A Comparison of American, Canadian, and European Home Energy Performance in Heating Dominated – Moist Climates Based on Building Codes

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A Thesis Presented

by

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A COMPARISON OF AMERICAN, CANADIAN, AND EUROPEAN HOME ENERGY PERFORMANCE IN HEATING DOMINATED – MOIST CLIMATES BASED ON BUILDING CODES

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ABSTRACT

A COMPARISON OF AMERICAN, CANADIAN, AND EUROPEAN HOME ENERGY PERFORMANCE IN HEATING DOMINATED – MOIST CLIMATES BASED ON BUILDING CODES

FEBRUARY 2014

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This research compares the energy performance of a code-built residential building within the moist climate zone classification in Canada, Europe, and the Northeastern United States. The primary objectives are to reveal how specific differences in code requirements in similar climates influence a building's energy profile, offer a means to quantify and evaluate the extent of energy savings as a result of each requirement, and provide a comparison of each location's building culture and how this affects the standards in place.

Using the building energy simulation tool, *DesignBuilder EnergyPlus Simulation*, a model single-family home was created and input energy code requirements for each location. An evaluation of each location's building culture is examined through such factors as the training of building professionals, commonly used materials and products, energy reduction goals, and cultural attitudes.

The results of this study point to the need for more advanced building

practices, stricter code mandates, and higher performing products based on energy savings achieved from buildings built to different standards in equivalent climate zones. This has the potential to drive the development and use of better performing building materials and assemblies in the future.

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CHAPTER 1

INTRODUCTION

Buildings and Energy

More than 40 percent of the primary energy consumed in the world goes to making and maintaining buildings (International Energy Agency, 2013). This includes both operating energy, i.e. the energy required for space heating and cooling, ventilation, lighting, refrigeration, water heating and other building functions, and energy embodied in the physical structure. These impacts are projected to become more significant as building construction increases. Currently, the United States is the largest consumer of world energy production at 20%, while China and Europe follow with 17% and 16%, respectively (U.S. Department of Energy, 2011b). This is due to the majority of existing U.S. buildings built before modern energy codes and at a time when fossil fuels were readily available and cheap. Consequently, in the U.S., this energy consumption costs accounts for over $500 billion (USD) annually, and represents almost 48% of greenhouse gas emissions (Battles & Burns, 2000). They also consume 12% of the total water supply, produce 65% of total waste, and are responsible for 71% of all the electricity use in the United States (USGBC, 2010). These impacts are becoming increasingly critical in light of national energy security and global climate change. To mitigate these effects, the Intergovernmental Panel on Climate Change (IPCC) projects developed countries will have to lower their emissions to 25-40% below 1990 levels by 2020 and 80-95% below 1990 levels by 2050 (Architecture 2030,

2010). According to the IPCC, the building sector has the greatest potential to reduce current levels of energy use, especially with respect to electricity consumption (Baker, 2007). Consequently, current efforts by builders, engineers and architects to reduce the impact of buildings and to create a more durable and healthy environment for building occupants through advanced building policies are promising. These policies can be grouped into the following categories: "economic incentives (e.g. taxes, energy pricing), informational programs (e.g. energy awareness campaigns, energy audits), or regulatory requirements (e.g. codes or standards)" (Janda, 2009). Furthermore, there has been an increase in voluntary programs such as the US Green Building Council's LEED programs to promote building standards beyond code.

Commercial and residential building codes vary among nations, states, counties, and cities and result in different building standards and practices. A 2009 study to assess the status of *energy* standards for buildings worldwide found that of the 81 countries surveyed 61 had some form of existing mandatory and/or voluntary standard, eleven had proposed standards, and nine had no standards (Janda, 2009). While the number of countries with existing mandatory or voluntary standards may seem encouraging, the reality of buildings constructed according to and enforcement of these standards may vary among each country. Moreover, regions with similar climates and heating degree-days may have stricter energy codes resulting in potentially better energy performance.

Problem Statement and Implications

There are two objectives this research will address. One is to determine how residential building codes at different locations with a similar climate to the northeastern United States (moist climate zone) affect energy performance. The three locations chosen for this research are Boston, Massachusetts, Hamilton, Canada, and Insbruck, Austria. The purpose is to reveal how specific differences in code requirements in similar climates influence a building's energy profile. This will be done through comparing the thermal requirements and system efficiency's of each location's building energy code. Each locations energy code requirements will then be analyzed through whole building simulation to offer a means to quantify and evaluate the extent of energy savings as a result of each requirement.

The second objective is to determine how building culture of each location affects the standards in place. The purpose is to understand the role of building culture on the actual energy performance of buildings. This will include comparing each location's building culture. The building culture may include factors such as the training of building professionals, compliance and enforcement, energy reduction goals, and cultural attitudes.

The findings from this study will offer a comparison of building energy codes for three locations within the same climate classification (heating dominated – cold). This comparison will address how each code requirement impacts the energy profile of each location. In doing so, it will provide a means to quantify the impact of each requirement. These findings can be used by the building industry to gain knowledge of code requirements of buildings in a similar climate to theirs.

Energy code requirements of each location is one useful metric of comparison; however, the building culture of each location plays a large role in the actual energy performance of buildings. This will provide insight into how the energy performance of buildings is affected by the building culture. This research is intended to provide the building industry with additional literature on the impact building culture can have on the actual energy performance of single-family homes with similar climate classifications.

CHAPTER 2

BACKGROUND AND LITERATURE REVIEW

History of U.S. Building Codes

Building codes have been around for thousands of years to set a standard for built structures and safety of occupants. The oldest known building code is found in The Code of Hammurabi (circa 3000 B.C.), the oldest surviving written text from the Old Babylonian period (L.W. King and C. Horne, 2008). The portion of the Code of Hammurabi pertaining to built structures included laws such as:

> 228. If a builder build a house for some one and complete it, he shall give him a fee of two shekels in money for each sar of surface.
> 229. If a builder build a house for some one, and does not construct it properly, and the house which he built fall in and kill its owner, then that builder shall be put to death.
> 230. If it kill the son of the owner the son of that builder shall be put to death.
> 231. If it kill a slave of the owner, then he shall pay slave for slave to the owner of the house.
> 232. If it ruin goods, he shall make compensation for all that has been ruined, and inasmuch as he did not construct properly this house which he built and it fell, he shall re-erect the house from his own means.
> 233. If a builder build a house for some one, even though he has not yet completed it; if then the walls seem toppling, the builder must make the walls solid from his own means (L.W. King, 1998).

While these laws seem harsh compared to modern day building codes, they provided a standard for and metric to evaluate buildings.

In present day, there are two factors to guide builders during construction: building standards and building codes. Building standards are developed through research on how buildings respond to regional weather and geographical hazards

by professional organizations such as the American Society for Testing Materials (ASTM), American Society of Civil Engineering (ASCE), and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). These organizations create standards for materials used in constructing the foundation, walls, roofs, ceilings, doors, and windows for commercial and residential buildings (ASTM, 2011). In addition, they also develop standards on heating, ventilation, air conditioning and refrigeration processes to maintain a safe and comfortable indoor environment (ASHRAE, 2009). These standards are not just guidelines and are not binding until they are written into the building code.

Building codes are written and enforced by regional and/or local authorities; this is the code that must be legally adhered to by anyone erecting a structure within these areas. Often times, the standards developed by professional organizations are written into code and in turn must be followed, if adopted by the local authority.

The United States did not employ a national building code until 1994, when the International Code Council (ICC) was formed to develop a single set of comprehensive national model construction codes (ICC, 2011). Before the ICC was formed, the unofficial beginning of building codes dates back to 1871, when a fire swept through the city of Chicago destroying 60,000 buildings (ICC, 2011). Citizens and officials alike realized better ordinances, regulated building construction, and fire prevention measures were needed to prevent another such occurrence. Another disaster in the building community occurred in 1906 when an earthquake leveled the city of San Francisco. The reaction from the scientific

community was to create codes and standards for buildings to withstand an earthquake event and establish a measure to be evaluated after such an event. This was primarily for areas in the western U.S. prone to earthquakes.

In the years that followed, three separate organizations were formed between 1915 and 1940, which each developed their own set of model building codes for a specific region in the U.S. The first organization was the Building Officials and Code Administration (BOCA), mainly used in the Northeast. BOCA developed the National Building Code (NBC), but it was not released in its entirety until 1950. In 1927 the International Council of Building Officials (ICBO), which was mainly used in the West, formed and released its own model code, the Uniform Building Code (UBC). The Southern Building Code Congress International (SBCCI) was formed in 1940, and was mainly used in the South to establish the Standard Building Code (SBC) in 1945 (Jain & Leiva, 2010).

While a model building code existed in regions of the South, East, and West, there still remained no single comprehensive and coordinated national model construction code for the entire U.S (ICC, 2011). In 1994 the three organizations (BOCA, ICBO, SBCCI) united to create the non-profit International Code Council (ICC). The intent was to create a nationwide code that represented the minimum standard for building construction. To date, all fifty states have adopted the ICC's International Building Code (IBC) at the state or local level, although each state or local jurisdiction may include additional region-specific amendments. The ICC publishes a variety of other international codes applicable to any region in the U.S.,

which include the International Residential, Fire, Energy, Plumbing, Fuel Gas, and Mechanical codes.

U.S. Energy Codes and Standards

Building energy codes are incorporated into state and local building codes to set a minimum standard for energy efficiency in a building. The level of stringency of energy codes differs from state-to-state and even local jurisdictions, due to amendments to the adopted energy code. Nationwide, there are two base building energy codes and standards for residential construction that have been adopted by the states – *the International Energy Conservation Code (IECC),* and the *ANSI/ASHRAE/IESNA Standard 90.2-2007 Energy Efficient Design of New Low-Rise Residential Buildings*. The 2012 IECC is the latest version of the IECC, which is governed by the International Code Council (ICC). It is also considered a Model Energy Code (MEC), which modifies requirements based on climate zones. Standard 90.2-2007, on the other hand, is developed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) and approved by the American National Standards Institute (ANSI), a national standard and consensus assessment system (ANSI, 2011).

States are not required to adopt an energy code. In fact, there are several states that have never adopted an energy code and several others that have adopted an energy code, but do not follow the latest version of the IECC or ASHRAE 90.2. The most current status of energy code adoption by state is shown in Figure 1.

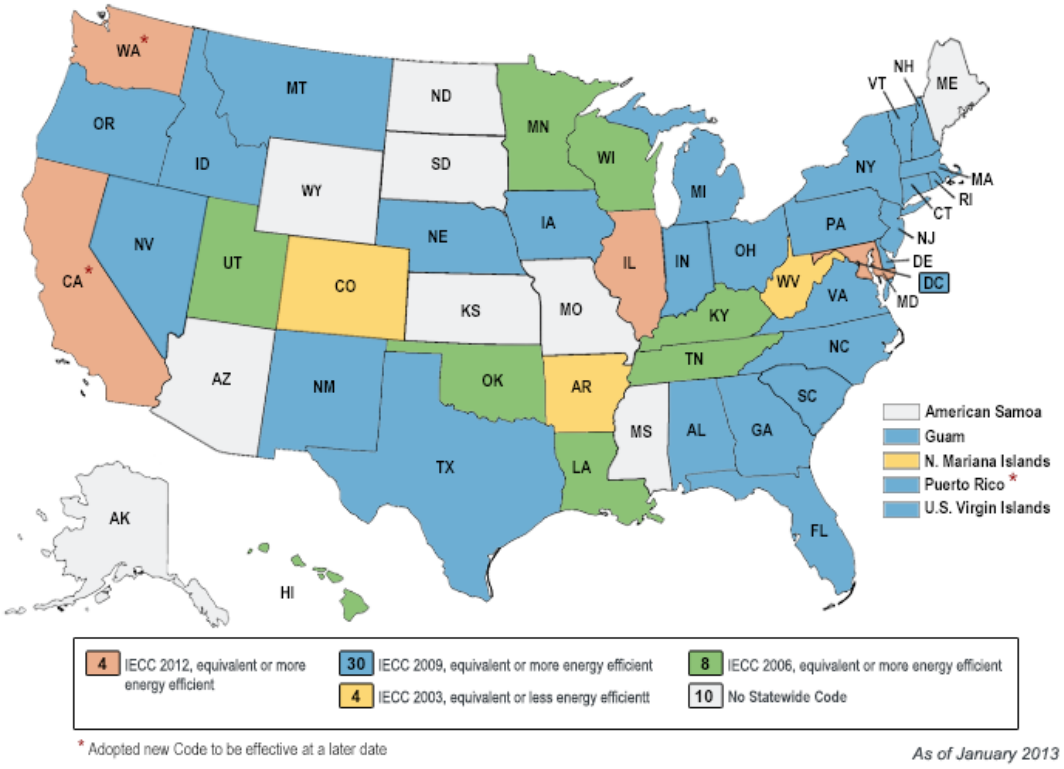

Figure 1: Status of Residential Energy Code Adoption (U.S. Department of Energy, 2012)

The more progressive states that have adopted the 2009 IECC equivalent or more stringent codes, may have also adopted a stretch code or a "beyond code" program. All of these programs, which are also referred to as green building programs or codes, stretch codes, above code programs, and beyond code programs, have one thing in common: they use the IECC and/or ASHRAE 90.1 as a baseline, with additional requirements included (U.S. Department of Energy, 2011f). The additional requirements are all aimed towards the common goal of creating a more energy efficient building that performs better than code. Furthermore, each program ranges in scope – from achieving 10% above the current energy code or standard, to requiring a building meet the standards set by a green building

program such as U.S. Green Building Council's Leadership in Energy and Environmental Design (LEED). According to the U.S. Department of Energy, as of August 2009 there were over 300 such programs adopted by states and local jurisdictions in the U.S. (U.S. Department of Energy, 2011f).

Code Compliance Paths

There are generally three ways to verify compliance of building codes and energy codes for a residential building. These include prescriptive, component performance, and computer modeling (U.S. Department of Energy, 2011e). Prescriptive forms are typically simple forms with a list of requirements for a particular climate zone noting specifics such as required R-factors (resistance to heat flow), equipment efficiencies, window and doors, etc. Component performance paths allow for trade-offs between component features. A software program is generally used and a report is generated verifying compliance. The third method of verifying compliance, computer modeling, has been gaining momentum in recent years. This is a more comprehensive method to verify code compliance and uses a computational building simulation package to predict the overall performance of a building based on inputs for occupant use, materials, and systems. Modeling performance tools can range in form from simple outputs of total calculated U-values to highly sophisticated models performing a range of functions.

Literature Review

Energy use in buildings has been an area of great interest to researchers in the United States since the early 1970s, beginning with the oil embargo of 1973 when the price of oil dramatically increased. With increasing energy consumption worldwide and limited energy supplies, there is a need for continued research on reducing building energy consumption and developing accurate measures for predicting performance in buildings. While this study focuses on residential energy performance in single-family residences, most of the existing literature on energy performance focuses on commercial buildings, which is included in the present review. The literature reviewed for this thesis topic includes relevant studies discussing simulation tools used for energy performance in buildings and energy simulation studies of residential and commercial buildings.

Commercially, there are approximately 395 building software tools used to evaluate energy performance, renewable energy, and sustainability of a building (U.S. Department of Energy, 2010). Mwasha et al. outlines the importance of using building assessment methods reflecting the climate, socio-economic, and political dimensions of a country or region (Mwasha, Williams, & Iwaro, 2011). Thus, the implication is that a building professional should choose a simulation tool that best reflects the unique characteristics of their region. While a tool that includes all of these characteristics does not exist currently, there are a variety of tools available that provides both energy code compliance and predicted performance beyond code measures. *EnergyPlus* is the most widely used simulation engine of present time and used worldwide. For the purposes of this study the graphical interface of

DesignBuilder is coupled with *EnergyPlus*. Studies using the two programs are the focal point of the present review.

EnergyPlus

The U.S. Department of Energy (DOE) sponsors several whole building simulation tools including *EnergyPlus, DOE-2, Building Design Advisor, Energy-10,* and *SPARK* to verify energy code compliance and beyond code goals. The DOE's most widely used and robust tool, *EnergyPlus*, is the platform for modeling analysis in this research.

EnergyPlus was developed by the DOE in 1996 for architects, builders, engineers, and researchers to model the performance of a building (U.S. Department of Energy, 2010). It provides energy analysis and thermal load simulations to determine and modify a building's energy performance. The outputs of *EnergyPlus* simulations are intended to aide in the design and calibration of real systems operating in a building (Kiliccote, Piette, & Watson, 2006). *EnergyPlus* models heating, cooling, lighting, ventilation, and other energy flows before construction of a building begins (U.S. Department of Energy, 2011a). It is widely used for simulating residential and commercial buildings worldwide. In addition, it has been validated using the Building Energy Simulation Tests (BESTEST) developed by the DOE's National Renewable Energy Laboratory (NREL), the International Energy Agency Solar Cooling and Heating Programme Implementing Agreement (IEA SHC) and ASHRAE. BESTEST was developed to create a standard

method of testing the validity of computer software designed to provide building energy analysis (U.S. Department of Energy, 2011c).

There have been a variety of case studies, research papers, and reports utilizing the *EnergyPlus* software as a stand-alone tool or in conjunction with a variety of graphical interfaces for both residential and commercial buildings. These studies range in scope from simulating the energy performance of different glazing systems to understanding the energy and cost benefit of renewable energy sources. In a 2010 study on creating a positive-net-energy residential building in Serbian conditions, researchers modeled a multi-family residence to predict yearly operation of a low and solar energy house (Bojić, 2011). The study used one building model with three scenarios of PV arrays to determine the daily energy distribution for each model. The *EnergyPlus* software allowed for accurate calculations due to the detailed weather files used to run simulations giving outputs of monthly and yearly energy demand of the building systems.

Other studies using *EnergyPlus* demonstrate the effects of window glazing, overhangs, and solar shades on building energy performance. In an Iranian residential study of advanced glazing and overhangs, *EnergyPlus* was used to help select the optimal window with different glazing, overhangs and side fins (Ebrahimpour & Maerefat, 2011). In a related study researchers used *EnergyPlus* to simulate the thermal and visual efficiency of solar shades in an office building. The resulting outputs illustrate the balance between providing natural day lighting and limiting solar gains in order to minimize both the cooling and lighting demands (David, Donn, Garde, & Lenoir, 2011). Furthermore, *EnergyPlus*' annual

meteorological files can be used to generate hourly maps of luminance to determine the levels of natural day lighting based on the placement of solar shades.

In a comprehensive whole building study conducted in Raleigh, North Carolina of a new 40,000 ft^2 Whole Foods grocery store *EnergyPlus* was used to predict the amount of energy savings from three design standards: prescriptive specifications of ASHRAE Standard 90.1-2004, Whole Foods Market's New Store Standards, and energy efficiency measures (EEMs) suggested by the National Renewable Energy Laboratory (NREL). The *EnergyPlus* outputs indicate that the model with EEMs proposed by the NREL resulted in the lowest energy use intensity (EUI) of 208 $kBtu/ft^2$ and the largest percentage (41%) of savings over Standard 90.1-2004 (EUI 350 $kBtu/ft^2$) (Deru et al., 2011). The Whole Foods New Store Standards model resulted in an EUI of 294 $kBtu/ft^2$, a 16% savings over 90.1-2004.

While *EnergyPlus* is capable of presenting energy analysis as a stand-alone tool, when it is combined with a user interface, the graphical outputs can add significantly to the interpretation of the energy performance of a modeled building. The primary outputs of *EnergyPlus* are text-based and do not include a graphical interface. Therefore, *EnergyPlus* is most "user friendly" when paired with a user interface to help create input files, support computer-aided design files, and output easy-to-interpret tables and graphs. Using a graphic interface with EnergyPlus has many other user defined work flow benefits such as: fewer manual inputs, clearly defined building tree of inputs, building system schematics, visual

zone control, pre loaded schedules, templates, and building codes/standards, and user defined reporting.

DesignBuilder EnergyPlus Simulation

DesignBuilder interfaces with the solution engine of *EnergyPlus* to create a more user-friendly simulation tool. In addition to detailed weather data, databases of building materials, wall, floor and roof system components, windowpanes, gases, glazing, and blinds, and detailed HVAC modeling are combined to create an all-encompassing whole-building simulation tool. *DesignBuilder* (version 2.1.0) has been validated through the ANSI/ASHRAE Standard140-2007: Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs, an updated standard test paralleling the original BESTEST methods. The following studies illustrate the utility of *DesignBuilder* (DB) with *EnergyPlus*.

In a 2011 Australian study on thermal energy storage (TES), a demand-side management technology, DB was used to simulate the existing cooling systems (Rahman, Rasul, & Khan, 2011). Due to the subtropical climate of the Central Queensland area, cooling demand is the largest consumer of electricity by buildings. The TES system technology shifts the cooling load demand from peak hour to off-peak hour, resulting in energy storage and electricity savings. The cooling system simulated in DB was verified with real-time on-site measured data from smart metering devices to calculate monthly and yearly electricity use. The DB simulation was within nine percent (9%) of the measured data, which is within engineering error (Rahman, Rasul, & Khan, 2011).

DesignBuilder has also been employed to simulate the monthly and annual cooling load for a lecture theatre in the northern region of India using a variety of energy efficient measures (EEMs) (Kulkarni, Sahoo, & Mishra, 2011). The EEMs tested in DB included installation of a false ceiling, wall insulation, variety of glazing types, and installation of compact fluorescent lighting fixtures. It was found that by installing the various EEMs the annual savings would range from 17% to 19.8% and have an eight-year payback period (Kulkarni, Sahoo, & Mishra, 2011).

A recent study conducted at Harvard University of Gund Hall, the home to Harvard's Graduate School of Design, used DB as both an educational and energy simulation tool for students. The study served two purposes: the first was to demonstrate the capability of novice simulators using the DB tool and the second was to quantify the benefits of using custom versus default inputs in simulating an existing building. The study found that design students were able to successfully model a large, complex building with minimal input from modeling specialists. Overall the study concluded that using graphical interfaces such as DB, students are able create meaningful and easily interpret results from the energy models. It was found that by entering customized internal load schedules versus default schedules the relative error between predicted and real-time data was reduced from 18% to 0.2% (Wasilowski & Reinhart, 2009). The results of this study indicate that simulation tools are a valuable way to predict the energy load in a building. However, customized or specific occupant schedules most accurately reflect the demand of building systems.

Climate Zone Specific Energy Simulation Studies

The present study will build on existing studies related to energy performance in varied climate zones. Eskin et al. (Eskin & Türkmen, 2008) analyzed the performance of an existing office building in Istanbul, Turkey to measure its performance if located in Turkey's four major climate zones. The approach was to first validate the simulation model by comparing hourly building consumption data to the *EnergyPlus* simulation. It was found that the building's actual performance was within 5% of the simulated cooling load and 3% of the heating load. Once the model was validated, the building was then simulated using weather data for each location. The purpose was to determine how the energy demands of the building changed with respect to the different climates and control strategies. The results of this study were intended to help architects, building managers, and HVAC professionals understand the effect of different climates on a building and suggest strategies to improve performance. Another study by Jie and Sheng-xia modeled four external shading devices in *EnergyPlus* to determine the effects on yearly air-conditioning, heating, lighting and total energy consumed (Jie & Sheng-xia, 2011). The building, located in China, was modeled in four cities, each representing a different climate zone. This study allowed researchers to explore the effectiveness of external shading devices in different climate zones, allowing them to provide recommendations to the building community on proper placement, angles, and location of shading device based on specific climate conditions.

In a related study by Cornick et al., simulations of proposed high-performance residential wall systems in seven locations of the Canadian Arctic were analyzed (Cornick, Rousseau, & Parekh, June 2009). The study locations represented a range of heating degree-days (HDD) from 8,256 HDD65°F to 12,526 HDD65F (4,587 KD18 to 6,950 KD18). Four high performance wall designs were simulated against two standard (low altitude and typical arctic) wall assemblies using the HOT2000 v10.31 simulation tool. While this study modeled the change in space heating consumption due to each assembly's conductive heat flux, it did not take into account window-to-wall area, convective flow, or air leakage.

Al-Homoud (Al-Homoud, 1997) investigated optimum thermal design parameters for small - 1,524 m^2 (5,000 ft^2), medium - 15,453 m^2 (50,700 ft^2), and large - 42,672 m^2 (140,000 ft^2) office buildings in different climate regions within the United States and Saudi Arabian cities. The results indicate that building envelope design are critical for cold climates.

While the aforementioned studies represent an important contribution to the building simulation and modeling industry, the emphasis on research in commercial buildings remains dominant. More analyses of residential buildings are needed. This study aims to add to the research in two significant ways. Firstly, it will contribute new knowledge about the performance of code built single-family residences in similar climate zones. And, secondly, it will demonstrate the benefit in using simulation tools such as *DesignBuilder EnergyPlus* Simulation to accurately predict energy use.

CHAPTER 3

FRAMING THE BUILDING SCENE

Construction materials and practices vary depending on global location, climate zone, and economic and social circumstances. This section outlines significant historical events that have influenced construction practices in each of the three focus regions for this research: Northeastern United States, Ontario Canada, and Central Europe. These events combined with social influences, and advances in materials and practices are attributed to shaping the current landscape of single-family construction in each region.

At present, the design and construction of a building is seen as a science, integrating different professions, construction methods, and energy consumption patterns. This awareness of building as a science has not always been the case. In fact, architects and engineers did not recognize the contributions of the other's profession until The Foundation of the Institution of Civil Engineers and the Royal Institute of British Architects in London recognized the distinctions of engineer and architect within the other in 1818 and 1834, respectively (Cowan, 1978). Before the marriage of the two professions, the historical definition of an engineer was a military engineer working on engines (National Research Council, 1986); whereas, architects were looked to for designing monumental buildings (Cowan, 1978). These definitions have evolved over time to encompass more than one focus and overlap.

Understanding the relationship between architects and engineers helps to illustrate how and why buildings have evolved over time from a bare bones

structure only designed to protect people from the elements, to the more advanced and increasingly more energy efficient homes in which we live today. The next sections highlight the evolution of the single-family residence in the last century and a half. During this time period homes evolved in relation to the changing demands to engineering and architectural practices and their continual overlap. In addition, significant historical events shaping the use of common materials and construction strategies frame the current residential landscape of each region.

United States

Residential building practices in Heating dominated climate zones five and six (2009 IECC classification) are the primary focus of this section. These climate zones have the largest populations and a rich building history dating back to colonial times. While other regions of the world have experienced a long history of building and rebuilding due to the shifts and slippages of culture and conflict, the United States building scene has been shaped by the development of city infrastructure and the increased awareness of building structures that are safe and stable for living, working and entertaining.

Historical Characteristics

Homes in the U.S. are primarily built using wood construction methods. Timber framing, also called post and beam, required skilled labors to join heavy timber; no nails or adhesives were used. This method was traditionally used until the invention of balloon framing in 1832. Invented by George Washington Snow, balloon framing revolutionized wood frame construction (Cowan, 1978). The first

building constructed using this technique was Chicago's St. Mary's church in 1833 (Sprague, 1981). Balloon framing (Figure 2) caught on widely in the U.S. during the second quarter of the nineteenth century; the construction was easy for even unskilled labor to execute (Sprague, 1981). In addition, the U.S. had an abundance of forests to supply the lumber for several booms in single-family home construction.

The onset of balloon framing took the U.S. construction focus away from the traditional European masonry and cut stone techniques (Lienhard, 1997). It transitioned the building industry from "heavy" to "light" framed construction with smaller dimensional lumber. The name "balloon" was coined due to the lightness of materials and structure over the traditional timber framed homes.

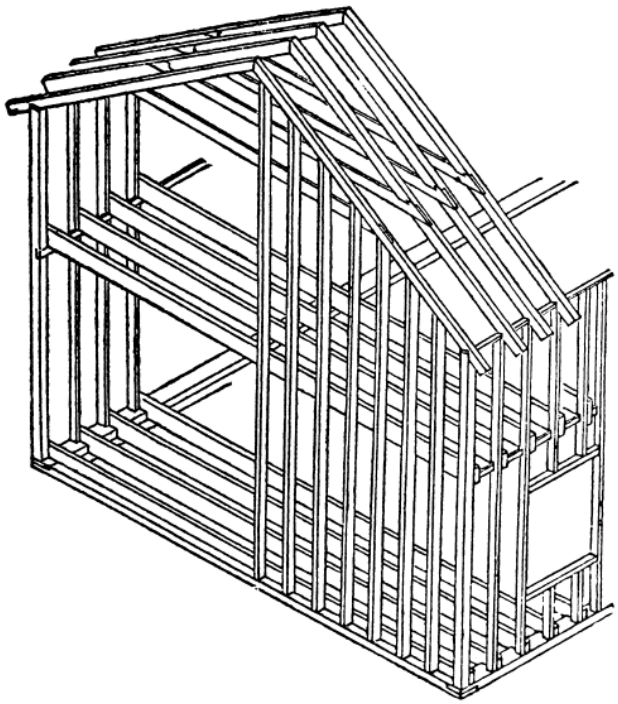

Figure 2. Balloon Framing (Sprague, 1981)

Balloon framed homes use a design that extends dimensional lumber, 2x4 or 2x6 studs, from the sill plate to the top plate of the wall, providing support to the roof and all floors. The lumber is continuous from one level to the next, creating open wall shafts or cavities. This method of framing required nails to hold the studs together and marked the beginning of manufactured nails (Cavanagh, 1984). The drawback of this type of framing was the heightened risk of fires spreading quickly because there were no fire stops in the construction. In addition, appropriate insulating materials had not been introduced into the construction industry in the mid-1830s. Therefore, a home had less wooden materials for the frame, but lacked thermal insulation.

In 1910 fiberboard was widely used for insulation, sheathing and interior décor (Jester, 1995). This was followed by the use of particle- and hard- board making its way on to the building scene in the 1930s and widely used by the 1950s (Cowan, 1978). In the early first half of the 1900s the United States was experiencing growth in population, new city infrastructures were being built, and indoor piping, electrical, and advances in heating and air conditioning were invented. Before boilers and radiators were used to heat homes, the open fireplace was the primary heating source for most homes. The open fireplace was used for cooking, boiling water for washing clothes and cleaning, and providing the space heating needs for the home. In more wealthy residences, a cast iron collection of chimneys (Figure 3) distributed hot air throughout the home from one fireplace on the lowest level.

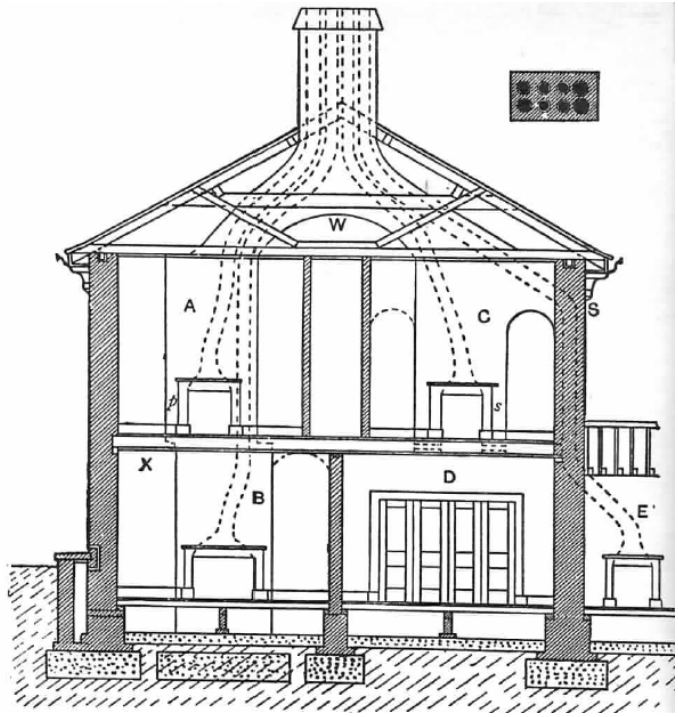

Figure 3. Collection of cast iron chimney flues into central stack, (Cowan, 1978)

As cities grew, fireplaces contributed to increased air pollution and poor air quality resulting in health and safety risks. The solution was to heat homes using boilers that supplied hot water or steam to a network of radiators throughout the house. At the early onset of boilers, they were fueled by coal, followed by oil, and most commonly used in present day, natural gas. This advancement created new infrastructure that architects had to now design around and was met with great resistance (Brucemann & Prowler, 1977). There was also the need for ventilation due to the combustible fuel sources and houses becoming tighter than previously before. In addition, the new advances in heating presented the need to provide greater thermal insulation in the buildings envelope to prevent pipes from bursting in cold climates.

Thermal insulation products were not widely used until the 1940s when they gained attention for saving energy (Cowan, 1978). The first U.S. insulation company was Owens Illinois Glass Co. and Corning Glass, today known as Owens Corning, who developed the first insulating glass wool. The 1940s was a decade of prosperity, growth, and changes in social mindset precipitated by the end of the Second Great War. With these economic and social changes came innovations in technology and design not only in the building industry, but in the automotive and transportation industries as well. With new roads, rail, and other methods of transportation, supplies of all kinds could make their way from state to state and even coast to coast faster than before. Manufacturing large quantities of materials became more economical and created a competitive market for building products. Universities and labs all over the world began to take note of thermal performance in buildings and its effect on energy savings. And government agencies were starting to recognize and devote research dollars to studies on thermal insulation and energy conservation.

By 1940 there were four primary types of insulating materials on the market: rigid or semi-rigid board, fill, blanket or batt, and reflective (Dowling, 2009). Each had different characteristics suited for installation in different places throughout a structure. These products were the dominant insulating materials until more government funding went into national labs in the 1970s during the oil crisis. Since the 1970s materials used to construct and insulate the US housing stock have increased both in number of products available and application. This

can mainly be attributed to stricter energy codes requiring higher levels of thermal insulation to decrease energy consumption.

Present Day Characteristics

The U.S. Census Bureau reports new single-family homes in 2011 consisted of the following characteristics (U.S. Department of Commerce, June 28, 2012)

2011 New Construction Single-family Home Characteristics	
Size	• 739 m^2 (2,392 ft^2) • 54% had 2+ stories
Bedrooms	• 48% - 3 bedrooms • 39% - 4 bedrooms
HVAC	• 88% had AC • 56% used warm-air furnace as primary heating system (Fuel Source: 88% gas, 11% electricity, 1% oil)
Exterior Wall Material	36% Vinyl siding
Foundation Type	• 53% had slab or other type of foundation • 30% had full or partial basement • 17% had crawl spaces
Average Price	$267,900

Light-frame construction has been the typical construction method for homes in the United States since the 1950s. Wood and brick are the most common building materials; 86% of all buildings built are wood framed and most are residential (Jester, 1995). Today, framing techniques have evolved from balloon framing to advanced (platform) framing, which uses even less lumber. Less lumber means that there are more (or larger) wall cavities that can be filled with insulation material thus increasing overall thermal performance. Advanced framing (Figure 4) techniques include wall studs, floor joists and roof rafters

spaced 24 inches on-center. The framing also eliminates headers in non-load-bearing walls, and is done so that the floor, wall and roof members are vertically aligned with each other, resulting in greater structural efficiency (National Renewable Energy Laboratory, 2000). This technique – also known as optimum value engineering (OVE) – was developed by the National Association of Home Builders (NAHB) Research Center in the 1970s to minimize material usage while still maintaining the structure's integrity (The Engineered Wood Association, 2012). Even though these advanced engineering strategies were developed in the 1970s, builders did not start implementing them until the late 1990s. This shift to advanced framing can be attributed to more stringent energy codes requiring builders to use more sophisticated and energy conserving technologies and materials. Because this technique saves materials and increases the overall effective thermal resistance (R-value) of a structure, it helps builders reduce cost while constructing a more resource efficient home. In general, the technique gives the entire structure an effective R-value that is 30% higher than balloon framing, resulting in fewer voids in insulation (U.S. Department of Energy, 2011d).

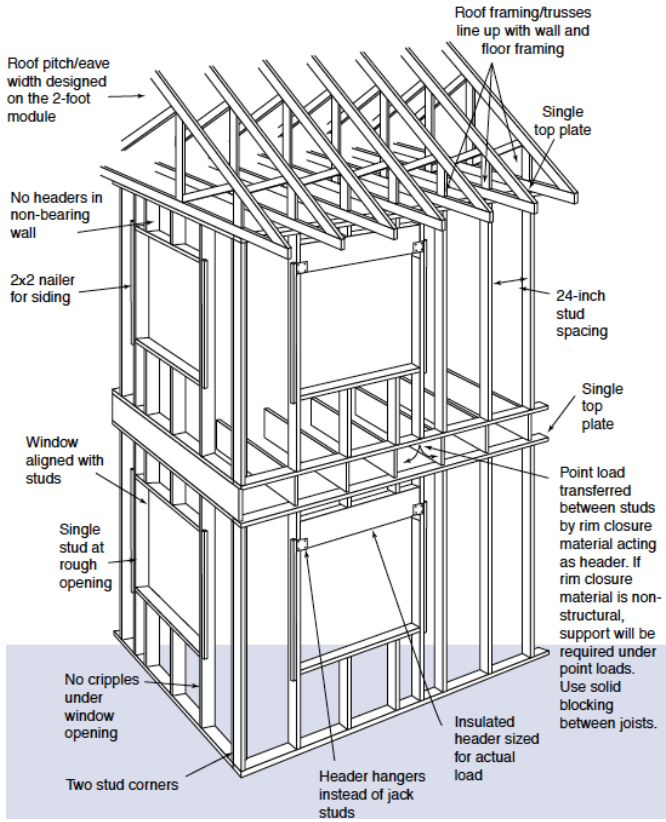

Figure 4. Advanced Framing, (Lstiburek, 2010)

With the introduction of advanced framing, more advanced insulating materials were introduced to the market. There are a variety of insulation types available today; however, only the most commonly used materials will be discussed here. Table 1 shows nine types of insulation, from the original fiberglass batts to advanced structurally insulated panels (SIPs).

Form	Insulation Materials	Where Applicable	Installation Method(s)	Advantages
Blanket: batt and rolls	Fiberglass Mineral (rock or slag) Plastic fibers Natural fibers	Unfinished walls, including foundation walls, and Floors and ceilings	Fitted between studs, joists, and beams	Do-it-yourself. Suited for standard stud and joist spacing, which is relatively free from obstructions.
Concret block insulation	Foam beads or liquid foam: -Polystyrene -Polyisocyanurate or polyiso -Polyurethane Vermiculite or perlite pellets	Unfinished walls, including foundation walls, for new construction and major renovations	Involves masonry skills	Autoclaved aerated concrete and autoclaved cellular concrete masonry units have 10 times the insulating value of conventional concrete.
Foam board or rigid foam	Polystyrene Polyisocyanurate or polyiso Polyurethane	Unfinished walls, including foundation walls; floors and ceilings; unvented low-slope roofs.	Interior applications: must be covered with 1/2-inch gypsum board or other building-code approved material for fire safety. Exterior applications: must be covered with weatherproof facing.	High insulating value for relatively little thickness. Can block thermal short circuits when installed continuously over frames or joists.
Insulating concrete forms (ICFs)	Foam boards or foam blocks	Unfinished walls, including foundation walls, for new construction	Installed as part of the building structure	Insulation is literally built into the home's walls, creating high thermal resistance.
Loose-fill	Cellulose Fiberglass Mineral (rock or slag) Wool	Enclosed existing wall or open new wall cavities; unfinished attic floors; hard-to-reach places.	Blown into place using special equipment; sometimes poured in.	Good for adding insulation to existing finished areas, irregularly shaped areas, and around obstructions.
Reflective System	Foil-faced kraft paper, plastic film, polyethylene bubbles, or cardboard	Unfinished walls, including foundation walls, and Floors and ceilings	Foils, films, or papers: fitted between wood-frame studs, joists, and beams	Do-it-yourself All suitable for framing at standard spacing. Bubble-form suitable if framing is irregular or if obstructions are present. Most effective at preventing downward heat flow; however, effectiveness depends on spacing.
Rigid fibrous or fiber insulation	Fiberglass Mineral (rock or slag) Wool	Ducts in unconditioned spaces and other places requiring insulation that can withstand high temperatures.	HVAC contractors fabricate the insulation into ducts either at their shops or at the job sites.	Can withstand high temperatures.
Sprayed foam and foamed-in-place	Cementitious Phenolic Polyisocyanurate Polyurethane	Enclosed existing wall or open new wall cavities; unfinished attic floors	Applied using small spray containers or in larger quantities as a pressure sprayed (foamed-in-place) product.	Good for adding insulation to existing finished areas, irregularly shaped areas, and around obstructions.
Structural insulated panels (SIPs)	foam board or liquid foam insulation core, Straw core insulation	Unfinished walls, ceilings, floors, and roofs for new construction	Builders connect them together to construct a house.	SIP-built houses provide superior and uniform insulation compared to more traditional construction methods; they also take less time to build.

Table 1. Types of Insulation, (U.S. Department of Energy, 2011d)

There have been considerable advances in insulating materials since the 1950s and product development continues to evolve as the building industry and homeowners face increasing energy prices. Currently, building codes require minimum R-values for different applications in a home depending on the climate zone and type of HVAC system. This includes, but is not limited to exterior walls, slab, foundation, floors, roof, ceiling, and HVAC ducting in unconditioned spaces. In addition to minimum insulation levels, minimum air sealing and ventilation requirements are specified in the current building codes. Air sealing helps to improve the energy efficiency, thermal comfort, and protect building materials from air and moisture damage. Due to the increased air tightness from insulation and air sealing requirements, ventilation in the home protects building materials and occupants from moisture introduced into the home by occupant behavior (i.e. showering, cooking, etc.) and other external environmental conditions. Mechanical ventilation has become increasingly more important as the building envelope is designed and constructed to be tighter and more efficient. This is not only for the integrity of the building materials, but also the health and safety of the occupants. Along with ventilation standards, there have been significant technological innovations in residential heating and cooling equipment.

Heating and cooling has evolved from open fireplaces in the early 1900s to mechanical systems used to keep the entire home comfortable in any climate. Mechanical system operations account for approximately 56% of the entire energy use in a typical U.S. home (U.S. Department of Energy, 2011d). Coupling an efficient heating and cooling system with energy efficient construction has the potential to

reduce overall energy demand. The majority of homes in the U.S. are heated with a furnace or boiler; however, there are a wide variety of other techniques and technologies used to heat a home. These include wood and pellet-fueled sources, electric resistance, active solar, radiant, small space heating sources, and heat pumps. Each system has particular advantages and disadvantages for different climate zones. For example, a heat pump is ideal for climates with moderate heating and cooling needs and would not be well suited for the cold-moist climate of Northeastern United States.

While the Northeastern U.S. is a heating dominated climate, it also experiences hot and humid summers requiring air conditioning in many homes. Unlike the variety of heating technologies commonly seen on the market, air conditioning typically involves either a small room air-conditioner or a central system. Central systems can either be split or packaged unit types. Air conditioners in cold-moist climates such as the Northeast are typically employed to dehumidify a home and make it more comfortable for its occupants.

The combination of framing and insulating materials and HVAC equipment discussed in this section are not considered separately (i.e. several components operating individually), but rather belonging to a single system, which is the whole building. The whole-building systems approach considers the interaction of each building feature and specific climates. This concept of building a home as one integral system enables architects, engineers, and builders design and construct more efficient structures.

Canada

Canada spans four climate zones that are based on annual averaged heating degree-days (HDD) ranging from 3500 to 8000 HDD based on an 18 degree Celsius threshold (Natural Resources Canada, 2011). Similar to the building history of the United States, this section focuses on one particular climate zone within the same HDD thermal band as Boston, Massachusetts. The region is the southern-most province of Quebec near Toronto. The majority of historical and present day information on housing is primarily derived from buildings located in cities and urban areas. This is because most of Canada's population is located near major cities such as Vancouver, Toronto, Montreal, and Winnipeg. Regulations in building construction are therefore focused on urban areas. The two primary drivers shaping Canadian building culture before the 1900s and what ultimately led to the formation of a national building code were fire and disease (Archer, 2003). The history of buildings in major Canadian cities, events leading to the formation of building codes, and present day building practices are discussed in this section.

Historical Characteristics

Due to Canada's geography and economic history, homes have been predominately built of wood and have seen architectural influences from the French, British, and U.S. (Humphreys & Sykes, 1980). European settlers brought their tradition of timber building to Canada. Some of Canada's first European

settlers were the French, who had a long history of building timber structures, these techniques included heavy timber framing, vertical wood members planted in the ground, and horizontal wood members dove-tailed at the corners (Richardson, 1973). Similar to the U.S., Canada also has a long history of heavy timber framing (Figure 5).

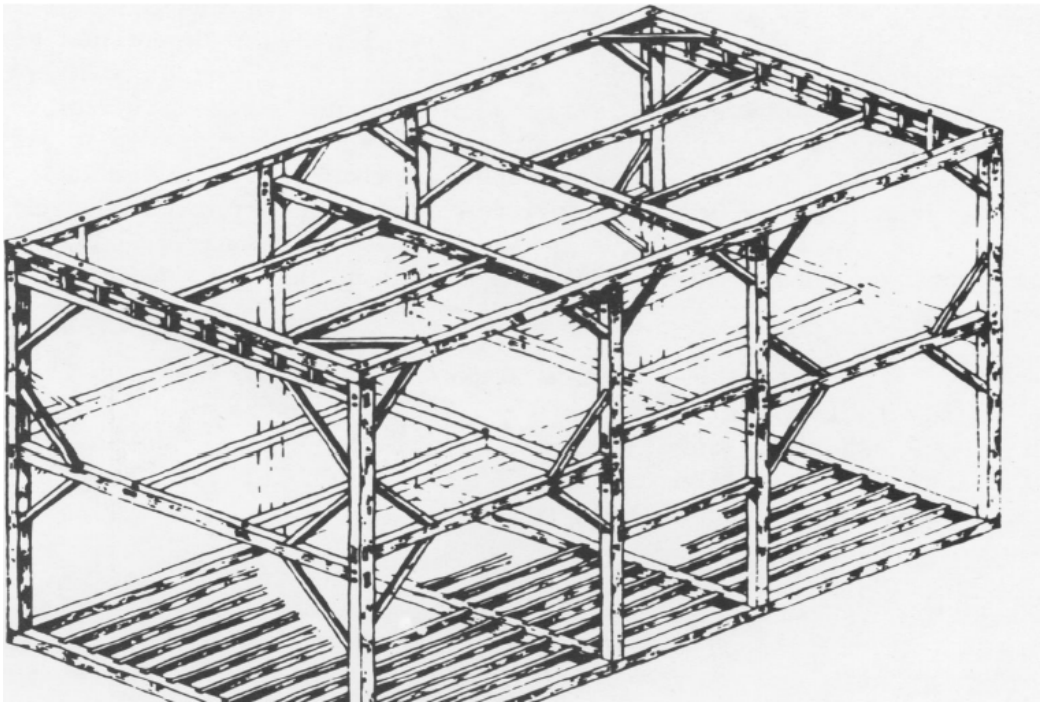

Figure 5. Fisher House, 1836, Toronto, Ontario (Rempel, 1969)

Heavy timber framing dates back to the 1800s with a variety of methods used to assemble the floor, load bearing features, and corner post connections. There were considerable advances in timber framing from the eighteenth to nineteenth centuries (Rempel, 1969). The main advancement was the strategic placement of bracings throughout the structure, resulting in using less bracing, but still maintaining structural integrity.

Each technique has several variations; for instance, vertical timber framing consisted of round logs or planks set on edge spaced anywhere from eight feet to less than a foot. Many times horizontal members were used as reinforcements that were either tenoned or fitted in-between the vertical members. There were several types of materials used to fill the walls to finish the construction. These included clay, straw, brick, masonry stone (Figure 6), or even rubble (Richardson, 1973). While these materials were easy to obtain, they did not form an airtight building with good thermal comfort. Vertical framing was the most widely used method of constructing homes during the 18th and 19th centuries.

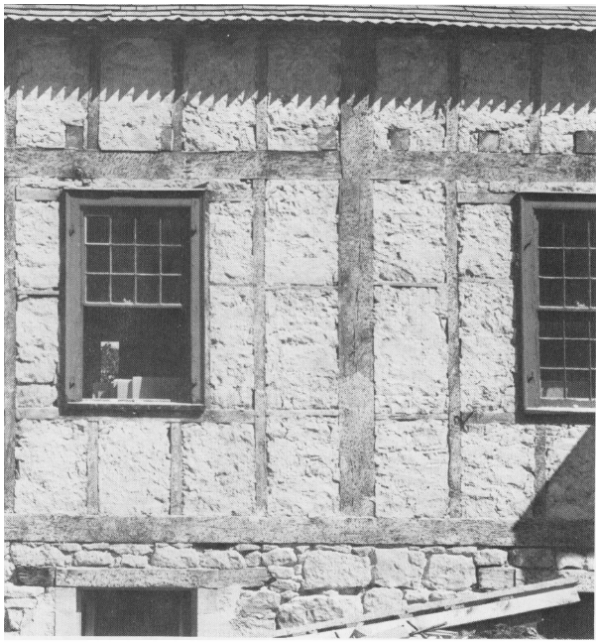

Figure 6. Stone masonry fill, (Richardson, 1973)

The third historical timber framing technique used in Canada- horizontal framing- is the least documented and was not broadly used. Historical documents identify that these buildings were either logs fitted into a frame or the timber was dovetailed at the corners. Dovetailing is considered to be the most common

technique to fit timber members together in Canada (Richardson, 1973). Not much else is known about the horizontal technique other than stone and rubble were used as fill between the planks or logs.

In many parts of Canada the adoption of lightwood framing methods has been the dominant type of framing since the late 1800s. With lightwood framing, other materials such as sheathing and insulation are used to enclose and insulate the structure. Before 1900 lightweight framing was widely used and the typical wall assembly consisted of the wood framing, sheathing, several layers of building paper, and finally the outermost layer of horizontal siding or shingles. The innermost layer typically consisted of plaster on wood lath, which worked to protect the occupants from the cold winter temperatures (Hutcheon & Handegord, 1980). Over time the concept of a layered wall assembly has remained common practice, with variations in technique and materials. Between 1900 and1920 there was a renewed interest in making homes more air tight and efficient, because advances in space heating were replacing the open fireplace. The Canadian government also started to take notice of the importance of insulating materials to save energy, which led to the first National Building Code in 1941. Since the 1940s Canada's building industry has seen major advances due to culture and changing energy prices (Figure 7).

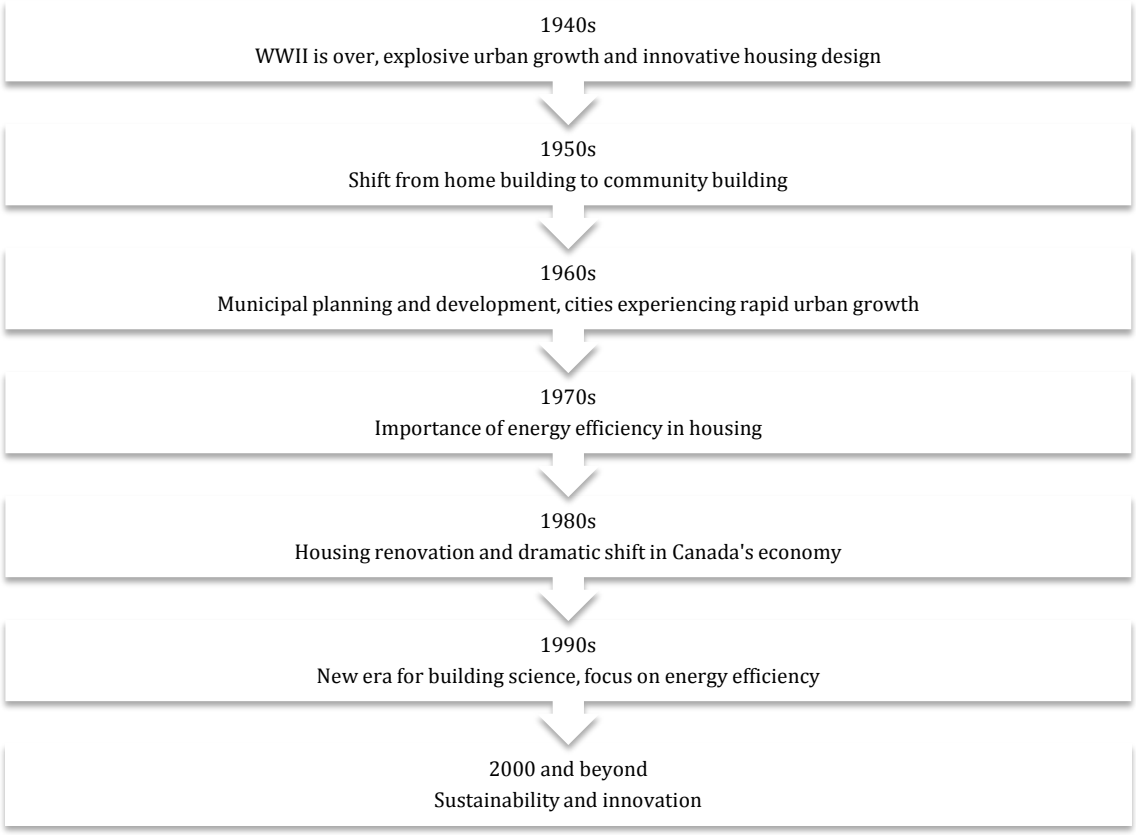

Figure 7. Major milestones in Canadian Housing Industry, (Canada Mortgage and Housing Corporation, 2012)

The first code for dwellings came during the time of the Great Depression when essentially construction of any type of building was halted due to the tough economic times (Richardson, 1973). However, once the economy started to recover and populations in many of the major cities started to increase the building code was enforced to avoid fire danger and save energy. A National Code for Dwelling Construction was created in 1950, and was designed for the construction of residential homes (Archer, 2003).

With the development of a National Code minimum requirements were established for areas such as the unfilled spaces in between walls. This space was

filled with a variety of products mainly consisting of different types of batts and blankets made from natural products. The most commonly used products were shavings and mineral wool batts for wall assemblies. In the attic and roof, loose mineral and glass fiber insulation were used (Hutcheon & Handegord, 1980). Shortly after insulation began to be widely used in homes, the issue of moisture and decay arose due to moisture from the warm side condensing on the cold back exterior of the sheathing layer. After many homes were damaged due to moisture intrusion, a vapor barrier material was introduced to the building assembly and widely used along with insulation. This stopped air and moisture transfer, creating a more airtight wall assembly.

Along with advances in well-insulated and airtight homes came mechanical heating sources. According to the Census of Canada in 1961, the two primary sources of mechanical heating in 1951 and 1961 were a steam or hot water furnace or a hot air furnace. The census reported that steam or hot water boilers were used in 18.2% and 15.5% of homes in 1951 and 1961, respectively while hot air furnaces were the dominant heating source in 49.2% and 30.9% of homes in 1951 and 1961, respectively (Dickens, 1962). The census also reported on the primary heating fuels used to heat homes during the 1950s and 60s (Table 2).

Heating Fuel	1951	1961
Coal or Wood	23.3%	70.0%
Oil	56.3%	22.7%
Gas	18.8%	4.8%

Table 2. Heating Fuel Characteristics, (Dickens, 1962)

Canada's primary heating fuel shifted significantly from oil to coal or wood in a matter of 10 years. This can be attributed to depletion of oil resources in

Canada and a switch to more plentiful resources found in timber harvesting and coal reserves.

Present Day Characteristics

Today energy is used to heat, cool, ventilate, and power Canadian homes and has evolved considerable since the early 1900s. Still, energy demand continues to rise in Canada by about 1.1% each year thus, making energy efficiency a primary focus for the federal government in their efforts to reduce dependency on fossil fuels. The majority of Canada's residential building stock was built before 1977 and 15% of the current stock was built from 1997-2007 (Parekh, Roux, & Gallant, 2007). In 2005 Canada's building stock comprised 2.2 billion square meters of total floor space, of this 71% was residential buildings, with the remaining 29% commercial buildings. Combined, residential and commercial buildings used about 31 Mega Tonnes of oil equivalent Mtoe of final energy in 2005 according to the International Energy Agency (IEA) (Shui B. & Evans, 2009).

Compared to the U.S., Canada's average house size has remained smaller in average square footage. Currently, an average home in Canada is 119m^2 (1,525 ft^2) (Table 3) while the average in the U.S. is well above 186 m^2 (2,000 ft^2).

	Number of Dwellings (in thousands)		Average Size	
Before 1946	1,832	14%	116 m^2	1,248 ft^2
1946-1960	1,278	10%	102 m^2	1,097 ft^2
1961-1977	3,353	26%	106 m^2	1,141 ft^2
1978-1983	1,544	12%	119 m^2	1,280 ft^2
1984-1995	3,019	23%	130 m^2	1,399 ft^2
1996-2000	1,002	8%	139 m^2	1,496 ft^2
2001-2004	938	7%	142 m^2	1,528 ft^2
Total	12,967			

Table 3. 2004 Canadian Housing Stock (Parekh, Roux, & Gallant, 2007)

Many of the same materials and practices that are used in the U.S. are also used in the Canadian residential construction industry. This is most likely attributed to similar climates, access to materials, and geographical proximity to the U.S. The Institute for Research in Construction at the National Research Council of Canada conducted a study, ASHRAE Research Project 1018, which evaluated and tested 35 of the most common building products used in North America. The result was a reliable and representative database of common building materials and their hygrothermal properties (Kumaran, 2006). Table 4 highlights each of the building materials and their most common use.

Material	Description	Use
Aerated Concrete	Block	Foundation, slab
Interior Gypsum Board	4 X 8, 1/2 in. board	Walls
Oriented Strand Board -1	4 X 8, 1/2 in. board, Poplar & Aspen	Walls
Oriented Strand Board -2	4 X 8, 3/8 in. board, Balsam, Poplar & Trembling Aspen	Walls
Oriented Strand Board -3	4 X 8, 7/16 in. board, Birch, Poplar & Aspen	Walls
Plywood - 1	4 x 8, 3/4 in., Douglas Fir	Walls and floors
Plywood - 2	4 x 8, 1/2 in., Douglas Fir	Walls and floors
Plywood - 3	4 x 8, 5/8 in., Douglas Fir	Walls and floors
Woodfibre Board	4 x 8, 7/16 in.	Walls
Eastern White Cedar	1" x 8" x 8' plank	Walls
Western Red Cedar	1" x 8" x 8' plank	Walls
Spruce	1" x 8" x 8' plank	Walls
Eastern White Pine	1" x 8" x 8' plank	Walls
Southern Yello Pine	1" x 8" x 8' plank	Walls
Composite Wood Siding	4' x 8' boards, 7/16"	Siding
Clay Brick	Extruded clay brick	Siding
Mortar	n/a	Siding
Stucco	n/a	Siding
Fibre Cement	4' x 8', 5/16" thickness	Roofing and cladding
Cement Board	4' x 8', 1/2" thickness	Flooring, siding, walls
Limestone	Slabs of varing sizes	Various
Low Density Glass Fibre Batt Insulation	4" thickness	Insulation (unfinished walls, including foundation walls, floors and ceilings)
Cellulose Fibre Insulation	n/a	Insulation (enclosed existing wall or open new wall cavities; unfinished attic floors
Expanded Polystyrene Insulation	n/a	Insulation (unfinished walls, including foundation walls, floors and ceilings, unvented low-slope roofs)
Extruded Polystyrene Insulation	4' x 4' board, 4" thickness	Insulation (unfinished walls, including foundation walls, floors and ceilings, unvented low-slope roofs)
Sprayed Polyurethane Foam Insulation	6" thickness	Insulation (enclosed existing wall or open new wall cavities; unfinished attic floors
Polyisocyanurate Board Insulation	4' x 8', 3" thickness	Insulation (unfinished walls, including foundation walls, floors and ceilings, unvented low-slope roofs)
Low-Density Sprayed Polyurethane Foam Insulation	n/a	Insulation (enclosed existing wall or open new wall cavities; unfinished attic floors

Table 4. Commonly Used Products, North America 2006, (Modified from (Kumaran, 2006)).

These materials have a variety of hygrothermal properties and can be used in several locations throughout a home for better thermal performance. The last "Housing and Dwelling Characteristics" survey conducted by the Canadian Census Bureau was in 2006. The survey evaluated 3,200 homes built within 10 years of 2006 in all regions of Canada. The survey revealed the current thermal characteristics of single family detached home consisted of the following:

Thermal Characteristics of Canadian Single-family Housing	
	Thermal Characteristic
Framing	2 x 6”
Wall Insulation (above grade)	R-20 (minimum)
Attic insulation	R-32 to R-38
Air tightness (at 50 Pa)	2.0 – 4.5 ac/h
Space heating index	434 MJ/m^2

Figure 8: Thermal Characteristics, Single-family Housing (Parekh, Roux, & Gallant, 2007)

With the building stock of the last decade having the above-mentioned thermal characteristics, houses built today consume approximately 34% less energy (per m^2) compared to a home built between the 1960s and 1980s, and are about 18% more energy efficient than a house built between 1985 and 1990 (Parekh, Roux, & Gallant, 2007). This improvement can be attributed to new space heating requirements, increased insulation levels, more airtight construction, and efficient space heating equipment.

Energy efficiency regulations for building products in Canada are relatively recent, within the last 25 years, in Canada. In 1995 the first Efficiency Regulations came into effect under the Energy Efficiency Act in 1992. This established regulations for “more than 30 products, including heating and cooling equipment, water heaters and lighting” (Shui B. & Evans, 2009). These regulations were just the beginning of the energy efficiency movement for the residential, commercial and industrial sectors in Canada. In 1997 Canada’s National Research Council (NRC) released the first version of Canada’s seven national building codes, the

Model National Energy Code for Houses (MNECH). A new version of the MNECH was released in 2012, as an addendum to the 2010 National Building Code of Canada (NBC) (NRC, 2012). The revised residential energy efficiency standards are used in this studies simulation for the model Canadian home.

Europe

Rebuilding after conflicts and depletion of forests has heavily influenced Europe's building scene. In addition, Europe has less geographical space compared to the U.S. and Canada. Europe's building history dates back centuries with many cities experiencing major transformation in architecture and building materials throughout history. Similar to the U.S. and Canada, Europe spans several climate zones resulting in a variety of building techniques and materials used throughout the region. The focus of this research is to analyze the building code of Austria, though the building history and traditions of other countries within the same climate zone (3500-8000 HDD based on18 degree Celsius) will also be discussed in this section. Austria is a mountainous region with approximately 80% of its housing stock located in urban areas, similar to many other European countries (UNECE, 2004). This section explores the history of Central European residential buildings and how the influence of developing energy codes has shaped the building stock over the last century.

Historical Characteristics

Of the current building stock in Europe 40% was built before 1960, this was before the building codes focused on a buildings energy features and occupant comfort (Economidou, 2012). A recent report from the Buildings Performance Institute of Europe (BPIE), classified the residential building stock throughout Europe into three age bands (Economidou & et.al, 2011):

Old: typically representing buildings up to 1960
Modern: typically representing buildings from 1961 to 1990
Recent: typically representing buildings from 1991 to 2010

Each age band represents a time period of significant changes in construction techniques and building regulations from the previous. This resulted in energy performance of buildings differing between time periods. Building energy codes started to take shape and become enforced during the 1970s throughout many countries in Europe when oil prices rose in the 1970s, similar to the U.S. and Canada.

The most common construction method used in Europe throughout history is wood and wood joist construction. The history of wood construction dates back the longest in Europe, Japan, and China with some of the oldest standing structures still in existence to this day. While this method dates back prior to the 20th century, the 20th century showed a range of construction forms, some still used in today. Before the two World Wars, log and skeleton construction were most commonly used. Log construction is often thought of as a primitive method of wood construction using horizontal members with vertical posts to support the structures weight (Zwerger, 2012). The jointing methods (Figure 9) of log construction were simpler than that of other wood construction methods due to the size and weight of the logs. In Germany, naturally forked timbers were used as multi-purpose horizontal and vertical supports (Zwerger, 2012). The forked timbers helped the transition between the wall and sloped roof by not only adding structural support, but also a unique aesthetic to the buildings structure.

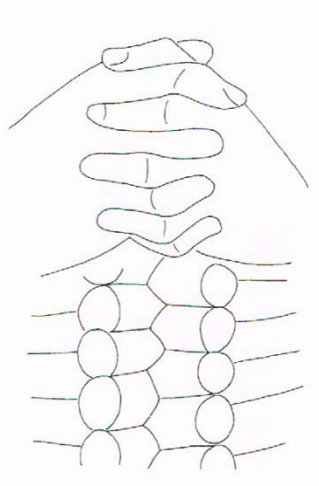

Figure 9. Simplicity of log construction joints (Zwerger, 2012)

The next era of building with wood in Europe, after log construction, came before the two World Wars was skeleton construction. Skeleton construction developed in parallel with post and beam, which evolved into column and beam. The three types of construction were previously outlined in the U.S. and Canadian sections. As in the U.S. and Canada, these methods of construction presented the need for the open cavities in the wall to be filled with other material than wood. The original fill consisted of stones, twigs, and spare timber (Figure 10), which many times also acted as structural bracing for the vertical timbers.

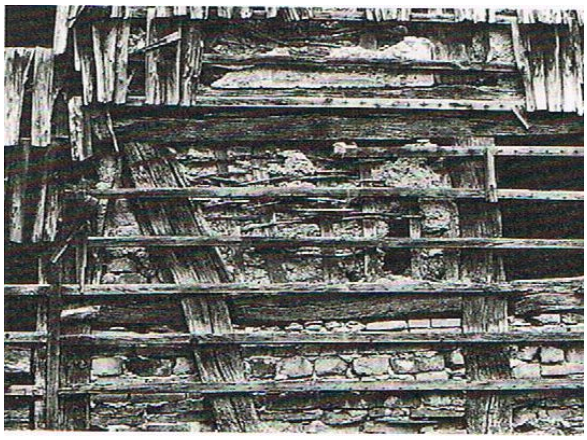

Figure 10. Stone and brick fill in skeleton construction (Zwerger, 2012)

The stone and brick fill seen in Figure 10 can also be considered a primitive method of insulating. This type of insulation or filling of space between timbers was soon replaced by fibrous (glass and wool) materials. These materials were lighter and provided better thermal insulating performance over stone or brick.

The period after the Second World War was a time of rebuilding in several European countries. During this time prefabricated homes were common in rebuilding entire communities affected by the war. This method of construction was fast and easy, but sparked architectural debate because it was not suited for long-term sustainability in the market due to its slow response to changing requirements (Wachsmann, 1995). As new building requirements are starting to be implemented throughout Europe after the wars, the market for pre-fabricated structures started to decline. In the late 1960s and early 1970s, many European countries started to create local standards for building. Many European countries were paying premium prices for energy resources in the 1970s; therefore, development of better construction methods and higher performing building materials was necessary. The changes in building standards and performance can be seen through the increase in insulation thickness in walls and roofs since the 1980s. Wall and roof insulation thicknesses' can be seen in Figure 11 and Figure 12, respectively. Some countries have nearly doubled in thickness requirements, mainly northern countries, while others have remained the same over the last thirty years.

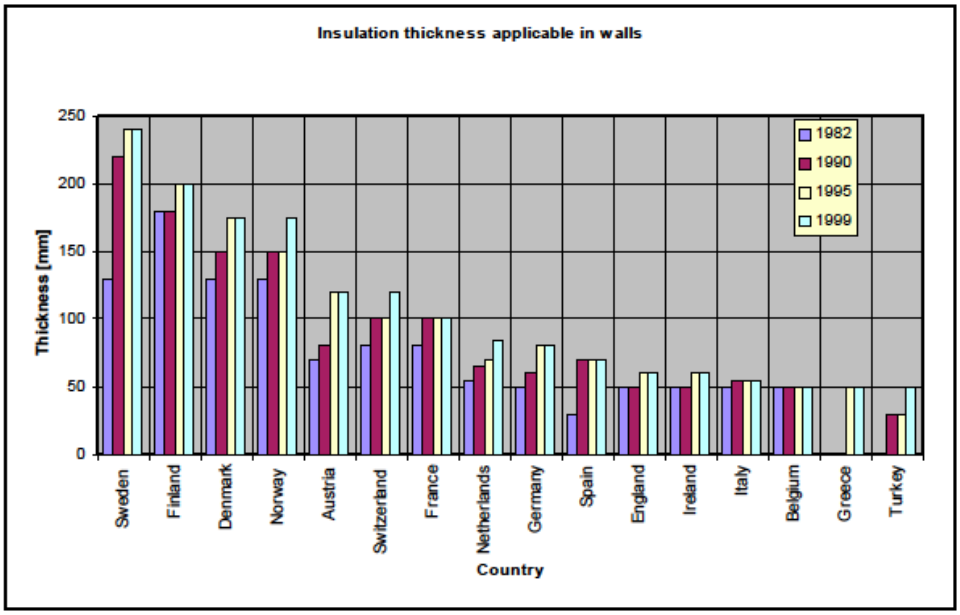

Figure 11. Typical insulation thickness in walls (Papadopoulos, 2005)

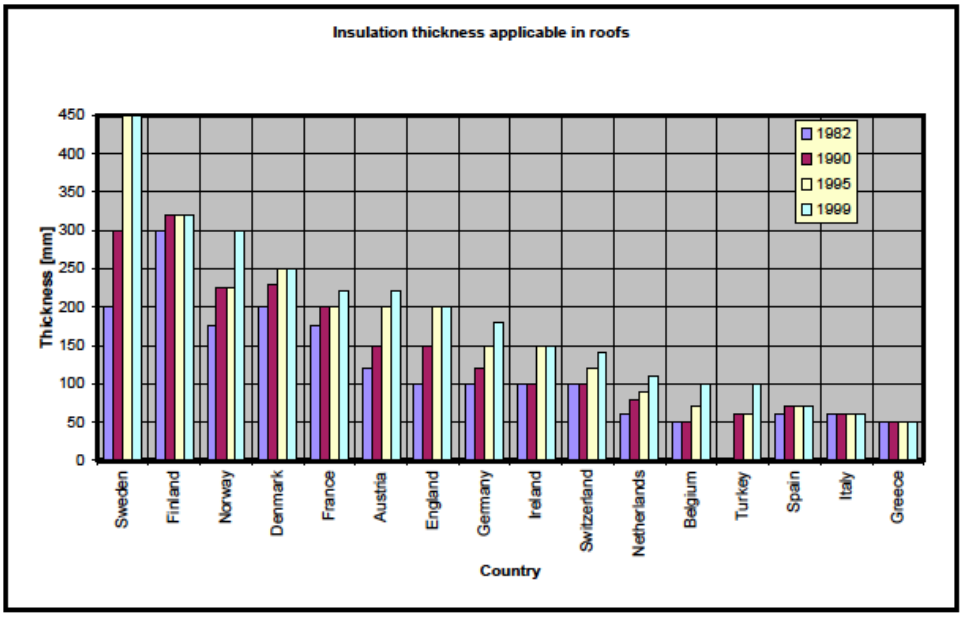

Figure 12. Typical insulation thickness in roofs (Papadopoulos, 2005)

Austria has nearly doubled the thickness in insulation since the early 1980s. This change can be attributed to new standards being developed and improved over

time. These historical observations present the building blocks for the residential building industry we see today all throughout Europe.

Present Day Characteristics

Present day characteristics of single-family residential housing in Europe vary depending upon country, climate zone, and local buildings codes. Energy codes in Europe are structured somewhat similar to the United States in that there is a national standard adopted by each member state with many member states also developing more stringent regional codes. In 2002 the European Commission – Energy Division created the first Energy Performance of Buildings Directive (EPBD) 2002/91/EC, the EU's first whole building energy standard (European Commission, 2012a). While each member state can determine their own minimum U-values (Figure 13) for new construction, the performance of the building must be geared toward low to zero-energy by 2021 (European Commission, 2012b).

	Roofs	Outer walls	Ground floors	Windows
Austria	0.2–0.3	0.3–0.4	0.4–0.5	1.0–1.5
Belgium (Flanders)	0.4–0.5	0.5–0.6	0.6–0.6	1.5–2.5
Denmark	0.1–0.2	0.2–0.3	0.1–0.2	1.5–2.5
Finland	0.1–0.2	0.2–0.3	0.2–0.3	1.5–2.0
France	0.2–0.3	0.4–0.5	0.3–0.4	1.5–2.5
Germany	0.2–0.3	0.5–0.6	0.4–0.5	1.0–1.5
Greece	0,4–0,5	0,5–0,7	0,7–1,9	2,5–3,5
Ireland	0.1–0.2	0.2–0.3	0.2–0.3	1.5–2.5
Italy	0.3–0.4	0.4–0.5	0.4–0.5	2.5–3.5
Lithuania	0.1–0.2	0.2–0.3	0.2–0.3	1.5–2.5
Norway	0.1–0.2	0.2–0.3	0.1–0.2	1.0–1.5
Portugal	0.6–0.6	0.6–0.6	0.6–0.6	2.0–3.0
Russian Federation	0.1–0.4	0.1–0.2	0.1–0.4	1.5–3.5
Spain	0.6–0.6	0.6–0.6	0.6–0.6	2.5–3.5
Sweden	0.1–0.2	0.1–0.2	0.1–0.2	1.0–1.5
Switzerland	0.3–0.4	0.3–0.4	0.6–0.6	1.0–1.5
UK	0.1–0.2	0.3–0.4	0.2–0.3	1.5–2.5
The Netherlands	0.2–0.3	0.2–0.4	0.2–0.3	1.5–2.5

Figure 13. 2005 Minimum European U-values (W/m²K) (Papadopoulos, 2005)

Since the 2002/91/EC was developed, the European Commission has released EPBD 2010/31/EC. This Directive still includes member states establishing minimum performance requirements for new and existing buildings, but it also requires the certification of building energy performance. In addition, it also requires regular inspections of boilers and air conditioning systems and keeps in line with all new buildings being 'nearly zero-energy buildings' by 2021 (European Commission, 2012a). The goal of 'nearly zero-energy buildings' by 2021 in residential construction is an aggressive goal for which the U.S. and Canadian residential codes do not touch upon.

In Austria, the EU member state this research is focusing on, the construction standards are created by the Österreichisches Institut für Bautechnik (OIB) (Austrian Institute of Construction Engineering). Their primary responsibility is for the "harmonization of building regulations" which may be used by any of Austria's nine states(OIB, 2011). For purposes of this research, OIB-guidelines 2001 chapter 6 - Energieeinsparung und Wärmeschutz (Energy Economy and Heat Retention) will be evaluated in the whole building analysis simulations.

According to the latest census, three quarters of Austria's building stock in 2001 consisted of residential buildings made up of one or two dwellings (STATISTICS AUSTRIA, 2010). A 2002 report on Housing Developments in European Countries released the current characteristics of Austria's housing stock (Table 5). Each decade since 1960 Austria's housing stock has grown between 12-16% and in 2002 the average size was 60-90 m^2 (645-968 ft^2).

Category		%
Main residences by date of construction	<1919	18.4
	1919-1944	8.4
	1945-1960	12.2
	1961-1970	15.8
	1971-1980	16.0
	1981-1990	12.7
	>1991	16.4
Main residences by availability of utilities	Bathroom, lavatory & central heat	87.3
	Bathroom, lavatory & Indv. Heat	8.5
	Lavatory & water in main Res.	0.9
	Water only or no utilities	3.3
Main residence by usable floor area	< 35 m^2	3.8
	35-45 m^2	5.8
	45-60 m^2	12.6
	60-90 m^2	33.1
	90-110 m^2	14.7
	110-130 m^2	12.0
	130-150 m^2	8.8
	>150 m^2	9.2

Table 5. Characteristics of Austria's Housing Stock, 2002 (Norris & Shiels, 2004)

Since 2004 a yearly household survey, Austrian Mikrocensus, consisting of 22,000 households is conducted to report on characteristics of the current building stock. In 2011 the average dwelling size was 99.5 m^2 (1,071 ft^2) (Wohnen, 2011), up slightly from 2002; however, still considerably smaller than homes in Canada 141 m^2 (1,525 ft^2) and the U.S 272 m^2 (2,932 ft^2). The difference in size between the U.S., Canada, and Europe can be attributed to access to available land. European cities tend to be more densely populated and land is at a premium. Whereas, in the U.S. and Canada there is more land area for growth outside of largely populated areas allowing for larger homes to be built.

Unlike the U.S. and Canada, 93% of Austrian residences are heated by one of three sources: district central heating, in floor and gas convectors, or a built-in electric heater (Wohnen, 2011). District heating is a centralized heat generation plant used for both residential and commercial buildings for space heating and water heating. There is a variety of ways central plants work and generate heat. Many are cogeneration plants that burn fossil fuels; however, biomass is also starting to become a predominant fuel source. Central district heating plants in the U.S. are typically seen on large corporate campuses or university settings, not commonly used in the residential sector.

While the type of space heating in Europe, specifically in Austria, may be different than what is commonly found in the U.S. and Canada, there is some overlap in materials used for thermal insulation of modern wood framed/timber construction found in present day Austrian homes. Timber is the most widely used

structural building material in Austria (Natterer, Herzog, & Volz, 1991). The most common insulating materials in Europe today are predominately made up of inorganic and organic materials. Figure 14 classifies the most commonly used insulation materials found in residential buildings. Fibrous inorganic materials such as glass wool or stone wool account for 60% of the market, while organic foamy materials represent 27% of the market (Papadopoulos, 2005).

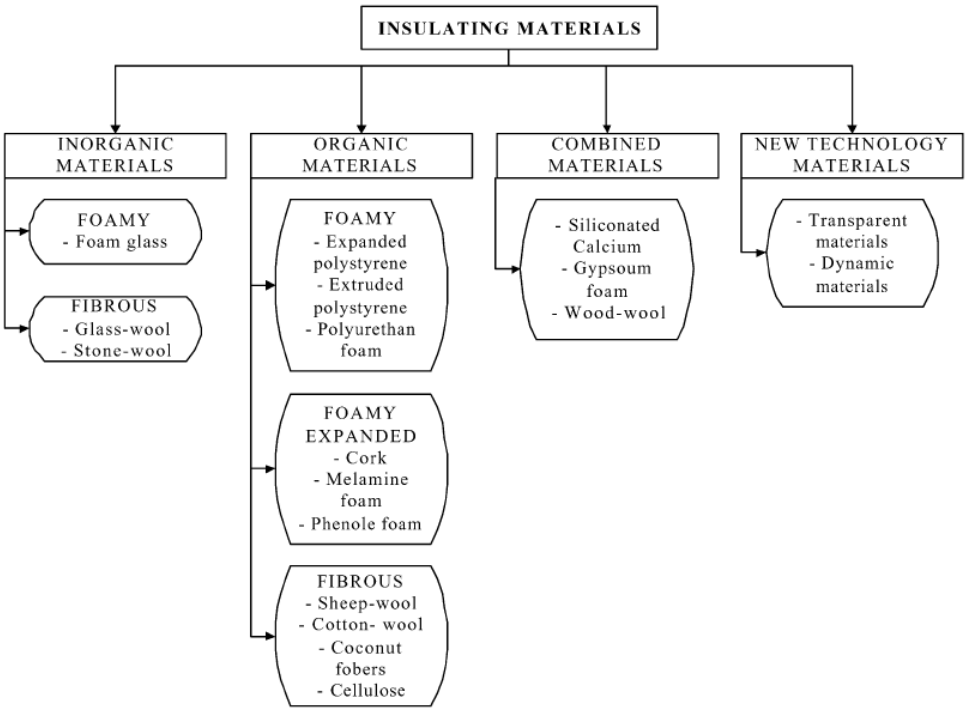

Figure 14. Common European insulating materials (Papadopoulos, 2005)

While each of the three global locations chosen for this research share some similarities in historical and present day building techniques and materials, they also have notable differences in thermal energy requirements. These differences are explored next through simulating each locations current energy codes on a model home with typical characteristics of an average U.S. home.

CHAPTER 4

METHODOLOGY

This chapter outlines the methodology used for this research. It includes a description of model assumptions, the simulation tool used, the house prototype, climate and location descriptions, and model inputs for the three geographic locations used for this research.

Assumptions

One inland location, in each of the geographical regions of the U.S., Canada, and Europe, within the same climate classification zone are investigated in this research through a whole building analysis. A model residential home with an average square footage of a single-family residential home in the U.S., which is estimated to be 2,392 sq. ft. according to the 2010 U.S. Census [5], is analyzed in each of the three selected locations. The difference in outputs from the heating and cooling loads and heat loss from the building materials, assemblies, and ventilation measures are presented. The goal is to determine the effectiveness of different energy efficient measures implemented in different locations within the same climate zone. The methodology and assumptions for the energy models are described below.

Simulation Tool

DesignBuilder EnergyPlus Simulation software was used to provide a comparison of the home's energy performance at each location. DesignBuilder uses

the DOE's EnergyPlus engine producing a model, which estimates the building energy use for all 8760 hours in a year. Figure 15 presents a visualization of the house prototype (described in next section) in DesignBuilders 3D graphical interface. The prototype house was first designed in Autodesk's Revit Architecture software and then imported into DesignBuilder.

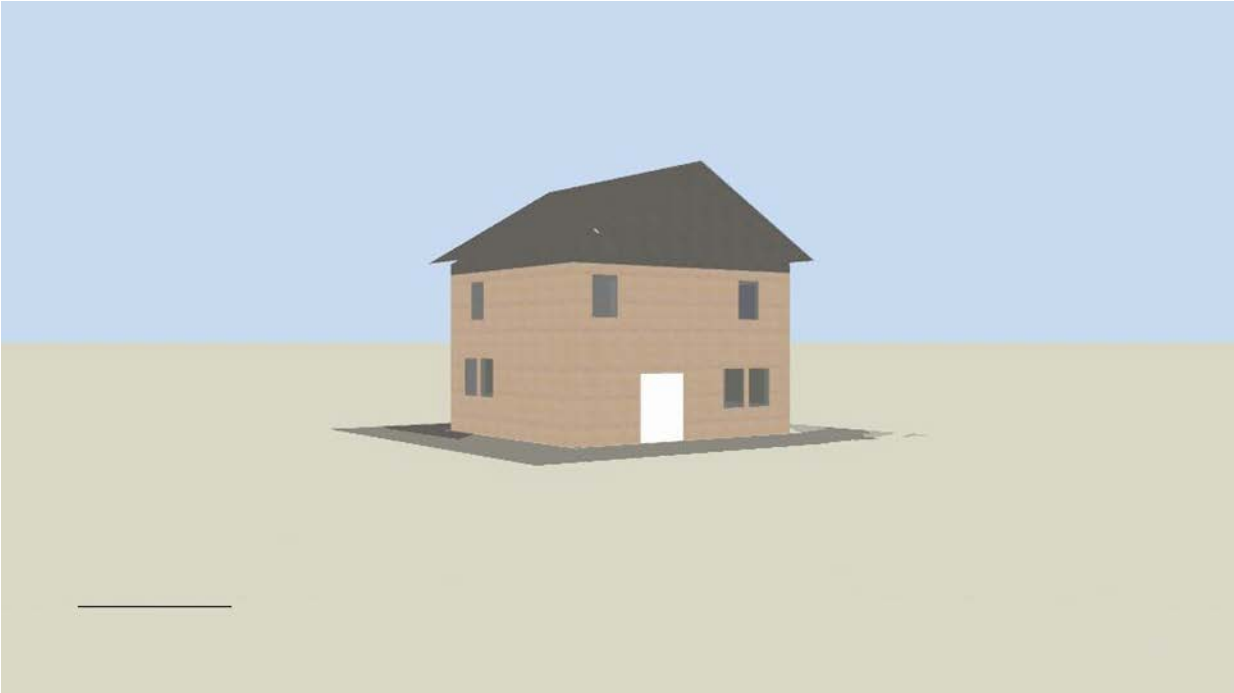

Figure 15: Screen shot of model in DesignBuilder EnergyPlus

House Prototype

The model home is a single-family detached residential building located in a suburban area. It is a two-story 2,392 square foot slab-on-grade home orientated due North. It has three bedrooms, one and a half baths, kitchen, dining room, and living room (Figure 16, Figure 17) and limited architectural features as seen in Figure 18 and appendices. The construction system for each home is the standard

practice for the region in which the home is located. The proposed glazing area is less than 15% (358 sq. ft.) of the conditioned floor area equally orientated in each cardinal direction. Conditioned space consists of two zones, living and sleeping areas. Heating with a natural gas furnace and no air conditioning are assumed. All heating and ventilation ducts are assumed to be located in the attic in conditioned space. The effective R-values of the roof system, wall assemblies, floor (slab), and windows and doors of each region, along with the HVAC requirements are outlined below.

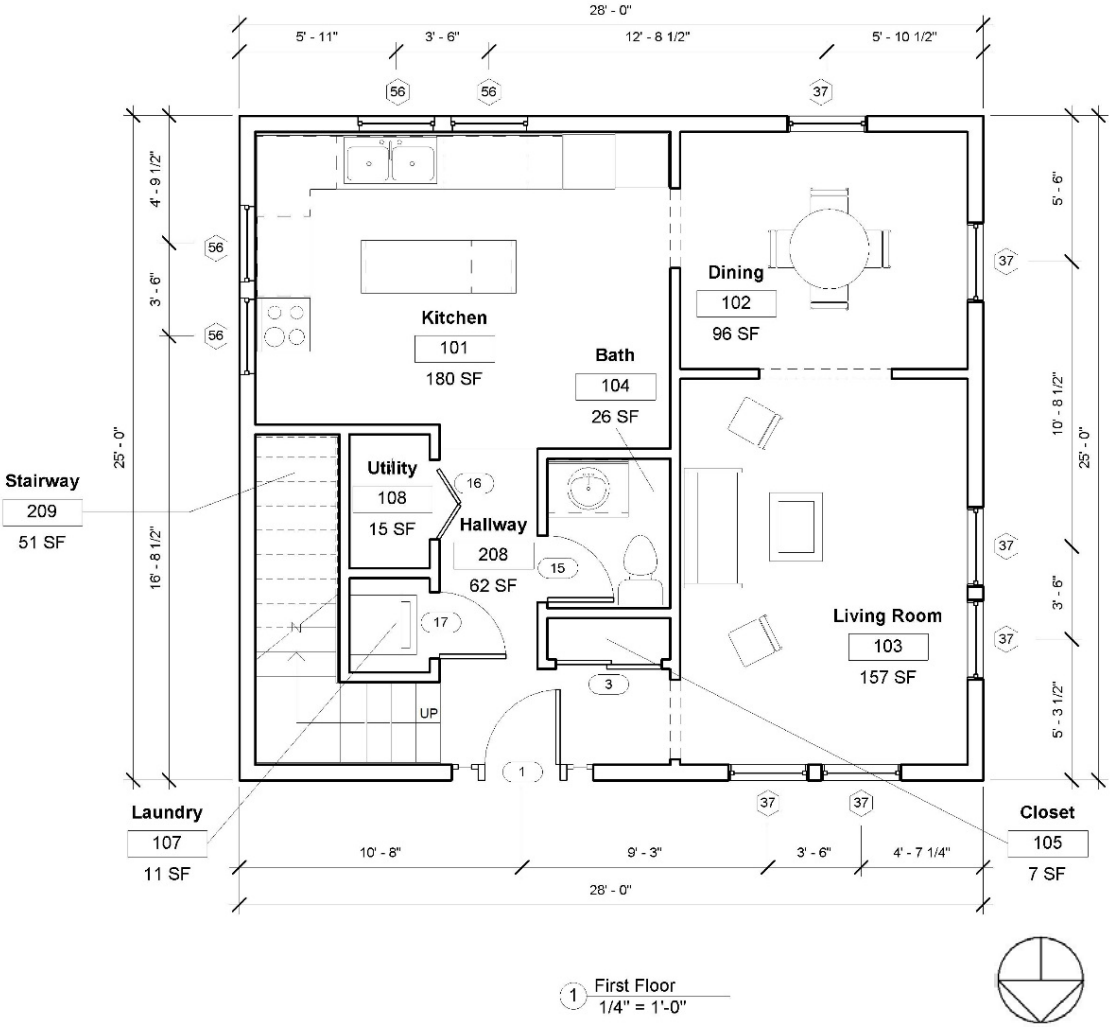

Figure 16: First Floor Plan

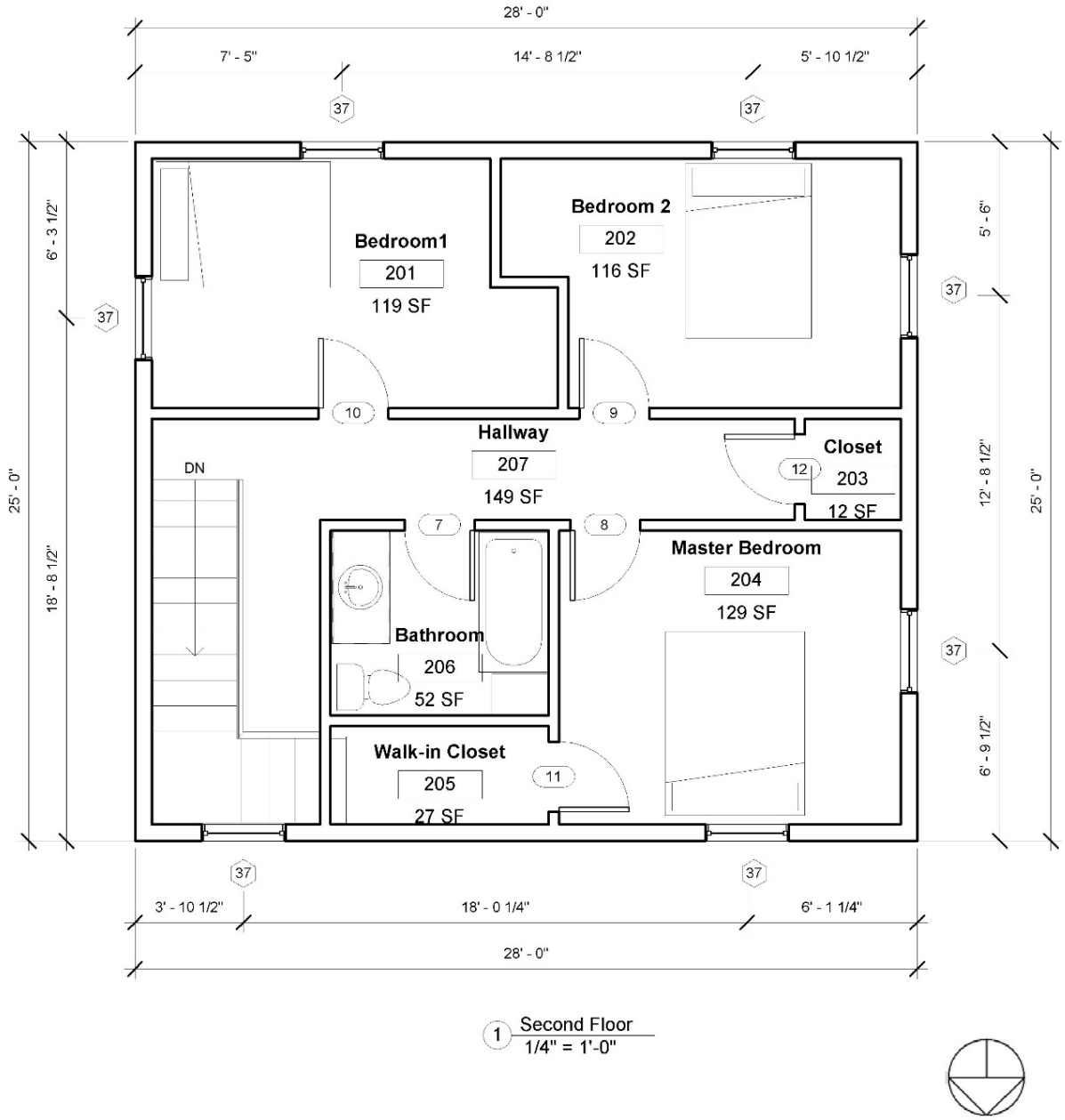

Figure 17: Second Floor Plan

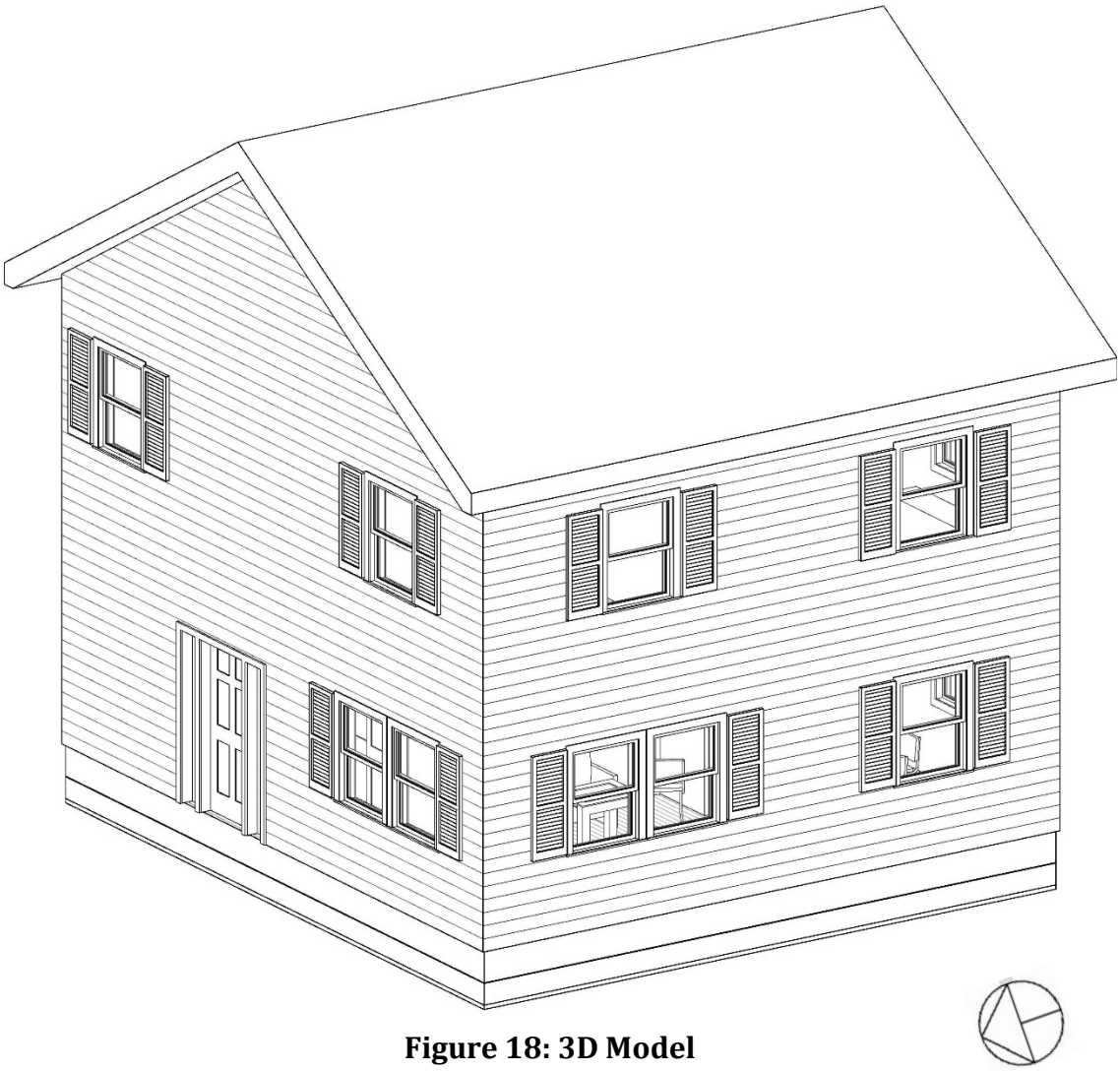

Figure 18: 3D Model

Climate/Locations

This research compares the energy performance of single-family residences in locations with heating dominated climates and similar climate classification. The climate classification used in this research is based on the Köppen-Geiger climate classification standard. Wladimir Köppen originally created the Köppen-Geiger climate map in 1900 and was later updated by Rudolf Geiger in 1961 and continues

to undergo updates by various sources (Kottek, Grieser, Beck, Rudolf, & Rubel, 2006). The standard uses three categories to classify a region these are: main climate, precipitation, and temperature. For the purpose of this research, locations were chosen with a similar classification (snow, fully humid, warmer summer) as the Northeastern United States. While the Köppen-Geiger climate classification is the most widely used classification, many regional studies have been done to create more fine-tuned climate classification for a particular region. In 2002 the IECC updated the climate classification zones for the United States as to better account for cooling degree climates. The updated classifications were first seen in the 2004 Supplement to the IECC and AHSRAE 90.1 in the 2004 edition (PNNL & ORNL, 2010). With updated temperature and precipitation readings spanning thirty years from the National Climatic Data Center (NCDC) the IECC provides new degree-days, annual and monthly averages of incident solar radiation, humidity parameters, and relevant design-day conditions (Building Energy Resource Center, 2012).

The most relevant factor, and basis for location selections, in the updated classification system are the thermal parameters. The current IECC parameters set the thermal bands of 1000 HDD18°C (1800 HDD65°F) for each climate zone. Although the climate classification for building energy codes and standards was originally modified for the U.S., the 2009 IECC determines international climate zones by applying the thermal criteria in Figure 18.

Zone Number	Zone Name	Thermal Criteria (I-P Units)	Thermal Criteria (SI Units)
1A and 1B	Very Hot-Humid (1A) Dry (1B)	9000 < CDD50^{0}F	5000 < CDD10^{0}C
2A and 2B	Hot-Humid (2A) Dry (2B)	6300 < CDD50^{0}F ≤ 9000	3500 < CDD10^{0}C ≤ 5000
3A and 3B	Warm – Humid (3A) Dry (3B)	4500 < CDD50^{0}F ≤ 6300	2500 < CDD10^{0}C ≤ 3500
3C	Warm – Marine (3C)	CDD50^{0}F ≤ 4500 AND HDD65^{0}F ≤ 3600	CDD10^{0}C ≤ 2500 AND HDD18^{0}C ≤ 2000
4A and 4B	Mixed – Humid (4A) Dry (4B)	CDD50^{0}F ≤ 4500 AND 3600 < HDD65^{0}F ≤ 5400	CDD10^{0}C ≤ 2500 AND HDD18^{0}C ≤ 3000
4C	Mixed – Marine (4C)	3600 < HDD65^{0}F ≤ 5400	2000 < HDD18^{0}C ≤ 3000
5A, 5B, 5C	Cool- Humid (5A) Dry (5B) Marine (5C)	5400 < HDD65^{0}F ≤ 7200	3000 < HDD18^{0}C ≤ 4000
6A and 6B	Cold-Humid (6A) Dry (6B)	7200 < HDD65^{0}F ≤ 9000	4000 < HDD18^{0}C ≤ 5000
7	Very Cold	9000 < HDD65^{0}F ≤ 12600	5000 < HDD18^{0}C ≤ 7000
8	Subarctic	12600 < HDD65^{0}F	7000 < HDD18^{0}C

Figure 19. International Climate Zone Definitions (International Code Council, 2012)

The three locations chosen for this research are located in IECC climate zones 5 with a thermal band of 3000 < HDD18^{0}C ≤ 4000 (5400 < HDD65^{0}F ≤ 7200) and considered to be Cool-Humid (5A). These locations where chosen as identifiable locations within the Cool-Humid climate zone classification. They are as follows: Boston, Massachusetts, Hamilton, Ontario (suburb of Toronto), and Innsbruck, Austria. All cities are located in climate zone 5 or 6 according to the Climate Classification for Building Energy and Codes Standards set by the IECC.

Weather Data

Each location's hourly weather data, which defines external conditions, was obtained from the *EnergyPlus* database of 'typical' data. These conditions include external dry bulb temperature, solar radiation, dew point, wind speed/direction, atmospheric pressure, visibility, precipitation type, and other atmospheric conditions (DOE, 2013). The data sets are in the form of Typical Meteorological Year 2 (TMY2) weather format, a common text-based weather file format. The weather data in the *EnergyPlus* database is a compilation of 20 sources from around the world. Currently, *EnergyPlus* has a weather database of over 21,000 locations. If weather data for a specific location is not available for download from *EnergyPlus,* the data files were obtained from the National Climatic Data Center housed at the National Oceanic and Atmospheric Administration (NOAA) (United States), Canadian Weather for Energy Calculations (CWEC)(Canada), and the International Weather for Energy Calculations (IWEC) (Europe).

Model Inputs

The inputs in Table 5 represent the effective R-values of the roof system, wall assemblies, floor, slab, and windows and doors of each region, along with HVAC requirements.

Energy Feature	Boston, Massachusetts, U.S.	Hamilton, Canada	Innsbruck, Austria
Energy Code	2009 IECC	National Building Code of Canada 2010 – Part 9	OIB-Richtlinien 2011
Construction	Light-weight wood-frame	Light-weight wood-frame	Light-weight wood-frame
Heating Degree Days	3120 HDD 18^{0}C (5648 HDD 65^{0}F)	3462 HDD 18^{0}C (6264 HDD 65^{0}F)	3395 HDD 18^{0}C (6143 HDD 65^{0}F)
Wall Insulation	U-0.057 (R-20)	U-0.062 (R-16)	U-0.062 (R-16)
Slab Insulation	U-0.10 (R-10)	U-0.11 (R-9)	U-0.071 (R-14)
Floor Insulation	U-0.033 (R-30)	U-0.038 (R-26)	U-0.034 (R-29)
Roof Insulation	U-0.026 (R-38)	U-0.031 (R-32)	U-0.035 (R-28)
Windows	U-0.35	U-0.55	U-0.25
Doors	U-0.35	U-0.55	U-0.31
Heating System	Gas Furnace 88% AFUE	Gas Furnace 92% AFUE	Gas Furnace 91% AFUE
Cooling System	None	None	None
Domestic Hot Water System	Gas Fired ≥76%	Gas Fired ≥80%	Gas Fired 86%
Duct Sealing	Located in Conditioned Space	Located in Conditioned Space	Located in Conditioned Space

Table 6. Model Assumptions by Location

Cooling energy was not modeled as the primary focus of this research is the heating and thermal aspects of each building code. In addition, cooling in Canada and Austria is not commonly installed due to moderate summer temperatures.

Set Points/Schedules

The thermal set points of the simulated model are input according to the ASHRAE Standard 90.2-2007 *Energy-Efficient Design of Low-Rise Residential Buildings* multi-zone thermostat settings (Figure 20).

Time of Day	Single Zone		Multiple Zone			
			Zone 1 Living		Zone 2 Sleeping	
	Heat	Cool	Heat	Cool	Heat	Cool
0600-0900	68	78	68	78	68	78
0900-1700	68	78	68	78	60	85
1700-2300	68	78	68	78	68	78
2300-0600	60	78	60	85	60	78

Figure 20. Thermostat Settings (°F) (ASHRAE, 2009)

The above heating and cooling set points define the ideal temperature (i.e. set point temperature on thermostat) in a space when heating or cooling is required and vary depending on time of day and occupancy schedule. Set points and setbacks are a mechanism to lower (or raise) the temperature in a building during unoccupied or designated setback periods. This helps maintain occupant comfort levels and reduce peak heating (or cooling) demands during months with extreme temperatures demanding a heating or cooling load. Setbacks in homes are typically during evenings and weekends when occupants are sleeping or occupancy is variable.

The occupancy schedule for the model follows assumptions based on ASHRAE standards shown in Figure 20 and the occupancy schedule remains the same seven days a week. The occupancy density for the model residence is four persons. The following explanation for occupancy schedule is assumed:

- A schedule value of 1 means that 4 people are assumed to be in the building during hat hour.

- A schedule value of 0 means that no people are assumed to be in the building during that hour.
- A value of 0.1 means that 4 * 0.1 = 0.4 people are assumed to be in the building during that hour.

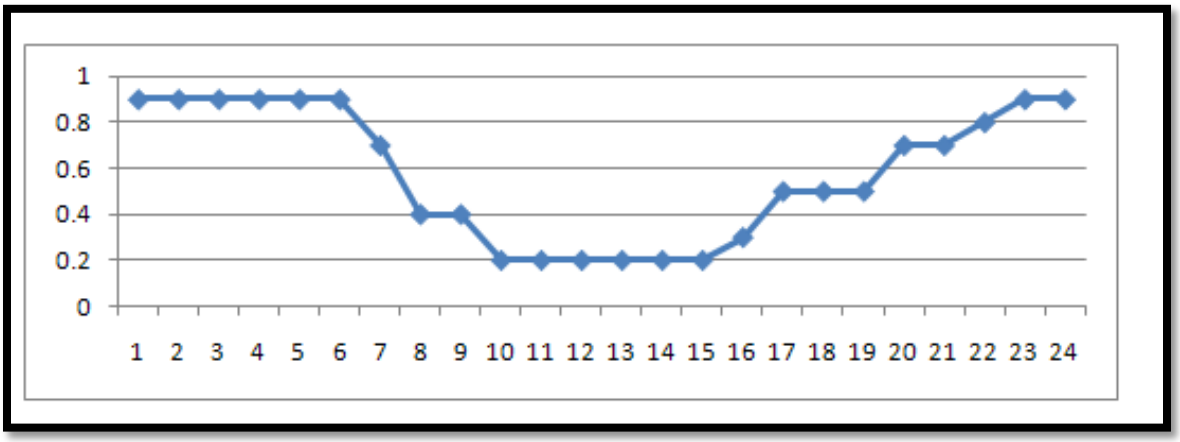

Figure 21. Residential occupancy schedule (24-hours) (Autodesk, 2011)

All of the model assumptions outlined above are the basis for comparing each building energy profile. The results of the three simulations are discussed in the next chapter.

CHAPTER 5

RESULTS

This chapter presents the results based on the methodology outlined in the previous chapter. In this research, specific differences in code requirements were evaluated through building energy simulation to determine their influence on a building's energy profile at three locations: the United States (Massachusetts), Canada (Ontario), and Europe (Austria). Three representative cities in each country were selected based on climate classification and Heating Degree Days similar to that of the Northeastern United States. These cities are Boston, Massachusetts, Hamilton, Ontario, and Innsbruck, Austria.

Using one common single-family residential house prototype, each location's energy requirements were investigated. The primary intent was to compare each building's performance profile based on building code requirements for effective R-values of each building assembly and mechanical system efficiencies.

Whole Building and Heating Energy Use

This section provides results for the simulation runs for each of the three locations. Figure 22 shows 'Whole Building Energy Use (kBtu/sf)' and 'HVAC Energy Use (kBtu/sf)' for each location's building energy code requirements. Other building systems energy use will be discussed in later sections. HVAC energy use is typically the largest end use in the building. For each location the HVAC energy use is between 62-76% of the total building energy use.

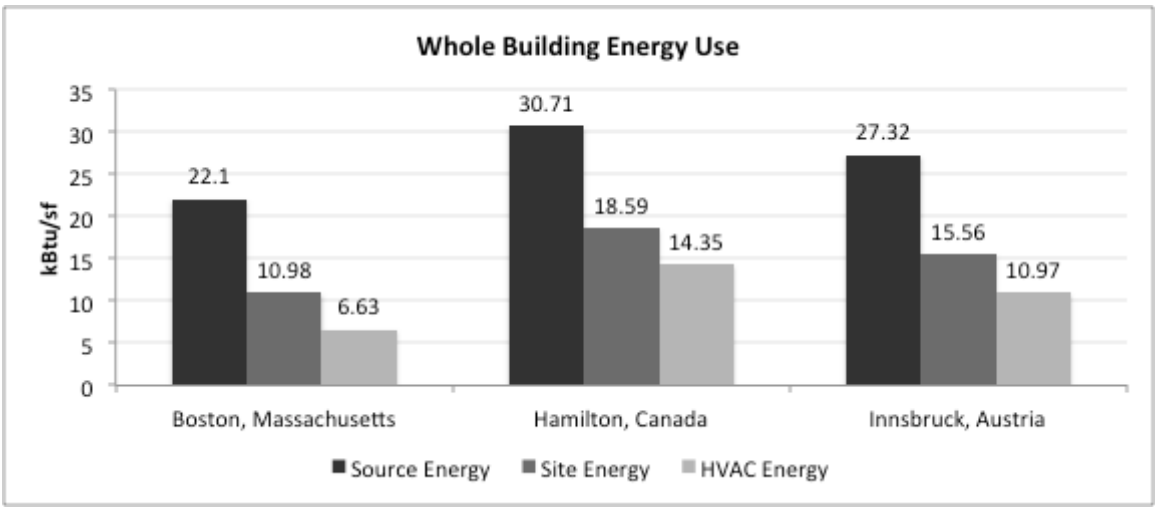

Figure 22. Whole Building Energy Use by Location

To understand the energy performance of a building site and source energy is evaluated. Site and source energy are different ways to look at a building's energy consumption. Source energy is the raw fuel used by a building to operate. This includes transmission, delivery, and production line losses – essentially accounting for all energy supplied to and used in a building. Site energy is the most common type of energy known by the end user; it is the amount of heating and electricity demanded by a building. This is what is reflected on consumers' utility bills. Site energy can be delivered to a building as either primary (raw fuel) or secondary energy (converted fuel). These two types of energy are not comparable because primary energy is raw fuel burned to create heat or electricity, and secondary energy is the energy product created from raw fuel (i.e. electricity purchased from the grid) (EPA, 2013a). Buildings can have varying proportions of each energy type; therefore, to assess the relative efficiencies of a building the two types of energy are converted into equivalent units of raw fuel, site energy.

In order to compare the "big picture" of a buildings energy impact, source energy is often the most common and complete assessment of energy efficiency (EPA, 2013a). This is done by using a site-to-source conversion factor to account for *all* energy supplied and consumed by the building into one type of energy. Conversion factors vary between states, regions, and countries depending on the fuel mix of the grid, and changes yearly. For example, the figure below shows the fuel mix of electricity in the U.S. Electricity purchased from the grid is a secondary form of energy consumed at the building and generated through a variety of methods including burning fossil fuels (e.g. coal, fuel oil, etc.), renewable resources (e.g. wind, biomass, etc.), and nuclear plants (ENERGY STAR, 2011). The primary fuel used to generate electricity in the U.S. is coal, representing approximately 50% of the grids fuel source. As seen in the figure below, this can vary between regions.

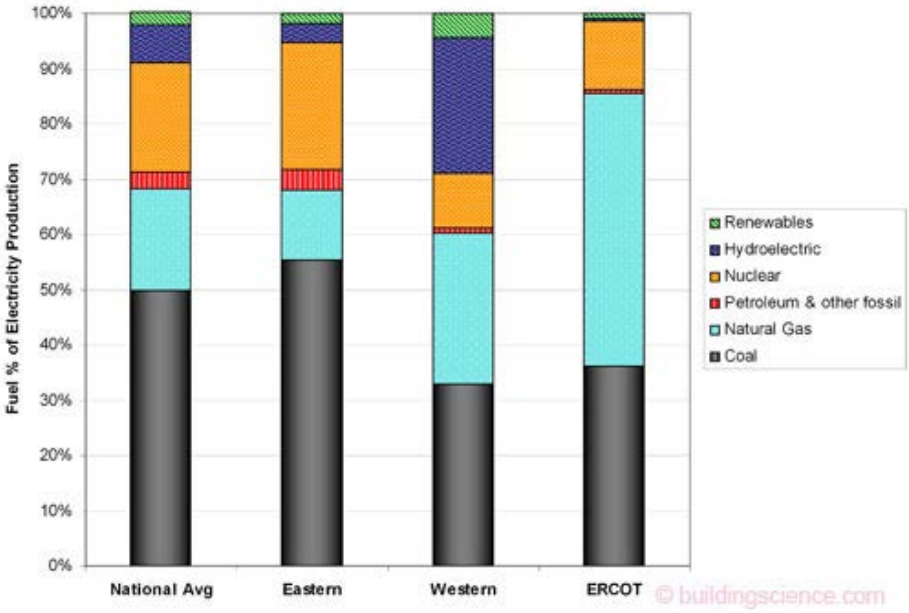

Figure 23. Electricity fuel (Ueno & Straube, 2010)

Another factor of site-source energy conversions is carbon emissions, typically measured in units of carbon dioxide equivalent ($CO_{2equivalent}$) expressed as mass (i.e. natural gas generates 0.088 lbs CO2equivalent for each $kWh_{equivalent}$ of delivered energy) (Ueno & Straube, 2010). The figure below represents the annual CO2 production for each location. Interestingly, while the Boston, Massachusetts model had the least amount of source energy (22.1 kBtu/sf) of the three models, it has the largest amount of annual CO2 production. This is because fossil fuels are the primary fuel to generate electricity in the Northeastern U.S. (Ueno & Straube, 2010). Coal is the primary fossil fuel used to generate electricity in the Northeastern U.S.; coal produces the most amount of CO2 emissions over other fossil fuels such as natural gas or oil (EPA, 2013b). Austria's electricity is primarily generated domestically through renewable sources (primarily hydro) (European Commission, 2007). Since renewables are non-polluting energy sources, it would be expected the Austrian model has the least CO2 production of the three locations even though it did not have the smallest amount of source energy consumed.

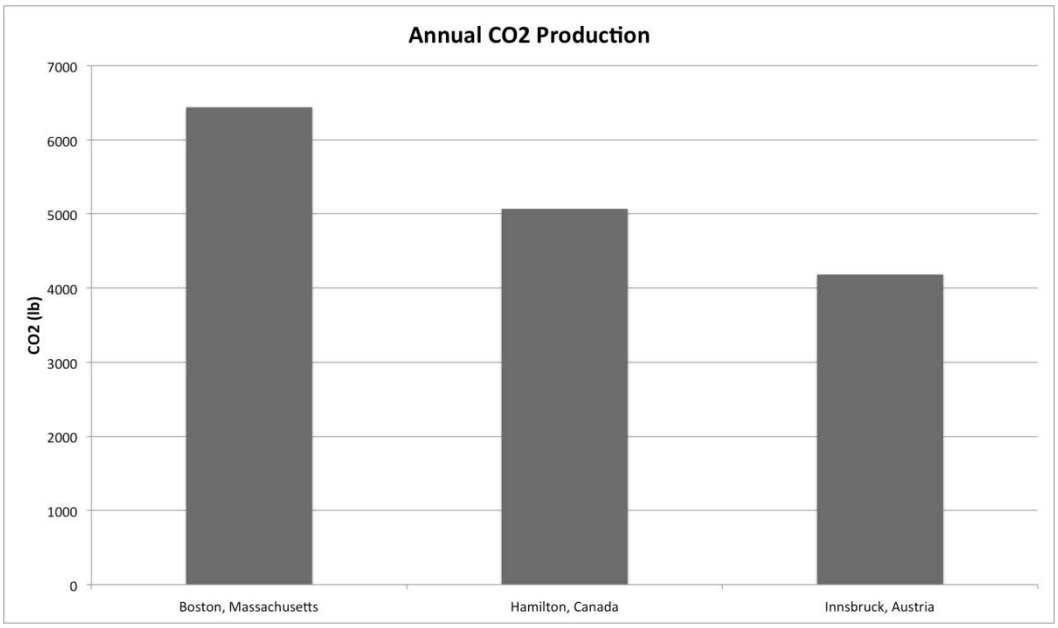

Figure 24. Annual CO2 Production

For the purposes of this research, evaluating both site and source energy was done to evaluate the energy consumption (site) of each model, but also the relative efficiencies of energy supplied to the building (source). The Boston, MA model has the least source and site building energy use, while the Hamilton, Canada model has the highest whole building energy use of the three locations. However, when comparing the source energy use of the buildings, it is equally important to evaluate the CO2 emissions produced by the building to understand the full energy impact of a building.

Heating System Design

Heating Loss

Heat losses (Figure 26) are broken down into the following categories: glazing, walls, solid floors, roofs, external infiltration, and external ventilation. The

program is designed to take the total heat loss in each zone and multiply it by a design margin of 1.2, which gives a recommended heating design capacity. This results in the heating system being oversized by 20%. The 20% safety design factor is an industry standard used when designing heating systems, and the default in many energy simulation programs. This is a conservative approach to sizing a heating system if only minimal information is known about the construction and air infiltration of the building, especially in existing, older buildings. However, the safety factor can be reduced in newer buildings by 5%-10% with better building design (Analysis North). This includes knowing construction details such as surface areas, R-values, air tightness, and internal gains. The 20% design factor was used for this research to provide a conservative heating design capacity for each model. Choosing an appropriate design factor is important in not over sizing space-heating equipment, which can result in higher initial system costs, reduces system efficiencies, and compromises occupant comfort.

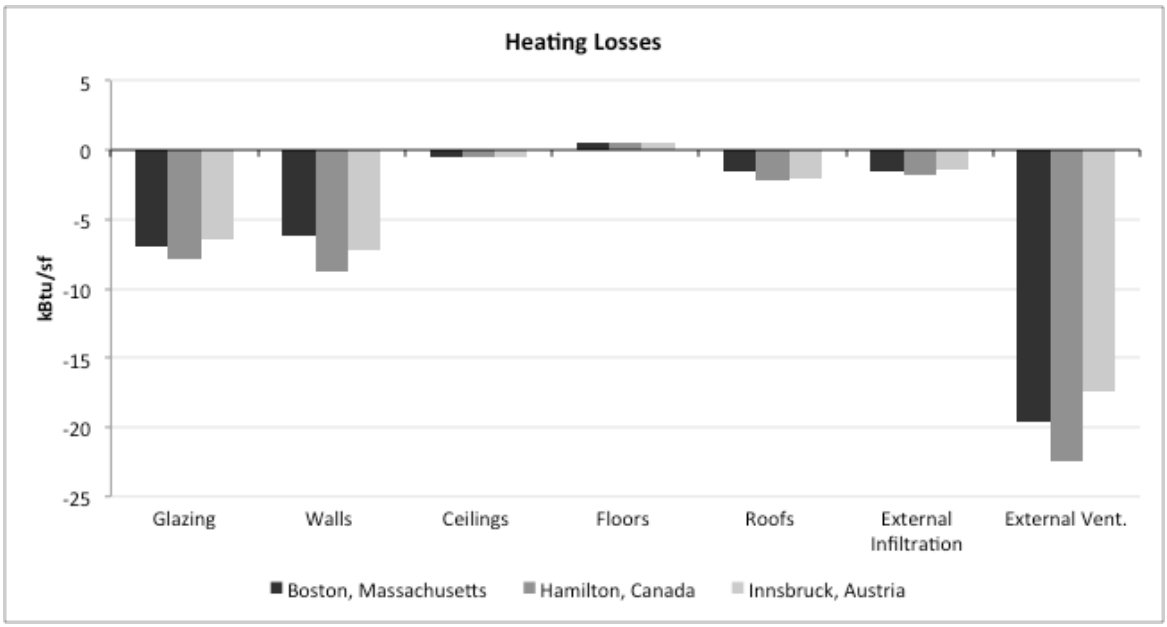

Figure 25. Heating Losses by Category

For all three locations, external ventilation, heat gain due to the entry of outside air through natural ventilation, proved to be the greatest heat loss, followed by walls and glazing. Of the three locations, Innsbruck had the least amount of heat loss from glazing, and Boston had the least amount of heat loss through exterior walls. Innsbruck code requires more efficient windows (U- 0.25) and Boston has the highest effective R-value requirement for exterior wall assemblies (R-20). Each building assembly has a required effective R-value by code; however, the 'effectiveness' lies in the nominal value of the insulation materials and the arrangement and materiality of the uninsulated components within the building assembly. Thermal bridges are parallel paths of heat flow through uninsulated components such as studs, which reduce the effective R-value of the assembly. Additionally, if the insulation is improperly installed, it can result in the actual R-value being less than the nominal, manufacturer-rated R-value (Lawton, 2010).

Therefore, depending on the framing type and spacing (i.e. wood or metal) and installation of the of insulation materials, thermal bridging can be reduced, and ultimately mitigate heat loss.

The building culture of a region plays a large role in ensuring buildings are built to the local energy code requirements. The effective R-value of each building assembly is only 'effective' if the insulation materials are installed properly and areas of thermal bridging are minimized. One way to ensure installation best practices and code requirements are met is through energy code enforcement and investing funding in training, outreach, implementation, and support enforcement. Code enforcement of each location is discussed and impact of missed energy savings is evaluated. Lack of compliance can result in buildings consuming more energy than designed. A recent code compliance savings study by the Institute for Market Transformation (IMT) estimates that widespread lack of code compliance in the U.S. is as high as 50% in some regions (Institute for Market Transformation, 2013). Most states leave enforcement of the code to the local jurisdiction or municipality, which is the case in Massachusetts. The study evaluated each state's potential energy and dollar savings if compliance with building energy codes were improved by 25% or 75%. The table below shows total savings of new residential and commercial buildings by annual - first year, annual - 10th year, and lifetime savings of 5 years construction (2013-2017).

	25% Compliance Improvement		75% Compliance Improvement	
Total Savings	Millions	MMBTU	Millions	MMBTU
Annual (1st year)	$1.36	58,761	$4.07	176,284
Annual (10th year)	$27.46	1,118,282	$82.39	3,354,847
Lifetime savings of 5 years construction (2013-2017)	$278.79	11,295,355	$836.36	33,886,066

Table 7. Estimated Potential Energy and Dollar Savings with Code Compliance Improvement for Massachusetts (Institute for Market Transformation, 2013)

The results of this study reveal the potential energy savings in Massachusetts with improved code compliance could save between 58,761 MMBTU (25% improvement) and 176,284 MMBTU (75% improvement) annually in the first year. This potential for energy savings if code compliance is improved indicates that even with strict energy code requirements new homes may not be as efficient as a home that complies with slightly less strict requirements.

In Canada, each province implements their own strategy of code enforcement, which commonly includes some or all of the following aspects (Shui & Evans, 2009):

- Design reviews,
- Inspections at several stages during construction,
- Penalties for non-compliance, including withholding construction and occupancy permits and charging fines,
- Training for building inspectors and other stakeholders, and
- Licensing of building trade workers and professionals.

Hamilton is located in the Canadian providence of Ontario; local jurisdictions or municipalities use different code enforcement strategies. The city of Hamilton

requires contractors to apply for a building permit and schedule various types of inspections, which include footings, foundation drains, framing/structural, plumbing, heating/ventilation, insulation/vapor barrier, fire separation, exits, fire protection systems, occupancy, final (City of Hamilton, 2013). When a building permit is applied for, the type of compliance path must be established as either EnerGuide80, a performance-based path, or supplemental, a prescriptive path such as the EnergyStar program (Bradford West Gwillimbury Building Division, 2012). The EnerGuide80 compliance path requires the builder to demonstrate the home's level of energy performance through submittal of the Design (drawings), software (HOT2000 computer software) compliance, and blower door test results to determine air leakage. The EnerGuide compliance path was started with the release of the new energy code in 2012; therefore, it is unknown how many builders are using the performance or prescriptive compliance path methods.

Compared to the U.S. and Canadian enforcement strategies, in 2006 Austria developed a performance-based code incorporating a mandatory enforcement strategy. The enforcement strategy is carried out by each state and considers air-tightness testing and thermal bridging considerations (Global Buildings Performance Network, 2013). On-site inspections are mandatory during construction and post completion. If a building does not comply with the performance standard, penalties can result in refusal of permission to construct or occupy (Global Buildings Performance Network, 2013). No data was available on the actual compliance rate of new residential housing in Austria; however, due to

the performance-based energy code and mandatory enforcement it can be assumed the compliance rate is at or near 100%.

The impact of heating losses on the design capacity and code compliance enforcement of each location is discussed further in the Interpretation section.

Heating Design

The heating design calculation in DesignBuilder is calculated to determine the size of the heating equipment to sustain comfort and performance on the coldest winter day. The heating design simulation in DesignBuilder was set to heated zones, which are heated constantly to achieve the heating temperature set point using a simple convective heating system. Based on the set points used (ASHRAE Standard 90.2-2007 *Energy-Efficient Design of Low-Rise Residential Buildings)* and each location's building assembly inputs, Figure 25 shows that Boston (42.95 kBtu/h) and Innsbruck (41.7 kBtu/h) have similar heating design capacities, while Hamilton has the largest heating design capacity of 51.50 kBtu/h.

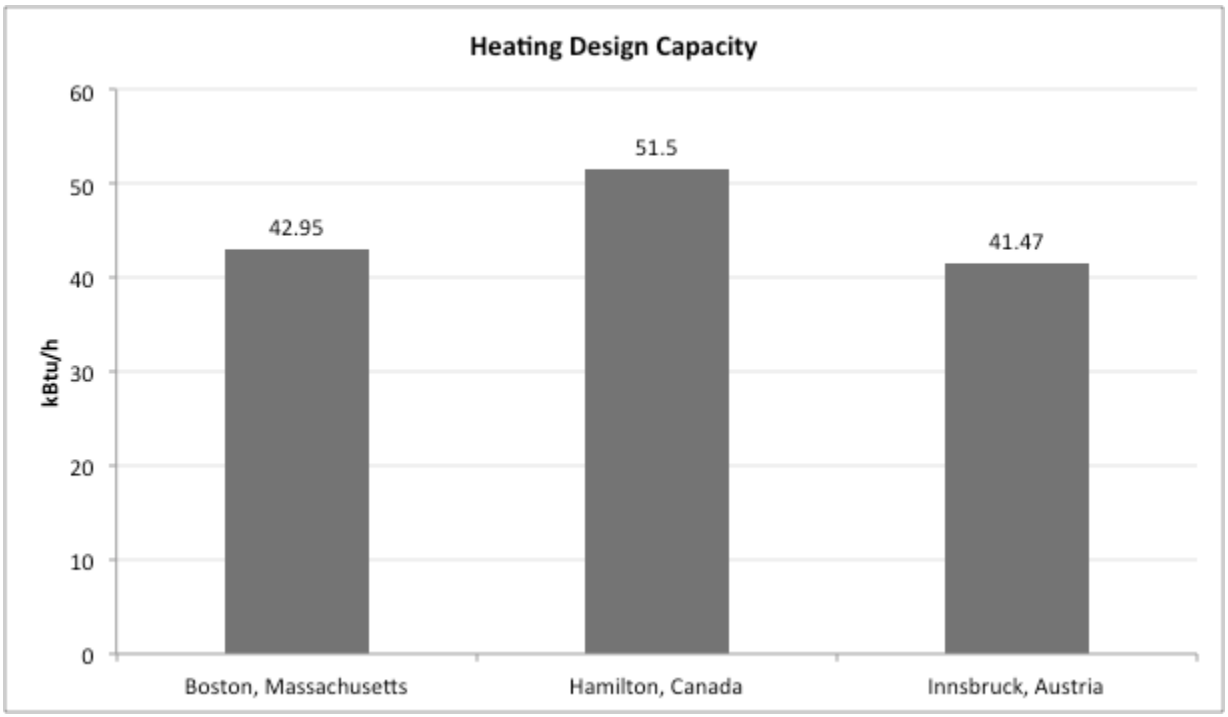

Figure 26. Heating Design Capacity by Location

Heating capacities are calculated by simulating the required capacity to maintain the temperature set points and associated heat loss in each zone. ASHRAE temperature set points were used in all three models to maintain consistency and are commonly used for occupant comfort and health, and for preventing mold or other damage to building materials (Zhivov, 2013). While these set points are general guidelines in heating design, different cultures may have different adaptive comfort levels resulting in higher cooling or lower heating temperature set points. This could result in the thermal set points ±2 degrees Fahrenheit or even greater, depending on the occupants' comfort threshold.

Based on the heat losses and set points, the results of the heating design capacities range from 41,470 BTUH to 51,500 BTUH and were lower than expected. This is most likely because the homes are slab on grade, and not modeled with a

conditioned basement. Homes with conditioned basements in climate zone 5 can have significant heat loss due to basements, resulting in a larger heating design capacity. Basements inherently have greater heat loss than slab foundations due to the increase in the area to surface ratio. The heat loss from the foundation cannot be calculated in the same way as other assemblies in the home, the impact from the ground must be factored into the calculation. The amount of heat loss, regardless of the foundation type, is a factor of three things: insulation levels and configuration of ground components, area to surface ratio, and climate (number of heating degree days) (Kennedy, 2007). The greatest loss in a slab (or basement) is around the perimeter. Therefore, exterior insulation along the perimeter will help reduce heat loss to the exterior due to the temperature differential between the ground and component surface area. A slab contains less surface area in contact with surrounding ground matter, while a basement has greater surface area (i.e. walls and floor) resulting in greater heat loss.

Along with greater heat loss, basements have other advantages and disadvantages over a slab foundation. Basements offer more square footage for a home, which can be used as a living space, placement of HVAC and other mechanical equipment, and additional storage for the occupants. However, there are also drawbacks to basements such as added moisture to the home. Due to ground matter surrounding the basement foundation and the temperature differential, an increase in moisture in the home can occur. With added potential for moisture from a basement foundation, the HVAC system must compensate to draw moisture out of the space resulting in increased energy use.

Whole Building Simulation

This section will present the yearly simulation results. Specifically, internal gains, fabric and ventilation (gains and losses), fuel breakdown, and yearly CO2 production are reported. The whole building simulation uses values over the entire year for a total of 8760 hours. The simulation was designed to run six time steps per hour, which results in the building thermal network solved six times per hour, and interpolates the hourly weather data into the zonetime step.

Internal Gains

Occupants, appliances and equipment (i.e. stoves, laundry machines, etc.), lighting, and solar gains (from exterior windows) all contribute to internal heat loads. Focus was directed to the thermal envelope and HVAC systems, excluding appliance and lighting from the simulation. While lighting and appliances do impact internal heat gains, they can vary greatly in residential applications due to type and frequency of occupant use. In addition, the size of appliances between the three locations also varies greatly. For example, the average refrigerator size for a family of four in the U.S. is between 18 and 22 cubic feet including a freezer (top or side door) (Energy Guide, 2013), which has an annual energy use of approximately 578 kWh/year (21 cu. ft unit) (ENERGY STAR, 2013). While the average refrigerator size in Canada is approximately 16-18 cubic feet with an average annual energy consumption of 454 kWh/year(Natural Resources Canada, 2010) In Europe space is at a premium, therefore appliances tend to be smaller and consume less energy. In addition, over 40% of European households have separate refrigerator/freezers

units (Energy Guide, 2013). Despite the unit differences an unofficial report indicated the average size of a European refrigerator is around 10 cubic feet (Eco Modernism, 2010) with an average annual energy use that is less than 400 kWh/year (Eco Modernism, 2010). With these differences in appliance size for each location, the differences in internal gains could vary greatly if the energy models were sensitive to these details. In an effort to create comparable models, appliance defaults were used.

The house prototype for each location displayed anticipated internal gain distributions (Figure 27). Internal gains from occupants is the lowest, while internal gains as a result of solar gains from exterior windows was the highest across all three locations. For the simulation, 'residential common area standing' was selected for the occupancy activity type. A different activity type has the potential to increase or decrease the internal gains from occupants.

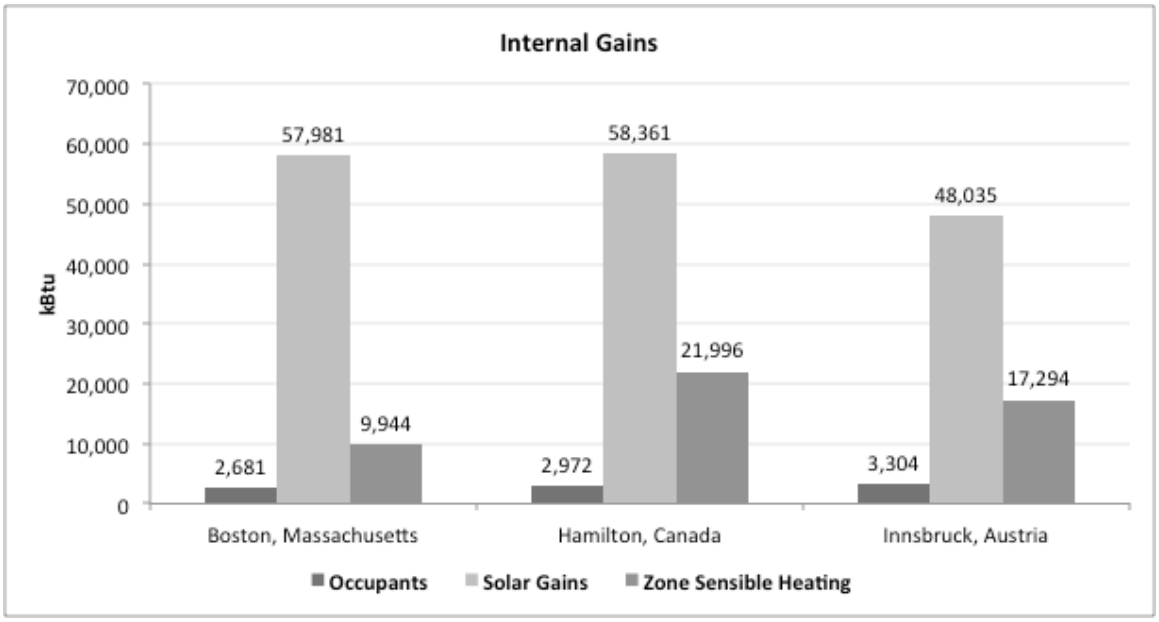

Figure 27. Internal Gains

Solar gains are the most significant internal heat gain in all three locations. While this is significant due to the heating dominated locations with relatively moderate summers, internal gains can aid the heating load during the winter months. Conversely, in the summer months this can add discomfort for occupants if air conditioning is not present. This is the case with many homes in Canada and Austria that have relatively cool summers. Air conditioning is found in many parts of the U.S., especially in regions with hot (i.e. southwest) and hot-humid summers (i.e. Midwest) (U S Census Bureau, 2010). However, in Canada and Austria many homes do not have air conditioning, which is also partly due to cultural comfort levels. Many European countries, even with warm summers, historically did not have air conditioning in residences because many holidays (vacations) are planned for hot summer months to escape the heat. In some European regions this has changed in the last decade due to a shift in cultural acceptance of air conditioners (Tagliabue, 2003).

Fabric and Ventilation

The results from the hourly simulation for the heat gains or losses through the fabric and ventilation of the home suggest that glazing type and percentage are significant. In DesignBuilder, 'fabric' is considered a surface that allows conductive heat gain to another internal space or the exterior. For each of the three locations, the most significant heat loss is from the glazing and walls. Net negative heat gain from glazing indicates short-wave radiation from the zone is transmitted through the window to the exterior. This is most apparent in the Canadian model (Figure

29), while the Massachusetts and Austrian models showed 9% and 17% less loss, respectively. The Canadian model has less heat loss from glazing even with a U-value of 0.55, which is the least efficient of the three energy codes. The second greatest heat loss is through walls. In each model, except in Massachusetts, the walls showed the most significant heat loss. Austrian and Canadian energy codes require a minimum R-16 wall assembly, while an R-20 assembly is required in the Massachusetts code. Interestingly, even with the R-16 requirement for both the Canadian and Austria codes, the Austrian model (Figure 30) performed 18% better than the Canadian model (Figure 29). This is most likely due to more heating degree-days in Hamilton, Canada (6264 HDD 65^{0}F) than in Innsbruck, Austria (6143 HDD65^{0}F)

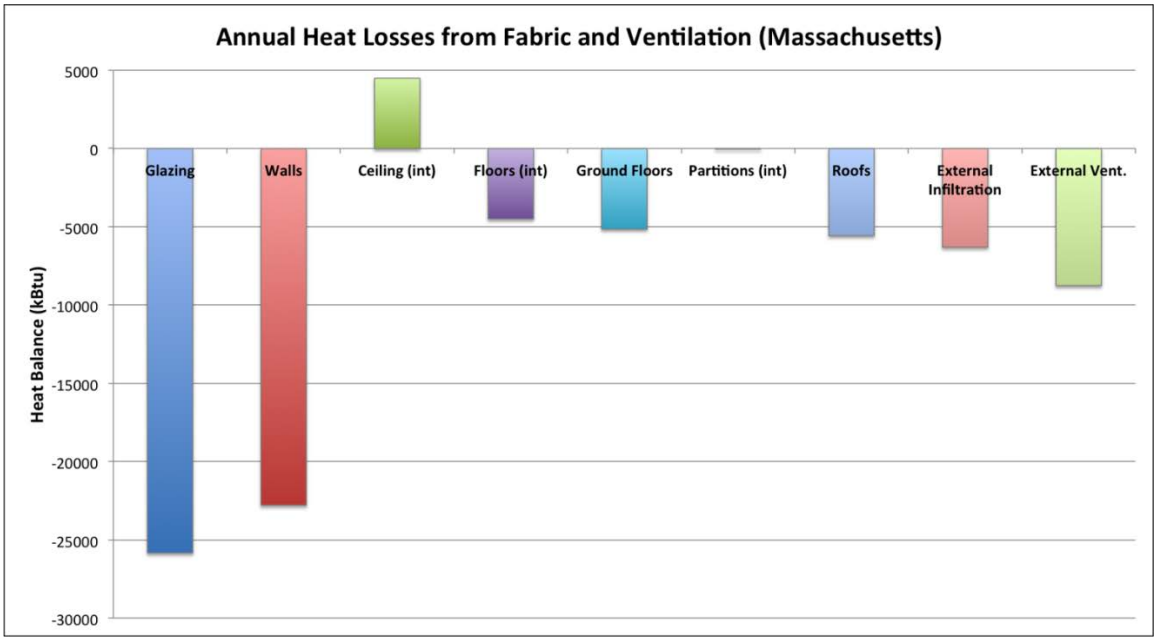

Figure 28. Fabric and Ventilation – Boston, Massachusetts

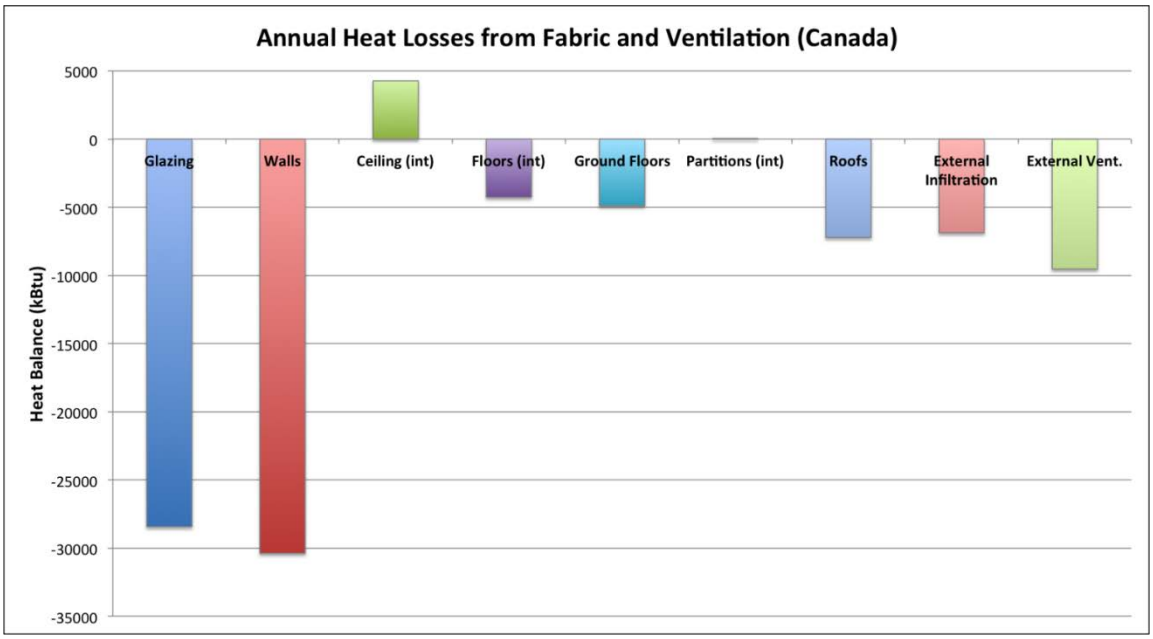

Figure 29. Fabric and Ventilation – Hamilton, Canada

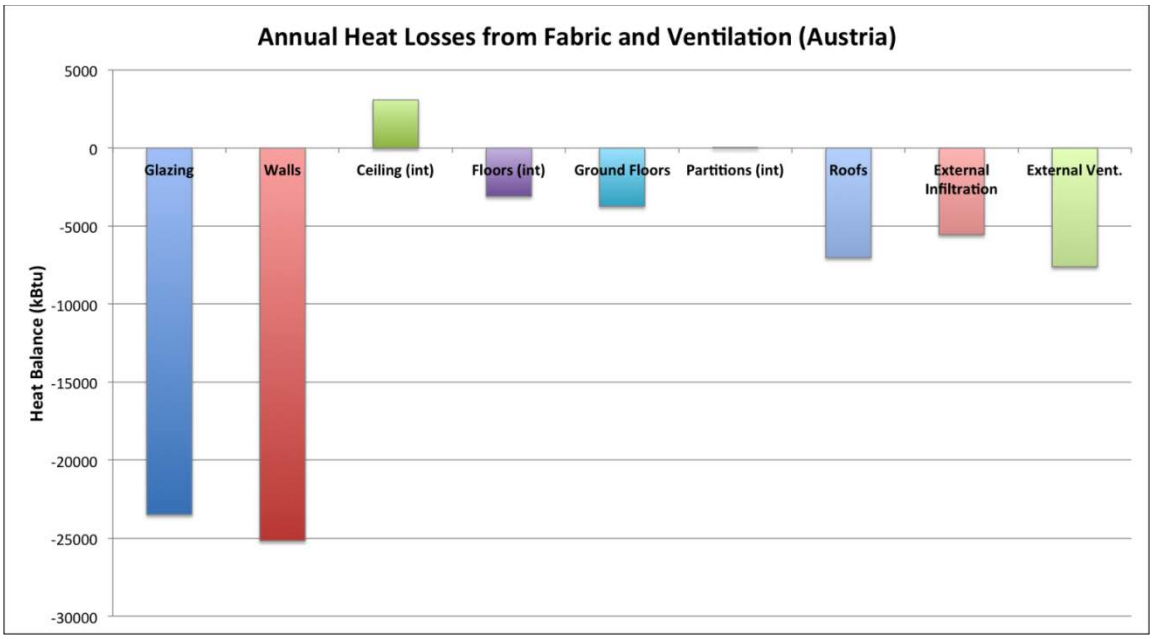

Figure 30. Fabric and Ventilation – Innsbruck, Austria

The heat gain from the ceilings (internal) and the heat loss from the floors (internal) are null as the gains and losses from these assemblies cancel each other out in each location. DesignBuilder defines external air infiltration as heat gain (or

loss) as a result of non-unintentional (i.e. natural ventilation) air entry through cracks and holes in building fabric. In each location, some heat loss through air infiltration is expected. This will vary depending on overall air tightness of the building as a result of construction methods for each location. Lastly, external ventilation or heat loss due to the entry of outside air through the air distribution system, results in nearly the same amount of loss for each location.

Fuel Breakdown

In this study, the HVAC system fans, heating, and domestic hot water energy use will be evaluated. Figure 31 outlines the yearly fuel breakdown of each location.

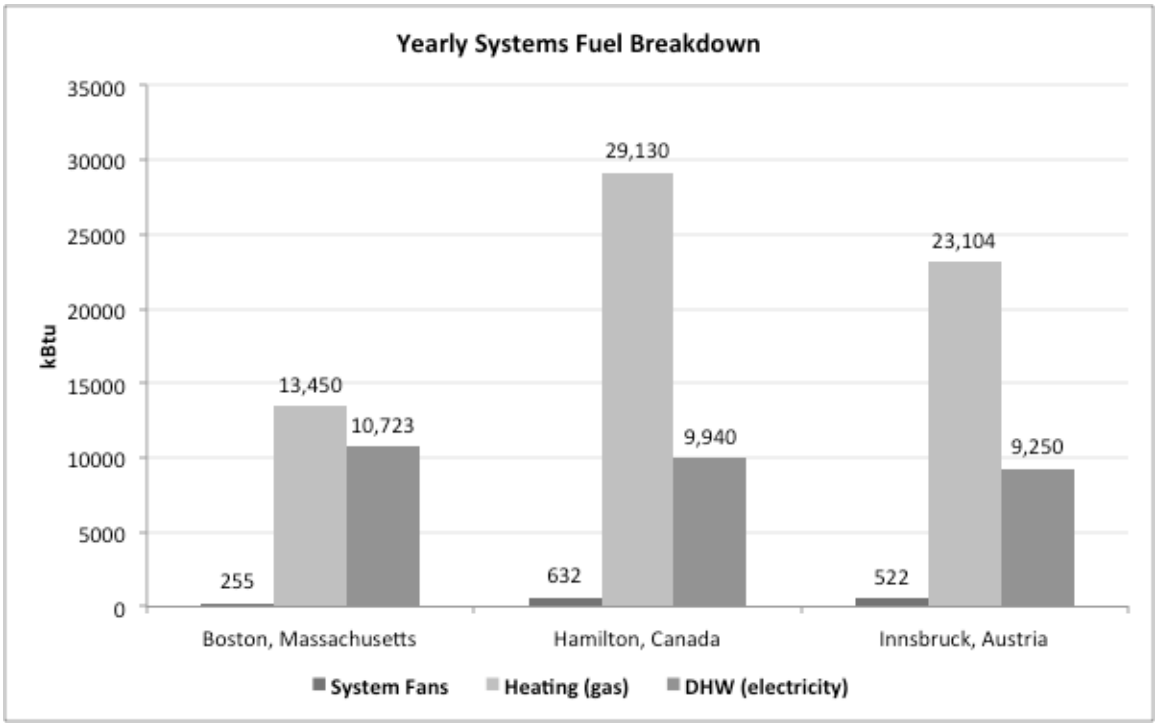

Figure 31. Yearly Fuel Breakdown by Location

Each of the three locations has a similar monthly profile (Figure *32*, Figure 33, Figure 34) for electrical energy to operate HVAC system fans. The energy needed to operate the HVAC fans has a direct relationship to the gas consumed to operate the heating system of each home. The Canadian (6264 HDD 65^0F) and Austrian (6143 HDD 65^0F) models have higher fuel usage during cold winter months, as a result of having more heating degree-days than Massachusetts (5648 HDD 65^0F). Therefore, a building with identical structures and insulation levels built in two different locations will consume different amounts of heating fuel depending on the difference in heating degree-days. Heating degree-days are calculated by adding the daily high and low then dividing that number by 2 to get the daily average which is then subtracted (in the case of heating-degree days) by the base temperature. A base temperature of 65 is commonly used in the United States and served as the base temperature for comparison among each location. If the daily average is greater than 65 degrees Fahrenheit (18 degrees Celsius) there are no heating degree-days for that day. If the daily average is below 65 degrees, then it is subtracted from 65 to find the number of heating degrees for that day. The base temperature chosen to calculate heating-degree days should be different for each building due to different heating on/off set points based on human comfort needs in a particular building. For example, an older existing building may have a greater number of heating degree days with a base temperature of 65 degrees (F), but a new building, with better overall building envelope efficiency, may use a lower base temperature of 50-55 degrees (F). A lower heating degree-day base temperature of 50-55 degrees indicates the temperature outside can be as low as

50-55 degrees before heating is called in the building; whereas, a base temperature of 65 indicates the heating is called once the outside temperature is lower than 65. If these two buildings were located in the same climate, the building with the base temperature of 50-55 degrees would call for less heating than that of the building with a base temperature of 65 degrees. However, a constant base temperature should be used when comparing the climate of one location to another. While the same base temperature was used in this research, the reality is each building may have a lower base temperature depending on construction methods and practices of each location.

Lastly, the total energy consumed by the domestic hot water systems varies by 14% and is a result of the system efficiencies. Innsbruck, Austria has the highest efficiency rating of 86%, resulting in the least energy consumed (9,250 kBtu). Whereas, the Boston, MA model had the least efficient system requirement of 76%, resulting in the most energy consumed of the three models (10,723 kBtu). The amount of energy consumed is directly related to the fuel type (gas in this case) and the system efficiency.

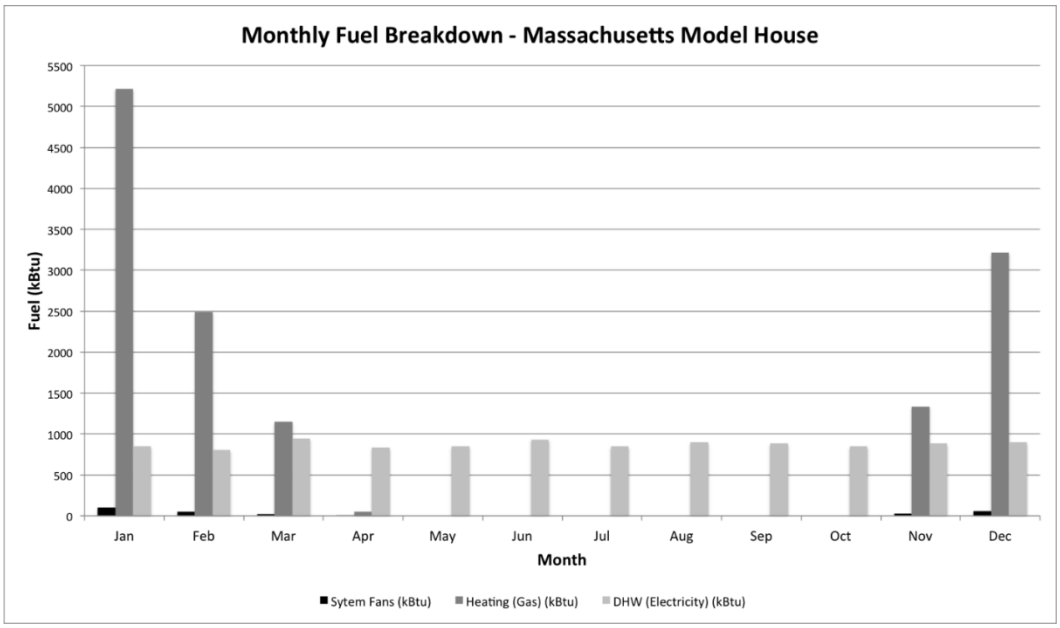

Figure 32. Monthly Fuel Breakdown – Boston, Massachusetts

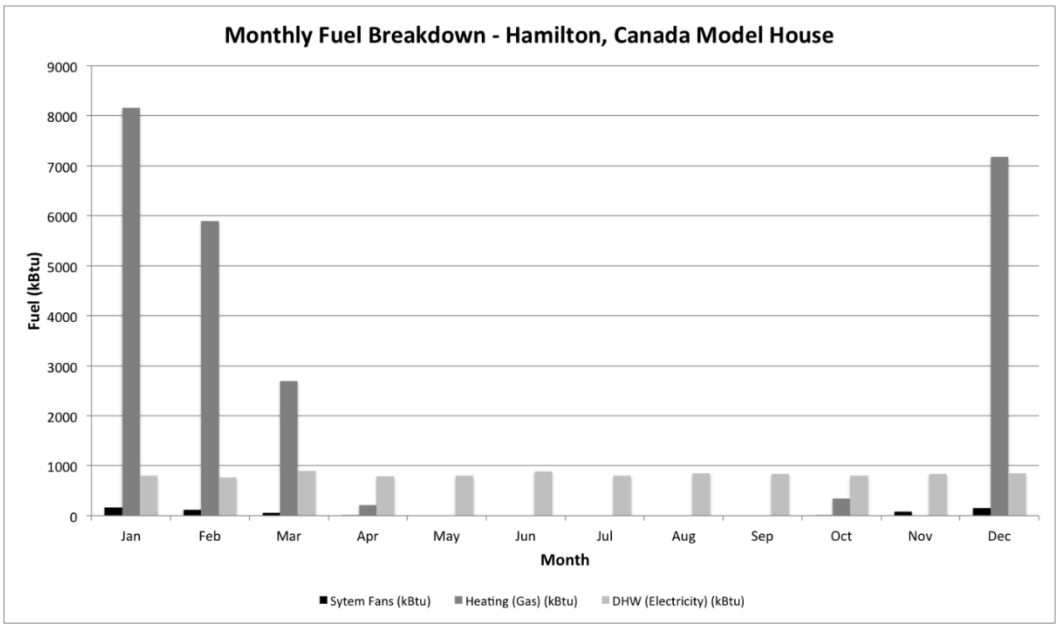

Figure 33. Monthly Fuel breakdown – Hamilton, Canada

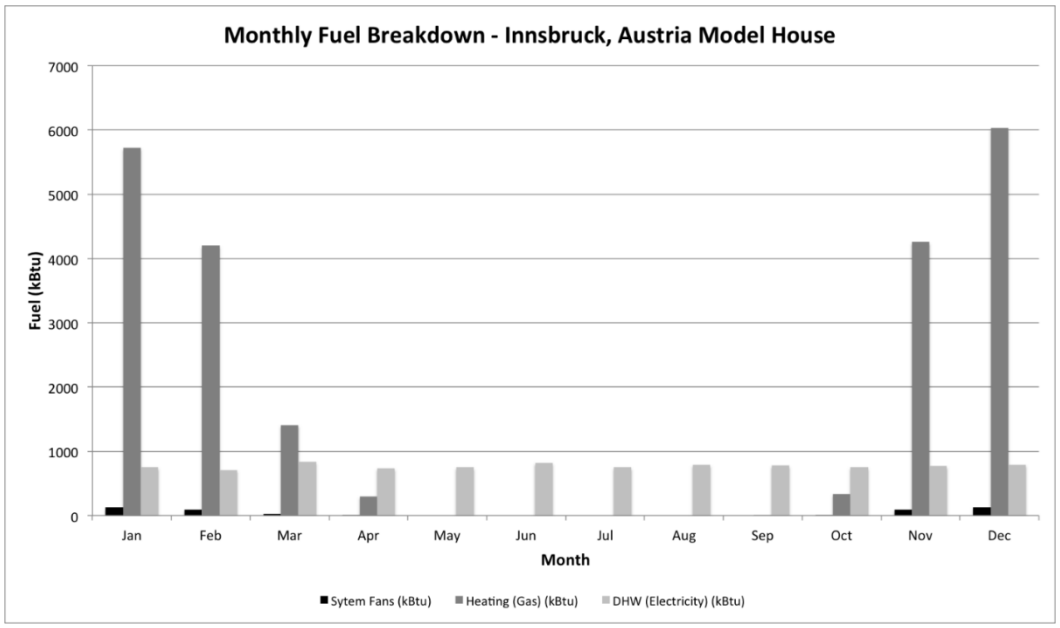

Figure 34. Monthly Fuel Breakdown – Innsbruck, Austria

The results presented in this chapter will be discussed in more detail in the next chapter. The discussion will include insights gained from comparing each model in relation to the inputs for each location. In addition, various other aspects of each location's building culture are evaluated.

CHAPTER 6

DISCUSSION OF FINDINGS

Analyzing the results presented in the previous chapter offers a means to quantify and evaluate the extent of energy savings as a result of each building code requirement. In addition, a comparison of each location's building culture and how this affects the standards in place is discussed. Building culture includes factors such as the training of building professionals and energy reduction goals.

Overall, the modeled inputs (Table 8) of the Massachusetts energy code resulted in the least whole building and HVAC energy use of the three models. However, these are predicted energy use assuming the home is actually constructed to meet the effective R-values of each assembly requirement. Based on the energy code requirements and number of heating degree-days of Massachusetts this model would demand less whole building and HVAC energy use over the Canadian and Austrian models. Due to these two factors, the predicted heating demand of the Massachusetts home is less than that of the Canadian and Austrian models, which have more heating degree-days. These and other factors such as building code compliance and enforcement, training, and building culture of each location, and their influence on the actual performance of a building are discussed in the sections below.

Energy Feature	Boston, Massachusetts, U.S.	Hamilton, Canada	Innsbruck, Austria
Heating Degree Days	3120 HDD 18^{0}C (5648 HDD 65^{0}F)	3462 HDD 18^{0}C (6264 HDD 65^{0}F)	3395 HDD 18^{0}C (6143 HDD 65^{0}F)
Wall Insulation	U-0.057 (R-20)	U-0.062 (R-16)	U-0.062 (R-16)
Slab Insulation	U-0.10 (R-10)	U-0.11 (R-9)	U-0.071 (R-14)
Floor Insulation	U-0.033 (R-30)	U-0.038 (R-26)	U-0.034 (R-29)
Roof Insulation	U-0.026 (R-38)	U-0.031 (R-32)	U-0.035 (R-28)
Windows	U-0.35	U-0.55	U-0.25
Doors	U-0.35	U-0.55	U-0.31

Table 8. Energy Code Effective R-values by Location

While Massachusetts's assemblies have the greatest overall effective R-values, the HVAC system efficiency requirement is the lowest of the three locations. Both the Canadian and Austrian codes require the heating system to have greater than 90% AFUE, while the Massachusetts code requires a minimum system efficiency of 88%. This small difference in HVAC system efficiency, in combination with the building assembly requirements, results in a 56% difference in HVAC energy use between the three models. A noticeable difference in the building envelope requirements between the three locations is the range of U-values for the windows and doors. The most efficient requirement for windows and doors is found in the Austrian energy code. The U-values of windows and doors is 0.25 and 0.31, respectively. While the Massachusetts and Canadian requirement for both windows and doors is 0.35 and 0.55, respectively. This equates to a 9% increase in heat loss in the Massachusetts model compared to the Austrian model, and a 17% increase in heat loss for the Canadian model compared to the Austrian model. This large difference can have a significant impact on the design loads and a home's overall energy profile if a home has a high window-to-wall ratio (WWR). The house

prototype designed for this research has a WWR of approximately 15%. Window to wall ratios in new U.S. residences typically do not go over 16%-18% (Holladay, 2011). As seen from the results of each model the heat loss from the glazing (windows) was significant in each model; however, due to the small WWR the impact on the buildings overall performance was minimal. If the WWR ratio were greater than 20%, it would have a significant impact on the design loads. The ICC requirement for a WWR threshold to determine if a home follows a prescriptive vs. performance path historically was set at 15% WWR. The ICC currently does not require a WWR ratio to be calculated for residential buildings. Rather, a total UA alternative (using prescriptive table U-factors and insulation levels) or the performance path can be followed (Holladay, 2011). The Canadian model would be impacted the most, due to its lower U-value requirement for windows and doors. Whereas, if the WWR was increased the same for the Austrian model, the impact would still be noticeable, but would result in less of an impact due to the efficient window requirements.

Simulating building energy performance is one way to determine the predicted energy performance of a building based on minimum energy code requirements for a region. However, the building culture of the location can also be a factor in a buildings actual performance, regardless of the minimum thermal requirements. Despite strict thermal envelope and mechanical system efficiencies, a home can be built to a low standard and therefore not perform as predicted. Issues such as code compliance and enforcement, training of building professionals, energy prices, and energy reduction goals of each location will be discussed below.

Impacts of Building Culture

Code Compliance and Enforcement

Code compliance and enforcement of energy codes is an important factor in a home's actual energy performance. The local building energy code may have strict standards for effective R-values, but if there is a lack of compliance and enforcement of the standards the home may not actually be performing to the standards it was designed to achieve. The table below summarizes the HVAC and whole building site energy of each model, the code compliance options, and level of enforcement, all outlined in the results section above. The intent in comparing the three metrics is to understand the actual performance of a building if built according to the energy code requirements of each location.

	HVAC Energy Use (kBu/h)	Whole Building Energy Use (kBtu/h)	Code Compliance Method	Enforcement
Massachusetts	6.63	10.98	Prescriptive or performance	Moderate
Hamilton	14.35	18.59	Prescriptive or performance	Moderate
Innsbruck	10.97	15.56	Performance-based	Mandatory

Table 9. Heating Design, Code Compliance, and Enforcement Comparison

Based on the simulation results of energy use, overall Massachusetts has the least amount of energy use. However, there are two options for code compliance: prescriptive or performance based. Regardless of the compliance method, onsite enforcement of the code is not mandatory and done infrequently. This means a contractor can build to either compliance method, but not all homes are verified to

meet code standards throughout construction. Therefore, while the Massachusetts model has the least amount of predicted energy use, they may not actually be achieving these savings due to lack of code enforcement. Whereas the Austrian model has 40% more HVAC energy use and 30% more site energy use than the Massachusetts model, but has a performance-based code compliance method only (with mandatory air tightness testing) and mandatory enforcement. Code compliance and its enforcement are very important in the actual performance of a building. Additionally, training of building professionals is also a key factor in ensuring the home is constructed to its designed standard and meeting the effective R-value requirements required by code.

Training of Building Professionals

Training of the building professional work force is essential to the actual performance of buildings built according to the base energy code of a specific location. First, contractor licensing requirements and building code enforcement of each location will be outlined, then the opportunities for education and trainings available will be discussed. In the state of Massachusetts, any one and two family dwellings less than 35,000 cubic feet of enclosed space must be constructed under the supervision of a licensed Construction Supervisor by the State Board of Building Regulations and Standards (Building License Training Institute, 2013). If a one or two story residence is above 35,000 cubic feet, the work must be done under the supervision of a licensed engineer or architect. The single-family prototype designed for this research is less than 35,000 cubic feet; therefore, the licensing of a

construction supervisor will be discussed. To obtain a contractor's license the candidate must have a minimum of three years of building construction or design experience and must also pass a written exam. The candidate is tested on the provisions of the MA State Building Code, along with other reference standards. Once a construction supervisor becomes licensed, he or she must maintain his or her license every two years by completing 6-12 hours of continuing education, depending on the type of supervisor designation licensed for. A wide variety of continuing education training programs are available; however, the MA Board of Building Regulations and Standards must approve them. There is a variety of course types ranging from online to field training courses. At present, there are 50+ course coordinators listed on the Commonwealth of Massachusetts website offering approved contractor continuing education courses. Course coordinators listed are state and local non-profits, energy alliances, private contractors, and building professional associations. While there are a variety of course types (i.e. classroom or field work), it is unclear if any portion of the continuing education hours are designated for hands-on field training. In any construction trade, field training is beneficial in constructing buildings to achieve energy efficiency goals. Field training provides an opportunity for trade professionals to develop skills beyond the theoretical teachings of the classroom. Additionally, standards compliance or inspections are other measures to ensuring a building is constructed to the local standards. Without field verification, the integrity of the building standards cannot be measured or verified.

In Canada, each province has different licensing requirements for construction and trade professionals. Even in each province the requirements and rules on how to obtain a license vary depending upon location (i.e. city or rural area). For example, in a larger city, like Toronto and Hamilton, every building trade must have a license obtained specifically for the region they are performing work. In Hamilton, repair and maintenance professionals are also required to have a license (HandyCanadian, 2013). The prerequisites needed to obtain a construction license are more stringent than those of Massachusetts due to the training and licensing requirements. In Ontario, the candidate must provide proof of completing an apprenticeship program in their designated trade. Apprenticeship programs vary by trade, but in general are a minimum of three years under a licensed tradesman with approximately 90% fieldwork 10% classroom learning. Industry standards on length of apprenticeship vary by trade. Once all training hours are approved by a certified tradesperson, a "Certificate of Qualification" is issued and the candidate is allowed to take a qualifying exam in order to become licensed.

Similar to Massachusetts, continuing education is required in Ontario; however, the requirements of renewal are less frequent and depend on changes to the building code and the particular trade license an individual holds. For building officials and construction supervisors, once a new building code is released they are required to take an exam on the updated building code including the energy code. In order to pass, self-study and in-classroom courses are offered by approved vendors listed on the Ontario Ministry of Municipal Affairs and Housing webpage. It is important to note that no field training is required to fulfill the requirement of

new code changes. However, many of the classes listed for continuing education do offer field training not only on new code changes, but the most relevant building practices.

Austria is made up of nine provinces, each with their own version of a building code, covering procedures and functional requirements, and ordinances which cover technical issues (European Commission, 2011). In 2009 the first country-wide building guidelines (OIB-2009) were developed and released by the Austrian Institute of Construction Engineering (OIB). OIB is currently the governing body for creating, updating and enforcing the regulations set forth in the building law. Under the OIB guidelines, the construction of a building must be supervised by an architect, engineer, or qualified builder (Baumeister). A qualified builder can design, construct and supervise other trades if in possession of a current license to practice (European Commission, 2011). A qualified builder's license is current for a lifetime and no continuing education courses are required for renewal. Different trades require different licenses; each trade has a module of training and a final examination for licensing.

Training building professionals can have a great impact on the construction and performance of a building. This is particularly important not only for safety reasons, but also in climates with extreme weather conditions to ensure the building assemblies are installed properly according to the building code. In order for prescriptive building code requirements to be effective and meet performance standards, proper installation of materials must be practiced. Proper installation techniques can be taught using hands-on job training through apprenticeships or

continuing education courses. Each helps to develop skills and transfer trade knowledge from generation to generation in addition to learning current energy efficient installation techniques.

Each of the three locations have different requirements for training of building professionals, some with more hands on field training involved, while others only require written examinations to be passed. Building codes typically do not have stringent requirements for building performance, at this time; however, many beyond code or green code programs require not only prescriptive based requirements, but performance requirements as well. In the next section, beyond code programs and energy reduction goals of each location are discussed.

Energy Reduction Goals

Around the world, energy use in residential buildings is driven by several factors- population, economic growth, building size, service demands, real energy prices, and efficiency of energy service demand delivery (U.S. Department of Energy, 2012). Most developed countries have energy reduction goals, which can have a direct effect on the regions building and energy codes. Setting these goals can be for a number of reasons, for example, reducing dependence on foreign resources, conserving local resources, cleaner air and water, and pressure from the international community to reduce consumption. This section presents energy reduction goals of each location, along with some of the beyond code programs assisting in these goals.

Each of the locations researched historically has had some form of a building code for safety and structural purposes since the early-mid 1900s; however, energy codes in the past ten years have improved drastically. The U.S. first started to put emphasis on energy reduction in new construction in the 1970s and then again in the late 1990s. Austria in 2009 developed its first national code with an emphasis on energy. Canada has had a building energy code since 1997, and released a new version in 2012. While relatively new energy codes have been developed or updated, a combined effort from the building community and beyond code programs to create more stringent standards will advance energy reduction goals.

The US has a variety of energy reduction goals in the commercial and residential sectors, and federal and state building standards. There are two federal energy requirements that impact federal buildings and new commercial buildings- the Energy Independence and Security Act of 2007 and the Federal Leadership in Environmental, Energy and Economic Performance (EO 13514). Both set energy efficiency requirements and sustainable building practices such as "zero net energy" design. Along with federal requirements there are also private sector organizations such as the US Green Building Council and Architecture 2030 that have set reduction goals and created design standards to assist the building community in reaching these goals.

For the US residential sector, there are no federal minimums beyond the currently adopted state energy code for energy reduction. It is the state and local jurisdictions that set mandates and regulations. For example, a jurisdiction can

improve the local building codes, incentivizing builders to build more efficient homes, create energy rating systems, develop or follow an existing voluntary program, or require home performance standards. EnergyStar Homes and LEED are two of the most commonly used rating and home performance standards adopted by local jurisdictions in the US.

Canada also follows energy reduction goals set forth by Energy Star Homes and Architecture 2030. On the federal level, Canada has overall goals of reducing greenhouse gas emissions (GHG). This is an effort adopted under the Copenhagen Accord to reduce GHG 17% below 2005 levels by 2020. This is also in accordance with the U.S. target (Environment Canada, 2013). The Ontario Ministry of Energy is in the process of reviewing and updating their Long-Term Energy Plan, as the current version is set to sunset in 2014. The main focus in the new Long-Term Plan is to continue to create a culture of conservation. The Ministry believes that by setting energy efficiency requirements, encouraging consumer behavior changes, implementing demand management, and creating load displacement their new aggressive goals can be met (Ontario Ministry of Energy, 2013).

In the private sector, Canada has its own Green Building Council (CaGBC) which is a sister council to the U.S. Green Building Council (USGBC). Similar to the USGBC, the CaGBC has created a LEED rating system for the building sector throughout Canada. This is a beyond code program which is voluntary, unless a local jurisdiction requires the standards be met for new construction or renovations. Additionally, other beyond code programs exist, mainly for larger cities in Ontario. These range from prescriptive programs to performance based

incentive programs. Lastly, many of Onatrio's larger cities have citywide conservation and energy reduction goals spanning all sectors.

After review of the energy reduction goals of the European Union and Austria's Ministry of Economy and Labour, the energy reduction goals set forth to be achieved by 2020 are aggressive and more specific than those of the US and Canada. Austria's Climate and Energy Strategy follows targets referred to as 20/20/20. These goals include (Federal Ministry of Economy, Family, Youth, 2013):

- A reduction in greenhouse gas emissions of at least 20% below 1990 levels.
- 20% of energy consumption to come from renewable resources.
- An increase in energy efficiency by 20% by 2020 as opposed to a business-as-usual scenario.
- Austria's 2020 Targets:
  - 34% share of renewable energy.
  - 16% reduction of GHG emissions in non-ETS sectors.

To achieve these goals, in 2006 the Ministry of Economy and Labour developed and enacted the 'Energy Certification Providing Act' ('Energieausweisvorlagegesetz EAVG'), which requires builders and landlords to provide energy certificates when buildings are sold or rented. This is a way to measure the energy performance of new and existing buildings to set a baseline of existing buildings needing renovation and new buildings being built to the current OIB standards. While national standards for certifying buildings in Austria is heavily mandated, the most commonly practiced, industry created, voluntary standard is the Passive Haus. The concept of a Passive Haus "is a building, for which thermal comfort can be achieved solely by post heating or post cooling of the fresh air mass, which is required to fulfill sufficient indoor air quality conditions – without a need for recirculated air

(Djalili, 2010)." The Passivhaus design has been sighted by CEPHEUS to save up to 80% on heating compared to a code built building. This is a significant design effort by the building community to design an energy efficient home that consumes little to no energy. This effort alone surpasses current US and Canadian sustainable building practices. Professors Bo Adamson of Sweden and Wolfgang Feist of Germany designed the Passivhaus concept in Germany in the early 1990s (Passivhaus, 2011). The designers wanted to push the envelope of building design to use the least amount of energy as possible. As a result of the Passivhaus, many of the most efficient building products and prefabricated assemblies are manufactured in Europe. Many of these products are not manufactured or available in the U.S. or Canada resulting in less stringent beyond code programs due such products not available.

Summary of Findings

Strict Energy Codes does not always equal energy efficient homes: The assumption can be made that the stricter the energy code, the more efficient a home is. However, in actuality this may not be the case due to faulty construction techniques or lack of compliance and enforcement to verify the home was built to the standards that apply. This research brought to light the energy code requirements of three locations and analyzed their energy profiles as a result of each requirement. It was found that the Massachusetts model had 41% less whole building energy use than the Canadian model, and 30% less than the Austrian

model. In reality these differences in whole building energy performance may be more or less depending on the practices of the local building culture.

Energy simulations offer a powerful way to compare code requirements: Energy simulation provides a means to compare code requirements and predict energy performance of each model. This study is based on hypothetical buildings; therefore, the actual performance of each building may vary. However, understanding the impact of each code requirement on the energy profile offers a means to quantify differences in each code.

Building culture acts as a medium between code requirements and actual performance: Building culture consists, but is not limited to, the following: training of building professionals, materials used, code compliance, and enforcement of local standards. The building culture of the three locations varies and offers insights into the reality of predicted versus actual energy performance of each locations residential building stock. Of the three locations, Massachusetts has the least stringent training for building contractors. While Austria and Canada have more long term training requirements through apprenticeship programs for contractors and tradesmen alike. Another factor in the actual performance of a building can be related to code compliance and enforcement. It was found that code compliance in the United States overall is less than 50%. With such low compliance, the actual performance of minimum code built homes may result in more whole building energy use than predicted through simulation. On the other hand, the Austrian code mandates each home provides a certificate of energy performance and is inspected

before occupancy certificate is issued. Likewise in Canada, there are 4+ different inspections throughout the construction process before occupancy that verify building standards are set in place according to code. As discussed previously, the actual energy performance of a home is heavily impacted by the building culture of each location.

Energy reduction goals reflect building culture and impact improvement of code requirements: Beyond code efforts (e.g. LEED) reflect a shift in building culture to require stricter construction and energy performance standards. The number of beyond code programs and the level of implementation sheds light on the importance of high performing buildings in a local culture.

CHAPTER 7

CONCLUSIONS AND FUTURE RESEARCH

Building energy code sets the minimum standards for a building's potential energy performance, the training of building professionals, materials used, and overall building culture play a large role in the actual performance of newly constructed buildings. This research focused on predicted energy performance of three location's current energy codes simulated using a model house prototype. In terms of whole building energy use, the Massachusetts model had the least energy use, followed by Innsbruck, Austria and Hamilton, Canada. The energy use at each location was within 20-29% of each other. Building simulation is a powerful way to compare performance requirements and understand the impact of varying requirements.

While the use of simulation is beneficial in many regards, understanding the building culture of each location provides insight into whether the minimum code requirements are being met or exceeded. Additionally, evaluating the beyond code efforts to set higher building standards is also an indicator of the impact building culture plays in the construction of homes. It is through programs such as these mentioned in the discussion that help set the bar for better, and more efficient, building standards.

Building upon this research, other interesting future work might include:

1. Comparison of beyond code programs practiced in each location to evaluate the minimal standard against the regions highest level of performance. Such a comparison would bring to light more cultural differences and advances in

building methods (i.e. techniques, new technologies, etc.) of each location. Additionally, it would offer a means to understand how the beyond code programs can drive the industry to achieve the energy reduction goals set by government or industry associations.

2. Analysis of the cultural, economic, and political history of each region and the influence each has had on rules and regulations of the building industry. In other words, what are the primary drivers of energy efficiency for codes and standards? Understanding of historical influences on a region's building codes can show the state of current standards, and provide guidance on the development of future standards.
3. Evaluation of cost-effective retrofit strategies of each location to meet the energy reduction goals. New construction codes are becoming increasingly strict; however, the average age of the existing housing stock is going on 39 years old (U.S. Census Bureau, Current Housing Reports, 2011). As discussed through this research, each country has short term and long term energy reduction goals; retrofitting existing housing plays a large part in meeting those goals in the long term. With aging building stocks and aggressive energy reduction goals, retrofit options and requirements need to be evaluated.

This research was intended to gain insight into the energy code requirements of two other locations with similar climate conditions. While evaluating the code requirements on paper can provide insight as to how strict the code of each location is, the real evaluation method of actual performance is seen in the building culture

and enforcement of the code. Therefore, when evaluating actual performance of a building one must take into account these factors if performance-testing information is not available for comparison. Building codes are more than just the requirements a builder must adhere to; they reflect the culture and history of the building trade in each location.

APPENDIX A

MODEL HOME: NORTH ELEVATION

APPENDIX B

MODEL HOME: EAST ELEVATION

APPENDIX C

MODEL HOME: SOUTH ELEVATION

APPENDIX D

MODEL HOME: WEST ELEVATION

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