that the GWP of either building type could change slightly if different typical structural systems were implemented. For example, designing a one-way slab system in the concrete building, instead of the two-way slab in this example, would vary the concrete building's GWP by a few lbs CO_2e/ft^2 in either direction, but it would still be very similar to the GWP of the steel building.

The GWP of a concrete building can further be reduced by implementing future improvements in concrete mix design. One option is to increase the supplementary cementitious material (SCM) substitution in concrete, such as ground granulated blast furnace slag (GGBFS), fly ash, and silica fume. Though there are a wide range of possible mix designs using SCMs, for simplicity, only fly ash is considered here. Using 25% fly ash content by volume substituted for cement in the concrete would lower the embodied GWP of the concrete by 15.1%. The embodied GWP values for buildings using these revised concrete mixes are shown in Table 4.8. These mixture adjustments would correspond to an overall reduction of 0.3% in the total GWP of a concrete building in Chicago with a 60-year lifespan, and a 0.4% reduction in a similar building in Phoenix.

Table 4.8 – Possible pre-use phase embodied GWP reductions with increased fly ash replacement of cement in concrete mix used in commercial buildings

	Concrete Chicago lbs CO_2e/ft^2 (kg CO_2e/m^2)	Steel Chicago lbs CO_2e/ft^2 (kg CO_2e/m^2)	Concrete Phoenix lbs CO_2e/ft^2 (kg CO_2e/m^2)	Steel Phoenix lbs CO_2e/ft^2 (kg CO_2e/m^2)
Concrete – 10% fly ash	39.5 (193)	47.6 (232)	39.6 (193)	47.6 (232)
Concrete – 25% fly ash	36.7 (179)	46.1 (225)	36.7 (179)	46.1 (225)
Percent Reduction	7.1%	3.2%	7.3%	3.2%

4.5.2 Daylighting study

A variety of building energy use improvements, as an example of further application of LCA in this scenario, are described in detail in Love (2011), prepared as part of this study. Variations in concrete façade systems, shading systems, and the massing of the buildings are analyzed in EnergyPlus for the effects they have on the overall energy use of the building over its lifetime. The daylighting study yields the greatest reduction in energy use. A control strategy was investigated to modify when the lights will be on. A daylight dimming system consists of a sensor that reads the lighting levels and a controller that responds to the readings by adjusting the electric lighting to meet a specified lighting illumination target. Multiple runs in EnergyPlus demonstrated that the best results occur with two sensors and continuous dimming, which reduces the lighting linearly with the fraction of illumination at the sensor divided by the target illumination. Perimeter zone lighting, in kWh/m^2, was reduced by 71% (Love 2011). Reducing the total energy consumed is favorable for concrete buildings, as the savings due to thermal mass become a larger portion of the total energy consumption.

4.5.3 Low Lift Cooling

Concrete can contribute to reducing operational energy consumption and costs if it is used intelligently. The high thermal capacity of concrete is unique relative to most other building materials. This thermal capacity can be utilized to shift loads, reduce peak demand, and reduce operational energy consumption if it is used as thermal energy storage. Because most floor systems of multi-story commercial buildings are constructed of concrete, a substantial mass of concrete is available for improved thermal storage in most buildings.

Conventional use of concrete as thermal storage relies on passive charging through the air to pre-cool exposed concrete or absorption of direct sunlight to store heat. The concrete's thermal capacity reduces daily peak loads and can provide some energy or cost savings. These energy savings, however, are typically limited to about 5 to 15 percent, as demonstrated by Love (2011) for this study. More thermal storage capacity can be utilized by actively pre-cooling concrete through embedded pipes through which to circulate water. This approach, more common in Europe, is called a thermo-active building system (TABS). These systems require less space than chilled water storage and allow for higher chiller efficiencies than ice storage systems.

Recent research at MIT and at the Pacific Northwest National Laboratory (PNNL), which was not part of this project, has studied predictive control of energy efficient chillers to actively pre-cool TABS concrete systems to achieve significant operational energy savings. Chillers designed for and operated at low pressure ratios, or low-lift chillers, can have much higher coefficients of performance (COP) than conventional chillers (Gayeski et al. 2010). By predicting a building's cooling load in advance using weather and load forecasts, these low-lift chillers can be predictively controlled to pre-cool thermal storage overnight and in the early morning under low-lift conditions. A scoping study by PNNL found that low-lift cooling systems can achieve annual cooling energy savings, including pump, fan and chiller energy consumption, in the range of 37 to 84 percent relative to DOE benchmark buildings depending on the climate and building type (Katipamula et al. 2010).

A model-predictive control algorithm to implement low-lift cooling with concrete TABS for thermal storage has been developed at MIT (Gayeski 2010). This control algorithm uses a data-driven model of concrete-core temperature response to predict the return water temperature to the low-lift chiller and thus its efficiency. A data-driven model of zone operative temperature, derived from measurements in a full-size MIT test chamber, is employed to ensure thermal comfort is maintained. The energy performance of this system in the test chamber was compared to a conventional split system air conditioner, common in new construction in hot climates, under typical summer week conditions for Atlanta and Phoenix. The low-lift cooling system showed operational cooling energy savings of 25% in Atlanta and 19% in Phoenix for the typical summer week relative to the conventional split-system air conditioner. These savings are reasonable relative to the expected savings based on the PNNL scoping studies (Gayeski 2010).

In summary, intelligent use and active-charging of concrete thermal storage can lead to significant reductions in the operational energy consumption of commercial buildings. Combining low-lift cooling systems with energy efficient lighting, appliances, and building envelopes has the potential to enable very low energy intensity buildings with low life cycle operational energy consumption. This technology is evolving rapidly with a need for further research on system configuration, control, and integration as well as demonstration projects in small and mid-size commercial buildings.

4.6 Conclusions

This chapter analyzed the life cycle emissions of a large office building, derived from a US DOE benchmark and modeled with both steel and concrete structural systems. It also offered possible methods of improvement for the concrete structure. The key results are summarized in Table 4.9.

Table 4.9 – Summary of the commercial building results for the entire 60-year life cycle

City	Building Type	Pre-Use Materials lbs/ft^2 (kg/m^2)	Pre-Use GWP lbs CO_2e/ft^2 (kg CO_2e/m^2)	Maintenance GWP lbs CO_2e/ft^2 (kg CO_2e/m^2)	Operational GWP/year lbs CO_2e/ft^2 (kg CO_2e/m^2)	End-of-Life total GWP lbs CO_2e/ft^2 (kg CO_2e/m^2)	Total for 60 years lbs CO_2e/ft^2 (kg CO_2e/m^2)
Chicago	Concrete	162 (791)	39.5 (193)	6.10 (29.8)	16.0 (78.1)	-3.2 (-15.6)	1002 (4892)
	Steel	106 (518)	47.6 (232)	6.10 (29.8)	16.3 (79.6)	-14.0 (-68.4)	1019 (4975)
Phoenix	Concrete	162 (791)	39.6 (193)	6.02 (29.4)	12.1 (59.1)	-3.3 (-16.1)	767.9 (3749)
	Steel	106 (518)	47.6 (232)	6.02 (29.4)	12.4 (60.5)	-14.2 (-69.3)	781.0 (3813)

The following conclusions can be drawn:

- The concrete commercial buildings have an embodied GWP of 42 lbs CO_2e/ft^2 (205 kg CO_2e/m^2) while the steel commercial buildings have an embodied GWP of 40 lbs CO_2e/ft^2 (195 kg CO_2e/m^2).
- For the large office building considered, thermal mass of the exposed concrete frame can provide HVAC savings of 7-9% compared to a steel frame. This accounts for 2% savings in annual operating emissions of the exposed concrete frame compared to the steel framed building with finishes.
- Over a lifetime of 60 years, the CO_2e emissions of the concrete building are roughly equivalent to the steel alternative for the large office building considered, with steel buildings having a 1.7% higher total GWP than concrete in both regions. The total GWP for concrete buildings ranges from 768-1002 lbs CO_2e/ft^2 (3750-4892 kg CO_2e/m^2).
- Increasing SCM substitution (such as fly ash) in the concrete building from 10% to 25% can decrease pre-use GWP by 7.3%.
- Lighting control and low-lift cooling can decrease the operating energy requirements for concrete buildings. Low-lift cooling takes advantage of the high volumetric heat capacity of concrete and is effective when building cooling loads have been reduced through control of internal and solar heat loads.
- In all cases, the steel and concrete buildings have very similar emissions over the full life cycle, and the choice of structural material does not dramatically influence the total emissions.

5 DISCUSSION

5.1 Introduction

This chapter summarizes the key findings and compares them to published values. The buildings examined in this report are based on benchmark building models established by the U.S. Department of Energy (DOE), which are based on surveys of buildings across the United States (Deru et al. 2011; Hendron and Engebrecht 2010). The use of a benchmark building provides greater utility than an isolated case study, as these buildings are more representative of the general building stock. Therefore, the life cycle results for residential and commercial buildings presented here provide an important reference point for others in the LCA community.

5.2 Discussion of Results and Trends

This study has performed LCAs for a series of buildings and the results are summarized in the following sections. The results are presented in terms of GWP, as expressed by mass of CO_2e emissions per unit gross area (lbs of CO_2e/ft^2 and kg CO_2e/m^2).

5.2.1 Embodied and Operating Global Warming Potential

Table 5.1 provides a summary of the embodied GWP due to materials and the annual operating GWP due to building energy consumption for the buildings analyzed in this study. In addition, a ratio of the embodied GWP to the annual operating GWP (which also represents the number of years of operating GWP it would take to equal embodied GWP) is included to provide an overview of the differences across a range of building types. In all cases the building total embodied GWP is equal to less than eight years of operating GWP, which means that the embodied emissions make up less than 12% of the total life cycle emissions over a 60-year period.

Table 5.1– Summary of embodied GWP and operating energy GWP for range of buildings

Global Warming Potential (GWP) in lbs CO_2e/ft^2 (kg CO_2e/m^2)							
		Embodied GWP (Pre-Use + Maintenance +		Annual Operational GWP		Ratio of Embodied to	
		ICF	Wood	ICF	Wood	ICF	Wood
Single Family Building	Chicago	69.4 (339)	61.5 (300)	12.7 (62.2)	13.6 (66.3)	5.5	4.5
	Phoenix	63.7 (311)	55.7 (272)	8.18 (39.9)	9.12 (44.5)	7.8	6.1
Multi-Family Building	Chicago	35.5 (173)	27.9 (136)	16.8 (82.1)	17.6 (85.9)	2.1	1.6
	Phoenix	35.2 (172)	26.9 (131)	12.6 (61.5)	13.4 (65.5)	2.8	2.0
		Concrete	Steel	Concrete	Steel	Concrete	Steel
Commercial Building	Chicago	42.4 (207)	39.7 (194)	16.0 (78.1)	16.3 (79.7)	2.7	2.4
	Phoenix	42.3 (207)	39.5 (193)	12.1 (59.1)	12.4 (60.3)	3.5	3.2

The embodied GWP for residential concrete construction ranges from 35-70 lbs CO_2e/ft^2 (171-339 kg CO_2e/m^2). For residential wood construction it is 27-62 lbs CO_2e/ft^2 (132-301 kg CO_2e/m^2). The concrete commercial buildings have an embodied GWP of about 42 lbs CO_2e/ft^2 (205 kg CO_2e/m^2) while the steel commercial buildings have an embodied GWP of about 40 lbs CO_2e/ft^2 (194 kg CO_2e/m^2). In terms of operational GWP, residential concrete construction has a range of 8-17 lbs CO_2e/ft^2 (39-83 kg CO_2e/m^2) annually; there is a similar range of 9-18 lbs CO_2e/ft^2 (44-86 kg CO_2e/m^2) annually for residential wood construction. For the commercial buildings, annual operational GWP ranges from 12-16 lbs CO_2e/ft^2 (59-80 kg CO_2e/m^2) for both concrete and steel construction. In the residential buildings, the concrete construction tends to have a higher embodied GWP than the alternative wood construction. The embodied GWP of a commercial concrete building is 6.4% higher than the embodied GWP of an equivalent steel building. For both commercial and residential buildings, the concrete structures have lower annual operational GWP irrespective of differences in climate. The building energy consumption values that these operational GWP results are based on are included in Appendix 8.8.

This study shows better energy performance for concrete construction (ICF and reinforced concrete) compared to alternative construction types (wood frame in residential and steel frame in commercial). While concrete construction tends to have equal or higher embodied GWP than alternative construction materials, the annual operating GWP for concrete buildings is lower. As a result, over a building lifetime of 60 years, the cumulative CO_2e emissions are slightly lower for concrete buildings and alternatives in wood or steel.

5.3 Comparison to Other Studies

This section compares the results of the current study to data obtained from other studies. For comparison of building embodied GWP, data from other building LCA studies are used. For comparison of building energy consumption, data from the U.S. Energy Information Administration (EIA) and the U.S. Department of Energy (DOE) are used.

5.3.1 Comparison of Embodied GWP

This section compares the embodied GWP of the buildings to previous LCA studies. Over the last decade, several studies have examined the GWP of single-family residential construction in either concrete or wood (Ochoa 2004; Canadian Wood Council 2011; Lippke et al. 2004). These results are compared to the current study in Figure 5.1. Although the results vary according to the scope and boundaries, the present study lies within the range of values found previously. Few previous LCA studies have examined the GWP of multi-family buildings so the residential comparisons are limited to single-family construction.

There have also been a series of previous studies examining the GWP of commercial building construction in concrete or steel (Eaton and Amato 1998; Junnila and Horvath 2003; Guggemos et al. 2005; Jönsson et al. 1998; Johnson 2006). These results are compared to the current study in Figure 5.2. The results vary widely according to the scope and boundaries, but again, the present study lies within the range of values found previously. Hsu (2010) has analyzed the reasons for discrepancies between various LCA studies, highlighting the need for a more consistent approach.

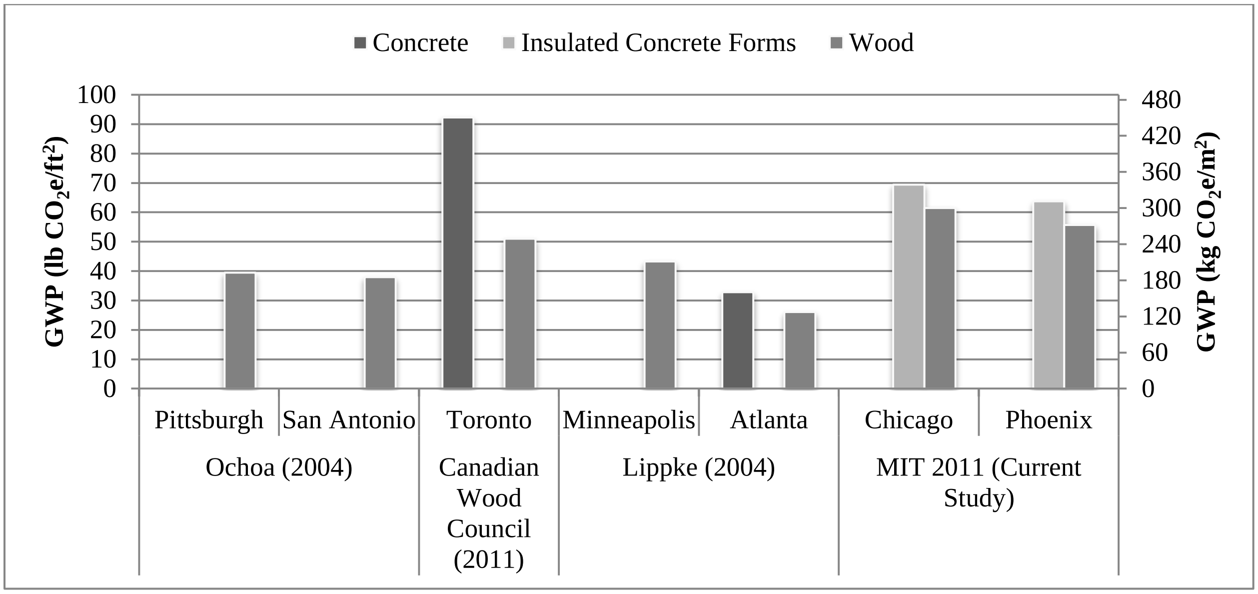

Figure 5.1 – Comparison of embodied global warming potential of single-family residential buildings normalized by floor area for climate regions comparable to Chicago and Phoenix

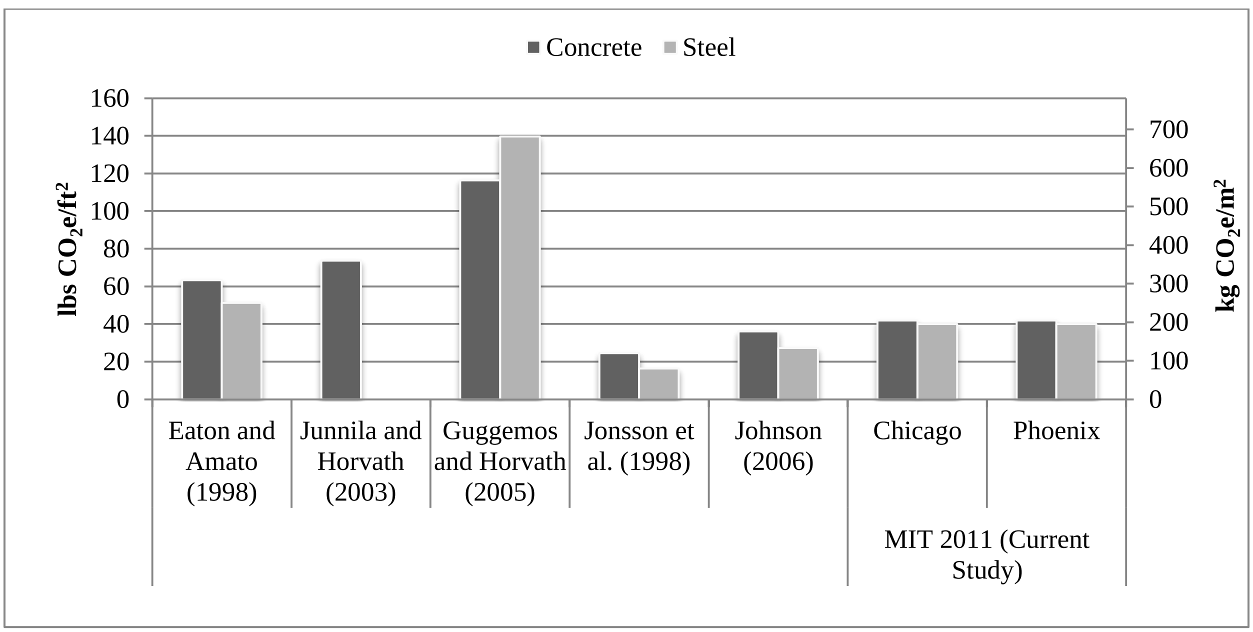

Figure 5.2 – Comparison of embodied global warming potential of commercial office buildings normalized by floor area

5.3.2 Comparison of Operating Energy

The Energy Information Administration (EIA) provides building site energy consumption from the Residential Energy Consumption Survey (RECS) and the Commercial Building Energy Consumption Survey (CBECS) (US EIA 2011c; US EIA 2011d). The data are adjusted for weather to yield energy consumption values that represent the amount of energy that would have been consumed had the weather experienced during the year of the survey conformed to "normal" weather patterns as predicted by the 30-year average (Climate Averages 2011). The method of calculation is provided in detail on the EIA website (US EIA 1999). It must also be noted that the RECS and CBECS data show some variability in building energy consumption over the years that the surveys have been issued (US EIA 2009a; US EIA 2009b). Figure 5.3 summarizes the EIA data from the past two surveys and compares them to the results for the residential and commercial buildings in the current study.

According to the 2001 and 2005 EIA RECS surveys, the average annual energy consumption for a single-family house in the Midwest region (encompassing Chicago) ranges from about 40-50 kBtu/ft^2 (126-158 kWh/m^2). For a single-family house in the Western region (encompassing Phoenix), the average energy consumption is expected to be slightly under 40 kBtu/ft^2 (126 kWh/m^2). The energy use from the current single-family study is about 10 kBtu/ft^2 (32 kWh/m^2) higher for Chicago and about 10 kBtu/ft^2 (32 kWh/m^2) lower for Phoenix than the expected values for each region. For multi-family buildings, the average site energy consumption should be between 50 and 70 kBtu/ft^2 (126 and 156 kBtu/ft^2) for the Midwest (Chicago) region, and 40 and 45 kBtu/ft^2 (126 and 142 kWh/m^2) for the Western (Phoenix) region and the current study produce similar energy consumption values for both locations. Differences between the EIA data and the current study are possibly due to regional averages, as will be discussed below.

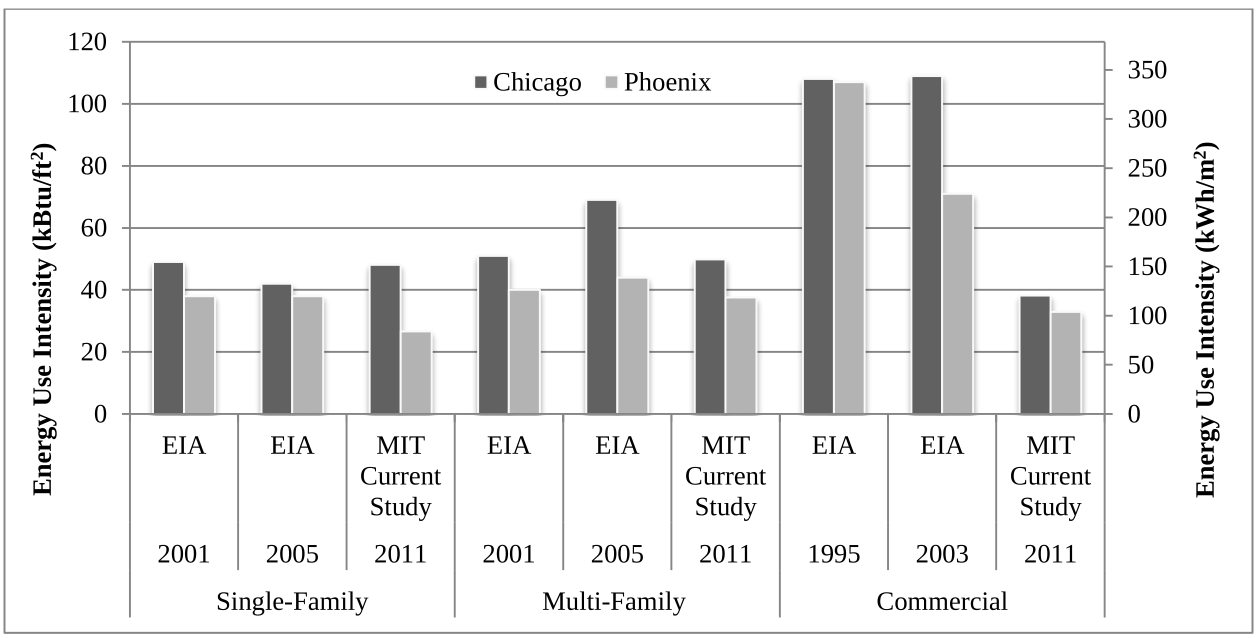

Figure 5.3 – Comparison of site energy use intensities from buildings analyzed in the current study to those published by the Energy Information Administration for existing buildings—RECS data used for residential comparison and CBECS data used for commercial comparison (US EIA 2009a; US EIA 2009b)

The operating energy predictions for the commercial building in the current study are significantly lower (about 60%) than the EIA survey data. It is important to remember that the commercial office building model used in this study is based on the DOE large office benchmark data updated to the efficiencies of ASHRAE standard 90.1-2007 from standard 90.1-2004. Running the unchanged EnergyPlus file provided for the original DOE benchmark shows annual energy requirements of approximately 45 kBtu/ft^2 (142 kWh/m^2), which is significantly lower (by about 50-60%) than the average values from the EIA, but slightly higher (by about 20-30%) than the results of the commercial building examined in the current study. The difference in energy consumption between the unchanged DOE commercial benchmark and the EIA data can be attributed to a variety of things including:

- The EIA data represents commercial office buildings of various sizes, while less than 1% of the buildings surveyed were over 500,000 ft^2 in area—the size of the large office commercial benchmark
- The most recent EIA data is based on the 2003 CBECS, and does not represent new construction for the past 8 years, where these newer buildings may use less energy than buildings currently represented in the CBECS and could potentially lower energy use intensity averages for commercial office buildings.
- Modeling assumptions made in the benchmark model differ from actual building operation practices which dictate the results of the CBECS. While much effort was made to create benchmark models that are as representative of real buildings as possible, lights and HVAC equipment tend to be left on longer in actual buildings than was accounted for in the model, in addition to having higher plug loads, overheating, over cooling and increased outdoor air intake.
- The thermal bridging that occurs in the building envelope of actual buildings is not accounted for in the energy model.
- There is a lack of enforcement of existing energy codes in actual buildings (effective codes enforcement is less than 40% nationwide), so while the commercial building examined in the current study meets the most current energy standard, many of the buildings included in CBECS may not (Holness 2011).

Furthermore, the differences between EIA data and the current study are partly due to the fact that the EIA data is based on regional averages—using the Midwest East North Central census region for Chicago, and the West Mountain census region for Phoenix—whereas the current study is specific to the cities of Chicago and Phoenix. Figure 5.4 compares the climate regions with the census regions, demonstrating that some census regions (such as West Mountain contain a range of climate regions. This may help to explain why regional building energy consumption averages do not correspond more closely to the results of the current study.

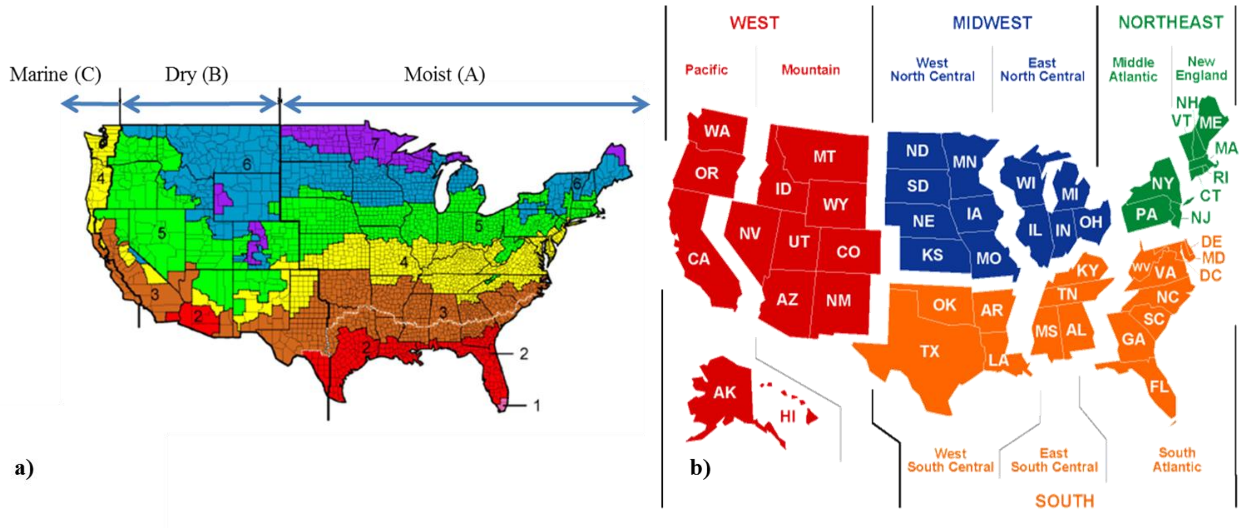

Figure 5.4 – a) ASHRAE climate regions; and b) U.S. census regions (Image source: DOE 2005; US EIA 2000)

5.4 Future of Concrete Low-Energy Buildings

As of 2010, buildings in the United States are responsible for 41% of the nation's total primary energy consumption and 39% of total CO_2 emissions, representing a significant portion of the country's emissions (US DOE 2011a; US DOE 2011b). These large numbers indicate a need to create more energy efficient buildings that generate significantly lower greenhouse gas emissions than the current building stock in order to reduce the nation's contribution to climate change. Several new initiatives are underway to promote improved building construction, including the 2030 Challenge, ASHRAE 189.1, and Passivhaus Standards. It is of interest to find ways for concrete buildings to meet these more stringent building standards in the future. The buildings modeled in the current study provide a baseline by which to build upon for future improvements.

5.4.1 Architecture 2030 and the 2030 Challenge

Architecture 2030 is a non-profit, independent organization that was founded in 2002 with the aim of transforming the U.S. building sector to reduce energy consumption and greenhouse gas emissions (Architecture 2030, 2011). Architecture 2030 has initiated the 2030 Challenge to encourage architects and building owners to adopt certain energy use and greenhouse gas reduction targets (Architecture 2030, 2011). For the year of 2010, the target was to reduce building fossil fuel use, greenhouse gas emissions, and site energy consumption by 60% from the regional average for that specific building type (as defined by the RECS conducted in 2001, and the 2003 CBECS/Energy Star Target Finder) for new construction or major renovations (2030 Challenge Targets 2011) For every five years after 2010, the energy target is an additional 10% lower, with the goal of achieving net-zero, carbon neutral buildings in the year 2030, which would push the nation towards relying more on renewable energy sources than fossil fuels, in addition to increasing the contribution of embodied emissions to total life cycle GWP. Figure 5.5 depicts the Architecture 2030 proposal to reduce the use of greenhouse gas emitting fuels necessary for the operation of new buildings to zero by the year 2030.

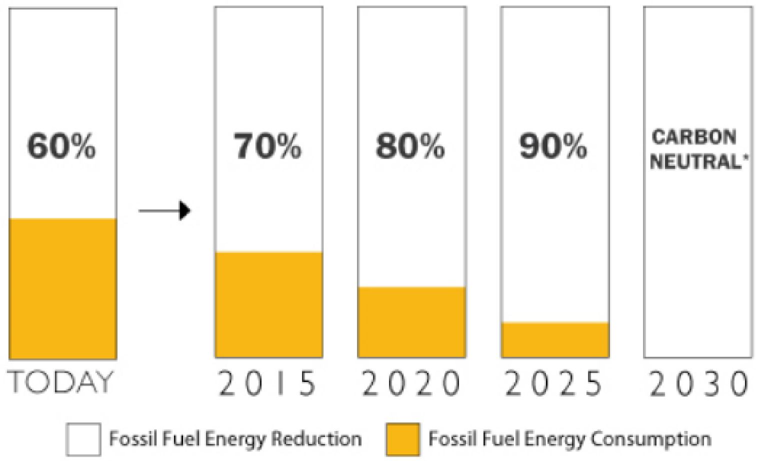

Figure 5.5 – 2030 Challenge goals for achieving carbon-neutral buildings in new construction by 2030, requiring no greenhouse gas emitting fuels for energy (Source: Architecture 2030, 2011)

The residential buildings assessed in this study do not achieve the current energy consumption goals of the 2030 Challenge (defined for 2010). However, the energy use intensities of the current study are representative of typical new construction in the U.S., and therefore demonstrate that greater improvements will be needed to meet the goals of the 2030 Challenge and other competitive processes in the coming decades.

5.4.2 ASHRAE 189.1

In 1975 ASHRAE created Standard 90-75—one of the first building standards that concentrated on building energy efficiency as opposed to occupant comfort, health and safety (Holness 2011). This standard was predicted to result in a 27% reduction in energy from building energy consumption at the time. Since then Standard 90.1 has become the baseline standard for energy efficiency under the Energy Policy Act in 1992, with each new standard increasing in energy efficiency from its predecessor (Holness 2011). The ASHRAE standard 189.1 for the Design of High Performance Green Buildings is geared towards low-energy buildings and is now in the final stages of development (ASHRAE 2009). This new standard is expected to reduce building energy use by 30% from ASHRAE 90.1-2007, which is an energy code that can be adopted by state or local jurisdictions (ASHRAE 2007). In addition, ASHRAE's Advanced Energy Design Guides (AEDG) provide guidance for 30% energy efficiency improvement over Standard 90.1-1999 targeting small buildings using off-the-shelf technologies to provide practical and cost-effective savings (Holness 2011). Changes in building energy requirement stipulated by ASHRAE 90.1 and 189.1, in addition to the AEDGs can have a large impact on building energy use in the United States, and therefore can play a major role in achieving low-energy goals, including those proposed by the 2030 Challenge.

The U.S. government is becoming more aggressive in the energy goals it sets for federal buildings. Under EPAct 2005, all new federal buildings are required to use 30% less energy than Standard 90.1-2004 when economically feasible (Holness 2011). The Energy Independence and

Security Act of 2007 (EISA) requires substantial reductions in fossil fuel consumption in federal buildings. Relative to energy use in 2003, this act requires the entire inventory of existing federal buildings to reduce fossil-fuel usage by 30% by 2015. Further, fossil fuel usage for new buildings, including that required for plug and process loads, is mandated to meet reductions relative to CBECS 2003 that will reach net-zero energy by 2030 (Holness 2011). In the face of these more stringent energy policies it may be questionable whether it is even possible to attain these goals, however a study done by NREL shows that site energy savings of at least 50% from ASHRAE 90.1-2004 in large commercial office buildings are possible (in most cases without the use of on-site energy generation technology) and can be cost effective (NREL 2010).

5.4.3 Passivhaus Standard

The intent of the Passivhaus (or Passive House) Standard is to ideally design a building that uses little to no energy to operate (Passive House Institute 2011). In practice, most passive houses strive to reduce building energy consumption by 90% in comparison to those built to code. In heating-dominated climates, passive houses are typically super insulated with high-efficiency windows, and with conscious efforts made to reduce thermal bridging and air infiltration. The implementation of this standard more widely throughout the U.S. can contribute to reaching low-energy goals for the future.

5.5 Summary

This chapter demonstrates that the operating requirements of buildings dominate the life cycle greenhouse gas emissions. The embodied emissions (due to construction, maintenance, and disposal of materials) are typically responsible for only 3% to 12% of the total emissions over an analysis period of 60 years. The embodied emissions for the current study are within the range of previous LCA studies, though the wide variation across studies demonstrates the need for greater consistency and transparency in the performance of building LCAs. The operating energy results for residential buildings in the current study are comparable to EIA survey data. However, the commercial building energy for the current study is significantly lower than EIA survey data, due to discrepancies between the DOE benchmark large office building and the CBECS survey. Finally, a range of new initiatives to promote low-energy buildings will provide both a challenge and an opportunity for concrete buildings in the future.

6 CONCLUSIONS

This report presents methodologies for life cycle assessment (LCA) and a limited life cycle cost assessment (LCCA) of the CO_2e emissions of buildings that incorporate concrete in their structural or enclosure systems. The LCA methodology is applied to single- and multi-family residential buildings and a commercial office building of different structural materials. In each case, the LCA process starts with descriptions of benchmark buildings made available from the U.S. Department of Energy and its national laboratories. The descriptions provide information about building size and operation. By designing structural systems and enclosures, greenhouse gas emissions associated with the materials are estimated. Simulations of building operation yield estimates of annual energy consumption, from which emissions over the estimated building lifetime are calculated. Emissions are location dependent; calculations are made for two North American locations, Chicago and Phoenix. The last step of the LCA process accounts for end-of-life disposal and recycling. The LCCA methodology is applied to single-family houses to investigate economic costs of building construction and the economic value of changes in construction that reduce life cycle emissions.

The application of the LCA methodology in this work exemplifies good practice by incorporating all phases of the life cycle and by promoting transparency and repeatability through the documentation of key modeling decisions and inputs. In addition, the simulation input files are available from the authors on request.

Key findings of this report include the following:

- Total embodied GWP is approximately 27-69 lbs CO_2e/ft^2 (128-339 kg CO_2e/m^2) across residential and commercial buildings constructed in concrete, wood, and steel.
- In general, residential concrete buildings have higher embodied GWP than the wood alternative, while the commercial concrete buildings are roughly equivalent to the steel alternative.
- Annual operating GWP per square foot is approximately 8-18 lbs CO_2e/ft^2 (39-88 kg CO_2e/m^2) for residential and commercial buildings in Chicago and Phoenix.
- In general, the concrete structures have lower annual operating GWP than the alternate designs in wood or steel (ranging from 3%-10% in savings).
- Over a 60-year life cycle, the lower operating GWP outweighs the initially equal or higher embodied GWP for concrete buildings. This results in total life cycle GWP lower than alternate designs in steel or wood. The largest life cycle GWP reduction was 8%, for the single-family ICF house in Phoenix.
- Embodied GWP is equal to 2-8 years of annual operating GWP for a range of building types and materials.
- Over a 60-year lifetime, 88%-98% of CO_2e emissions are due to the operating energy requirements for all buildings considered in this study.
- Increased substitution of fly ash or other SCMs, can reduce the embodied GWP of the concrete buildings considered here by 7% to 14%.
- While there are opportunities in the pre-use phase of the life cycle of concrete buildings, most carbon-reduction opportunities exist in the operating phase, including radiant cooling systems with chilled-water pipes embedded in concrete slabs.

- For residential buildings, life cycle cost analysis shows that reducing air infiltration in concrete houses and increasing the thermal resistance of concrete wall assemblies can be economically as well as environmentally attractive.

Improving the environmental performance of concrete buildings will require the attention of industry, government and the research community. A number of steps can be taken:

- Adopt life cycle design in the early design phase of new buildings, through LEED, state building codes and other means;
- Include in the life cycle design process both life cycle assessments based on key environmental metrics and life cycle cost assessments of the improved environmental performance;
- Include in cost assessments the downsizing of space conditioning equipment due to improvements to the building enclosure;
- Improve the formulation and application of concrete in buildings;
- Develop a public database of the simulated and measured performance of concrete buildings to more accurately assess the placement and amount of concrete and insulating materials in wall assemblies;
- Carry out field tests and document the performance of building space conditioning systems that enhance heat storage in thermal mass for a range of climates;
- Develop and promote low-carbon building design, complementing such current efforts as ASHRAE's Advanced Energy Design Guidelines to specify elimination of thermal bridges in building facades regardless of construction material and improved use of thermal mass.

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8 APPENDICES

8.1 Material Transportation Distances

Table 8.1 – Chicago transportation distances

Chicago	Vendor	Distance in Miles
Aluminum	Alcoa Aluminum (Point Comfort, TX)	1202
Aluminum Window	Milgard (Aurora, IL)	48
Asphalt	IKO (Ashcroft, BC →Danville, IL →	2379
Batt Insulation	Certainteed (Milwaukee, WI)	81
Carpet	Georgia Carpet Industries (Dalton, GA)	860
Concrete	Ozinga (Chicago, IL)	10
Gravel	Joliet Sand & Gravel (Joliet, IL)	42
Gypsum	National Gypsum (Waukegan, IL)	43
ICF	Amvic (Nixa, MO)	525
Landfill	CID Landfill (Chicago, IL)	20
Lumber	Deltic Timber (El Dorado, AR)	765
Paint	Benjamin Moore (Dallas, TX)	926
Plywood	Georgia Pacific (Fordyce, AR)	717
Sand	Joliet Sand & Gravel (Joliet, IL)	42
Steel, Doors	Goldy Locks (Tinley Park, IL)	27
Steel, Galvanized	Clingan Steel (Elk Grove, IL)	22
Steel, Hot-rolled	Central Steel Fabrication (Chicago, IL)	10
Steel Lath, PVC expansion	Amico (Bourbonnais, IL)	56.5
Steel, Rebar	Central Steel Fabrication (Chicago, IL)	10
Stucco	Local Contractor (Chicago, IL)	10
Wood I-Joists	Georgia Pacific (Torsby, AL)	705
XPS	Owens Corning (Rockford, IL)	89

Table 8.2 – Phoenix transportation distances

Phoenix	Vendor	Distance in
Aluminum	Alcoa Aluminum (Point Comfort, TX)	1136
Aluminum Window	Milgard (Phoenix, AZ)	10
Asphalt	Paramount Petroleum (Paramount, CA)	374
Batt insulation	Certainteed (Chowchilla, CA)	625
Carpet	Georgia Carpet Industries (Dalton, GA)	1961
Concrete	Ready Mix, Inc (Tolleson, AZ)	12.5
Gravel	Pioneer Landscaping Materials (Gilbert, AZ)	22
Gypsum	National Gypsum (Phoenix, AZ)	10
ICF	Amvic (Salt Lake City, UT)	658
Landfill	27th Avenue Solid Waste Management Facility	10
Lumber	Sierra Pacific (Chinese Camp, CA)	701
Paint	Benjamin Moore (Dallas, TX)	1068
Plywood	Alliance Lumber (Eagar, AZ)	223
Sand	Pioneer Landscaping Materials (Gilbert, AZ)	22
Steel, Doors	Steel Door (Tucson, AZ)	116
Steel, Hot-rolled	Schuff (Phoenix, AZ)	10
Steel Lath, PVC Expansion	Los Angeles, CA	378
Steel, Rebar	Schuff (Phoenix, AZ)	10
Stucco	Western 1-Kote (Glendale, AZ)	10
Wood I-Joists	Georgia Pacific (Thorsby, AL)	485
XPS	Owens Corning (Rockford, IL)	1750

8.2 Electricity Mixes

Table 8.3 – Electricity Mixes, NERC (North America Electric Reliability Council) Regions (EPA eGrid 2007)

	Chicago (RFC) (%)	Phoenix (WECC) (%)
Hard Coal	64.35	30.13
Natural Gas	6.54	31.38
Heavy Fuel Oil	0.54	0.42
Nuclear	26.45	9.61
Solid Biomass	0.70	1.18
Hydro	0.54	23.08
Other Renewable (wind, solar, geo-thermal)	0.14	3.77
Other Fossil	0.74	0.43
Grid Loss Factor	*6.47*	*4.84*

8.3 Example R-value calculation

Note: This calculation is for the multi-family, wood building in Chicago.

Table 8.4 – Exterior wall details for Chicago multi-family wood building

EXTERIOR WALL	Thickness (m)	Conductivity (W/mk)
Stucco	0.01905	0.6918
XPS	0.034925	0.026
Plywood (5/8")	0.015875	0.1
Wood/Insulation	0.1397	0.0532
Gypsum	0.015875	0.16

In order to find the conductivity of the wood/insulation later, the properties of these were taken as a weighted average based on surface area.

Table 8.5 – Exterior wall structure breakdown for Chicago multi-family wood building

Exterior Wall	Chicago	Conductivity
Wood	14.77%	0.141
Insulation	85.23%	0.038
Total		0.0532

Where 0.0532 = 0.1477*0.141+0.8523*0.038

The R-value in IP units is the inverse of 0.0532 times the thickness times 5.678.

8.4 Blower Door Test Procedure

This is a brief description of the process in ASTM standard E779-2010

Methodology

- Seal the house and create a uniform pressure throughout
- Install air moving equipment
- Increase the pressure from 10 to 60 Pa, in steps of 5 or 10 Pa
- Determine the airflow to maintain the pressure
- Measure indoor and outdoor temperature, and elevation

Calculation

- Correct the pressure based on the average zero-flow measurement
- Correct the flow based on the indoor and outdoor densities
- Calculate the natural logarithm of the correct pressures and flows
- Find the variances and the covariances of these natural logarithm values
- Calculate n and C in the following equation

$$Q = C\Delta P^n$$

$$Q = \text{flow, } m^3/s$$

$$n = \frac{Covariance}{Variance(\ln(\Delta P))}$$

$$C = \exp(\overline{\ln(Q)} - n * \overline{\ln(\Delta P)})$$

- Then find the corrected C, C_0, using the following equation

$$C_0 = C\left(\frac{\mu}{\mu_0}\right)^{2n-1}\left(\frac{\rho}{\rho_0}\right)^{1-n}$$

$$\mu = \frac{1.458 * 10^{-6}(T+273)^{.5}}{1+\frac{110.4}{T+273}} \quad \text{, kg/(msK}^{.5}\text{)}$$

$$\mu_0 = \mu(T = 20\ C)$$

$$\rho = 1.2041\left(1 - \frac{.0065 * 600}{293}\right)^{5.2553}\left(\frac{293}{T + 273}\right)$$

T = indoor or outdoor temperature, C

- Finally, the air leakage can be calculated

$$A_L = C_0\left(\frac{\mu}{\mu_0}\right)^{2n-1}\left(\frac{\rho}{\rho_0}\right)^{1-n}, \ m^2$$

The confidence limits of n, C and A_L are found using the variance of these values and the two-sided t statistic.

8.5 Air Tightness Calculations

The air tightness of a home is how much air leaks in and out of a home through unplanned openings. Air leakage is a measure of air tightness. It is the size of the holes in the outer envelope of a building, generally in cm^2. The following equation is a common method of normalizing air leakage.

$$NL = 1000\frac{ELA}{Af}\left(\frac{H}{2.5m}\right)^{0.3}$$

NL = Normalized Leakage

ELA = Effective Leakage Area (Air Leakage), cm^2

Af = Floor Area, m^2

H = Height, m

Blower door tests are used to determine air leakage. The planned openings (ie windows) in a home are sealed and then the home is pressurized for a range of values using a fan installed in a doorway. The flow through the fan is then measured. Using a method from the American Society for Testing and Materials, the air leakage can be calculated from these measurements (ASTM E779, 2010).

Determining NL of ICF Homes

MIT has collected 43 blower door tests of ICF homes. However, 31 were used in the histogram (Figure 8.1) and the calculations below. There are two reasons for removing 12 homes from the dataset. First, the data includes a row of ten identical homes by the same builder. These homes were found to have very similar air-tightness values, as would be the case if the same house were tested multiple times. The median of these homes was kept in the data set, and the other nine homes were removed. In addition, three of the homes were reported without test data; only the final calculated leakage area was given. These tests were removed from the data set to maintain consistency because the same calculations could not be performed.

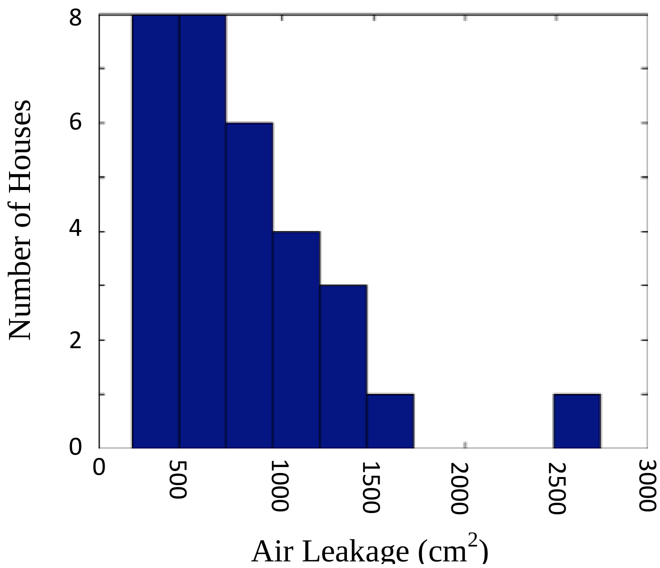

Figure 8.1 – Histogram of the edited ICF air tightness data set

The house with the very large air leakage doesn't seem to have any unusual attributes. There could have been a problem with the test, such as failing to close a window.

This data was normalized by floor and height, as in the equation above, to create normalized leakage values of ICF homes. The outliers, based on the default definition in Matlab, were removed and the median, minimum and maximum values of the data set were found (Matlab, 2010). Using NL and the dimensions of the modeled home (A_f = 222 m^2, H = 4.8768 m), the effective leakage areas can be calculated. The ELA can be used to calculate Q, the flow in m^3/s, using the following equation.

$$Q = ELA\sqrt{\frac{2*4Pa}{1.2kg/m^3}}\frac{1m^2}{(100cm)^2}$$

Assuming n = 0.65 and Pr = 4 Pa, C is found (Sherman, 2004).

These C and n values were input into the Energy Plus single-family model to represent average, tight and leaky homes, respectively.

Table 8.6 – Values of C for ICF Homes

Average	0.050
Tight	0.011
Loose	0.092

8.6 Material Quantities and Concrete Mixes

Table 8.7 – Concrete Mix Designs (adapted from Marceau et al. 2007)

Concrete Mix Designs		*Commercial*		*Residential*	
Fly Ash	*%*	10%	25%	10%	50%
Strength	*psi (MPa)*	5000 (35)	--	3000 (20)	--
Unit Weight	*lb/ft^3 (kg/m^3)*	148 (2371)	--	145 (2323)	--
Cement	*lb/yd^3 (kg/m^3)*	508 (301)	423 (251)	338 (201)	188 (112)
Fly Ash	*lb/yd^3 (kg/m^3)*	56 (33)	131 (77.7)	38 (23)	188 (112)
Water	*lb/yd^3 (kg/m^3)*	237 (141)	237 (141)	237 (141)	237 (141)
Coarse Aggregate	*lb/yd^3 (kg/m^3)*	2000 (1187)	2000 (1187)	1900 (1127)	1900 (1127)
Fine Aggregate	*lb/yd^3 (kg/m^3)*	1200 (712)	1200 (712)	1400 (831)	1400 (831)

The mixes are adapted from those published by Marceau et al. (2007), with the only change being the introduction of 10% fly ash replacement for cement. This mix does not represent a standard mix used in practice because fly ash – when incorporated into a concrete mix – is generally used at quantities greater than 15%. The assumption of 10% fly ash corresponds to a national average use of fly ash in concrete.

Table 8.8– Pre-use phase material quantities for the single-family houses (IP Units)

Single Family (IP)	*Chicago ICF*		*Chicago Wood*		*Phoenix ICF*		*Phoenix Wood*	
Gross area	*ft²*	2529.1	*ft²*	2464.	*ft²*	2529.	*ft²*	2440.7
Useable area	*ft²*	2400	*ft²*	2400	*ft²*	2400	*ft²*	2400
Roof	*lbs*	*lbs/ft²*	*lbs*	*lbs/ft²*	*lbs*	*lbs/ft²*	*lbs*	*lbs/ft*
Asphalt	5814	2.3	5814	2.4	5814	2.3	5814	2.4
Insulation, Batt	700	0.3	700	0.3	700	0.3	700	0.3
Wood	8888	3.5	8888	3.6	8058	3.2	8058	3.3
Staircase, wood	1080	0.4	1080	0.4	1080	0.4	1080	0.4
Load Bearing								
Wood	2408	1.0	2408	1.0	2094	0.8	2094	0.9
Insulation	173	0.1	173	0.1	173	0.1	173	0.1
Drywall	5627	2.2	5627	2.3	5627	2.2	5627	2.3
Paint	193	0.1	193	0.1	193	0.1	193	0.1
Cladding								
Paint	112	0.0	112	0.0	112	0.0	112	0.0
Stucco	4428	1.8	4428	1.8	4428	1.8	4428	1.8
Steel Lath	391	0.2	391	0.2	391	0.2	391	0.2
Aluminum Window	2161	0.9	2161	0.9	2161	0.9	2161	0.9
Aluminum Frames	218	0.1	218	0.1	218	0.1	218	0.1
Glass	1942	0.8	1942	0.8	1942	0.8	1942	0.8
PVC Expansion	268	0.1	268	0.1	268	0.1	268	0.1
Exterior Wall								
Concrete	147984	58.5	0	0.0	14798	58.5	0	0.0
Steel rebar	1192	0.5	0	0.0	1192	0.5	0	0.0
Plastic ties	1522	0.6	0	0.0	1522	0.6	0	0.0
EPS insulation	2301	0.9	0	0.0	2301	0.9	0	0.0
Fiberglass	0	0.0	428	0.2	0	0.0	269	0.1
Wood	0	0.0	11072	4.5	0	0.0	8089	3.3
Perimeter Footing and Wall								
Concrete	129790	51.3	12409	50.4	55229	21.8	49537	20.2
Steel reinforcement	470	0.2	470	0.2	132	0.1	132	0.1
EPS	1075	0.4	0	0.0	134	0.0	0	0.0
Plastic ties	711	0.3	0	0.0	89	0.0	0	0.0
XPS	0	0.0	1433	0.6	0	0.0	179	0.1
Isolated Footings								
Concrete	14490	5.7	14490	5.9	0.0	0.0	0.0	0.0
Steel	68	0.0	68	0.0	0.0	0.0	0.0	0.0
Slab on Grade								
Concrete	58000	22.9	58000	23.5	58000	22.9	58000	23.8
Gravel	63000	24.9	63000	25.6	63000	24.9	63000	25.8
XPS	66	0.0	66	0.0	0	0.0	0	0.0
Polyethylene Film	212	0.1	212	0.1	212	0.1	212	0.1

Floors								
Wood	1131	0.4	1131	0.5	10588	4.2	10588	4.3
Drywall	3840	1.5	3840	1.6	3840	1.5	3840	1.6

Table 8.9 – Pre-use phase material quantities for the single-family houses (SI Units)

Single Family (IP)	*Chicago ICF*		*Chicago Wood*		*Phoenix ICF*		*Phoenix Wood*	
Gross area	*m^2*	234.9	*m^2*	228.9	*m^2*	234.9	*m^2*	226.7
Useable area	*m^2*	222.9	*m^2*	222.9	*m^2*	222.9	*m^2*	222.9
Roof	*kg*	*kg/m^2 (gross)*	*kg*	*kg/m^2 (gross)*	*kg*	*kg/m^2 (gross)*	*kg*	*kg/m^2 (gross)*
Asphalt	2643	11.3	2643	11.5	2643	11.3	2643	11.7
Insulation, Batt	318	1.4	318	1.4	318	1.4	318	1.4
Wood	4040	17.2	4040	17.7	3663	15.6	3663	16.2
Staircase, wood	491	2.1	491	2.1	491	2.1	491	2.2
Load Bearing								
Wood	1094	4.7	1094	4.8	952	4.1	952	4.2
Insulation	79	0.3	79	0.3	79	0.3	79	0.3
Drywall	2558	10.9	2558	11.2	2558	10.9	2558	11.3
Paint	88	0.4	88	0.4	88	0.4	88	0.4
Cladding								
Paint	51	0.2	51	0.2	51	0.2	51	0.2
Stucco	2013	8.6	2013	8.8	2013	8.6	2013	8.9
Steel Lath	178	0.8	178	0.8	178	0.8	178	0.8
Aluminum	982	4.2	982	4.3	982	4.2	982	4.3
Aluminum	99	0.4	99	0.4	99	0.4	99	0.4
Glass	883	3.8	883	3.9	883	3.8	883	3.9
PVC Expansion	122	0.5	122	0.5	122	0.5	122	0.5
Exterior Wall								
Concrete	67265	286.4	0	0.0	67265	286.4	0	0.0
Steel rebar	542	2.3	0	0.0	542	2.3	0	0.0
Plastic ties	692	2.9	0	0.0	692	2.9	0	0.0
EPS insulation	1046	4.5	0	0.0	1046	4.5	0	0.0
Fiberglass	0	0.0	195	0.9	0	0.0	122	0.5
Wood	0	0.0	5033	22.0	0	0.0	3677	16.2
Perimeter Footing and								
Concrete	58995	251.2	56408	246.5	25104	107.1	22516	96.1
Steel	213	0.9	213	0.9	60	0.3	60	0.3
EPS	489	2.2	0	0	61	0.3	0	0
Plastic ties	323	1.4	0	0	40	0.2	0	0
XPS	0	0.0	651	2.9	0	0.0	81	0.4

Isolated Footings								
Concrete	6586	28.0	6586	28.8	0.0	0.0	0.0	0.0
Steel	31	0.1	31	0.1	0.0	0.0	0.0	0.0
Slab on Grade								
Concrete	26364	112.2	26364	115.2	26364	112.2	26364	116.3
Gravel	28636	121.9	28636	125.1	28636	121.9	28636	126.3
XPS	30	0.1	30	0.1	0	0.0	0	0.0
Polyethylene Film	96	0.4	96	0.4	96	0.4	96	0.4
Floors								
Wood	514	2.2	514	2.2	4813	20.5	4813	21.2
Drywall	1746	7.4	1746	7.6	1746	7.4	1746	7.7

Table 8.10 – Pre-use phase material quantities for the multi-family buildings (IP Units)

MULTI-FAMILY (IP)	*Chicago ICF*		*Chicago Wood*		*Phoenix ICF*		*Phoenix Wood*	
Gross area	*ft²*	36125	*ft²*	34784	*ft²*	36125	*ft²*	34784
Useable area	*ft²*	33763	*ft²*	33763	*ft²*	33763	*ft²*	33763
Roof	*lbs*	*lbs/ft²*	*lbs*	*lbs/ft²*	*lbs*	*lbs/ft²*	*lbs*	*lbs/ft²*
Asphalt	13918	0.4	13918	0.4	14233	0.4	14209	0.4
Gravel	42869	1.2	42869	1.2	42869	1.2	42869	1.2
Insulation, Batt	4142	0.1	4107	0.1	4107	0.1	4107	0.1
Wood	47402	1.3	47803	1.4	47402	1.3	48010	1.4
Flashing, Galvanized Steel	612	0.0	364	0.0	612	0.0	301	0.0
Staircase, wood	7094	0.2	7094	0.2	7743	0.2	7743	0.2
Load Bearing Walls								
Wood	27676	0.8	27676	0.8	27676	0.8	27676	0.8
Insulation	3177	0.1	3177	0.1	3177	0.1	3177	0.1
Drywall	179516	5.0	179516	5.2	179516	5.0	179516	5.2
Paint	11456	0.3	11456	0.3	11456	0.3	11456	0.3
Cladding								
Paint	2400	0.1	2342	0.1	2430	0.1	2363	0.1
Stucco	151759	4.2	148064	4.2	153652	4.3	149386	4.3
Steel Lath	3325	0.1	3170	0.1	3366	0.1	3198	0.1
Aluminum Window	20761	0.6	20761	0.6	20761	0.6	20761	0.6
Aluminum Frames	2721	0.1	2721	0.1	2721	0.1	2721	0.1
Glass	18041	0.5	18041	0.5	18041	0.5	18041	0.5
PVC Expansion Jt.	815	0.0	803	0.0	824	0.0	807	0.0

Exterior Wall								
Concrete	1732972	48.0	0	0.0	1684998	46.6	0	0.0
Steel rebar	31565	0.9	0	0.0	31107	0.9	0	0.0
Plastic ties	20251	0.6	0	0.0	19689	0.5	0	0.0
EPS insulation	12225	0.3	0	0.0	11917	0.3	0	0.0
Fiberglass Insulation	0	0.0	2311	0.1	0	0.0	2311	0.1
Wood	0	0.0	54185	1.6	0	0.0	54486	1.6
XPS	0	0.0	3809	0.1	0	0.0	0	0.0
Continuous Footing								
Concrete	496238	13.7	409684	11.7	394995	10.9	91480	2.6
Steel reinforcement	43151	1.2	33683	1.0	34347	1.0	8015	0.2
Isolated Footings								
Concrete	154350	4.3	154350	4.4	154350	4.3	154350	4.4
Steel	2278	0.1	2278	0.1	2278	0.1	2278	0.1
Slab on Grade								
Concrete	410944	11.4	416802	12.0	410944	11.4	416802	12.0
Gravel	300081	8.3	304359	8.7	300081	8.3	304359	8.7
XPS	661	0.0	1301	0.0	0	0.0	0	0.0
Polyethylene Film	495	0.0	502	0.0	495	0.0	502	0.0
Steel, Rebar	11670	0.3	11836	0.3	11670	0.3	11836	0.3
Sand	132307	3.7	134197	3.9	132307	3.7	134197	3.9
Wood sill	0	0.0	1749	0.1	0	0.0	1749	0.1
Floors, wood	137726	3.8	137726	4.0	137726	3.8	137726	4.0
Columns, wood	16870	0.5	17451	0.5	16870	0.5	17451	0.5
Carpetting								
Rubber pad	14560	0.4	14560	0.4	14560	0.4	14560	0.4
Carpet	5627	0.2	5627	0.2	5627	0.2	5627	0.2
Elevator Core								
Concrete	112501	3.1	112501	3.2	112501	3.1	112501	3.2
Steel	9783	0.3	9783	0.3	9783	0.3	9783	0.3
Interior Wood doors	2800	0.1	2800	0.1	2800	0.1	2800	0.1
Exterior Steel doors	483	0.0	483	0.0	483	0.0	483	0.0

Table 8.11 – Pre-use phase material quantities for the multi-family buildings (SI Units)

MULTI-FAMILY (SI)	***Chicago ICF***		***Chicago Wood***		***Phoenix ICF***		***Phoenix Wood***	
Gross area	*m^2*	3356	*m^2*	3232	*m^2*	3356	*m^2*	3232
Useable area	*m^2*	3137	*m^2*	3137	*m^2*	3137	*m^2*	3137
Roof	*kg*	*kg/m^2*	*kg*	*kg/m^2*	*kg*	*kg/m^2*	*kg*	*kg/m^2*
Asphalt	6313	1.9	6313	1.9	6456	1.9	6445	2.0
Gravel	19445	5.8	19445	6.0	19445	5.8	19445	6.0
Insulation, Batt	1879	0.6	1863	0.6	1863	0.6	1863	0.6
Wood	21501	6.4	21683	6.7	21501	6.4	21777	6.7
Flashing, Galvanized Steel	278	0.1	165	0.1	278	0.1	137	0.0
Staircase, wood	3218	1.0	3218	1.0	3512	1.0	3512	1.1
Load Bearing Walls								
Wood	12554	3.7	12554	3.9	12554	3.7	12554	3.9
Insulation	1441	0.4	1441	0.4	1441	0.4	1441	0.4
Drywall	81427	24.3	81427	25.2	81427	24.3	81427	25.2
Paint	5197	1.5	5197	1.6	5197	1.5	5197	1.6
Cladding								
Paint	1089	0.3	1062	0.3	1102	0.3	1072	0.3
Stucco	68837	20.5	67161	20.6	69696	20.8	67760	21.0
Steel Lath	1508	0.4	1438	0.4	1527	0.5	1451	0.4
Aluminum Window	9417	2.8	9417	2.9	9417	2.8	9417	2.9
Aluminum Frames	*1234*	0.4	*1234*	0.4	*1234*	0.4	*1234*	0.4
Glass	*8183*	2.4	*8183*	2.5	*8183*	2.4	*8183*	2.5
PVC Expansion Joint	369	0.1	364	0.1	374	0.1	366	0.1
Exterior Wall								
Concrete	786064	234.2	0	0.0	764303	227.7	0	0.0
Steel rebar	14318	4.3	0	0.0	14110	4.2	0	0.0
Plastic ties	9186	2.7	0	0.0	8931	2.7	0	0.0
EPS insulation	5545	1.7	0	0.0	5406	1.6	0	0.0
Fiberglass Insulation	0	0.0	1048	0.3	0	0.0	1048	0.3
Wood	0	0.0	24578	7.6	0	0.0	24714	7.6
Continuous Footing								
Concrete	225090	67.1	185830	57.0	179167	53.4	41495	12.8
Steel reinforcement	19573	5.8	15278	4.7	15580	4.6	3636	1.1
Isolated Footings								
Concrete	70012	20.9	70012	21.7	70012	20.9	70012	21.7
Steel	1034	0.3	1034	0.3	1034	0.3	1034	0.3
Slab on Grade								
Concrete	186401	55.5	189059	58.5	186401	55.5	189059	58.5
Gravel	136114	40.6	138055	42.7	136114	40.6	138055	42.7

XPS	300	0.1	590	0.2	300	0.1	590	0.2
Polyethylene Film	225	0.1	228	0.1	225	0.1	228	0.1
Steel, Rebar	5293	1.6	5369	1.7	5293	1.6	5369	1.7
Sand	60013	17.9	60871	18.8	60013	17.9	60871	18.8
Wood sill	0	0.0	793	0.2	0	0.0	793	0.2
Floors, wood	62471	18.6	62472	19.3	62471	18.6	62472	19.3
Columns, wood	7652	2.3	7916	2.4	7652	2.3	7916	2.4
Carpetting								
Rubber pad	6604	2.0	6604	2.0	6604	2.0	6604	2.0
Carpet	2552	0.8	2552	0.8	2552	0.8	2552	0.8
Elevator Core								
Concrete	51029	15.2	51029	15.7	51029	15.2	51029	15.8
Steel	4437	1.3	4437	1.4	4437	1.3	4437	1.4
Interior Wood doors	1270	0.4	1270	0.4	1270	0.4	1270	0.4
Exterior Steel doors	219	0.1	219	0.1	219	0.1	219	0.1

Table 8.12 – Pre-use phase material quantities for the concrete commercial buildings

COMMERCIAL CONCRETE BUILDING				
Materials	*lbs*	*lbs/ft^2 (gross)*	*kg*	*kg/m^2*
Metals				
Steel Rebar for Columns	253,929	0.5	115,180	2.4
Steel Rebar for Foundation	157,464	0.3	71,424	1.5
Steel Rebar for Deck Slabs	4,385,956	8.6	1,989,436	41.8
Steel Rebar for Retaining	84,240	0.2	38,211	0.8
Steel Rebar for Elevator and	474,240	0.9	215,112	4.5
Steel Rebar for Foundation	136,575	0.3	61,950	1.3
Steel Rebar for Stairs	32,893	0.1	14,920	0.3
Aluminum Window Frames	32,935	0.1	14,939	0.3
Aluminum Studs	15,941	0.0	7,231	0.2
Aluminum Cladding	174,654	0.3	79,222	1.7
Metal Doors	5,161	0.0	2,341	0.0
Cementitious Materials and				
Concrete Columns	2,946,933	5.6	1,336,706	28.1
Concrete Deck Slabs	60,257,860	117.7	27,332,506	574.9
Concrete Foundation Slab	1,810,836	3.5	821,381	17.3
Concrete Retaining Wall	968,760	1.9	439,422	9.2
Concrete Footings	1,570,617	3.1	712,420	15.0
Concrete Elevator and Stair	5,453,760	10.7	2,473,784	52.0
Concrete Stairs	378,268	0.7	171,579	3.6
Asphalt Roofing	58,119	0.1	26,362	0.6
Ballast Roofing	688,905	1.3	312,482	6.6
Gypsum Board	320,479	0.6	145,367	3.1
Insulations				
Extruded Polystyrene	132,822	0.3	60,247	1.3
Glazing				
Window Glass	320,918	0.6	145,566	3.1
Other				
Air/Vapor Barrier	7,032	0.0	3,190	0.1
Paint	21,153	0.0	9,595	0.2
Sand Foundation Layer	656,100	1.3	297,602	6.3
Gravel Foundation Layer	1,377,810	2.7	624,964	13.1

Table 8.13 – Pre-use phase material quantities for the steel commercial buildings

COMMERCIAL STEEL BUILDING				
Materials	*lbs*	*lbs/ft^2 (gross)*	*kg*	*kg/m^2*
Metals				
Steel Columns	1,027,127	2.0	465,897	9.8
Steel Beams and Girders	2,482,532	4.9	1,126,058	23.7
Steel Deck	1,796,369	3.5	814,819	17.1
Steel Rebar for Foundation	157,464	0.3	71,424	1.5
Steel Rebar for Deck Slabs	1,283,126	2.5	582,016	12.2
Steel Rebar for Retaining Wall	84,240	0.2	38,211	0.8
Steel Cores	2,737,140	5.3	1,241,546	26.1
Steel Rebar for Foundation Footings	136,575	0.3	61,950	1.3
Steel Rebar for Stairs	32,893	0.1	14,920	0.3
Steel Base Plates	345	0.0	156	0.0
Steel Connections	328,912	0.6	149,192	3.1
Aluminum Window Frames	32,935	0.1	14,939	0.3
Aluminum Studs	15,941	0.0	7,231	0.2
Aluminum Cladding	174,654	0.3	79,222	1.7
Metal Doors	5,161	0.0	2,341	0.0
Cementitious Materials and Stone				
Concrete Deck Slabs	34,459,157	67.3	15,630,411	328.8
Concrete Foundation Slab	1,810,836	3.5	821,381	17.3
Concrete Retaining Wall	968,760	1.9	439,422	9.2
Concrete Footings	1,570,617	3.1	712,420	15.0
Concrete Stairs	378,268	0.7	171,579	3.6
Asphalt Roofing	58,119	0.1	26,362	0.6
Gravel Ballast Roofing	688,905	1.3	312,482	6.6
Gypsum Board	320,479	0.6	145,367	3.1
Insulation				
Extruded Polystyrene	132,822	0.3	60,247	1.3
Glazing				
Window Glass	320,918	0.6	145,566	3.1
Other				
Fireproofing	1,274,136	2.5	577,938	12.2
Air/Vapor Barrier	7,032	0.0	3,190	0.1
Paint	21,153	0.0	9,595	0.2
Sand Foundation Layer	656,100	1.3	297,602	6.3

8.7 GWP Results

Table 8.14 – GWP Results summary for the single-family houses (IP Units)

		Chicago ICF		Chicago Wood		Phoenix ICF		Phoenix Wood	
	(IP Units)	*lbs CO_2e*	*lbs CO_2e /ft^2*	*lbs CO_2e*	*lbs CO_2e /ft^2*	*lbs CO_2e*	*lbs CO_2e /ft^2*	*lbs CO_2e*	*lbs CO_2e /ft^2*
Pre-Use	Concrete	33,258.5	13.2	18,666.5	7.6	25,251.8	10.0	10,601.2	4.3
	Steel	3,153.0	1.3	1,666.0	0.7	2,724.8	1.1	1,260.2	0.5
	Wood	6,702.5	2.7	9,800.7	4.0	7,878.2	3.1	10,686.0	4.4
	Insulation	12,692.3	5.0	3,610.6	1.5	13,609.2	5.4	3,069.9	1.3
	Other	33,449.8	13.2	33,449.7	13.6	31,309.8	12.4	31,332.0	12.8
Use	Maintenance	81,229.6	32.1	81,297.2	33.0	76,966.6	30.4	76,966.9	31.5
	Operating Energy	1,933,110.3	764.4	2,006,697.6	814.4	1,240,918.9	490.7	1,335,154.4	547.0
E.O.L.	End-of-Life	4,949.8	2.0	2,953.2	1.2	3,360.0	1.3	1,921.8	0.8
	Total	2,110,411.8	833.5	2,158,141.5	875.8	1,402,019.2	554.4	1,470,992.4	602.7

Table 8.15 – GWP Results summary for the single-family houses (SI Units)

		Chicago ICF		Chicago Wood		Phoenix ICF		Phoenix Wood	
	(SI Units)	*kg CO_2e*	*kg CO_2e /m^2*	*kg CO_2e*	*kg CO_2e/m^2*	*kg CO_2e*	*kg CO_2e /m^2*	*kg CO_2e*	*kg CO_2e /m^2*
Pre-Use	Concrete	15,085.8	64.2	8,467.0	37.0	11,454.0	48.7	4,808.6	21.2
	Steel	1,430.2	6.1	755.7	3.3	1,236.0	5.3	571.6	2.5
	Wood	3,040.2	12.9	4,445.5	19.4	3,573.5	15.2	4,847.1	21.4
	Insulation	5,757.1	24.5	1,637.7	7.2	6,173.0	26.3	1,392.5	6.2
	Other	15,172.6	64.6	15,172.6	66.3	14,201.9	60.4	14,212.0	62.7
Use	Maintenance	36,845.2	156.8	36,875.8	161.1	34,911.5	148.6	34,911.6	153.9
	Operating Energy	876,845.1	3,731.9	910,223.8	3,976.1	562,872.0	2,395.6	605,616.6	2,670.9
E.O.L.	End-of-Life	2,245.2	9.6	1,339.5	5.9	1,524.1	6.5	871.7	3.9
	Total	957,266.7	4,074.1	978,917.7	4,276.2	635,946.0	2,706.6	667,231.7	2,942.6

Table 8.16 – GWP Results summary for the multi-family buildings (IP Units)

		Chicago ICF		Chicago Wood		Phoenix ICF		Phoenix Wood	
	(IP Units)	*lbs CO_2e*	*lbs CO_2e /ft^2*	*lbs CO_2e*	*lbs CO_2e /ft^2*	*lbs CO_2e*	*lbs CO_2e /ft^2*	*lbs CO_2e*	*lbs CO_2e /ft^2*
Pre-Use	Concrete	275,448.8	7.6	103,538.4	3.0	262,317.1	7.3	83,185.9	2.4
	Steel	134,343.1	3.7	82,173.6	2.3	122,897.5	3.4	61,283.4	1.8
	Wood	68,370.8	1.9	84,371.4	2.4	88,166.4	2.4	108,280.4	3.1
	Insulation	122,423.6	3.4	35,600.3	1.0	111,205.9	3.1	25,549.4	0.7
	Other	316,604.4	8.8	321,830.7	9.2	319,682.2	8.9	318,392.9	9.2
Use	Maintenance	327,752.6	9.1	338,497.7	9.7	334,444.9	9.3	331,283.2	9.5
	Operating Energy	36,465,073.0	1009.4	36,713,535.0	1047.0	27,292,616.0	755.5	28,010,515.0	805.3
End-of-Life	End-of-Life	38,427.7	1.1	12,915.5	0.4	31,629.0	0.9	6,577.2	0.2
	Total	37,748,444.0	1,044.9	37,692,462.4	1,075.0	28,562,959.0	790.7	28,945,067.4	832.1

Table 8.17 – GWP Results summary for the multi-family buildings (SI Units)

		Chicago ICF		Chicago Wood		Phoenix ICF		Phoenix Wood	
	(SI Units)	*kg CO_2e*	*kg CO_2e /m^2*	*kg CO_2e*	*kg CO_2e /m^2*	*kg CO_2e*	*kg CO_2e /m^2*	*kg CO_2e*	*kg CO_2e/m^2*
Pre-Use	Concrete	124,941.6	37.2	46,964.3	14.4	118,985.2	35.4	37,732.5	11.7
	Steel	60,937.1	18.2	37,273.3	11.4	55,745.4	16.6	27,797.7	8.6
	Wood	31,012.5	9.2	38,270.3	11.8	39,991.6	11.9	49,115.2	15.2
	Insulation	55,530.5	16.6	16,148.0	5.0	50,442.2	15.0	11,589.0	3.6
	Other	143,609.5	42.8	145,980.1	44.8	145,005.6	43.2	144,420.8	44.7
Use	Maintenance	148,666.3	44.3	153,540.2	47.1	151,701.8	45.2	150,267.7	46.5
	Operating Energy	16,540,298.6	4,928.4	16,652,999.2	5,112.0	12,379,737.1	3,688.7	12,705,371.0	3,931.7
End-of-Life	End-of-Life	17,430.5	5.2	5,858.4	1.8	14,346.7	4.3	2,983.4	0.9
	Total	17,122,426.5	5,101.8	17,097,033.7	5,248.4	12,955,955.7	3,860.4	13,129,277.3	4,062.8

Table 8.18 – GWP Results summary for the commercial buildings (IP Units)

		Chicago Concrete		Chicago Steel		Phoenix Concrete		Phoenix Steel	
	(IP Units)	*lbs CO_2e*	*lbs CO_2e /ft^2*	*lbs CO_2e*	*lbs CO_2e /ft^2*	*lbs CO_2e*	*lbs CO_2e /ft^2*	*lbs CO_2e*	*lbs CO_2e /ft^2*
Pre-Use	Concrete	9,642,993	18.8	5,149,220	10.1	9,642,993	18.8	5,149,220	10.1
	Steel	6,886,661	13.5	15,357,093	30.0	6,886,661	13.5	15,357,093	30.0
	Wood	-	-	-		-	-	-	
	Insulation	336,688	0.7	336,688	0.7	336,688	0.7	336,688	0.7
	Other	3,360,394	6.6	3,388,807	6.6	3,526,197	6.9	3,540,232	6.9
Use	Maintenance	3,123,911	6.1	3,123,911	6.1	3,080,263	6.0	3,080,263	6.0
	Operating Energy	491,282,073	960	501,237,267	979	371,340,902	726	379,464,848	741
End-of-Life	End-of-Life	-1,662,376	-3.2	-7,181,333	-14.0	-1,675,895	-3.3	-7,242,077	-14.2
	Total	512,970,343	1002	521,455,744	1019	393,137,810	768	399,686,266	781

Table 8.19 – GWP Results summary for the commercial buildings (SI Units)

		Chicago Concrete		Chicago Steel		Phoenix Concrete		Phoenix Steel	
	(SI Units)	*kg CO_2e*	*kg CO_2e /m^2*	*kg CO_2e*	*kg CO_2e /m^2*	*kg CO_2e*	*kg CO_2e /m^2*	*kg CO_2e*	*kg CO_2e /m^2*
Pre-Use	Concrete	4,373,988	92.0	2,335,647	49.1	4,373,988	92.0	2,335,647	49.1
	Steel	3,123,737	65.7	6,965,860	146.5	3,123,737	65.7	6,965,860	146.5
	Wood	-	-	-	-	-	-	-	-
	Insulation	152,719	3.2	152,719	3.2	152,719	3.2	152,719	3.2
	Other	1,524,249	32.1	1,537,137	32.3	1,599,456	33.6	1,605,822	33.8
Use	Maintenance	1,416,982	29.8	1,416,982	29.8	1,397,184	29.4	1,397,184	29.4
	Operating Energy	222,841,800	4687	227,357,400	4782	168,437,400	3543	172,122,360	3620
End-of-Life	End-of-Life	-754,041	-15.9	-3,257,398	-68.5	-760,173	-16.0	-3,284,951	-69.1
	Total	232,679,434	4894	236,528,347	4975	178,324,311	3751	181,294,641	3813

8.8 Building Energy Consumption

Table 8.20 – Summary of Building Energy Consumption

Building Energy Consumption in kBtu/ft^2 (kWh/m^2)							
		Annual		60 Years		75 Years	
		ICF	Wood	ICF	Wood	ICF	Wood
Single-Family Building	Chicago	46.3 (146)	50.0 (158)	2777 (8759)	2999 (9459)	3471 (10949)	3748 (11824)
	Phoenix	25.0 (78.8)	28.2 (89.1)	1498 (4727)	1694 (5344)	1873 (5909)	2118 (6680)
Multi-Family Building	Chicago	48.6 (153)	51.0 (161)	2917 (9201)	3060 (9653)	3646 (11501)	3825 (12066)
	Phoenix	36.4 (115)	38.8 (122)	2181 (6881)	2325 (7335)	2726 (8601)	2907 (9169)
		Concrete	Steel	Concrete	Steel	Concrete	Steel
Commercial Building	Chicago	37.6 (119)	38.8 (122)	2256 (7115)	2325 (7336)	2819 (8894)	2907 (9170)
	Phoenix	32.5 (102)	33.5 (106)	1949 (6148)	2008 (6336)	2436 (7685)	2510 (7919)