1-1-2011

Least cost analysis for Canadian new housing : identifying the most cost-effective specifications to achieve improved energy efficiency standards

Aya Dembo
Ryerson University

LEAST COST ANALYSIS FOR CANADIAN NEW HOUSING - IDENTIFYING THE MOST COST-EFFECTIVE SPECIFICATIONS TO ACHIEVE IMPROVED ENERGY EFFICIENCY STANDARDS

By

Aya Dembo

B.A.Sc. in Architectural Science

Ryerson University, Toronto, 2003

A thesis

presented to Ryerson University

In partial fulfillment of the

requirements for the degree of

Master of Applied Science

in the program of

Building Science

Toronto, Ontario, Canada, 2011

Author's Declaration

I hereby declare that I am the sole author of this thesis.

I authorize Ryerson University to lend this thesis to other institutions or individuals for the purpose of scholarly research.

I further authorize Ryerson University to reproduce this thesis by photocopying or by other means, at the request of other institutions or individuals for the purpose of scholarly research.

Borrower's Page

Ryerson University requires the signatures of all persons using or photocopying this thesis. Please sign below, and give address and date.

LEAST COST ANALYSIS FOR CANADIAN NEW HOUSING - IDENTIFYING THE MOST COST-EFFECTIVE SPECIFICATIONS TO ACHIEVE IMPROVED ENERGY EFFICIENCY STANDARDS

Aya Dembo

Master of Applied Science

Department of Architectural Science

Ryerson University, Toronto, Ontario, Canada, 2011

Abstract

This thesis presents the methodology developed to identify the most cost-effective specifications that could be applied to the currently practiced new housing constructions in Canada to achieve improved energy efficiency standards, while maintaining an adequate level of thermal comfort.

The results showed that, based on the life cycle cost analysis of 30 years, the optimal solutions (or upgrades) comprised of improvement in the thermal resistance of the building envelope, and installation of the most efficient heating, ventilating, and air-conditioning systems, resulting in up to 31% reductions in the estimated annual energy consumption and the greenhouse gas emissions, while achieving an EnerGuide Rating of 80, thereby meeting the new requirements of the upcoming 2012 Ontario Building Code.

With the installation of a residential photovoltaic system, the estimated profit of up to $89,035 could be achieved through Ontario's micro Feed-in-Tariff (FIT) program, allowing a homeowner to pay for the implementation of additional upgrade(s).

Acknowledgements

This thesis would not have been possible without the kind support of the two of the faculty members whom I had the pleasure to meet and learn from during my graduate studies at Ryerson: Dr. Alan S. Fung, and Dr. Robert (Bob) Roseberry. Their ongoing patience, guidance, and dedication in sharing their expertises with their students have enabled me to complete this thesis successfully.

I would like to extend my gratitude to my family and my boyfriend for their constant support and encouragement throughout this entire process.

I would also like to acknowledge the support and help of the following organizations and individuals:

First, the Canada Mortgage and Housing Corporation (CMHC) and the Centre for Urban Energy (CUE) for their financial support in this research project.

Aspen Ridge Homes, Country Wide Homes, Heathwood Homes, Mason Homes, Rosehaven Homes, and Terra Brook Homes for their participations in the survey.

Mr. John Overall of Union Gas, and Mr. Ken Elsey of Canadian Energy Efficiency Alliance (CEEA) for their valuable suggestions and constructive criticisms.

Last but not least, the fellow undergraduate and graduate students of the Mechanical and Industrial Engineering program, Mr. Amir Fereidouni-Kondri, Mr. Farhan Khaddad, and Mr. Tanveer Sayed for their technical knowledge of heating, ventilating, and air-conditioning (HVAC) systems, and for their insight on the content of this thesis.

Table of Contents

List of Tables

List of Figures

List of Appendices

Nomenclatures

AC	Air-Conditioning
ACH	Air-Change per Hour
AFUE	Annual Fuel Utilization Efficiency
AIM-2	Air Infiltration Model
ASHP	Air-Source Heat Pump
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BA	Building America
BEopt	Building Energy Optimization
BESTEST	Building Energy Simulation Test and Diagnostic Method
BFSS	Brute Force Sequential Search
Btu	British Thermal Units
CaGBC	Canadian Green Building Council
CCHT	Canadian Centre for Housing Technology
CFL	Compact Fluorescent Lighting
CFM	Cubit-Feet per Minute
CHBA	Canadian Home Builders' Association
CMHC	Canada Mortgage and Housing Corporation
CPEI	Cumulative Primary Energy Input [kWh/m^2]
CPI	Consumer Price Index
CREEM	Canadian Residential Energy End-use Model
DHW	Domestic Hot Water
DOE	Department of Energy
DWHR/GWHR	Drain/Grey Water Heat Recovery
EC(PM)M	Electronically Commutated (Permanent Magnet) Motor
EF	Energy Factor
EGNH	EnerGuide for New Houses
EGR	EnerGuide Rating
EIA	Energy Information Administration
EPA	Environmental Protection Agency
ESNH	ENERGY STAR for New Homes
FIT	Feed-in-Tariff
GA	Genetic Algorithms
GCHP	Ground-Coupled Heat Pump
GHCC	GreenHouse Certified Construction
GHG	Green House Gas
GJ	Gigajoule
GSHP	Ground-Source Heat Pump
GTA	Greater Toronto Area
GWh	Giga-Watt Hour
HDD	Heating Degree Days
HERS	Home Energy Rating System

HRV	Heat Recovery Ventilator
HVAC	Heating, Ventilating, and Air-Conditioning
ICFs	Insulated Concrete Forms
IEA	International Energy Agency
J	Joule
kWh	Kilo-Watt Hour
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCCA	Life Cycle Cost Analysis
LEED(H)	Leadership in Energy and Environmental Design (for Homes)
Low-E	Low-Emissivity
LPG	Liquefied Petroleum Gas
MBH	Million BTU per Hour
MJ	Megajoule
MMAH	Ministry of Municipal Affairs and Housing
MNECB	Model National Energy Code for Buildings
Mt	Megatonnes
NAHB	National Association of Home Builders
NBCC	National Building Code of Canada
NEB	National Energy Board
NPV	Net Present Value
NRCan	Natural Resources Canada
NRCC	National Research Council of Canada
NZE or ZNE	Net Zero (or Zero Net) Energy
OBC	Ontario Building Code
OME	Ontario Ministry of Energy
OMF	Ontario Ministry of Finance
ON	Ontario
Pa	Pascal
PJ	Petajoule
PV	Photovoltaic
RSI or R-value	Thermal resistance [m^2K/W or ft^2hrF/Btu]
SEER	Seasonal Energy Efficiency Ratio
SHEU	Survey of Household Energy Use
SHGC	Solar Heat Gain Coefficient
SIPs	Structural Insulated Panels
SIR	Saving-to-Investment Ratio
TRNSYS	TRaNsient Systems Simulation
U or U-value	Overall coefficient of heat transfer [W/m^2K or Btu/ft^2hrF]
U.K.	United Kingdom
U.S.	United States

Chapter 1

1 Introduction

1.1 Background

With an escalated awareness for limited energy resources, the urgent need to reduce energy consumption and greenhouse gas (GHG) emissions in the residential sector has been brought to the forefront. The residential sector in Canada accounts for 17% of the total secondary energy consumed, which is equivalent to about 70 megatonnes (Mt) of GHG emissions being released a year (Canada Mortgage and Housing Corporation [CMHC], 2008). In 2007, it was estimated that 63% of the energy was used as a result of heating the indoor space of the home to provide thermal comfort to the occupants (Natural Resources Canada [NRCan], 2011). Both natural gas and electricity are the dominant energy sources used in heating the majority of households in Canada, and thereby increasing the importance of finding alternatives to reduce the use of these non-renewable energy sources.

There is also an increased demand in the residential sector to advance and implement energy saving measures that can be incorporated into currently practiced new housing constructions. However, one of greatest barriers for such implementation is cost. A recent study conducted by EnerQuality Corporation (2009) reported that today's consumers are willing to pay an average additional cost of $13,183 or more for an energy efficient home, and 40% of them are willing to pay an additional $10,000 for a home with additional energy efficient features, for example, air-conditioning system, windows, appliances, furnaces, lighting, drain water heat recovery, and heat pump, despite the current declining economic situation.

If energy saving measures were applied to current conventional new housing, two financially induced scenarios would emerge: First, the incremental costs (i.e., equipment and installation) associated with the energy saving measures (hereon upgrades), which would results in a higher initial capital cost or mortgage payment: Second, the upgrades would reduce the energy consumption of the home resulting in lower energy cost (Anderson et al., 2006; Christensen et al., 2005). In Ontario, the mumicipalities claim that, if a new home were to be built in accordance with the 2012 Building Code of EnerGuide 80 (effective December 31, 2011), it could have up to 35% of estimated energy savings, despite having an estimated increase in capital cost of up to $6,600, and will pay back within seven to eight years (Ministry of Municipal Affairs and Housing [MMAH], 2008). Depending on the quantity, type, and cost of the upgrades, interest rates and mortgage period, energy prices, house characteristics, climatic variables, availability of materials and resources, among others, there may be a fluctuation in the total monthly or annual cost of energy plus mortgage to the homeowner.

This thesis will investigate the potential upgrades that can be implemented as "least cost upgrades" into current new housing construction methodology; which will consequently result in improved energy efficiency and reductions of GHG emissions, while providing an adequate level of thermal comfort, yet maining a minimal additional overall expense to the homeowner based on the life cycle cost analysis (LCCA).

1.1.1 Overview of the residential energy consumption in Canada

The residential sector in Canada comprises four distinct housing types; single detached homes; single attached (double/row) houses; low- and high-rise apartments; and mobile homes. The housing stock in 2007 (Figure 1-1) shows that 58% of the homes were single detached; 16% single attached; 25% apartments; and the remaining (1%) was mobile homes (NRCan, 2010c; NRCan, 2010d).

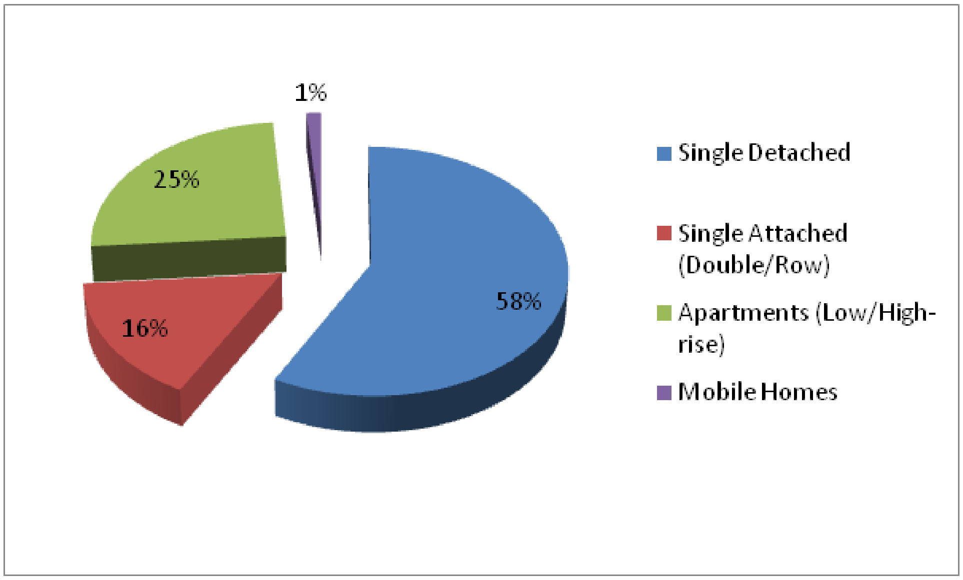


Figure 1-1: Breakdown of housing types built in Canada, 2007 (NRCan, 2010c; NRCan, 2010d)

Multiple studies stated that the residential sector in Canada is responsible for the consumption of approximately 17% of the total secondary energy. Figure 1-2 summarizes the breakdown of energy use by end-sector in 2007.

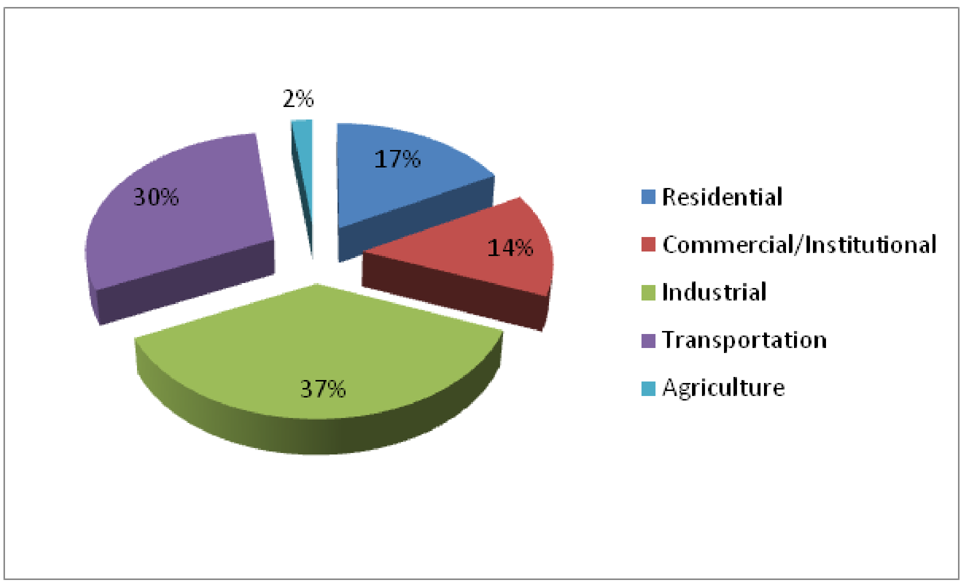


Figure 1-2: Breakdown of energy use by end-sector, 2007 (NRCan, 2011)

In the same year, it was estimated that 63% of the energy was used as a means of heating the indoor space of the home to provide thermal comfort to the occupants, whereas the remaining 37% of the energy was used for water heating (17%); appliances (14%); lighting (4%); and space cooling (2%), respectively (NRCan, 2011).

As Canada is considered as part of the cold-climate region, the dominant use of energy is for space heating, which accounts for approximately 908.1 petajoules[1] (PJ) of the total energy consumed, equivalent to producing 44.2 Mt of GHG emissions in the year 2007 (NRCan, 2010a).

Furthermore, as shown in Figure 1-3, it was found that 42% of households were heated by natural gas; 36% electricity; 8% heating oil, which includes coal and propane; 4% wood, 4% came from dual source, meaning a combination of two sources of fuel used to run the primary and secondary heating systems; and the remaining (6%) included other sources of fuel, neither identified nor stated (NRCan, 2010c; NRCan, 2010d; Statistics Canada, 2007). Thus, both natural gas and electricity are the principal heating sources in the majority (78%) of households in Canada, and thereby increase the urgency to find alternatives to reduce the use of these non-renewable energy sources.

[1] One petajoule (PJ), which is a quadrillion (10^{15}) joules (J), or a million (10^{6}) gigajoules (GJ), where the latter is commonly used to express the amount of energy used, is equivalent to the energy required by 9,000 households in one year (NRCan, 2011).

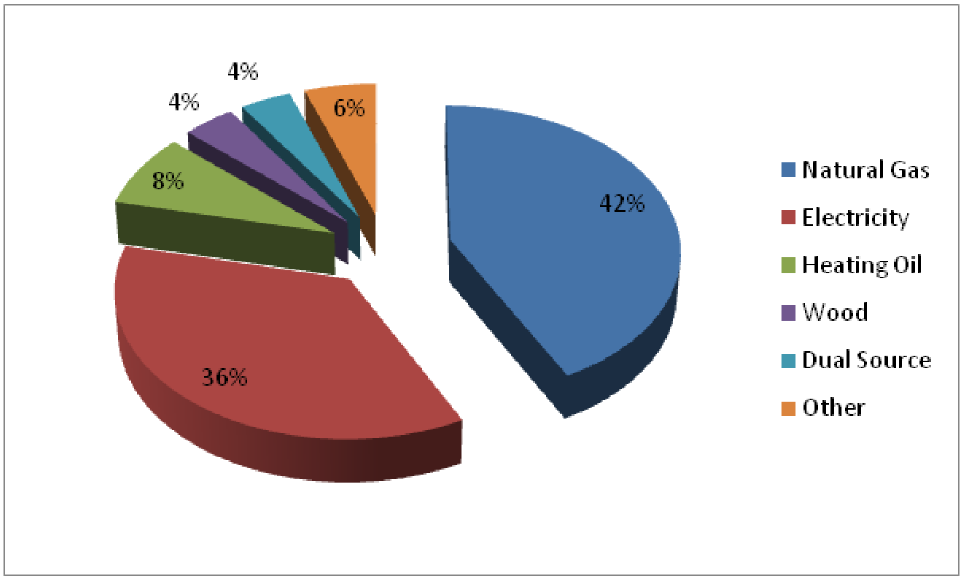


Figure 1-3: Breakdown of fuel types used in Canadian new housing, 2007
(NRCan, 2010c; NRCan, 2010d; Statistics Canada, 2007)

Figure 1-4 summarizes the principal energy sources used in space heating by different regions in Canada (NRCan, 2010c).

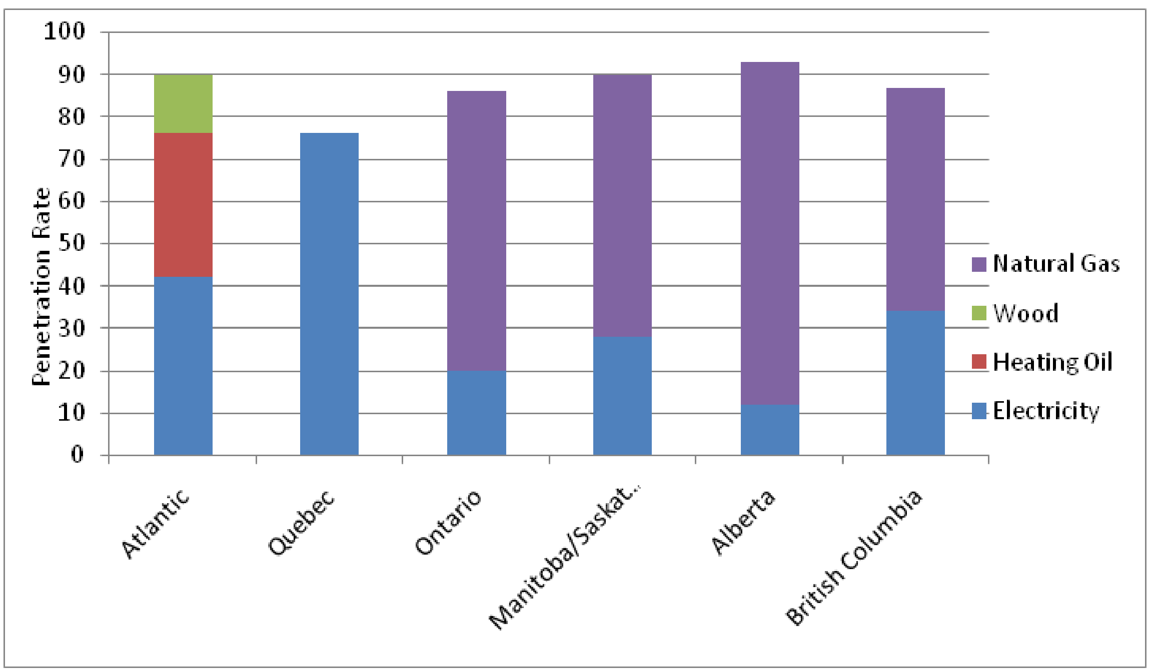


Figure 1-4: Principal energy source for heating by region, 2007 **(NRCan, 2010c)**

As Figure 1-4 indicates, most of the regions in Canada use natural gas as the primary fuel for space heating purposes. However, regions such as Quebec and Atlantic Canada use electricity as the primary fuel, and the latter uses both electricity and heating oil to heat the indoor spaces of the home to provide thermal comfort.

Statistics Canada (2011) concluded based on the 2006 Census that Toronto was the most populated city in Canada with over 5.4 million residents in 2007. Additionally, the most populated province in 2007 (Figure 1-5) was Ontario with approximately 13 million residents, followed by Quebec (7.7 million), British Columbia (4.3 million) and Alberta with over 3.5 million residents (Statistic Canada, 2010).

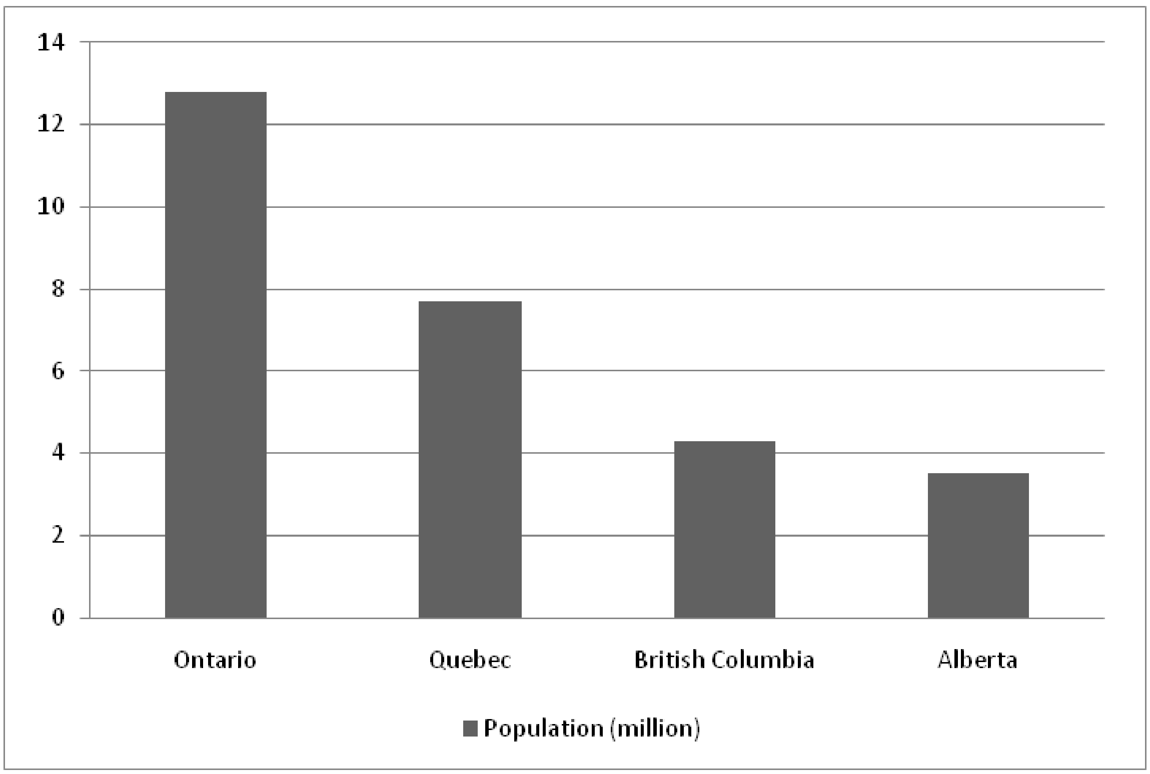


Figure 1-5: Most populated provinces in Canada, 2007 (Statistic Canada, 2010)

In regards to the total energy use with respect to the population in 2007, it took a total of 790.8PJ of energy to heat the four major and the most populated provinces; 38% of the energy was needed to heat the homes in Ontario; 24% in Quebec; and 15% in Alberta. Only 10% of the energy was needed to heat the homes in British Columbia; this could be attributed to its moderate climatic conditions, despite being more populated than Alberta (NRCan, 2010c).

Likewise, the amount of GHG emissions being released with respect to the population are as follows: 14.3 Mt of GHG emissions were produced in Ontario, and 6.4 Mt in Alberta. Although Alberta was less populated and consumed less energy than Quebec, it produced 3 Mt of GHG emissions more than Quebec, adding to a total GHG emission as a result of space heating, of 30.6 Mt across Canada (NRCan, 2010c).

Figure 1-6 summarizes the energy consumption and GHG emissions as a result of space heating for the most populated provinces in Canada (NRCan, 2010c).

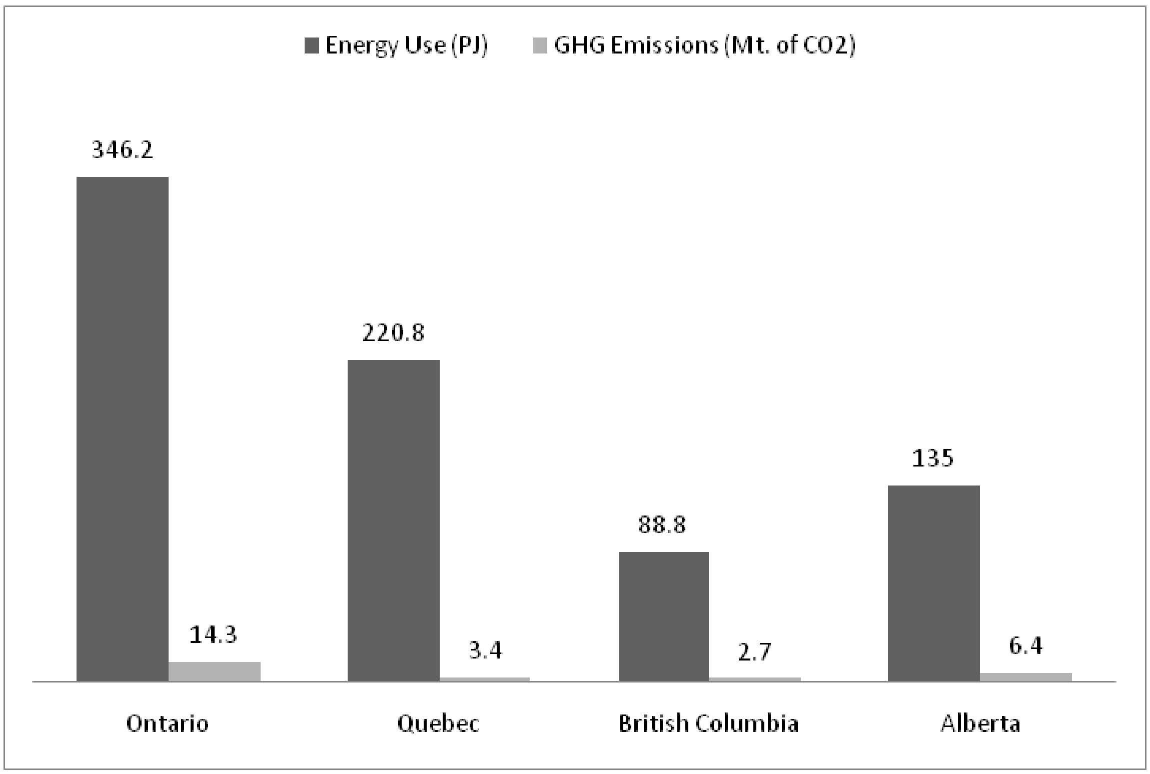


Figure 1-6: Space heating consumption for the most populated provinces in Canada, 2007 (NRCan, 2010c)

1.1.2 Overview of the National/Provincial Building Codes in Canada

As shown in Figure 1-7, provinces such as New Brunswick, Newfoundland and Prince Edward Island have adopted the National Building Code of Canada (NBCC) as the standard practice for new housing constructions (National Research Council of Canada [NRCC], 2009). However, most of the provinces in Canada (i.e., British Columbia, Alberta, Manitoba, Saskatchewan, Ontario, Quebec and Nova Scotia) have developed and published their own building codes to meet their provincial needs, although the specifications were based on the NBCC, and the Model National Energy Code for Buildings[2] [MNECB] (NRCC, 2009).

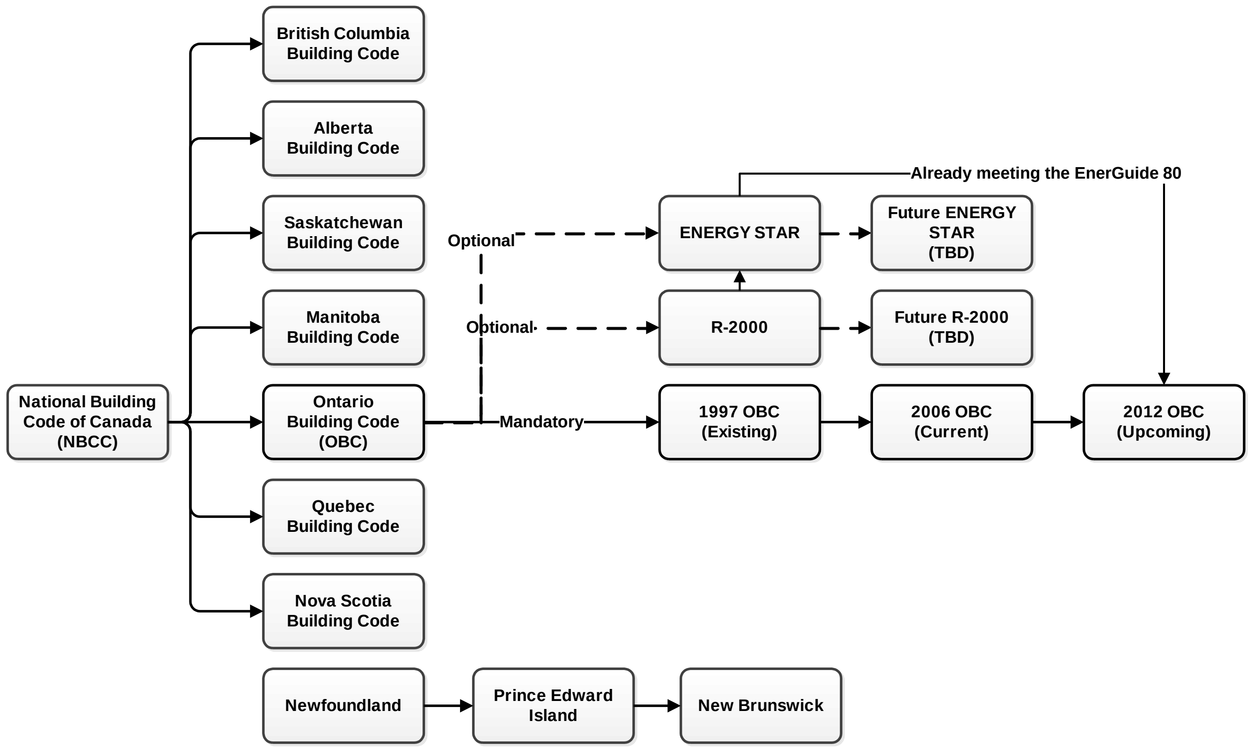


Figure 1-7: National and provincial building codes in Canada

In Ontario, the latter case applied, and all newly constructed houses must comply with the regulations as specified in the 2006 Building Code Compendium, which came into effect on

[2] This only applies to Ontario (NRCC, 2009).

December 31, 2006 (MMAH, 2008). Prior to the introduction of the 2006 Building Code, the 1997 Ontario Building Code (OBC) served the similar function of laying down the regulations for with which new houses were required to comply.

However, in order to meet the increased demand of the residential sector in Canada to reduce energy consumption and GHG emissions, various changes were made to the existing national and provincial building codes, and the new regulations were introduced, which became the basis of the revised building codes.

Some of the changes made to the existing 1997 OBC are stated as follows (MMAH, 2008):

- Insulation levels of ceilings in houses increased by 29%
- Insulation levels of walls in houses increased by 12%
- Insulation levels of basement walls of houses increased by 50%
- Energy efficiency of windows in houses increased by 67%

To illustrate the changes above, Table 1-1 summarizes the minimal thermal resistance (RSI) of insulation to be installed in a house as specified by the 1997 and 2006 Building Codes, respectively.

Table 1-1: Comparison of required insulation (RSI) of the 1997 and 2006 Building Codes

Building Element Exposed to the Exterior or to Unheated Space	**1997 Ontario Building Code]**	**2006 Building Code**	**% of Increase**
Ceiling below attic or roof space	**5.40 (R31)**	**7.00 (R40)**	**29.6%**
Roof assembly without attic or roof space	3.52 (R20)	4.93 (R28)	40.1%
Wall other than foundation wall	**3.00 (R17)**	**3.34 (R19)**	**11.3%**
Foundation walls enclosing heated space	**1.41 (R8)**	**2.11 (R12)**	**49.6%**
Floor, including floor over unheated space	4.40 (R25)	4.40 (R25)	N/A
Slab-on-ground containing heating pipes, tubes, ducts or cables	1.76 (R10)	1.76 (R10)	N/A
Slab-on-ground not containing heating pipes, tubes, ducts or cables	1.41 (R8)	1.41 (R8)	N/A

As Table 1-1 indicates, according to the 2006 Building Code, there is no specification for a required RSI of a foundation wall, if a basement is not heated. There is however, a specification for an enclosed space that is not heated, yet is separated from a heated space by glazing (e.g., a sun porch, enclosed veranda or vestibule): The code specifies that such space "*may be considered to provide thermal resistance of 0.16* m^2*°C/W, or the equivalent of one layer of glazing"* (MMAH, 2008b, p. 11). Therefore, the specification that best meets this type of scenario (i.e., if a basement is not heated) would have to be an insulation with a minimum RSI of 4.40 (R25) embedded in a floor over the basement.

Regarding the changes made with respect to the energy efficiency of a window, the previous building code (1997 OBC) specifies that the RSI of a window "*shall not be less than 0.30* m^2*°C/W*" (MMAH, 1998b, p. 108). However, in the 2006 Building Code, the minimal RSI of a window is defined by an overall coefficient of heat transfer (U), and it "*shall be not more than 2.0 W/*m^2*°C*" (MMAH, 2008c, p. 7). This is equivalent to the RSI of 0.50 m^2°C/W (RSI = 1/U), and the percentage of increase from the 1997 to 2006 Building Code is 66.7%, thereby validating the change mentioned above.

Additional changes in the 2006 Building Code are stated as follows:

- All gas and propane-fired furnaces in houses needed to have a high-efficiency rating of 90% (MMAH, 2008; MMAH, 2008d)
- New houses require a basement insulation to extend down to 380 mm (15 in.) above the basement floor (i.e., "near-full-height basement insulation") (MMAH, 2008e)

Furthermore, effective as of June 20, 2006 is the permitted use of green technologies outlined by the 2006 Building Code (MMAH, 2006). Such technologies include:

- Active solar hot water systems
- Gas-fired emergency generators that can contribute to the power grid
- Motion sensors for room and minimum lighting
- Rooftop storm water retention
- Solar photovoltaic (PV) systems
- Storm water and grey water use

- Wastewater heat recovery (DWHR/GWHR) systems

Ministry of Municipal Affairs and Housing (MMAH) (2008) conducted a study to determine the estimated energy savings, increased capital cost and simple payback periods of a typical 186m^2 (2,000ft^2) gas-heated house in the Greater Toronto Area (GTA), built in accordance with varying changes/regulations as outlined in the 2006 Building Code. Table 1-2 summarizes the results.

Table 1-2: Estimated costs, energy savings and payback periods for a house in Toronto

The 2006 Building Code - effective as of:	Estimated Energy Savings	Estimated Increased Capital Cost	Simple Payback Periods
December 31, 2006	21.5%	$1,600	3 years
December 31, 2008	28.0%	$2,700	4.4 years
December 31, 2011	35.0%	$5,900 - $6,600	6.9 - 7.9 years
Note: The figures are compared to the 1997 Ontario Building Code (MMAH, 2008)			

As Table 1-2 indicates, effective as of December 31, 2011 is the introduction of the 2012 Building Code, developed based on the 2006 Building Code with revisions to include new regulations, which are stated as follows: In 2012, all newly constructed houses must comply with standards that "*shall meet the performance level that is equal to a rating of 80 or more when evaluated in accordance with NRCan, 'EnerGuide for New Houses: Administrative and Technical Procedures*" (MMAH, 2008f, p. 4).

Despite the fact that the 2012 Building Code has been legislated, and will be mandated by the municipalities in Ontario starting December 31, 2011, how the new regulations will be applied to the current method of constructing new houses raises an issue that needs to be resolved immediately. At the same time, there are numerous energy efficiency standards such as R-2000, and LEED (acronym used for "Leadership in Energy and Environmental Design") Canada for Home that exist, and because of their stringent requirements in comparison to what is being specified in the building code, new houses were built far more energy efficient than those built in accordance with the code (i.e., 2006 Building Code). In fact, some exceeded the 2012 Building Code requirements of EnerGuide 80 (Dupuis, 2009).

1.2 Objectives of the Thesis

The overall objective of this thesis is to develop potential "least cost upgrades" that can be implemented into the currently practiced new housing constructions in Canada to achieve significant energy savings. This thesis will focus on identifying the most cost-effective specifications to achieve improved energy efficiency standards, including the EnerGuide 80 (2012 requirements of the OBC) and beyond, ultimately reaching the net zero energy level. It will consider the initial capital cost, the life cycle cost implications of achieving such standards, while maintaining an adequate level of thermal comfort.

In order to do that, the objectives are to:

1. Define the current new housing constructions methodology by understanding the specifications of the national and/or provincial building codes, which will determine the base case for the proposed study.
2. Conduct a sensitivity analysis to determine the "least cost upgrades" by evaluating the potential energy saving measures that are being implemented by local production homebuilders based on the results of a survey.
3. Perform, once the least cost upgrades are determined, a building energy simulation using HOT2000 program to model the upgrades independently to study their overall energy performances. Finally, the data obtained from the simulation are used to conduct life cycle cost analyses to determine the total annual cost of energy plus mortgage to the homeowner over the maximum mortgage period.

To reach these objectives, the following scenarios are considered:

1. Different design configurations of building envelope and mechanical systems.
2. Using energy simulation tools including HOT2000 in order to meet the scope and objectives of the thesis.
3. Various energy saving targets to be considered, for instance Net Zero Energy (NZE). As a first step, this thesis will focus on identifying the most cost-effective specifications to achieve the EnerGuide 80 (2012 requirements of the OBC).

1.3 Scope of the Study

This thesis will take a similar approach to the study conducted by Anderson et al. (2006), entitled "Analysis of Residential System Strategies Targeting Least-Cost Solutions Leading to Net Zero Energy Homes". The analysis was based on the concept of "*whole-building performance and cost optimization, including interactions between advanced envelope designs, mechanical and electrical systems, lighting systems, space conditioning systems, hot water systems, appliances, plug loads, energy control systems, and onsite power generation*" (Anderson et al., 2006).

As stated in this study, it is important to investigate the relationship that exists among multiple upgrade options. For instance, if the improvements were to be made on the building envelope system to increase the thermal resistance of ceiling, wall, floor and foundation by adding insulation, this will result in the selection of a heating, ventilating, and air-conditioning (HVAC) system based on much smaller heating and cooling loads to maintain thermal comfort to the occupants. Similary, if improvements were made by replacing the existing major appliances with higher efficiency units, this will consequently result in the reductions of energy consumption and GHG emissions as a result of space heating and cooling.

Therefore, for this thesis, in particular, economic analysis will consider potential initial capital cost benefits from a reduced heating and/or cooling systems when the building envelope is improved.

1.4 Structure of the Thesis

The summary of the work carried out to form this thesis is outlined with brief contents of the individual chapters as follows:

Chapter 2: Literature review on similar studies done in Canada, the United States, and Europe

Chapter 3: Proposed methodology, including a compliance with the national/provincial building codes used to determine the benchmark, potential least cost upgrades, and cost estimation of upgrades by conducting a survey

Chapter 4: Sensitivity analyses including a comparative analysis of HOT2000™ and TRNSYS (acronym used for “TRaNsient SYstems Simulation”), typical parameters, lighting and appliances scenarios with reduction in hot-water consumption, and extreme weather conditions considered in the thesis

Chapter 5: Least cost analyses for Toronto, Ottawa, Thunder Bay, and Windsor using the “Least Cost Principal" as a ranking tool to determine the most optimal or least cost upgrades

Chapter 6: Conclusion and recommendations

Chapter 2

2 Literature Review

2.1 Background

Statistics Canada (2007) reported that the average household in Canada consumed 106 GJ of energy[3] in 2007. While in the United States (hereafter U.S.), the average American household consumed 94.9 million British thermal units (Btu) of energy in 2005, which is equivalent to 100 GJ of energy comprised of electricity, natural gas, oil and other fuels including kerosene, liquefied petroleum gas (LPG), and wood (U.S. Energy Information Administration [EIA], 2005). This could be attributed to the increase in average size of new homes that have been built over the past decades in both Canada (Dong et al., 2005), and the U.S., where the latter has increased by 73% within the last 35 years, from 1970 to 2005 (Parker, 2008).

As a result, the residential sector in North America is facing an urgent need to reduce its primary energy that is being consumed by the existing residential buildings. As previously mentioned in Chapter 1 of the thesis, the residential sector in Canada has implemented the changes to both the national and provincial building codes to amend the ways Canadians have built homes for previous decades; while in the U.S., the U.S. Department of Energy (DOE) has recently set a target to reduce energy consumption by an average of 50% by 2015, and 90% by 2025, resulting in the consumption of only 10% of the original energy (Anderson et al., 2006).

[3] This is comprised of all fuel types including electricity, natural gas, oil, propane, wood and wood pellets (Statistics Canada, 2007).

Meanwhile, numerous studies have been carried out, both nationally and internationally, to put into practice various energy efficiency upgrade solutions in both new and existing residential buildings to determine the most cost-effective specifications to achieve improved energy efficiency of the building based on the life cycle assessment (LCA).

In Canada, Guler et al. (2008; 2001) conducted a study to evaluate a series of energy efficiency upgrade solutions to determine their effects on annual energy consumption (Guler et al., 2001) and GHG emissions[4] (Guler et al., 2008) of the residential sector in Canada. The Canadian Residential Energy End-use Model (CREEM) (Guler et al., 2008; Guler et al., 2001; Fung et al., 2000; Farahbakhsh et al., 1998; Fung et al., 1997) was developed to represent and assess the Canadian residential sector, and contained 8,767 housing data collected from various sources including the results of the 1993 Survey of Household Energy Use (SHEU) (Statistics Canada, 1993), the Modified STAR-HOUSING (acronym used for “STAtistically Representative HOUSING stock”) database (Ugursal & Fung, 1996; Scanada, 1992), the 1993-1994 “200-House Audit” project database (NRCan, 1994), HOT2000 building energy simulation program default values (NRCan, 2010), and minor contributions from other sources (Guler et al., 2008; Guler et al., 2001; Fung et al., 2000; Fung et al., 1997).

Another study has been conducted by Dong et al. (2005), where an existing 4-bedroom, single detached house, located in Toronto, Ontario, with the total area of 240 m^2 (2,583 ft^2) was considered with different years of construction (1930s, 1960s, and 1980s). Distinct housing construction methods were established for each year of construction, and evaluated for their energy performances: For instance, solid masonry construction was used to represent a standard construction practice in the 1930s; wood frame construction comprised of 38x89 mm (2x4 in.) wood framing member and a moderate level of insulation was used in the 1960s; and for the 1980s construction, another wood frame construction method was used, but this time, a 38x140

[4] GHG emissions include carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_20) (Guler et al., 2008).

mm (2x6 in.) wood framing member and a higher level of insulation than that of the 1960s construction was used. It should be noted, the latter closely represents the currently practiced new housing constructions of today. The objective of the study was to investigate whether it would be cost-effective to retrofit the existing house with varying years of construction, or to demolish it and construct a new house using new or recycled construction materials and technologies to achieve improved energy efficiency standard known as the R-2000 (NRCan, 2005). Advantages and disadvantages of retrofitting the existing house as opposed to constructing a new house were analyzed based on the resulting life cycle energy, as well as estimated reductions in the environmental impact including GHG emissions, air and water pollutions, and solid waste generation.

In the U. S., numerous studies (Parker, 2008; Anderson et al., 2006; Norton & Christensen, 2006; Torcellini & Crawley, 2006; Torcellini et al., 2006; Christensen et al., 2005; Torcellini et al., 1999) have been conducted on the new residential buildings with the objectives to not only meet the target as set out by the U.S. residential sector, but also, to enhance the currently practiced new housing constructions to achieve improved energy efficiency standards: As an example, in the study done by Anderson et al. (2006), the objectives were first, to determine the most cost-effective (or least cost) solutions to achieve the energy saving goals, and to establish the design solutions that could meet higher energy efficiency standards, which will lay out the groundwork to conduct further analyses on residential system performance in the near future. A two-storey, single-family dwelling with the total area of 167 m^2 (1,800 ft^2) and an attached two-car garage was used to represent the typical American household.

Another similar study was done by Norton & Christensen (2006), which presented a case study of how a standard 3-bedroom, single-family dwelling with the total area of 111 m^2 (1,200 ft^2) reached the highest energy performance level in cold climates such as Denver, Colorado, while holding the overall operating energy cost down to a minimum; therefore, homeowners including those with limited economic resources could afford to pay the cost of operating energy.

Furthermore, various types of residential space heating and cooling systems with varying degrees of efficiency were considered as alternatives to the conventional systems in the study conducted by Lutz et al. (2006). The study was conducted not only to evaluate the feasibility of owning and operating the heating and cooling systems that are more energy-efficient than the conventional ones, but also, to evaluate the practicability of achieving higher efficiency in the standard systems as the existing efficiency standards were under review by the U.S. DOE. A similar study was done two years later, by Bolling & Mathias (2008), where the optimal space heating and cooling systems were considered for various climatic conditions in the U.S., and included, in addition to a condensing furnace with central air-conditioning (AC) unit, a ground source heat pump (GSHP), absorption AC unit with direct heating, solar-thermal collector, and a thermally driven heat pump.

In the United Kingdom (hereafter U.K.), multiple studies (Gorgolewski et al., 1996; Gorgolewski, 1995) have been carried out on an existing high-rise residential building to develop a methodology to assess the thermal and economic performances of different optimal retrofit solutions. A typical high-rise apartment in West London was used for the purpose of the studies, where one study (Gorgolewski, 1995) looked at the thermal performance of a 70 m^2 (753 ft^2), 2-bedroom corner-apartment, located on an intermediate floor of a 12-storey building; whereas in another study (Gorgolewski et al, 1996), the first- and tenth-floor apartments were considered to determine the difference in their thermal performances.

Similar to the studies referenced above, other countries in Europe have conducted studies to identify the optimal energy efficiency upgrade solutions to achieve improved energy efficiency standards known as the Passive House (Brunklaus et al., 2010; Feist, 1997), or the Low Energy House (Wojdyda, 2009; Feist, 1997). For example, in Sweden, Brunklaus et al. (2010) evaluated and compared the environmental performance of several passive houses to that of the conventional houses using the LCA methodology, and proved that passive houses consumed less energy than conventional houses; however, when considering the environmental impact of energy production, the outcome showed that conventional houses performed equally as well as passive houses with respect to global warming and waste reductions.

In Germany, Hermelink (2009) developed a methodology to determine the optimal level in cost for retrofitting an existing residential building by evaluating and identifying the drawbacks in some of the commonly used methods of calculating the energy and cost savings of the identified improvement measures over the life of the building. The results showed that the LCCA based on net present values (NPV) yielded a basis for a successive development of a common methodology for determining optimal level in cost for retrofitting an existing residential building.

Some of other studies include:

- Wojdyga (2009) in Poland, where the author investigated the space heating consumption of an existing, single-storey house with the total area of 242 m^2 (2,605 ft^2) over a study period of 5 years. This house was designed to achieve low energy status with the implementation of solar domestic hot water (DHW) system.
- Karlsson et al. (2007) in Sweden, where the authors conducted a study to determine the difference in the estimated energy requirement using building energy simulations against that of the measured data of an existing house, which was also designed to achieve low energy status.
- Feist (1997) in Germany, where the author established and compared the cumulative primary energy input (CPEI) over a study period of 80 years for six distinct housing construction standards including low energy and passive houses.

Although the studies done in Canada, the U.S., and Europe have varied in applications, whether they were conducted for existing residential buildings or for new housing constructions, these studies have presented the most cost-effective specifications that could be applied to the currently practiced new housing constructions in Canada as potential optimal or least cost upgrade solutions to achieve improved energy efficiency standards.

A literature review was conducted as part of this thesis. Various materials comprised of scholarly journals, theses, qualitative research reports, and conference proceedings were used to gather background information and related studies to understand the issues of current and future residential energy use, energy efficiency, and optimization in energy cost by conducting a life cycle analysis. In this chapter of the thesis, the discussion of results from the studies referenced above are presented and categorized into subsections as follows:

Section 2.2: Energy efficiency upgrade solutions considered for new and existing residential buildings

Section 2.3: Life cycle assessment (LCA) methodology used to determine the overall energy, environmental, and cost savings of the identified energy efficiency upgrade solutions

Section 2.4: Optimization in energy costs determined using a brute force sequential search (BFSS) method or a genetic algorithm (GA) method

Section 2.5: Overview of building energy simulation

The energy efficiency upgrade solutions and research methodology that are considered in this thesis, were developed based on the results of some of the studies referenced in this chapter, and will be explained in Chapter 3 of the thesis.

2.2 Energy Efficiency Upgrade Solutions for Residential Buildings

Dong et al. (2005) argued that most of the studies done on the existing residential buildings in the past have focused mainly on developing the energy efficiency retrofit solutions by determining the life cycle energy of the building from the time when it was erected to when it was demolished. Dong et al. (2005) further argued that in order to reduce the energy consumption as well as the environmental impacts (i.e., reduction in GHG emissions) of the residential sector in Canada, it is rather important to improve the overall, both energy and the environmental performances of the existing residential buildings than those of new homes.

This may be valid; however, it can be concluded based on other studies that the most currently practiced new housing constructions in Canada as well as other nations are not optimal in terms of energy performance. Dong et al. (2005) support this argument by stating that the standard new housing construction practiced in Canada is "not sustainable", despite the fact that the energy efficiency of the Canadian residential sector has improved over the past years as a result of the 1970s oil crisis, which emphasized the importance of building a much more energy-efficient home by increasing the minimum amount of thermal insulation in the building envelope (ceiling, walls, floors and basement), improving the fuel efficiency of the space heating and hot water heating systems by changing the commonly used fuel sources to less carbon intensive ones, and paying close attention to the details to reduce air infiltration during the construction.

This section of the chapter summarizes the energy efficiency upgrade solutions that were considered in the past studies for both existing (Section 2.2.1) and new (Section 2.2.2) residential buildings worldwide to draw similarities and differences in some of the technologies that have already been introduced and implemented into the design of the buildings to achieve improved energy efficiency.

2.2.1 Energy efficiency upgrade solutions for existing residential buildings

When improvements were made to an existing residential building, various energy efficiency measures were considered to improve the overall energy performance of the building. Numerous studies have been conducted worldwide, and although there were differences in the selection of construction materials and varying degrees of efficiency in the equipment used, the solutions to achieve improved energy efficiency were very much similar, and they include: improvement in the thermal resistance of the existing building envelope by adding or increasing the thickness of insulating materials; replacement of the existing windows, heating and/or cooling systems with higher efficiency units; and reduction in the air infiltration by introducing a continuous air barrier/sealing mechanisms to reduce the air leakage potentials. These solutions were referred to as what Dong et al. (2005) stated as the "commonly practiced energy efficiency improvements for the existing residential buildings".

In the study done by Guler et al. (2008; 2001), the results showed that replacing the existing heating system by a higher efficiency unit provided the largest energy saving potentials, followed by increasing the thermal resistance of the basement walls by adding insulation, and by replacing the existing single-glazed windows with argon filled, low-emissivity (low-E) soft-coating, triple-glazed windows.

Dong et al. (2005) also considered the similar solutions for retrofitting an existing residential building. Contrary to the conclusion made by Guler et al., Dong et al. (2005) proposed a solution to reduce air infiltration potentials by sealing the joints to improve the overall air-tightness of the house; however, the solutions to improve the efficiency of the existing window and/or mechanical systems were eliminated in the study due to the potential increase in the initial investment cost that could result by choosing such alternatives, although the authors believed that these improvements could achieve significant energy savings. Guler et al. (2008; 2001) also accounted for the increase in the installation, material, and equipment costs that could result by replacing the existing windows, mechanical and/or appliance systems with higher efficiency units and, therefore, classified these improvement measures as “major upgrade scenarios”, whereas those upgrade scenarios that had relatively lower installation and equipment costs than those of the major upgrade scenarios were considered as “minor upgrade scenarios”, and included improvements in lighting fixture, thermostat, and showerhead.

Gorgolewski (1995) and Gorgolewski et al. (1996) also considered, in addition to the improvement measures that were considered in both studies by Guler et al. (2008; 2001), and Dong et al., (2005), the alternative heating systems to reduce the space heating energy requirement of the existing high-rise residential building. Contrary to the conclusion made by Guler et al., but in agreement with Dong et al., Gorgolewski et al. (1996) proposed that reducing the air infiltration by installing draught-stripping to improve the air-tightness of the building was the most cost-effective solution to improve the energy performance of the building. Furthermore, in agreement with Guler et al., improving the existing windows by installing double-glazed windows also resulted in the reduction of overall energy consumption due to a resultant decrease in the space heating energy requirements of the building.

Interestingly, Gorgolewski et al. (1996) concluded that increasing the thickness of both interior and exterior wall insulations was the most insignificant, and also the least cost-effective solution in reducing the space heating energy requirements, as well as the overall energy consumption of the building. Although a such conclusion was made, the results showed that increasing the thickness of insulating material from 25 mm (0.98 in.) to 50 mm (1.96 in.) of interior insulation, and from 50 mm (1.96 in.) to 100 mm (3.92 in.) of exterior insulation, respectively, improved the overall thermal resistance of the building as a result of the reduction in the space heating energy requirements by 30% (345 kilo-watt-hour [kWh]) and 22% (315 kWh), respectively.

Increasing the thickness of insulating material could be perceived as the least cost-effective solution due to the increase in both quantity and cost of the material, and this could be attributed to the reasons why the other studies (Guler et al., 2008; Dong et al., 2005; Guler et al., 2001) neither considered this as one of the improvement measures nor expected this as one of the most cost-effective improvement measures. Gorgolewski et al. concluded in their study (1996) that, "since the insulating material was only a small part of the cost of installing wall insulation, thicker insulating layers added little to the capital [investment] cost".

2.2.2 Energy efficiency upgrade solutions for new housing constructions

When constructing a new home, the same solutions as the ones considered for the existing residential buildings can be applied to achieve improved energy efficiency. In addition to the ones that are mentioned in the previous section of this chapter, there is a need to determine the baseline case or the benchmark, which will determine the minimum level with respect to energy performance, environmental performance and so forth. This is not the case for the existing residential buildings, because the original state of the building before any improvements were made determines the baseline case or the benchmark for the comparison purposes.

Thus, to enhance the overall energy performance of the currently practiced new housing constructions, the determination of the baseline case or the benchmark is critical in order to evaluate the feasibility of various new and emerging energy efficiency upgrade solutions and technologies over a conventional method of constructing a new home that is used in today's practices. This can be done, as an initial step, by understanding and analysing the requirements as stated in the national/provincial building codes, which can be used to determine the minimum energy performance level or the baseline case, as in the case of this thesis.

In this section of the chapter, the discussion of results from the studies done in the U.S., as there are no similar studies done for the new residential buildings in Canada, is used to draw similarities and differences in some of the advanced and innovative energy efficiency designs that are comprised of advanced building envelope, HVAC and renewable energy systems to achieve the highest level of energy performance that has recently been practiced in the U.S.

As mentioned in the beginning of the chapter, the residential sector in the U.S. has recently set out the target to reduce energy consumption starting in 2015. As an initiative to meet such demand, the U.S. DOE formed the Building America (BA) program to conduct residential energy efficiency related research, and introduced the "analysis-based system research approach" (Anderson et al., 2006; Norton & Christensen, 2006). This approach was used to develop and implement energy efficiency upgrade solutions into the currently practiced new housing constructions that combined both innovative designs and the use of renewable energy systems to not only cost-effectively increase overall product value and quality of a building, but also, significantly reduce energy consumption and use of raw materials, especially when used on a mass-production basis (Anderson et al., 2006).

Anderson et al. (2006) applied this analysis-based system research approach in their study, and concluded that it was critical to use such an analytical approach for a study that involved evaluating the feasibility of new and innovative energy efficiency designs and technologies over a conventional approach used in today's construction practices. The energy efficiency designs that were considered in their study were as follows: advanced building envelope systems, space conditioning systems, hot water systems, major appliances, lighting systems, and renewable energy systems that included the residential PV system. It should be noted, miscellaneous electric energy requirements other than the major appliances were not considered in the study.

However, according to Anderson et al. (2006), the proposed methodology was limited to determining the minimum energy requirements based on marginal cost and energy performance of the identified design and technology combinations that were considered as feasible to achieve the optimal level. Anderson et al. (2006) further argued that further analyses would be needed to examine the impacts of factors such as durability, reliability, ease of installation, availability of regional supply, service and support centres, and warranty and call-back costs, which were eliminated in their study.

Another objective of the BA program is to establish practical and yet marketable net zero energy homes by 2020 (Norton & Christensen, 2006). Net zero energy (NZE), sometimes referred to as zero net energy (ZNE)[5], simply refers to a home that is designed and built to produce as much energy onsite as it consumes on a yearly basis (Anderson et al., 2006; Christensen et al., 2005; Norton & Christensen, 2006). The house is typically equipped with a residential PV system, which is connected to the utility power grid (Norton & Christensen, 2006). One of the advantages of the NZE homes is that the excess energy that is produced by the PV system will be delivered back to the grid to be stored until it will be used in the house. If, on the other hand, the PV system is not generating enough energy (i.e., during winter season), the amount of energy needed in the house will be drawn from the grid directly to the house, and not from the original energy that is delivered to the site (Norton & Christensen, 2006).

To achieve a NZE status in a new home, the house would require as little energy as possible to run the HVAC and other electric systems. An improved energy-efficient building envelope and HVAC system would thereby reduce the energy consumption of the house down to a minimum. There are numerous advanced and innovative technologies that are available in today's housing market, and multiple studies have been conducted to evaluate the energy performance of these emerging technologies: For instance, in the study conducted by Norton & Christensen (2006), the proposed building envelope solutions included a double stud wall system, which was chosen over other advanced wall framing systems including structural insulated panels (SIPs), insulated concrete forms (ICFs) and straw bale, because the former had lower material costs and ease of construction techniques.

Norton & Christensen (2006) chose double-glazed window with low-E soft-coating for the south-facing windows, because they not only resulted in the maximum heating reduction without increasing cooling demand over the standard window constructions (due to the resultant U-value of 0.30 Btu/hr-F-ft^2, and solar heat gain coefficient (SHGC) of 0.58), but also, reduced the

---

[5]NZE can also be defined as "net zero site energy"; "net zero source (or primary) energy"; "net zero energy costs"; or "net zero energy emissions" (Torcellini et al., 2006; Torcellini & Crawley, 2006).

overheating potential since it was not a common practice in Denver to install an AC unit in any new houses.

A combination of direct-vent natural gas furnace (mainly in the living and dining room), and baseboard electric resistive heaters (in the bedrooms), both equipped with separate thermostat to control the indoor temperature of each room, was selected for space heating purposes, because according to Norton & Christensen (2006), the systems had relatively lower cost, and ease of installation over other systems including active solar-thermal with radiant floor heating, and ground-coupled heat pump (GCHP), which were also considered as potential energy efficiency upgrade solutions in the study.

The reduction in electricity consumption from major appliances and lighting was also a critical factor in order to meet the NZE status, and Norton & Christensen (2006) achieved this by the use of compact fluorescent lighting (CFL) throughout the house, and also by installing ENERGY STAR qualified appliances. Contrary to Anderson et al., Norton & Christensen (2006) stated that the miscellaneous electric energy requirements were assumed to include other electric devices such as TV, hair dryer, toaster oven, and computer, in addition to the major appliances that were turned on at the preference of a homeowner, although such assumptions were defined in the study by Hendron (2005)[6].

[6]Hendron (2005) has developed a detailed specification of a building to define a benchmark with respect to building envelope, space conditioning and air-distribution equipment, lighting equipment, appliances and other miscellaneous loads including the time-of-use profiles for occupancy, hot water use profile, and onsite energy generation. This well-defined reference was available for use by all the researchers within the U.S. residential sector.

As a strategy to achieve improved energy efficiency standards that could be applied to both new and existing residential buildings, as Dong et al. (2005) proposed in their study, the alternative solutions are to replace the commonly used, non-renewable energy sources such as natural gas and electricity with renewable energy sources (solar, wind, and geothermal) that could reduce the potential of producing excessive GHG emissions and other air pollutants; and to reduce the amount of raw materials used in today's new housing construction practices by making use of recycled materials from the demolition of existing residential or other types of buildings, and applying them to new housing constructions to balance out the negative environmental impacts of the existing residential buildings.

2.3 Life Cycle Assessment (LCA) Methodology

To evaluate the feasibility of various energy efficiency upgrade solutions, including the ones that are mentioned in the previous section of the chapter, numerous studies (Brunklaus et al., 2010; Anderson et al., 2006; Lutz et al., 2006; Dong et al., 2005; Feist, 1997; Gorgolewski et al., 1996; Gorgolewski, 1995) have been conducted in the past to assess the overall energy, environmental and economic performances and their associated savings over the duration of the life of either a new or existing residential building using the LCA methodology (Figure 2-1).

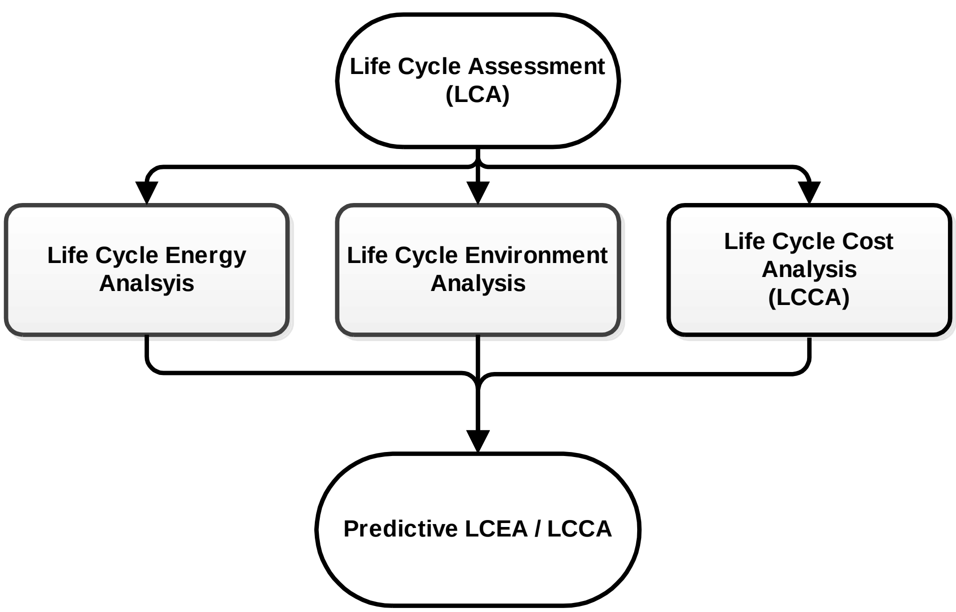


Figure 2-1: Life cycle assessment (LCA) methodology

In this section of the chapter, the results of the studies referenced above are presented to draw similarities and differences in the applications of the LCA methodology, which is used to compare the overall performance and its associated savings of a new/existing residential building with respect to energy (Section 2.3.1), environment (Section 2.3.2), and cost (Section 2.3.3.).

2.3.1 Life cycle energy analysis

Feist (1997) used the life cycle energy analysis to determine and compare the CPEI of the six distinct housing construction standards (the German 1984 Ordinance; Low Energy House; Low Energy House with a reduction in overall household electricity consumption; Passive House; Future Passive House; and Self Sufficient Solar House) over the life span of 80 years.

Feist (1997) concluded that improved insulation, as in the case of the Low Energy House[7] resulted in the CPEI reduction of 22%, when compared to that of the house designed in accordance with the German 1984 Ordinance, and of an additional 40%, if the former was further improved by reducing the overall household electricity consumption.

It should be noted, this study included neither the results of the energy simulations nor the life cycle cost analyses of the identified energy efficiency upgrade solutions considered to achieve different energy efficiency standards. Feist (1997) suggested as a recommended future study to include the development of the design solutions for the cost-effective passive house, which were in progress at the time when the study was conducted.

[7] The low-energy house contained an adequate level of thermal insulation, reduced thermal bridging, improved air-tightness, well-insulated glazing, and mechanical ventilation consisting of cost-effective exhaust air ventilation systems (Feist, 1997).

2.3.2 Life cycle environmental analysis

Dong et al. (2005) conducted the life cycle environmental and economic analyses of an existing residential building with varying degrees of year of construction over the study period of 40 years. A 40-year life span was chosen for the study, although Dong et al., (2005) argued that this was "a conservative estimate" as there were numerous residential buildings in Toronto that lasted for more than 40 years. Based on the results, Dong et al. (2005) concluded that retrofitting an existing residential building would result in the reduction of embodied energy; environmental impacts such as water pollution, solid waste generation, and the use of resource materials; capital and life cycle costs; and simple payback period, whereas new housing constructions would lower the operating energy, life cycle energy, global warming potential, air pollution, and annual operating costs.

Brunklaus et al. (2010) used the LCA methodology to evaluate and compare the environmental performance of the several passive houses to that of the conventional houses over the life span of 50 years. Contrary to Dong et al., Brunklaus et al. (2010) concluded based on the results that passive houses consumed less energy than conventional houses; however, when considering the environmental impact of energy production, the outcome showed that conventional houses performed as well as passive houses with respect to global warming and waste reductions.

2.3.3 Life cycle cost analysis (LCCA)

Last but not least, the life cycle cost analysis (LCCA) is the methodology used to evaluate the feasibility of various energy efficiency upgrade solutions, and to determine the overall economic performance over the life span of either a new/existing residential building.

Numerous studies were conducted in the past using this methodology, and according to Hermelink (2009), the LCCA based on net present values provided a foundation for a successive development of a common methodology for determining optimal level in cost for retrofitting an existing residential building.

To understand the terminology used in the typical LCCA, Lutz et al. (2006) conducted a detailed study using this methodology to determine the cost-effectiveness of a more energy-efficient furnace and boiler than a conventional unit. The results of the study can be applied to the Canadian residential sector as well, because it is proven based on the statistics that both furnace and boiler are the most commonly used space heating systems in the majority of households in Canada (NRCan, 2007a).

The two main components of the LCCA are defined based on the determinations of the followings: *installation cost*, and *operating cost* of either a building material, equipment used, or even a building itself. From the study conducted by Lutz et al. (2006), the life cycle cost is calculated using the following equation:

$$LLC = Installtion\ Cost + \sum_{n=1}^{Lifetime} \frac{Operating\ Cost}{(1 + Discount\ Rate)^n} \qquad [\mathrm{Eq.}\,1]$$

In the case of both new and existing residential building, the installation cost is the capital or initial investment cost associated with purchasing and installing a new (or replacement as in the case of an existing building) material and/or equipment. Lutz et al. (2006) defined the term as the cost in which the homeowner pays to have a material and/or equipment installed in his/her house, including all of the labour and hours it takes to complete the installation.

As the [Eq. 1] indicates, the life cycle cost is derived based on the sum of the initial cost and the operating cost over the life span (represented as "*n*" in the equation) of the material, equipment or the building itself. The operating cost, as Lutz et al. (2006) defined it is the sum of the total monthly utility costs (i.e., natural gas, oil, and electricity), plus the maintenance cost. It should be noted, the definition of discount rate varies depending on whether the rate is applied to a material or equipment to be installed in a new house or an existing one as a replacement. For instance, in the case of a new housing construction, the term is defined based on the determination of a mortgage interest rate, and is dependent on the location and the year in which the house is to be built.

The following subsections summarize the results from the other studies using the approach used in Lutz et al. (2006) as an example for the comparison purposes:

Bolling & Mathias (2008) derived the installation cost based on the determination of initial additional or incremental cost of the identified space heating and cooling systems against that of the baseline systems (hereafter, the benchmark), and defined it as the “recovery cost” (in negative values) for their study.

For the operating cost, Bolling & Mathias (2008) used the sum of the difference in the operating costs of the benchmark against the identified systems, to the identified recovery cost. An interest rate of 1.4% was added to the identified recovery at the end of each study period (of 20 years).

The decision factor in choosing the best alternative system(s) among a series of space heating and cooling systems that were considered in the study was the determination of the overall recovery cost, resulting in positive value. Bolling & Mathias (2008) concluded that, if the overall recovery cost resulted in a negative value, then the alternative system was considered to be at least as cost-effective as the benchmark as a result of increase in the initial incremental cost of the former, whereas if the overall recovery cost was positive, then the alternative system was considered to be a more cost-effective option than the benchmark, with resultant savings, or as Bolling & Mathias (2008) defined them as “added savings” at the end of the 20-year period.

Anderson et al. (2006) conducted an LCCA of various energy-efficient building envelope designs and HVAC systems based on the determination of the first cost and the lifetime cost. The estimation of the first cost of the material and associated labour including the overhead and profit was based on the published cost data from the *RSMeans Residential Cost Data 1999*, a similar approach to the proposed thesis, which will be explained further in Chapter 3. Furthermore, the cost for the equipment and installation of the windows, HVAC and appliances was determined based on the manufacturers’ quotes, and as for the lighting, the overall cost was derived based on the cumulative hours of use.

Anderson et al. (2006) used a period of 30 years to define the lifetime of the study based on the determination of the mortgage period, with the identified parameters as follows: a 7% interest rate, a general inflation rate of 3%, and a 5% discount rate. As part of the lifetime cost, the utility costs were determined using the existing price of natural gas and electricity, where the latter varied depending on the location, and the former was assumed to be constant. The future price for both fuels was assumed to escalate at the rate of inflation of 3% (Anderson et al. 2006).

It should be noted that the study by Anderson et al. (2006) includes neither the maintenance cost nor additional costs associated with warranty and call-back that were not accounted for as part of the operation and maintenance costs. Anderson et al. (2006) further stated that their LCCA did not take into consideration the state/local financial incentives and rebates, although the authors believed that these factors may have had a significant influence on the decision making towards the implementation of new systems, especially from a builder's perspective.

In the study by Dong et al. (2005), an LCCA using a net present value was conducted by determining the initial investment cost and the operating energy costs over a study period of 40 years. The estimation of material and construction costs including the overhead and profit (of 10%) for the identified energy efficient retrofit solutions was based on the published cost data from the *RSMeans Repair and Remodelling Cost Data 2002*, a similar approach to the study conducted by Anderson et al., (2006).

However, it should be noted, the material and installation costs from the RSMeans were listed in U.S currency and, therefore, these figures were converted to Canadian dollars using the "Location Factor" (RSMeans, 2010). Dong et al. (2005) used the conversion factor for Toronto, ON, which was based on the location of the existing house, to estimate the overall material and installation costs for the identified retrofit solutions considered in the study. In addition, the material and installation costs associated with the improvement of the air-tightness option were determined based on the approximate values obtained from an industry source, and typically range between $500 to $2000 in Canadian dollars (Woods, 2002; NRCan, 2007b).

For the determination of the operating energy cost, a fuel escalation rate of 4% was used to estimate the total utility costs, and a discount rate of 7% was used to calculate the overall life cycle cost in net present value. As mentioned previously, a 40-year period was chosen as the life span for the study by Dong et al. (2005), and the authors argued that increasing the life span beyond 40 years would cause uncertainty in predicting future energy prices due to; 1) a constant fluctuation in energy prices as a result of "the influence of global political and economic factors"; and 2) the fact that energy prices were likely to increase annually "as a result of the current climate of increased pressure to reduce energy related environmental impacts, as well as insecurities of the future supply of oil". It should also be noted, neither the cost for the repair and/or maintenance nor a salvage (residual) value for the identified retrofit solutions was considered in the study.

Gorgolewski (1995) used the LCA methodology to assess and compare the overall performance, as well as cost benefits of the identified energy efficiency retrofit solutions over the studied period of 30 years. Similar to the study by Anderson et al., Gorgolewski (1995) chose 30 years as the study period to conduct an LCCA, but using the identified parameters as follows: a discount rate of 4%, and contrary to Anderson et al., different time-of-use electricity and gas prices were determined based on the local unit energy rates.

Also contrary to any of the studies referenced above, Gorgolewski (1995) considered and applied two financially opposing scenarios in the study, accounting for the relationship between the initial investment cost and the operating cost, which is stated as follows: If any energy efficiency retrofit solutions with an expected lifetime of less than the study period of 30 years, for instance the glazing, ventilation control, and alternative heating sytsems, were to be re-installed at the end of each life, then the initial invenstment cost associated with the replacement would be discounted to present values, thereby adding to the total investment costs, whereas on the other hand, if there are any retrofit solution(s) with an expected life beyond the study period of 30 years, for instance the thermal insulation, then a salvage (residual) value would be discounted to the present value, but in this case, deducted from the total investment costs.

Gorgolewski (1995) evaluated the economic feasibility of the identified retrofit solutions using the indicator called the "Saving-to-Investment Ratio (SIR)" (Ruegg & Marshall, 1990), which was calculated using the following equation:

$$SIR = \frac{Present\ value\ of\ the\ total\ lifetime\ energy\ saving\ (PVc)}{Investment\ cost} \qquad [\text{Eq. } 2]$$

Similar to the study by Gorgolewski (1995), there was another study conducted by Guler et al. (2008; 2001), which did not include an LCCA of the selected energy efficiency upgrade solutions. Guler et al. (2008; 2001) although recommended that this should be done as a future study, evaluated the feasibility of the identified solutions using the following indicators: 1) megajoule (MJ) of energy savings per dollar (MJ/$); 2) GHG reductions per dollar of saving (g/$); and 3) the "energy savings per retrofitted house (MJ/year/house)", which was expressed in MJ of energy savings per year for each of the retrofitted houses in the CREEM database.

In summary, the LCA, in particular the LCCA is the common methodology used to evaluate the feasibility of various energy efficiency upgrade solutions considered in both the new and existing residential buildings. As numerous studies, some of which are referenced in this section of the chapter, have been conducted using the application of the LCA methodology, there were only a few studies that considered and estimated the actual cost savings of these improvement measures over the life span of the building. This could be attributed to the limitation in the equation [Eq. 1] used in the study by Lutz et al. (2006), which only accounts for the initial cost and the operating cost of the building as a whole, and not the overall savings, which will require an additional calculation to determine and compare the difference in the life cycle cost of one measure against another, similar to the equation [Eq. 2] used in the study by Gorgolewski (1995).

2.4 Optimization Techniques

In this last section of the chapter, the discussion of the methodology used in some of the studies, which in addition to the LCA/LCC analysis, determined the most cost-effective energy efficiency upgrade solutions among various improvement measures through the optimization in energy costs using two distinct methods: a brute force sequential search (BFSS) method (Section 2.4.1), and a genetic algorithm (GA) method (Section 2.4.2).

2.4.1 Brute force sequential (BFSS) method

Gorgolewski (1995) examined the relationship that existed among the various energy efficiency upgrade solutions as more than one upgrade interacted with another upgrade, and by doing so, identified the most cost-effective combination of upgrade solutions.

The methodology, which Gorgolewski (1995) referred to as the "optimisation process" was used not only to identify the most cost-effective upgrade (i.e., the one with the highest SIR), but also, to evaluate the effects of combining the most cost-effective upgrade solution with the remaining solutions by making adjustments to their capital costs, and determining a new SIR for each upgrade. Gorgolewski (1995) continued this process until all the identified upgrade solutions were either accepted, resulting in a SIR of greater than or equal to 1, or rejected if any upgrade resulted in a SIR of less than 1, after readjusting their capital investment cost.

A similar study was conducted by Gorgolewski et al. (1996), which investigated the effect of combining two individual building envelope measures (i.e., thermal insulation and glazing) together as one improvment measure. Gorgolewski et al. (1996) argued that in general, the energy savings of the combined measures considered in a building tend to be less than those of the individual measures that were added together to determine the overall energy savings. Gorgolewski et al. (1996) further argued that this could be attributed to the resulting change in the thermal characteristics of the building, although the authors believed that it would depend on the relatioship of what types of retrofit solutions were considered as one.

Based on the results, Gorgolewski et al. (1996) concluded that there was a resultant increase in annual space heating energy consumption when the thermal insulation and glazing measures were simulated together, but the differences in the overall space heating energy reduction were minimal, resulting in less than 3% of difference in comparison to that of the same measures when they were simulated independently. Gorgolewski et al. (1996) believed that the result was due to an increase in the mean internal temperature, which resulted in a greater temperature difference between the inside and outside of the building, and also due to an increase in the heat loss as a result of other envelopes that had not had improved insulation installed. It should be noted, as Gorgolewski et al. (1996) stated in their study, that such results occured only in the case of combining the two building envelopement improvement measures and, therefore, if either the thermal insulation or the glazing measure were to be combined with the other measures such as space heating and/or hot-water heating system improvements, for example, the outcome would not be the same; in fact, it would be the opposite.

Another example of using a BFSS method would be the studies (Anderson et al., 2006; Christensen et al., 2005) done in the U.S., where the optimization process was developed as a result of combining advanced building envelope designs with the implementation of renewable energy systems into the space heating/cooling systems to achieve NZE status. This methodology, referred to in the study as the "optimal least-cost path to net zero energy" was developed.

Figure 2-2 illustrates the conceptual marginal curve of the optimal least cost path to net zero energy (Anderson et al., 2006; Christensen et al., 2005), and is explained using the results from the study done by Anderson et al. (2006) as follows:

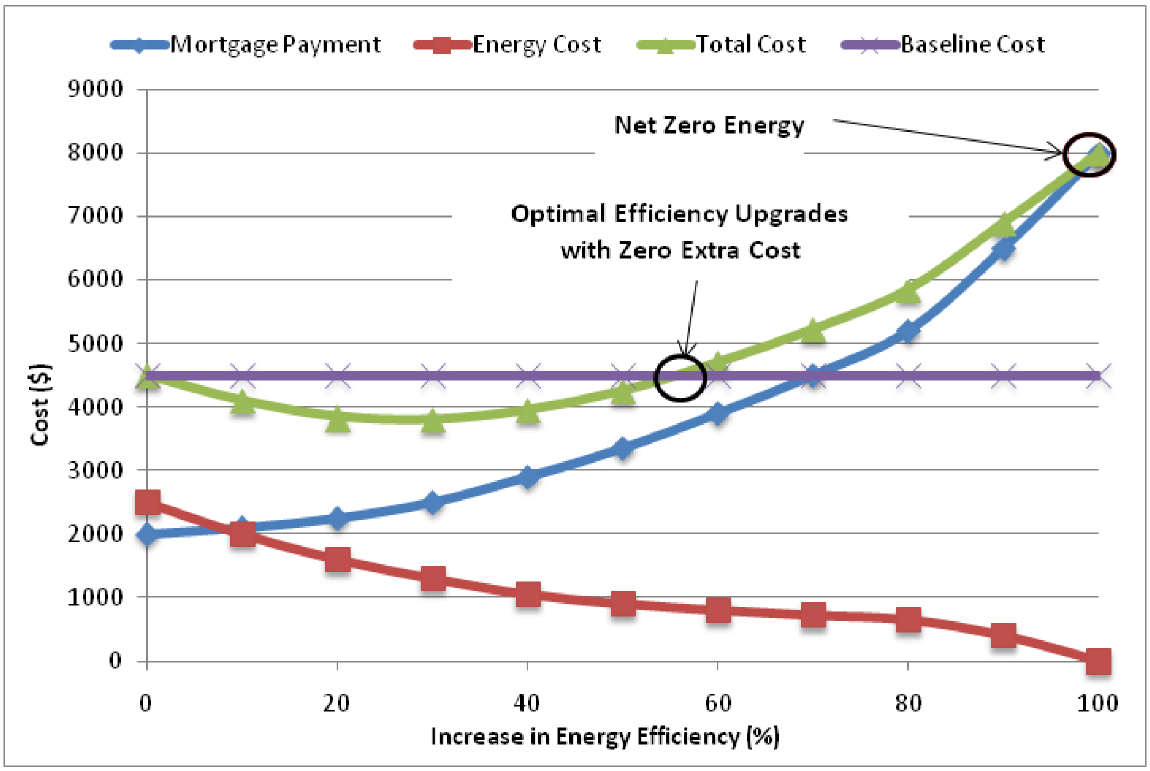


Figure 2-2: Conceptual path to net zero energy

First, the energy performance of a baseline building was determined. In the study done by Anderson et al. (2006), a baseline building referred to a building that was built in accordance with either the building code or currently practiced new building constructions, or a representative of some other reference building. The baseline building resulted in 0% increase in the energy efficiency.

From the baseline case, energy consumption of the baseline building decreased due to the outcome of the identified energy efficiency upgrade solutions, resulting in a minimum total operating energy cost with the estimated increase in energy efficiency of between 20 to 40%. The total operating energy cost was determined based on the sum of monthly energy costs (whether it was natural gas or electricity), and the mortgage payments at the end of each year. Furthermore, all of the costs were expressed in terms of net present value. Anderson et al. (2006) determined the minimum total annual cost based on the lowest guaranteed results from all possible upgrade solutions considered in the study.

Net zero energy status was achieved when the 100% increase in energy efficiency and the resultant zero energy cost were exclusively a result of installing an onsite/renewable energy system. In the case of a study done by Anderson et al. (2006), the residential PV system was chosen as an onsite/renewable energy system, although the authors believed that other renewable energy systems would soon be available in the housing market.

2.4.2 Genetic algorithm (GA) method

Another way to determine the most cost-effective energy efficiency upgrade solutions through an optimization in energy costs is by using a genetic algorithm (GA) method. It should be noted, due to the complexity in nature, only the application of such methodology is discussed in this chapter through the examples of studies done by Sambou et al. (2009), and Verbeeck & Hens (2007), respectively.

The GA method was used in both studies to determine the optimization of a building wall by maximizing thermal insulation and thermal inertia (Sambou et al., 2009), and an extremely low-energy house with respect to energy use, environmental impact, and energy costs over the life cycle of the building (Verbeeck & Hens, 2007). Based on the results from these studies, it can be concluded that the GA method is useful when there are more than one objective required to achieve optimization, in other words, energy, environment, and overall cost.

As it is the objective of this thesis to identify the most cost-effective energy efficiency upgrade solutions through an optimization in overall energy cost using a brute force sequential method, all subsequent references to “optimization” in this thesis should be interpreted as cost optimization.

2.5 Building Energy Simulation

Building energy simulation is a useful tool in determining how much energy a building, whether new or existing, is predicted to consume over the course of a year. Numerous building energy simulation programs have been developed to date, and used by many professionals such as architects, engineers, researchers, government officials, to name a few, allowing them to perform varying degrees of energy performance analysis in various types of buildings.

In Canada, the application of building energy simulation can be used to influence not only the design process, but also, the regulatory process of the new and existing buildings. One of the commonly used building energy simulation programs for residential application is the HOT2000, developed by the Natural Resources Canada (NRCan, 2010). This program was used in the studies by Guler et al. (2001; 2008) to determine the annual energy consumption of the identified energy efficiency retrofit solutions for the existing residential houses in Canada. The same program was used in the study conducted by the CMHC (2005) to a) evaluate the performance of electronically commuted permanent magnet (ECPM) motor technology used in the residential forced-air heating and cooling applications; and b) quantify any increase in natural gas consumption during the heating season, and any decrease in air-conditioning consumption during the cooling season, respectively. The HOT2000 program was also used to form the prescriptive requirements of the proposed 2012 OBC, which was discussed briefly in Chapter 1.

However, due to its easy-to-use design with a graphical user interface that allows architects, engineers and builders to perform a simulation in a timely manner, HOT2000 as a simulation program has many limitations in practice, some of which have been identified in the studies done by Dembo et al. (2009; 2010). These limitations can be addressed by conducting sensitivity analysis to evaluate and compare the results from the HOT2000 program to those of a more advanced simulation program, for instance, TRNSYS, which is another simulation program, but unlike HOT2000, is capable of conducting the energy performances of not only the buildings, but also solar and other renewable energy systems using a time step of one hour or less (Kummert et al., 2004; Crawley et al., 2008; Kummert & Bernier, 2008b).

2.5.1 Overview of HOT2000

HOT2000 (Figure 2-3) is a residential energy analysis program that is used extensively not only in North America, but also in Europe and Japan (Haltrecht & Fraser, 1997). Since the introduction of the program in the late 1980s, HOT2000 has used a bin method[8] and long-term monthly weather data to analyse the performance of a house (Haltrecht and Fraser, 1997), allowing the users to determine how much energy the house, whether new or existing, consumes on a monthly and yearly basis. The program also allows the users to evaluate the design of the house for its thermal effectiveness, and passive solar heating potentials, as well as the operation and performance of heating and cooling systems (Canadian Home Builders' Association [CHBA], 1991; Haltrecht & Fraser, 1997).

---

[8]Bin method, also known as "temperature frequency method" (American Society of Heating, Refrigerating and Air-Conditioning Engineers [ASHRAE], 1985), is a method used to calculate, either by hand or using a computer program, the energy required for heating or cooling in order to maintain the conditioned (indoor) space at a desired temperature with respect to the outdoor (dry-bulb) temperature conditions, which are grouped in the form of 2.8°C (5°F) in size, or "bins", with the hours of occurrence for each bin (McQuinston et al., 2005). The bins are often collected in three daily 8-hour shifts (e.g., day and night), and are used to calculate latent cooling loads for infiltration and ventilation purposes by taking the mean coincident wet-bulb temperature for each bin (ASHRAE, 1985; McQuinston et al., 2005). There are two types of bin method used, the "classical" and "modified", where the example of the former is the calculation of the energy requirements (for heating only) of a residential heat pump (ASHRAE, 1985).

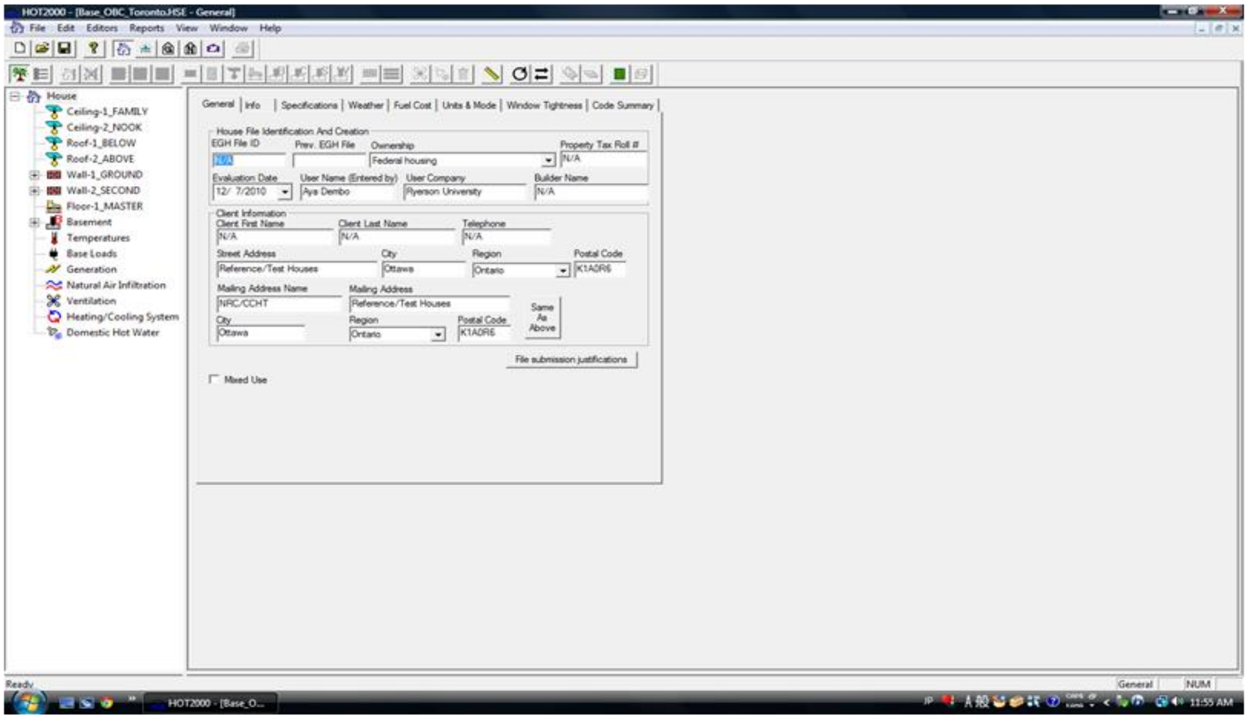


Figure 2-3: Demonstration of HOT2000 Window

2.5.2 Overview of TRNSYS

TRNSYS was originally developed at the Solar Energy Laboratory within the University of Wisconsin-Madison, and made commercially available in 1975 (Bradley et al., 2004a; Bradley et al., 2004b; Kummert et al., 2004; Van der Veken et al., 2004). Using a fully integrated visual interface, known as the TRNSYS Simulation Studio, and a dedicated visual interface, known as the TRNBuild (Figure 2-4), TRNSYS is capable of conducting the energy performances of not only the buildings, but also, solar and other renewable energy systems (Kummert et al., 2004; Crawley et al., 2008), and is believed to be the “most advanced program for the simulation of active solar systems sponsored by the U.S. DOE” (Judkoff & Neymark, 1995a, p.10).

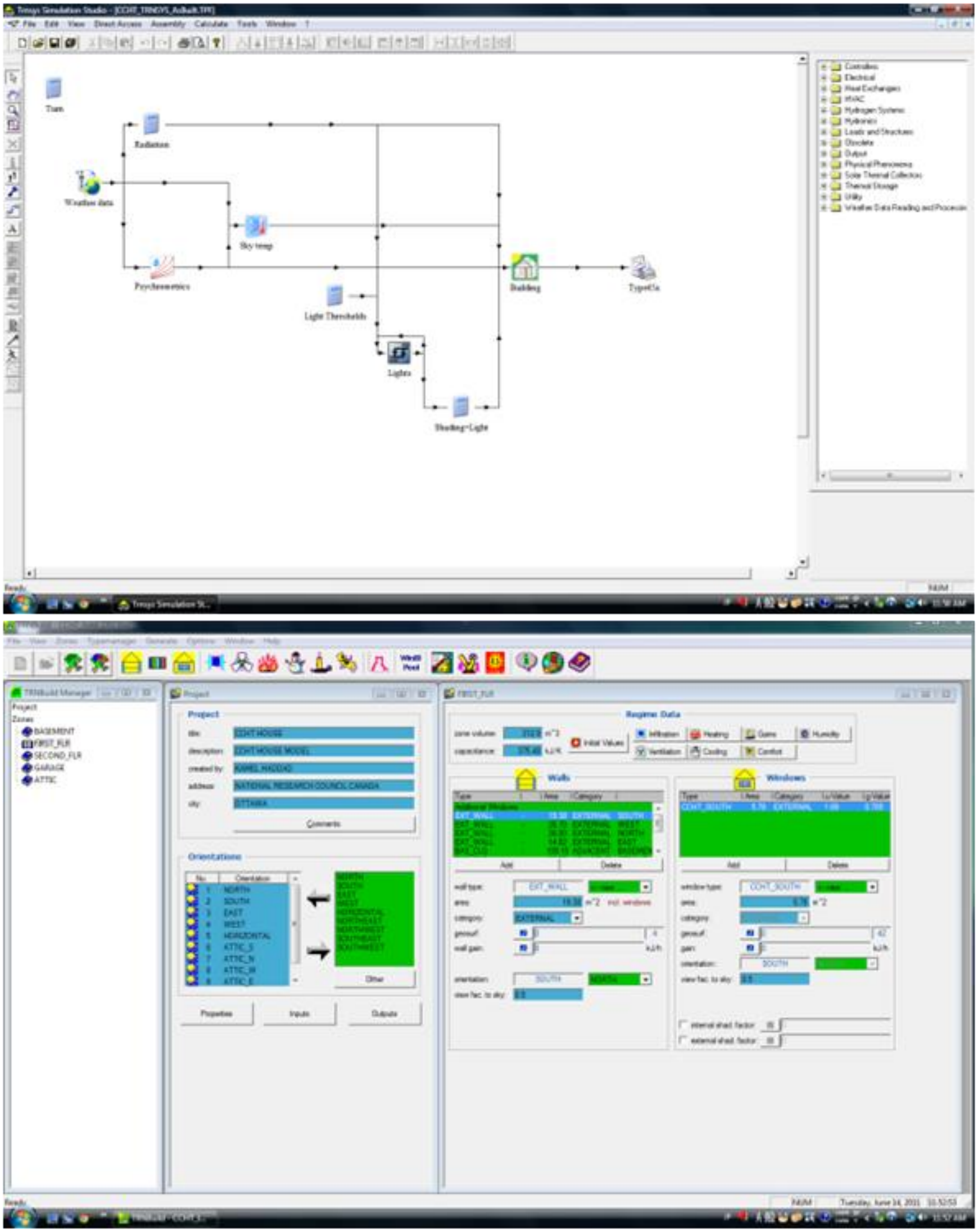


Figure 2-4: Demonstration of TRNSYS Simulation Studio (top) and TRNBuild (bottom) Windows

Since the introduction of the program, the application of TRNSYS has influenced the design process of many advanced HVAC systems, as was evidenced in the numerous studies done worldwide. These studies include;

- the design of a chilled water plant used for the cooling of a recently constructed institutional building in the U.K. (Kummert et al., 2009)
- a combined photovoltaic-geothermal gas-fired absorption heat pump system used for space conditioning and domestic hot-water heating purposes to meet the climatic conditions of Canada (Kummert & Bernier, 2008a)
- the ground-coupled heat pump systems used for Canadian residential applications (Kummert & Bernier, 2008b), and
- the heating controls used in the passive solar buildings, one in Belgium and another one in Greece, respectively (Kummert et al., 2006)

The use of TRNSYS further extends to the commissioning process of the building. An example of this was the study done by Zheng and Pan (2007), which investigated the functionality and ease of use, in support of the commissioning process, of several existing HVAC system simulation programs including TRNSYS. Zheng and Pan (2007) argued that although not originally developed as commissioning tools, these simulation programs aid the users to perform not only a comparative analysis of different HVAC system functions and performances, but also a detailed analysis of parameters that influenced such performances.

Meanwhile, a new type of building energy simulation program was in its development, and in the U.S., multiple studies have been conducted to evaluate the energy performance of various energy efficiency upgrade solutions using the Building Energy Optimization (BEopt) program, an hourly energy simulation that uses TRNSYS and DOE2 building energy simulation programs (Christensen et al., 2005; Anderson et al., 2006; Norton & Christensen, 2006). This simulation program was developed not only to identify the optimal building design solutions that could achieve the net zero energy level, but also, to find the near-optimal solutions, allowing the users to develop design solutions that could achieve various levels of energy savings with total costs as close to being that of the optimal level (Anderson et al., 2006).

2.5.3 Similarities and differences of HOT2000 and TRNSYS

In addition to both programs having a graphical user interface as their featured capabilities, the other similarity between HOT2000 and TRNSYS is that these programs simulate a house by dividing it into three distinct zones; the basement, main floors, and attic (Haltrecht and Fraser, 1997; Kummert & Bernier, 2008b), where the former takes into account the specified passive solar and internal heat gains, and heat transfer between zones to calculate the space heating and cooling energy requirements of the house (Haltrecht and Fraser, 1997).

As for the differences between HOT2000 and TRNSYS, there are several distinct differences that are identified as follows:

First, HOT2000 calculates the effective thermal resistance (RSI or R-value) of an envelope component, whether it be an attic, wall, or floor, based on the considerations of its framing area, thermal bridging, and interior and exterior film coefficients (Haltrecht and Fraser, 1997); whereas, TRNSYS considers “the thermal capacitance of all envelope components, and calculates the internal temperature and humidity response to external conditions and to the HVAC system” (Kummert & Bernier, 2008b, p.33).

In HOT2000, the thermal capacitance of all envelope components is determined based on the effective thermal mass of the house, which is defined by a value known as the Effective Mass Fraction (NRCan, 2010). Four different thermal mass levels are identified in HOT2000, and thermal capacity (in $MJ/K{\cdot}m^2$) for each thermal mass level is predetermined as follows: Light, wood frame (0.060), Medium, wood frame (0.153), Heavy, masonry (0.415), and Very heavy, concrete (0.810) (NRCan, 2010). It should be noted that the baseline case was set to “Light, wood frame” with the identified thermal capacity of 0.060 $MJ/K{\cdot}m^2$, and for the sensitivity analysis, the thermal mass levels of “Medium, wood frame”, and “Heavy, masonry” were considered with the identified thermal capacity of 0.153, and 0.415 $MJ/K{\cdot}m^2$, respectively.

Another difference between HOT2000 and TRNSYS is that the current version (ver. 8.0 and up) of the former is built with a residential foundation heat-loss algorithm, known as the BASESIMP (Beausoleil-Morrison & Mitalas, 1997), which replaced the original heat-loss model, known as the Mitalas Heat-Loss Method (Mitalas, 1982; CHBA, 1991) that was used to calculate heat loss from the basement by accounting for seasonal variation in soil temperatures, as well as the effect that the placement, and amount of insulation at various portions of the basement wall and slab floor has on heat loss (CHBA, 1991; Haltrecht and Fraser, 1997). TRNSYS, on the other hand, uses the undisturbed ground temperature to calculate heat loss from the basement, because such a detailed model is not included in TRNSYS (Kummert & Bernier, 2008b).

Lastly, unlike HOT2000, TRNSYS is incapable of calculating air infiltration rate internally (Kummert & Bernier, 2008b). This is due to the fact that the former is built with another detailed model, known as the Alberta Air Infiltration Model or AIM-2 (Walker & Wilson, 1990; Bradley, 1993) that is used to calculate infiltration rate by accounting for wind and stack effect, as well as the interaction with mechanical ventilation (Haltrecht and Fraser, 1997). TRNSYS, on the other hand, calculates the infiltration rate based on the wind speed, ambient temperature, and indoor temperature of a building (Kummert & Bernier, 2008b). It should be noted that a new, validated model was developed to implement the AIM-2 in TRNSYS (Walker & Wilson, 1998; ASHRAE, 2005).

2.5.4 Validation of HOT2000 and TRNSYS

In addition to those studies as referenced above, numerous studies have been conducted worldwide to compare the capability of various building energy simulation programs. Among these studies are:

- Karlsson et al. (2007) conducted a study using three different dynamic simulation programs to calculate the energy demand for heating and the indoor temperatures of a low-energy house in Sweden.
- In the U.S., Crawley et al. (2008) conducted a study to compare the capabilities of twenty well-known building energy simulation programs including TRNSYS with respect to building envelope; day-lighting and solar; infiltration, ventilation, and multi-zone airflow; renewable energy systems; electrical systems and equipment; HVAC systems and equipment, and other variables.

These studies represent an example of “comparative testing”, which is one of the three methods used to evaluate the accuracy of a building energy simulation program (Judkoff et al., 2008). The methods are described as follows:

The first method is the **empirical validation** in which the results of a building simulation program are compared to the monitored or experimental data obtained from an existing building or laboratory experiment (Judkoff & Neymark, 1995a; Witte et al., 2001; Judkoff & Neymark, 2006). Kummert et al. (2006) argued that adding TRNSYS simulation results to the experimental comparison of different heating system controllers allowed the authors to not only estimate annual energy savings, but also, study the behaviour of controllers with various weather or occupancy conditions, thereby adding useful information to the experimental comparison in their study.

The **analytical verification** is the second method used to compare the results of a building simulation program to those of mathematical solutions (Witte et al., 2001), or what Judkoff and Neymark (2006; 1995a, p.7) stated as “a known analytical solution or a generally accepted numerical method for isolated heat transfer mechanisms under very simple, highly contrained boundary conditions."

The third method is the **comparative testing** in which the results of a building energy simulation program are compared to other programs that have been previously validated to be more detailed and physically accurate (Judkoff & Neymark, 1995a; Witte et al., 2001; Judkoff & Neymark, 2006). It should be noted that this method was used to conduct the sensitivity analysis of HOT2000 and TRNSYS as presented in this thesis.

It has been reported by multiple studies that HOT2000 was validated using the Home Energy Rating System Building Energy Simulation Test, known as HERS BESTEST (Judkoff & Neymark, 1995b), a comparative testing method developed by the National Renewable Energy Laboratory (NREL) to compare the results of a testing program against the results from the three reference programs, BLAST 3.0, DOE 2.1E-W54, and SERIRES/SUNCODE 5.7 (Haltrecht and Fraser, 1997; Zmeureanu et al., 1999; Stein & Meier, 2000).

TRNSYS on the other hand, was validated using the Building Energy Simulation Test and Diagnostic Method, known as BESTEST (Judkoff & Neymark, 1995c), the same comparative testing method as the HERS BESTEST; but it is a more detailed test, developed by the International Energy Agency (IEA) with an intention to find and diagnose errors in the building energy simulation programs by comparing the results of a testing program against the results from the eight state-of-the-art simulation programs (Haltrecht and Fraser, 1997; Witte et al., 2001). The BESTEST was later restated into a Standard Method of Test (Witte et al., 2001; Judkoff & Neymark, 2006) in ANSI/ASHRAE Standard 140-2004 (ASHRAE, 2004), where the latter was used as a validation tool in the development of a new version (ver. 16.0) of TRNSYS (Bradley et al., 2004a; Bradley et al., 2004b; Kummer et al., 2004). It should also be noted that the HERS BESTEST is an augmentation of the IEA BESTEST (Judkoff & Neymark, 1995c).

Chapter 3

3 Methodology

3.1 Background

The proposed methodology considers the initial capital cost, and the life cycle cost implications of achieving such standards that result while maintaining an adequate level of thermal comfort using life cycle cost analysis (LCCA), and optimizing energy-related costs using a brute force sequential search (BFSS) method.

A series of potential least cost upgrade solutions comprise building envelope, and HVAC systems were considered, and chosen to meet various levels of thermal and energy performances while taking into account the use of local materials and resources, ease of construction and installation, but most importantly, adoption by the Canadian and/or Ontario housing industry.

Figure 3-1 shows the overview of the proposed methodology developed to achieve the objective stated in Section 1.2, followed by the description of each process in the next sections of the chapter.

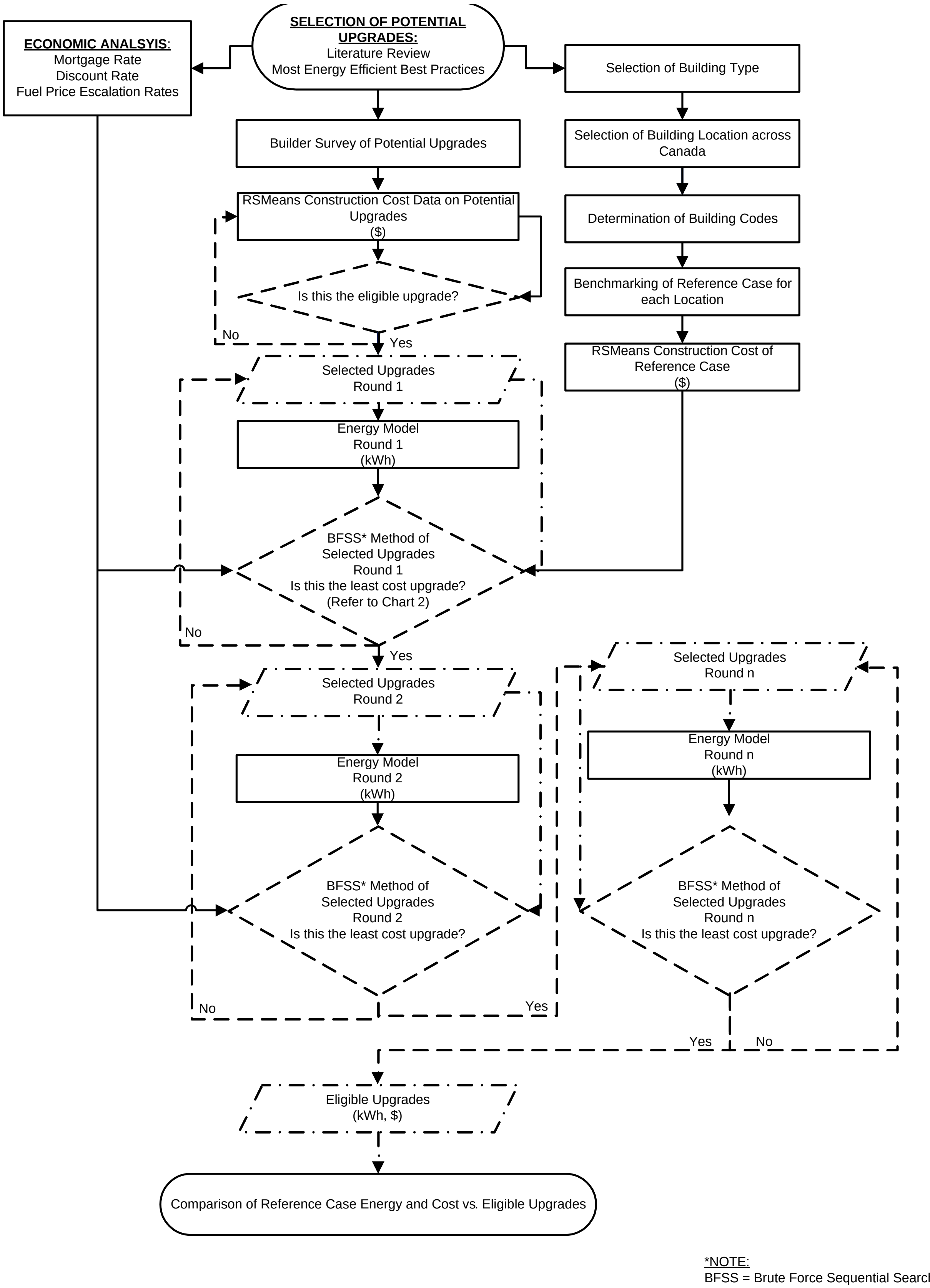


Figure 3-1: Overview of the Least Cost Upgrade Solutions Methodology

3.2 Selection of Building Type

3.2.1 House characteristics considered in the thesis

The Canadian Centre for Housing Technology (CCHT) Reference House (Entchev et al., 2004; Barry & Elmahdy, 2007; Haddad et al., 2008; Manning et al., 2007; Manning et al., 2008; Swinton et al., 2007; Ouazia et al., 2009), an existing two-storey single-family dwelling with an attached two-car garage was used to represent a typical Canadian new house for this thesis, not only because of the fact that its style and finish were representative of current houses available on the local housing market (Entchev et al., 2004), but also, because it was built by one of the large-volume builders in Ontario.

The front side of the house faced south with an estimated window area of 16.2 m^2, covering 46% of the total window area (Barry & Elmahdy, 2007; Haddad et al., 2008; Manning et al., 2007; Manning et al., 2008; Swinton et al., 2007; Ouazia et al., 2009). Figure 3-2 shows the front orientation of the CCHT Twin Research Houses in Ottawa, ON.

Figure 3-2: The CCHT Twin Research Houses, Test House (left), and Reference House (right) in Ottawa, ON (Barry & Elmahdy, 2007; Haddad et al., 2008)

The house had a total floor area, excluding the basement, of 210 m^2 (2260 ft^2), and a total window area of 35 m^2 (377 ft^2), respectively (Barry & Elmahdy, 2007; Haddad et al., 2008; Manning et al., 2007; Manning et al., 2008; Swinton et al., 2007; Ouazia et al., 2009).

Table 3-1 summarizes the characteristics of the house, which were used for the building energy simulation purposes. It should be noted that building configuration/geometry, as well as the construction details were based on the drawing set of the Reference House obtained from the CCHT (refer to Appendix A).

Table 3-1: Characteristics of the Reference House

House Area and Volume		
Floor area	m^2	210
Internal ceiling height	m	5.48
Total space volume	m^3	1198
Windows		
Total window area	m^2	35
Window-to-wall ratio for the: -South facing (= front orientation) -West facing -North facing -East facing **Overall**	%	 34 5 24 16 **22**

3.2.2 The Reference House built to the R-2000 Standard

It should be noted that the Reference House was built in accordance with the R-2000 Standard (Barry & Elmahdy, 2007; Haddad et al., 2008; Manning et al., 2007; Manning et al., 2008; Swinton et al., 2007; Ouazia et al., 2009). This standard contained stringent regulations for with which the new houses were required to comply: For instance, the air-tightness level of a house must be "*less than or equal to 1.5 air-change per hour (ACH) at 50 Pascal (Pa)"*, and due to a reduced infiltration rate, the house must be equipped with a mechanical ventilation system

(NRCan, 2005, p. 3). The featured characteristics of the Reference House in compliance with the R-2000 Standard are summarized in Table 3-2.

Table 3-2: Featured characteristics of the Reference House
(Barry & Elmahdy, 2007; Haddad et al., 2008; Manning et al., 2007; Manning et al., 2008; Swinton et al., 2007; Ouazia et al., 2009)

Component	Characteristic
Attic	RSI 8.6 (R49)[1]
Walls	RSI 3.5 (R20)[1]
Basement walls	RSI 3.5 (R20)[1]
Basement slab	Concrete slab with no insulation (*RSI not identified*)
Rim joists	RSI 3.5 (R20)[1]
Windows	Double-glazed windows with low-E coating, insulated spacer, and argon-gas filled with argon concentration measured to 95% *(U-value not identified)*
Air barrier system	Exterior, taped fiberboard sheathing with laminated weather resistant barrier. Also taped penetrations including windows
Air-tightness	Measured 1.07 ACH at 50 Pa and thereby meeting the R-2000's air-tightness requirement of 1.5 ACH at 50 Pa
Ventilation	High efficiency heat recovery ventilator(HRV) at 84% nominal efficiency
Space-conditioning (heating/cooling) system	High efficiency, condensing gas furnace at 91% efficiency as measured
DHW system	Conventional, induced draft at 67% efficiency as measured
AC system	High efficiency AC unit at nominal Seasonal Energy Efficiency Ratio (SEER) of 12
Note: 1. The values reported in the table are nominal RSI (R) values.	

If a new house were to be built in accordance with the R-2000 Standard, it means that the energy performance of the house "*have met the [R-2000] energy target, which is equivalent to a rating of 80 under the EnerGuide for Houses rating system*" (NRCan, 2005, p.7). Table 3-3 summarizes the thermal resistance (RSI) of the building envelope components in compliance with the 2006 Building Code and the R-2000 Standard for comparison purposes.

Table 3-3: Summary of the 2006 Building Code and the R-2000 Standard

Thermal Resistance (RSI) of the Building Envelope Components	2006 Building Code[1]	R-2000 Standards[2]
Ceiling below attic or roof space	7.00 (R40)	8.60 (R49)
Roof assembly without attic or roof space	4.93 (R28)	Not identified
Wall other than foundation wall	3.34 (R19)	3.50 (R20)
Foundation walls enclosing heated space	2.11 (R12)	3.50 (R20)
Slab-on-ground containing heating pipes, tubes, ducts or cables	1.76 (R10)	Not identified
Slab-on-ground not containing heating pipes, tubes, ducts or cables	1.41 (R8)	Not identified

Notes:
1. Refer to the Table 12.3.2.1 under "Zone 1 Less than 5000 Degree-Days" (MMAH, 2008a)
2. Defined based on the featured house characteristics of the Reference House (Barry & Elmahdy, 2007; Haddad et al., 2008; Manning et al., 2007; Manning et al., 2008; Swinton et al., 2007; Ouazia et al., 2009)

As Table 3-3 indicates, the thermal resistance level of the insulations specified by the R-2000 Standard exceeds those of the 2006 Building Code. In addition, the annual energy consumption of the CCHT Reference House was determined using the HOT2000 program for further comparison of the 2006 Building Code and the R-2000 Standard. Table 3-4 summarizes the results.

Table 3-4: Estimated Energy Consumption of the 2006 Building Code and the R-2000 Standard

Estimated Annual Energy Consumption (kWh/year)	2006 Building Code	R-2000 Standards
Space Heating	24,818	16,356
Space Cooling	824	875
DHW Heating	7,590	6,621
Appliance and Lighting	8,760	8,390
Total Estimated Annual Energy Consumption	**41,992**	**32,242**
Has met the R-2000 Energy Target?	No	Yes
EnerGuide Rating	78	81

Based on the comparative analysis of the 2006 Building Code and the R-2000 Standard, it can be concluded that a new house built in accordance with the latter achieved the EnerGuide 80, thereby meeting the proposed requirements of the 2012 Building Code.

3.2.3 Occupancy, appliances and lighting assumptions considered in the thesis

For the building energy simulation purposes, the occupancy was assumed based on the Reference House having the simulated occupancy of two adults and two children (Manning et al., 2007; Manning et al., 2008), although, based on the 2006 Census, the average Canadian household has occupancy of less than three (2.5 for Canada, and 2.6 for Ontario) persons (Statistics Canada, 2007; NRCan, 2011).

The appliances and lighting assumptions considered in this thesis were based on the standard operating conditions used in the HOT2000 program, which assumed that the occupancy of two adults and two children were present 50% of the time, and using 24 kWh (81,891 Btu) per day of electricity consumption for appliances and lighting (NRCan, 2010).

In addition, sensitivity analysis of the identified appliances and lighting assumptions was conducted to evaluate the effectiveness of the potential least cost upgrades by reducing electricity consumption for appliances and lighting. The results will be discussed in the next chapter.

3.3 Determination of Building Codes

As briefly explained in Chapter 1, the national and/or provincial building codes were used to determine the benchmark.

Provinces such as New Brunswick, Newfoundland and Prince Edward Island have adopted the national building code as the standard practice for new housing constructions (NRCC, 2009). However, most of the provinces in Canada have developed and published their own building codes to meet their provincial needs, and in Ontario, all newly constructed houses must comply with the regulations as specified in the 2006 Building Code (NRCC, 2009).

Effective as of December 31, 2011 is the introduction of the 2012 Building Code, developed based on the 2006 Building Code with revisions to include new regulations, the compliance with the EnerGuide Rating of 80 or more (MMAH, 2008f).

3.4 Selection of Potential Least Cost Upgrade Solutions

As mentioned previously in the beginning of the chapter, a series of potential least cost upgrade solutions were considered to meet various levels of thermal and energy performances while taking into account the use of local materials and resources, ease of construction and installation, but most importantly, adoption by the Canadian and/or Ontario housing industry.

Various energy efficiency upgrade solutions were considered based on literature review however, due the fact that the Reference House used a 38 x 140 mm (2x6 in.) thick timber framed construction (Entchev et al., 2004), the potential upgrades considered for this thesis were limited to what was achievable for a 139.7 mm (5.5 in.) deep framed construction.

It should also be noted that this thesis was limited to an investigation of a south-north orientation, and to maintaining the original architectural configuration of the Reference House. Therefore, the implications of other orientations (i.e., east-west), as well as the impacts of having the external shading to reduce solar heat gain were eliminated, and thus recommended for future studies.

The potential least cost upgrades for the building envelope systems included increasing the thermal resistance of the building envelope (i.e., attic, exterior walls, basement walls, floors, and basement slab/foundation) by installing additional insulation on the exterior side, and both interior and exterior sides of the envelope to determine what would be the most cost-effective (or least cost) solution to increase the overall thermal resistance of the envelope.

In addition to increasing the insulation levels of the envelope, the potential least cost upgrades also considered the installation of high-performance windows, and/or the reduction in the air-leakage potentials by implementing the continuous air barrier to increase the overall air-tightness of the envelope.

For the HVAC system upgrades, the following systems/technologies were considered:

- Furnace with ECMs
- Combination or combo boiler
- DHW heater (i.e., changing the efficiency level)
- Ventilation including an HRV
- AC system
- Renewable energy systems including;
  - DWHR/GWHR systems
  - Solar-assisted DHW heater
  - Residential PV systems

It should be noted, the potential renewable energy systems that were considered for this thesis were chosen to evaluate the feasibility of their application into the currently practiced new housing constructions in Canada.

Prior to finalizing the potential upgrade solutions, a survey to the local homebuilders in Ontario was conducted to perform a detailed review of the suitability of considered upgrades, and to determine accurate estimations of the initial (material and installation) costs to implement such upgrades into the currently practiced new housing constructions to achieve improved energy efficiency standards.

3.5 Builder Survey

The survey was broken down into two parts, where the first part was developed to perform a detailed review of the appropriateness of considered upgrades by analyzing what types of advanced technologies the local homebuilders have already put into practice. With the introduction of the 2012 and the future 2016 Building Codes, it was critical to understand the current state of new housing constructions in Ontario, and based on the analysis, the survey was developed to identify what would be the major changes in the current practice if the local homebuilders were to consider implementing any one of the identified upgrades to meet the requirements of the new codes.

The survey was conducted, over the phone and/or in-person, by seven local homebuilders in Ontario. Despite the low sample size, these were the large volume builders with each building up to 300 houses a year, thus making the survey result more representative of the housing market[9].

3.5.1 Suitability of considered upgrades for the Ontario housing market

The results of the survey showed that all participant builders have responded that they were involved in the energy efficiency labelling program known as the ENERGY STAR for New Homes (ESNH), a commonly adopted energy efficiency standard in Canada, developed based on the U.S. DOE and the Environmental Protection Agency (EPA)'s ENERGY STAR program.

In addition to the ESNH program, a few builders have participated in other labelling programs such as the NRCan's EnerGuide for New Houses (EGNH) program, EnerQuality Corporation's GreenHouse Certified Construction (GHCC) program, and the Canada Green Building Council (CaGBC)'s LEED Canada for Homes (LEEDH), where the latter is another commonly adopted energy efficiency standard in Canada, developed based on the U.S. Green Building Council (USGBC)'s LEED for Homes program, and modified to suit the nature and practices of the residential sector in Canada.

It was interesting to note that none of the homebuilders have participated in the R-2000 program, which was created by the NRCan in partnership with the CHBA in 1981, and became the basis for many of the commonly adopted energy efficiency standards such as the ESNH, EGNH and LEEDH in Canada.

[9] It was reported by the CMHC (2011) that the total number of single-family dwellings built in the GTA in year 2010 was 11,079, while the number of new houses built by the participant builders was estimated to be 1,653, thus representing 15% of the housing market.

This could be attributed to the program's targeted air-tightness level of 1.5 ACH at 50 Pa, as evidenced by the responses received from the survey, which indicated that none of the houses built by the participant builders achieved the air-tightness level of 1.5 ACH at 50 Pa or lower. This could be attributed to the potential increase in the initial (materials and labour) costs associated with air sealing the entire surface of the house, which would typically cost, depending on the size and complexity of the house and work required, from $500 to $2000 (NRCan, 2007b).

As shown in Figure 3-3, the majority of the houses built by the participant builders achieved an air-tightness level, ranging from 1.51 to 2 ACH at 50 Pa (43%), and from 2.01 to 2.5 ACH at 50 Pa (29%), respectively. It was also interesting to note that 28% of the houses built have not been subjected to the depressurization test (also known as the blower door test) to evaluate the air-tightness level of the house. This could be attributed to the targeted air-tightness level as well as the program requirements as specified by each labelling program in which the participant builders were involved.

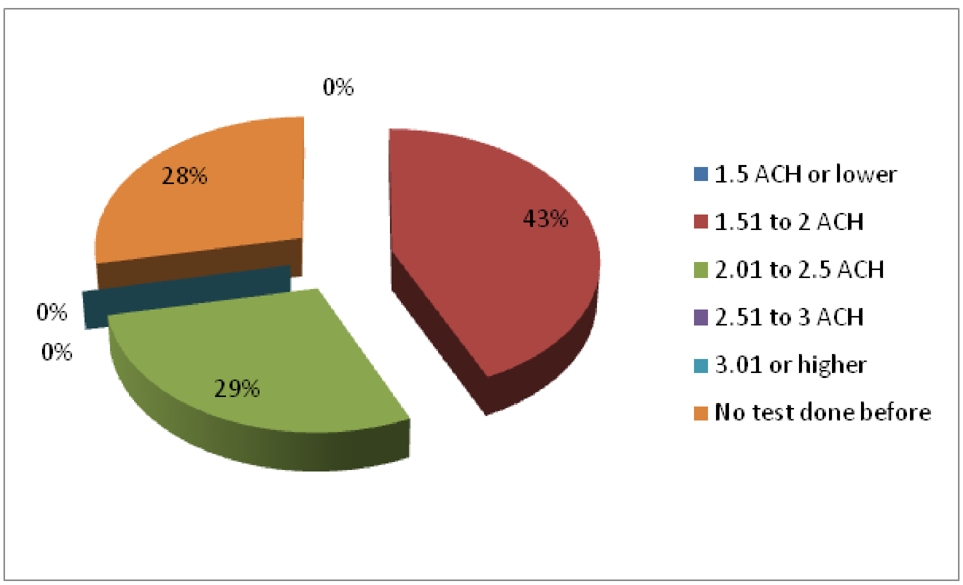


Figure 3-3: Breakdown of air-tightness level achieved by the participant builders

With respect to the potential building envelope upgrades, based on the results of the survey, it was apparent that all participant builders who have responded to the survey were building their homes to the current (2006) OBC and/or the ESNH Standard.

Further analysing the results in detail, 43% of the participant builders responded that their current exterior wall construction practices use timber-framed construction, where the studs are spaced at 400mm (16 in.) on-centre, and with RSI 3.34 (R19) wall insulation placed in between the studs. Out of these, 29% were considering upgrading the existing wall insulation to RSI 3.87 (R22), and the remaining 14% were considering upgrading it to RSI 4.23 (R24) (comprising of installing RSI 3.34 (R19) interior wall insulation, and RSI 0.90 (R5) exterior wall insulation) in the near future.

The remaining 57% of the participant builders on the other hand, responded that they have began to construct the exterior walls by using the same timber-framed construction, but with studs spaced at 600mm (24in.) on-centre, and with higher levels of insulation than RSI 4.23 (R24). Out of these, 43% had no intention of upgrading the existing wall insulation in the near future, although the remaining 14% were considering using advanced framing technologies such as prefabricated panels including SIPs. Figure 3-4 summarizes the result.

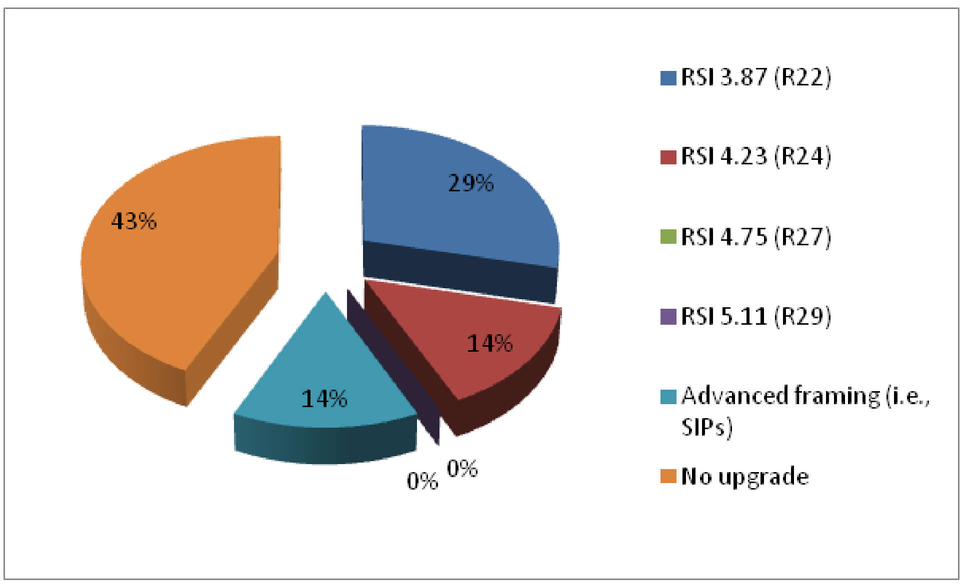


Figure 3-4: Breakdown of exterior wall insulation upgrade options considered by the participant builders

For the attic construction, it was interesting to note that 43% of the participant builders were considering upgrading their existing attic/ceiling insulation of RSI 7.00 (R40) to RSI 8.80 (R50) in the near future, while the remaining 57% were reluctant to upgrade their current attic/ceiling construction practices by installing an insulation of RSI 8.80 (R50) or higher. This could be attributed to the fact that such an upgrade is neither required by the homeowners and, therefore, no benefit to the builders, nor specified by the current (2006) OBC or the ESNH Standard at this point.

The same conclusion was made with respect to the participant builders' views on upgrading the current basement wall construction practices, as was evidenced by the responses received from the survey, which indicated that upgrading the basement wall insulation from RSI 2.11 (R12) to RSI 3.52 (R20) or higher would not be considered a viable option, because such an upgrade is, at present, required neither by the current (2006) OBC nor by the ESNH Standard, and also there is no market demand.

Lastly, with respect to windows, all participant builders responded that most of the houses built have double-glazed, low-E, argon filled windows installed, as per the requirements of the ESNH Standard. Out of these, all participant builders responded that they were considering upgrading their current windows to those with U-value of 1.6 (29%), 1.8 (43%), or 2.0 (14%), respectively. It should be noted that consensus could not be achieved with respect to this question due to the fact that the remaining 14% of the participant builders had no response, which could imply that they had no intention of upgrading their current windows in the near future.

For the HVAC systems, it was evidenced by the responses received from the survey that a furnace with ECM was the most commonly used system for space heating (with 46%), followed by the combination or combo boiler (39%), DHW heater (8%), and other systems including a high-efficiency furnace without the ECM (8%), as shown in Figure 3-5.

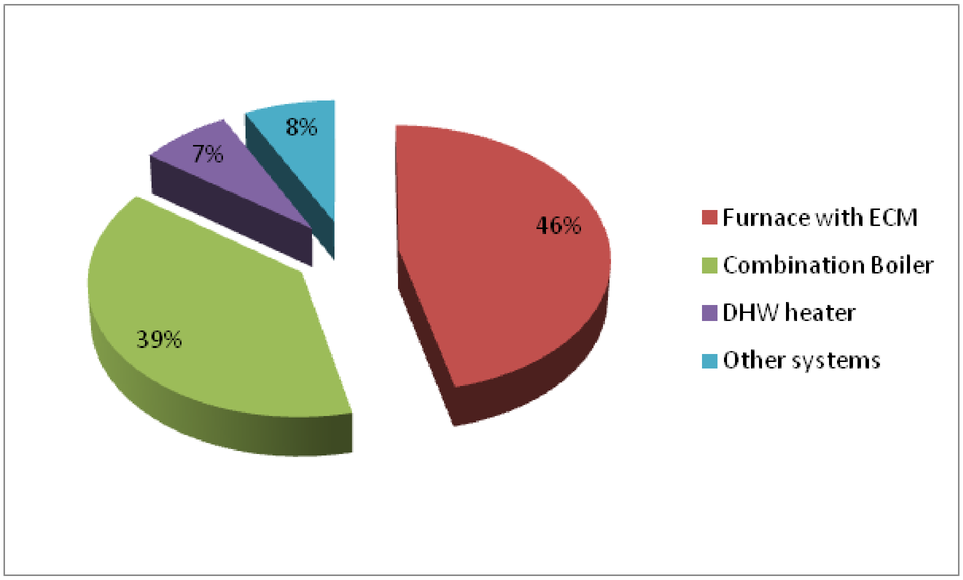


Figure 3-5: Breakdown of space-heating systems used by the participant builders

A total of 43% of the participant builders responded that they were installing a furnace with 90% annual fuel utilization efficiency (AFUE) as per the current (2006) OBC and/or ESNH Standard, and out of these, almost all of them responded that they were considering upgrading their existing furnace to one with higher AFUE of 92%, 94% and 95%, respectively in the near future. The remaining 43% of the participant builders responded that they have begun to install the same system with AFUE of 92 or higher. It should be noted that consensus could not be achieved with regard to these questions due to the fact that the remaining 14% of the participant builders had no response. This could imply that these houses were built with no furnace installed or such equipment was on lease.

As for the DHW heater, 57% of the participant builders were installing the system with 0.57 Energy Factor (EF) or higher, and out of these, 14% were considering upgrading it to 0.80 EF, although the remaining 86% were not considering upgrading their existing systems unless such an upgrade were to be required by the future OBC or the ESNH Standard.

Lastly, a total of 43% of the participant builders were installing the HRV system with 55% efficiency, and out of these, 29% were considering upgrading it to 70% efficiency, although the remaining 71% were not considering upgrading their existing systems to higher efficiency due to the lack of market demand at this point, unless otherwise required by the future OBC or the ESNH Standard. The complete results of the survey are summarized in Appendix B.

3.6 Cost Estimations of the Potential Least Cost Upgrades

Once the potential upgrades were identified, the incremental cost of each upgrade was determined based on data obtained from the "Building Construction Cost Data" (RSMeans, 2010), and a study done by Fung et al. (2009), which was based on the detailed cost information given by one of the major residential HVAC equipment suppliers in Ontario/Canada.

The cost of each building envelope upgrade was determined first, by selecting a series of construction materials from the RSMeans cost data publications. The costs for materials, and installation determined the overall construction costs based on the overall square footage of the Reference House.

The incremental cost of each identified upgrade was then established based on the difference in material cost, installation cost, and overall cost of the identified upgrades against the baseline case, where the costs of the latter were determined based on the prescriptive-based specifications of the 2006 Building Code.

It should be noted, the costs for the materials, installation and overall construction in the RSMeans cost data publications were based on the U.S. currency and, therefore, in order to determine the overall costs for a specific location in Canada, these costs had to be adjusted by multiplying the base cost by the "Location Factors", and dividing it by 100 (RSMeans, 2010, p. 737). Table 3-5 summarizes the location factors for various cities in Canada.

Table 3-5: Location factors for different provinces in Canada (RSMeans, 2010)

Province/City	Canadian Factors (reflect Canadian currency)		
	Material Cost	Installation Cost	Total Cost
Alberta/Edmonton	130.6	86.2	111.0
Alberta/Lethbridge	119.9	88.3	105.9
British Columbia/Vancouver	128.7	78.6	106.6
British Columbia/Summerland[1]	116.4	86.9	103.4
Manitoba/Winnipeg	127.7	66.7	100.8
Manitoba/The Pas[2]	115.0	72.9	96.4
New Brunswick/Fredericton[3]	115.8	69.2	95.2
Newfoundland/St John[3]	115.9	69.2	95.3
Nova Scotia/Halifax[3]	117.4	74.6	98.5
Ontario/Ottawa	**121.5**	**90.1**	**107.6**
Ontario/Thunder Bay	**112.9**	**89.1**	**102.4**
Ontario/Toronto	**122.5**	**95.8**	**110.7**
Ontario/Windsor	**112.0**	**89.4**	**102.0**
PEI/Charlottetown[3]	116.1	60.5	91.6
Quebec/Montreal	120.8	89.7	107.1
Quebec/Sept Iles[4]	112.8	89.4	102.5
Saskatchewan/Saskatoon	112.7	66.8	92.4
Saskatchewan/Swift Current[5]	114.2	67.0	93.4

Notes:

1. The location factor for Summerland was not available in the 2010 RSMeans cost data publications and, therefore, the factor for Kamloops was chosen as the latter is in close proximity (216 km) to the former.
2. The location factor for The Pas was not available in the 2010 RSMeans cost data publications and, therefore, the factor for Brandon was chosen as the latter is in close proximity (451 km) to the former.
3. It should be noted only one city per province in Atlantic Canada (New Brunswick, Nova Scotia, Newfoundland and Prince Edward Island) was selected due to availability of corresponding weather file in both HOT2000™ and TRNSYS.
4. The location factor for Sept Iles was not available in the 2010 RSMeans cost data publications and, therefore, the factor for Chicoutimi was chosen as the latter is in close proximity (544 km) to the former.
5. The location factor for Swift Current was not available in the 2010 RSMeans cost data publications and, therefore, the factor for Regina was chosen as the latter is in close proximity (226 km) to the former.

3.6.1 Cost estimations of the HVAC system upgrades

Additional analysis was conducted to determine the historical prices of the commonly used HVAC systems in the residential applications based on the last ten years of the RSMeans cost data publications. They were then compared against the data obtained from the study done by Fung et al. (2009), where the costs of the latter were determined based on the wholesale prices provided by a well-known distributor.

Due to the limited selection of the HVAC systems that were listed in the RSMeans cost data publications, difficulty arose when conducting the comparative analysis of the initial (equipment and installation) costs for the identified HVAC systems used in the study done by Fung et al. (2009), namely the renewable energy systems such as the heat pumps, drain water heat recovery, HRV and solar-assisted DHW heater.

Therefore, the analysis was limited to an investigation of the commonly used HVAC systems in the residential applications, and includes a furnace, boiler, and an AC unit. The results were summarized as follows:

3.6.1.1 Gas and electric furnaces

Based on the historical prices obtained from the 2001-2010 RSMeans cost data publications[10], it was apparent that the electric furnace price has increased annually for both Toronto and Ottawa, whereas the price of the gas furnace has decreased after having peaked in 2009, as shown in Figure 3-6.

[10] The price was determined based on the specification used in the RSMeans for both the electric and gas furnaces, respectively: For an electric furnace, the identified cost was based on a 34.1 thousands of BTU per hour (MBH) furnace with blowers, standard controls, and no gas, oil or flue piping; and for a gas furnace, the cost was based on a 45.0 MBH input furnace with up-flow position, and direct drive standard model.

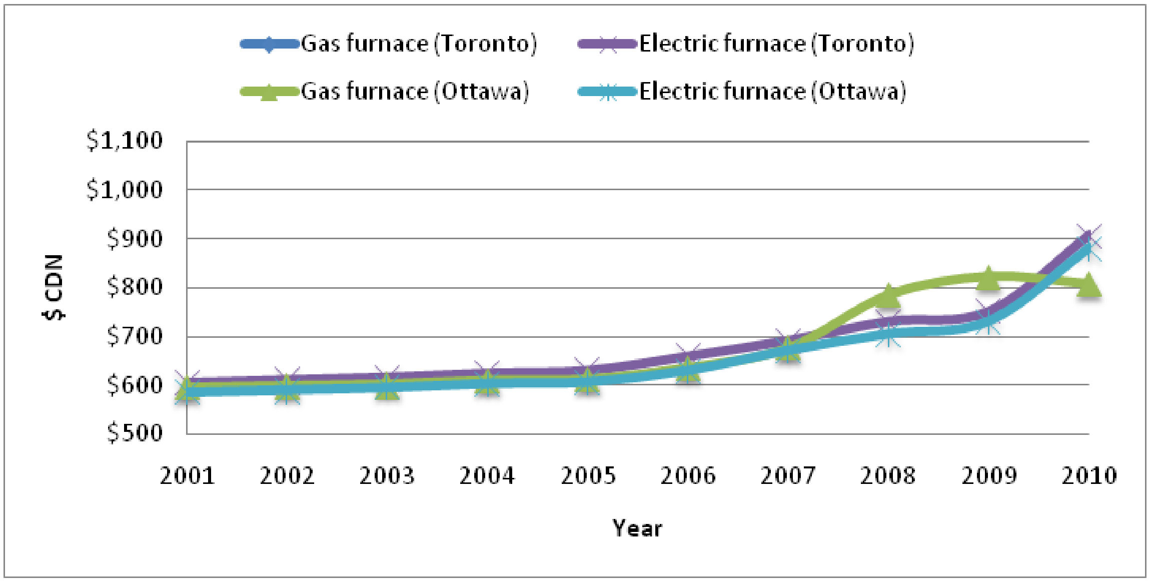


Figure 3-6: Historical prices of gas and electric furnaces for Toronto, and Ottawa, Ontario

The estimated initial costs based on the RSMeans cost data publications could be adjusted by accounting for the 10% overhead and profit, as shown in Figure 3-7.

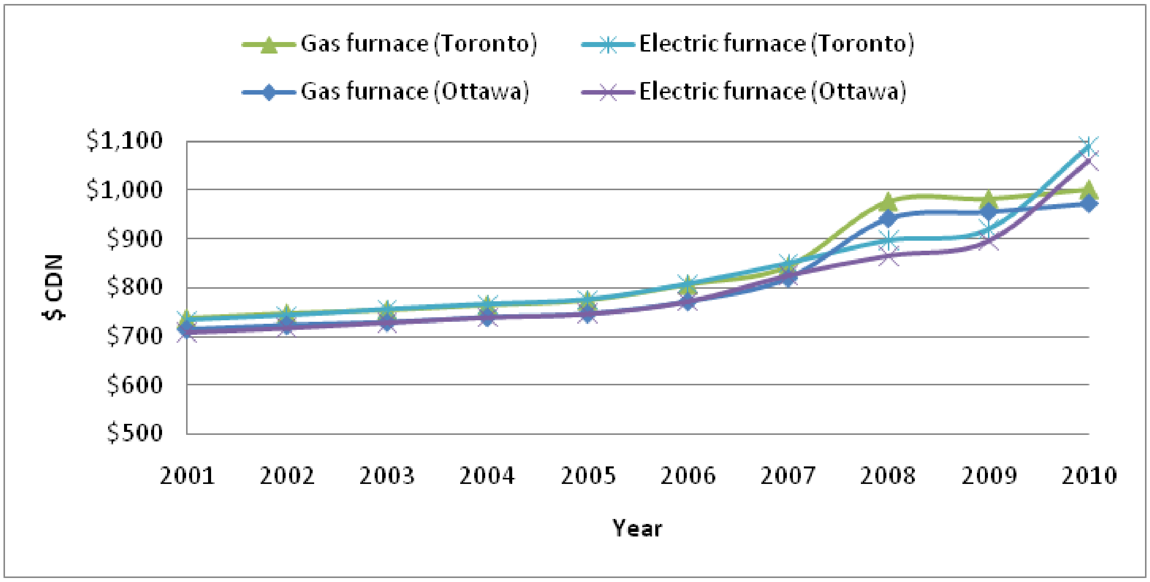


Figure 3-7: Historical prices of gas and electric furnaces for Toronto, and Ottawa, Ontario (including overhead and profit)

Furthermore, the price of a gas furnace listed in the 2010 RSMeans cost data publications was compared to that of the identical equipment used in the study done by Fung et al. (2009) to ensure the cost obtained from the former was properly identified. It was interesting to note that the estimated initial cost including the 15% overhead and profit using the RSMeans was fairly close, with approximately $3 less than what was reported by Fung et al. (2009). The comparison was based on a typical house in Toronto, having a 45 MBH gas furnace with up-flow position. It was also interesting to note that, based on the study done by Fung et al. (2009), it would cost approximately $1008 for a homeowner to install an 80% AFUE, single-stage gas furnace with multi-speed, and either up-flow or horizontal positions.

The RSMeans cost data publications accounted for 5 to 15% (where 10% was the average) overhead and profit and, therefore, the identified cost for the gas furnace would vary if the overhead and profit used in the study by Fung et al. (2009) were more than 15%. Further analysis was conducted using the identified cost of the gas furnace from the RSMean by adjusting the cost using 20%, 25% and 30% overhead and profit, respectively. The results showed that the overall costs increased by 13% with the 30% overhead and profit. The final estimated initial cost of $1136, which has already included the overhead from the wholesale price based on the study done by Fung et al. (2009), would be the cost that a homeowner would be required to pay to install a two-stage gas furnace rather than a single-stage with the same level of efficiency.

3.6.1.2 Gas and electric boilers

Based on the historical prices obtained from the 2001-2010 RSMeans cost data publications, it was apparent that both gas and electric boiler prices have increased annually for both Toronto and Ottawa, as shown in Figure 3-8.

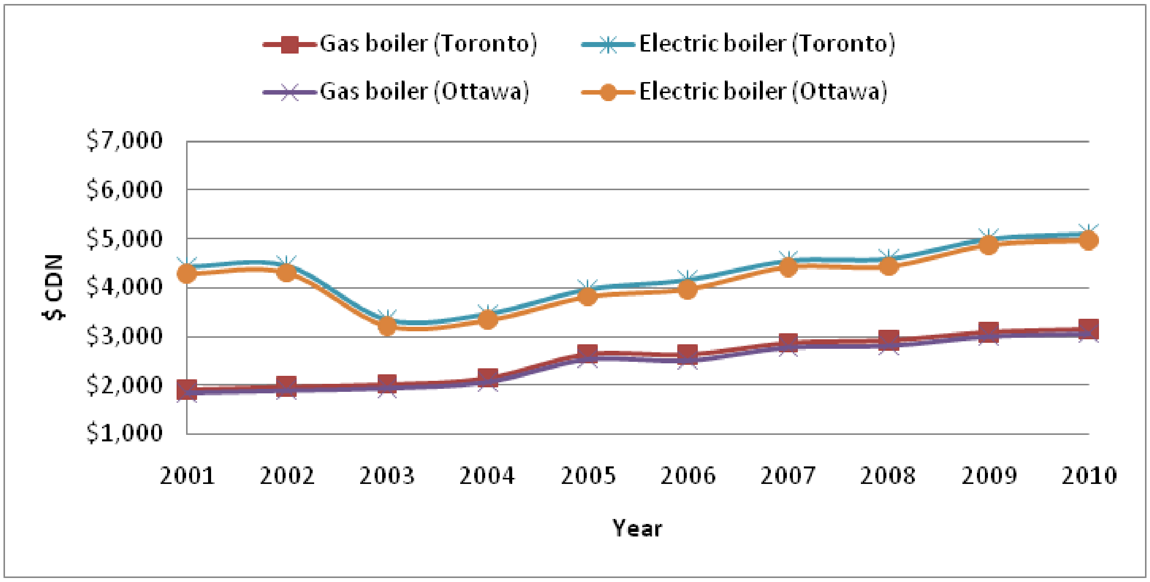


Figure 3-8: Historical prices of gas and electric boilers for Toronto, and Ottawa, Ontario

The estimated initial costs based on the RSMeans cost data publications could be adjusted by accounting for the 10% overhead and profit, as shown in Figure 3-9.

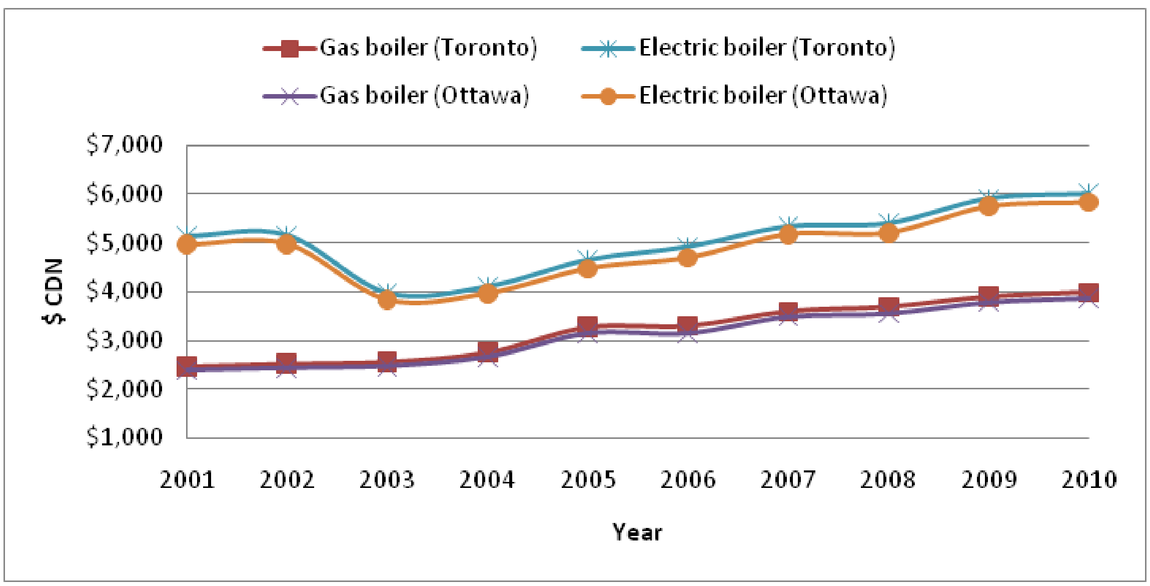


Figure 3-9: Historical prices of gas and electric boilers for Toronto, and Ottawa, Ontario (including overhead and profit)

Similarly, the price of a gas boiler listed in the 2010 RSMeans cost data publications was compared to that of the identical equipment used in the study done by Fung et al. (2009) to ensure the cost obtained from the former was properly identified. It was interesting to note that the estimated initial cost including the 5% overhead and profit using the RSMeans was fairly close to what was reported by Fung et al. (2009), exceeding their estimate by approximately $20. The comparison was based on a typical house in Toronto, having a 200 MBH (58.62 kW) output capacity gas boiler. It was also interesting to note that, based on the study done by Fung et al. (2009), it would cost approximately $3910 for a homeowner to install an 85% AFUE, condensing gas boiler with up to 200 MBH (58.62 kW) capacity.

3.6.1.3 Air-conditioning unit

Based on the historical prices obtained from the 2001-2010 RSMeans cost data publications, it was apparent that the AC unit price has remained constant, despite the fact that there was a huge drop in the price of the unit in 2004 for both Toronto and Ottawa, as shown in Figure 3-10.

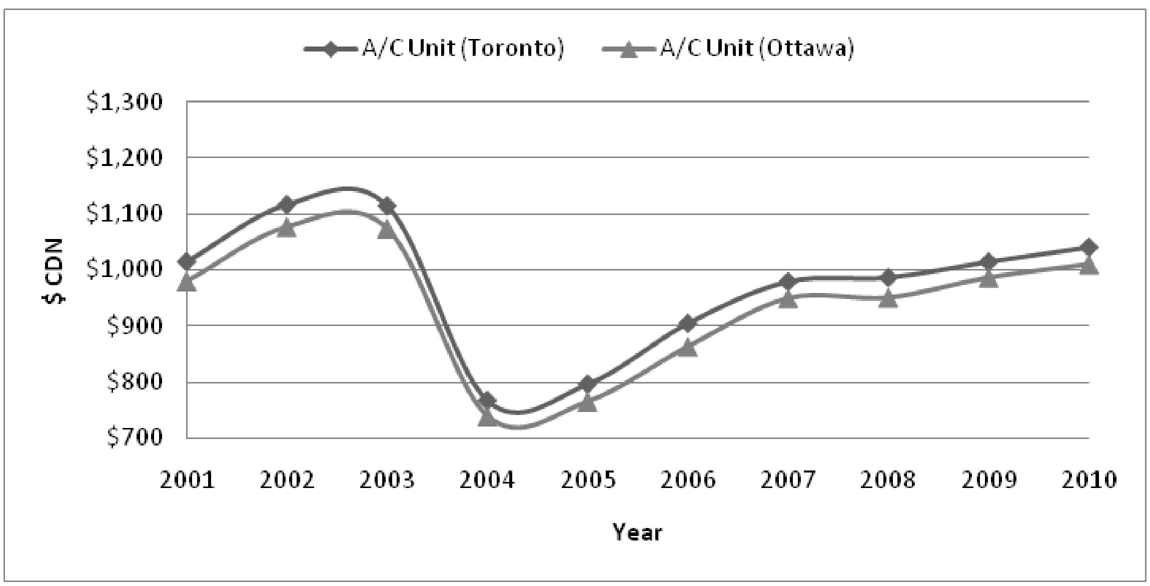


Figure 3-10: Historical prices of an AC unit for Toronto, and Ottawa, Ontario

The estimated initial costs based on the RSMeans cost data publications could be adjusted by accounting for the 10% overhead and profit, as shown in Figure 3-11.

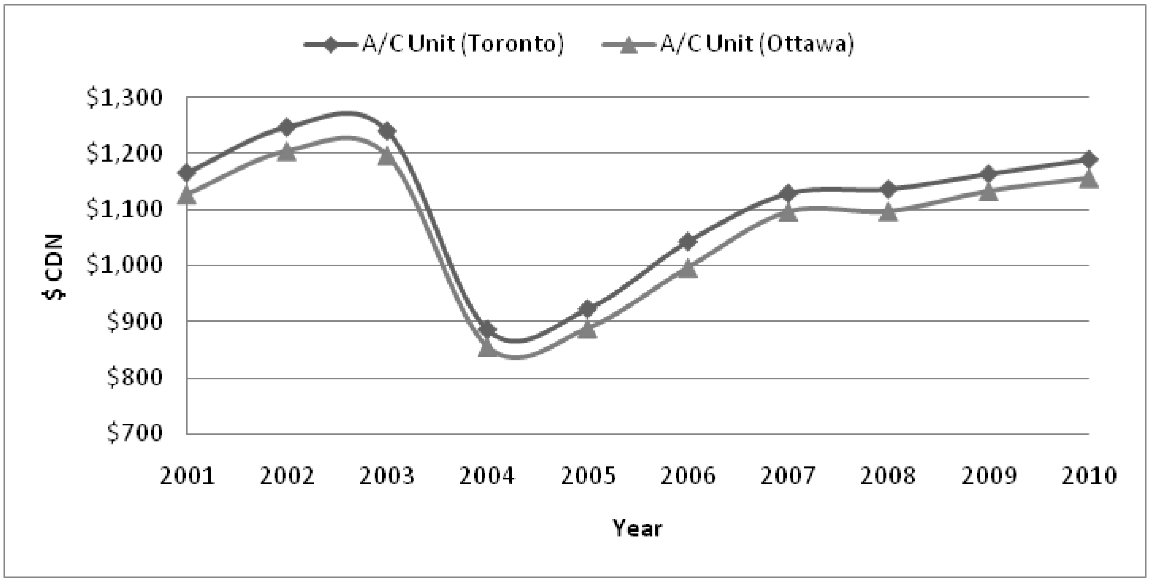


Figure 3-11: Historical prices of an AC unit for Toronto, and Ottawa, Ontario (including overhead and profit)

Similarly, the price of an AC unit listed in the 2010 RSMeans cost data publications was compared to that of the identical equipment used in the study done by Fung et al. (2009) to ensure the cost obtained from the former was properly identified. It was interesting to note that the estimated initial cost including the 5% overhead and profit using the RSMeans was reasonably close to what was reported by Fung et al. (2009), exceeding their estimate by approximately $549. The comparison was based on a typical house in Toronto, having the AC with approximately 36,000 Btu/hr (3 ton) cooling capacity. It was also interesting to note that, based on the study done by Fung et al. (2009), it would cost approximately $4445 for a homeowner to install a 13 SEER, single phase AC with 35,400 Btu/hr cooling capacity.

3.6.2 Comparative analysis of the identified upgrade costs

The second part of the survey was conducted to perform comparative analysis of the RSMeans cost data publications against the average construction costs obtained from the local homebuilders in Ontario to ensure the cost of each upgrade was properly identified. Tables 3-6 and 3-7 summarize the results.

Table 3-6: Average construction cost obtained from the survey

Upgrade	Description of Upgrade	Estimated Incremental Cost ($)/Sq. Ft.	Variance[1] -10% ($)	Variance[1] +10% ($)	Average Construction Cost obtained from the Participant Builders	Source(s) used
Ceiling	RSI 8.8 (R50)	552	496	607	$496, or less	RSMeans Survey
	RSI 10.5 (R60)	1,397	1,257	1,536	$1,257, or less	RSMeans Survey
Exterior Walls	Studs spaced at 600 mm (24 in.) on-centre	721	649	793	Could not be verified[2]	RSMeans Survey
	RSI 3.9 (R22)	1,321	1,189	1,453	$1,189, or less	RSMeans Survey
	RSI 4.2 (R24)	721	649	793	Consensus could not be achieved[3]	RSMeans Survey
	RSI 4.8 (R27)	4,161	3,744	4,577	$3,744, or less	RSMeans Survey
	RSI 5.1 (R29)	4,978	4,480	5,475	$4,978 to $5,475	RSMeans Survey
	Advanced framing (i.e., SIPs)	20,367	18,331	22,404	Could not be verified[2]	RSMeans Manufacturer's Quote Survey
Basement	RSI 3.5 (R20)	1,681	1,513	1,849	1,513, or less	RSMeans Survey
	RSI 3.9 (R22)	3,392	3,053	3,731	Consensus could not be achieved[3]	RSMeans Survey
	RSI 4.2 (R24)	2,893	2,603	3,182	$3,182, or more	RSMeans Survey
	ICFs	12,245	11,021	13,470	Could not be verified[2]	RSMeans Manufacturer's Quote Survey
Floor	RSI 5.5 (R31)	394	355	433	$394 to $433	RSMeans Survey
Basement Slab	RSI 2.1 (R12)	1,694	1,525	1,864	$1,525, or less	RSMeans Survey
	RSI 3.5 (R20)	3,295	2,965	3,624	$3,624, or more	RSMeans Survey

Table 3-7: Average construction cost obtained from the survey (Cont.)

Upgrade	Description of Upgrade	Estimated Incremental Cost ($)/Unit	Variance[1] -10% ($)	Variance[1] +10% ($)	Average Construction Cost obtained from the Participant Builders	Source(s) used
Window	Double-glazed, low-E	87	78	96	$78, or less	RSMeans Survey
Furnace	92% AFUE, with ECM	472	424	519	Consensus could not be achieved[3]	Fung et al. (2009) Survey
Combo boiler	0.92 EF	875	788	963	Could not be verified[2]	Fung et al. (2009) Survey
	90% efficiency	1,757	1,581	1,932	Consensus could not be achieved[3]	Fung et al. (2009) Survey
HRV	80% efficiency	835	752	919	$835 to $919	Fung et al. (2009) Survey
AC unit	SEER 14	65	59	72	$72, or more	Fung et al. (2009) Survey
Heat pump (HP)	Air-source (ASHP)	13,440	12,096	14,784	$13,440, or less	Fung et al. (2009) Survey
	GSHP	18,140	16,326	19,953	Could not be verified[2]	Fung et al. (2009) Survey
DWHR/GWHR system		968	871	1,064	$871, or less	Fung et al. (2009) Survey
Solar-DHW heater		4,050	3,645	5,111	Consensus could not be achieved[3]	Fung et al. (2009) Survey

Notes:

1. ±10% of the estimated incremental cost for each upgrade was used to determine the difference in the average construction cost reported by the participant builders.
2. The incremental cost could not be verified due to the lack of responses received from the participant builders.
3. Consensus could not be achieved on the incremental cost as a result of difference in the average construction costs reported by the participant builders.

As Tables 3-6 and 3-7 indicate, it should be noted that the incremental cost of some of the potential least cost upgrades could not be verified due to the fact that; a) lack of responses received from the participant builders (i.e., only one of the three builders responded); or b) consensus could not be achieved as a result of difference in the average construction costs reported by the participant builders.

3.7 Eligible Upgrades for the Least Cost Analysis

Figure 3-12 summarizes the eligible upgrade solutions chosen based on the results of the survey and the cost estimations using the RSMeans. It should be noted that the upgrade solutions for windows (UPG6) and electrical heating (UPG9b) were not included in this thesis due to the insufficient amount of data collected to proceed with the analysis.

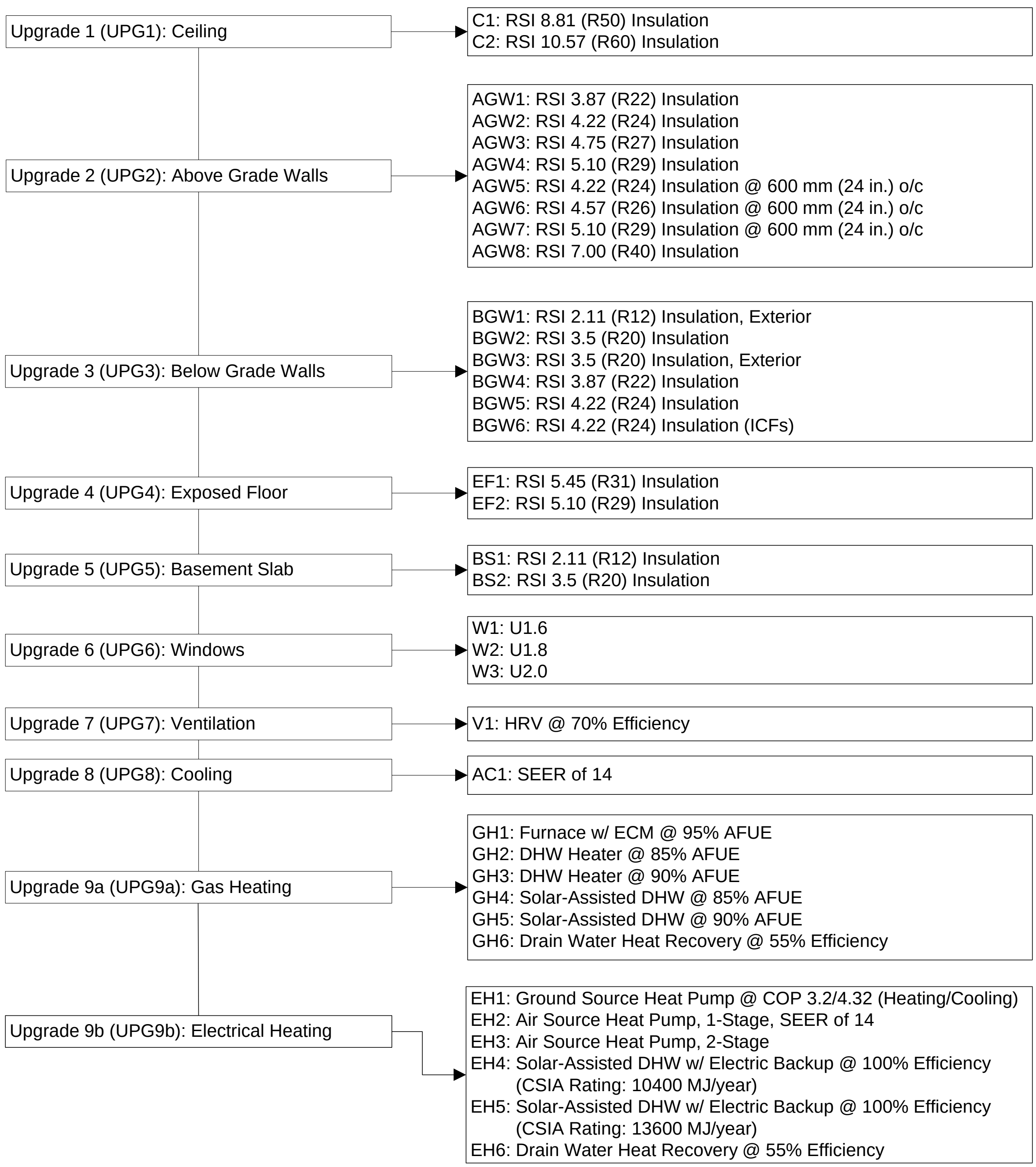


Figure 3-12: Eligible upgrades for the Least Cost Analysis

3.7.1 Life expectancy of the eligible upgrades

The life expectancy of the eligible HVAC system upgrades was determined based on the study reported by the National Association of Home Builders [NAHB] (2007) for the LCC analysis purposes. Table 3-8 summarizes the life expectancy of the some of the commonly used HVAC systems in the residential applications.

Table 3-8: Summary of life expectancy for the HVAC system upgrades (NAHB, 2007)

Equipment	Description	Life Expectancy[1]
AC unit	13 SEER	12
	14 SEER	
ASHP	2 ton	15
	3.5 ton	
DHW heater	Natural gas DHW heater at 0.57 EF	21
	Natural gas DHW heater at 0.60 EF	
	Natural gas DHW heater at 0.80 EF	20
	Natural gas DHW heater at 0.90 EF	21
DWHR/GWHR	-	50
Furnace	Natural gas condensing furnace at 90% AFUE	15
	Natural gas condensing furnace at 93% AFUE	
	Natural gas condensing furnace at 95% AFUE, with ECM	
GSHP	GSHP with boreholes (488m [1600ft] in depth)	16
	GSHP with boreholes (549m [1800ft] in depth)	
	GSHP with horizontal piping (335m [1100ft] in length)	
HRV	70% efficiency, 80 cubic-feet per minute (CFM) supply and exhaust	20
Solar DHW heater	Solar DHW heater with PV panels	20

Note:
1. The life expectancy of the identified HVAC equipment was obtained from the study reported by the NAHB (2007)

It should be noted, the life expectancies for the materials used in the building envelope upgrades were assumed to last beyond the identified maximum mortgage period of 30 years (Department of Finance Canada, 2011) and, therefore, were not considered in this analysis.

3.8 Determination of the Identified Parameters

For the LCCA purposes, the initial costs (capital cost and installation cost) of the identified upgrades were assumed to be paid at the end of the first year. Mortgage rate was used to calculate the present value of all the payments; however, assuming a real-life situation, the initial costs were spread over the mortgage period, and discount rate was used for the present value calculations. Hence, the incremental costs, therefore, had to be spread over the mortgage period using mortgage rate, and then, brought to the present value using discount rate. This methodology was applied for the calculation of the initial costs of the upgrades.

It should be noted, for those upgrades that had a life expectancy of less than the identified mortgage period of 30 years, in this case the HVAC system upgrades, additional costs that occurred at a later point in the identified life span were treated as one-time expenses.

Figure 3-13 shows the example of a cash flow, over the life cycle of 30 year, of a typical house having an upgrade with expected life of 12 years.

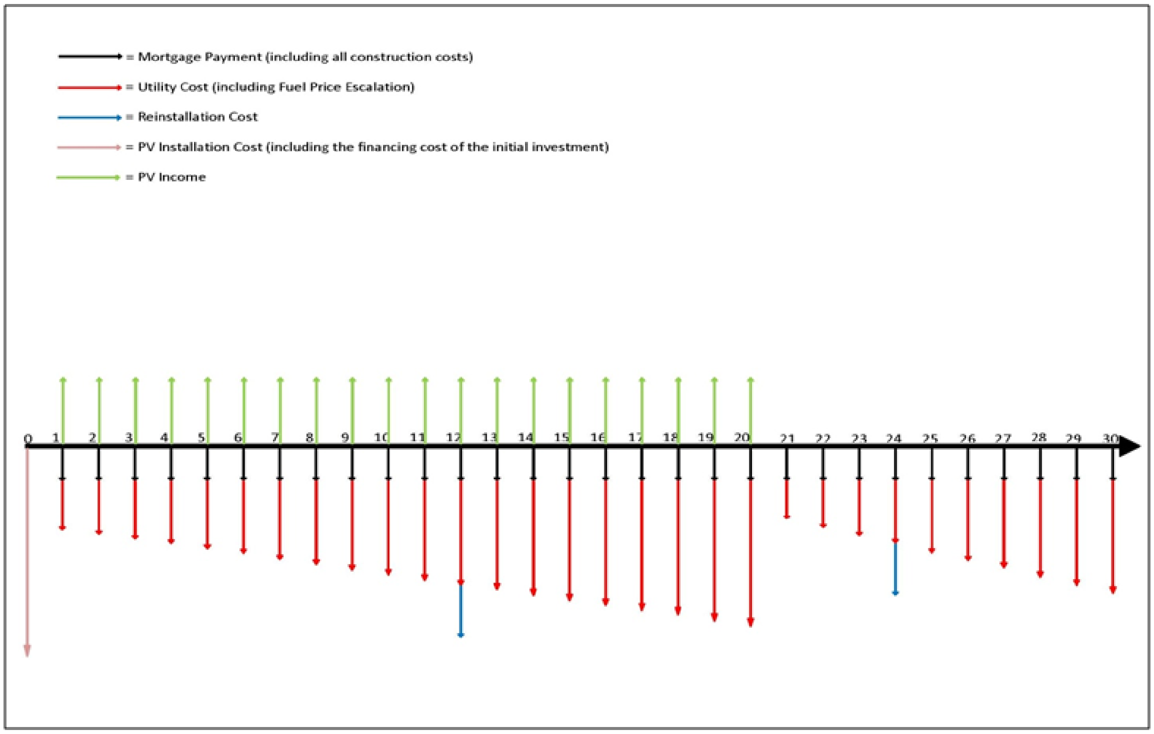


Figure 3-13: Cash flow diagram of a typical house with an AC unit installed

The following parameters were determined based on data obtained from various sources:

3.8.1 Mortgage rate

Mortgage rate was determined based on the historical mortgage rate for a five-year term (Statistics Canada, n.d.a). Based on the statistics, it was assumed that mortgage rate was at the lowest value in 2009 with 5.05%, as shown in Figure 3-14.

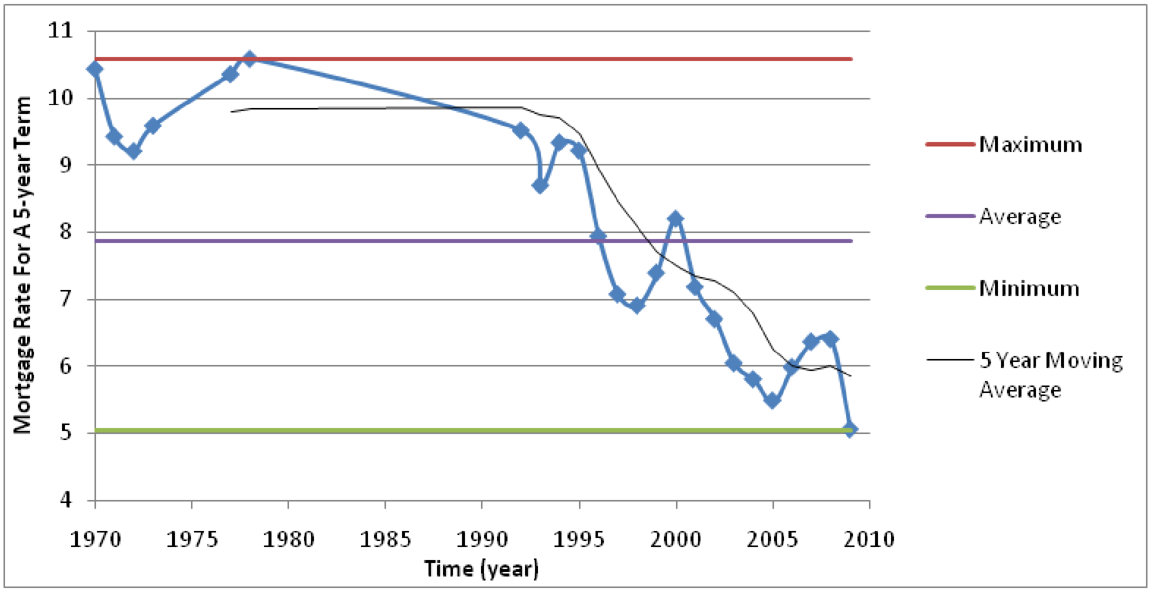


Figure 3-14: Mortgage rate vs. time (Statistics Canada, n.d.a)

As a result, 5.05%, 7.87%, and 10.59% were used as minimum, average, and maximum mortgage rates in the proposed methodology, respectively.

3.8.2 Discount rate

Discount rate was derived based on the historical discount rates from 1995 to 2009 for Ontario, Canada (Ontario Ministry of Finance [OMF], 2010). Based on the statistics, as shown in Figure 3-15, the average discount rate was determined to be 1.99%, which was based on the determination of minimum and maximum discount rates of 0.40% and 3.10%, respectively, and used as the identified discount rate for further calculations.

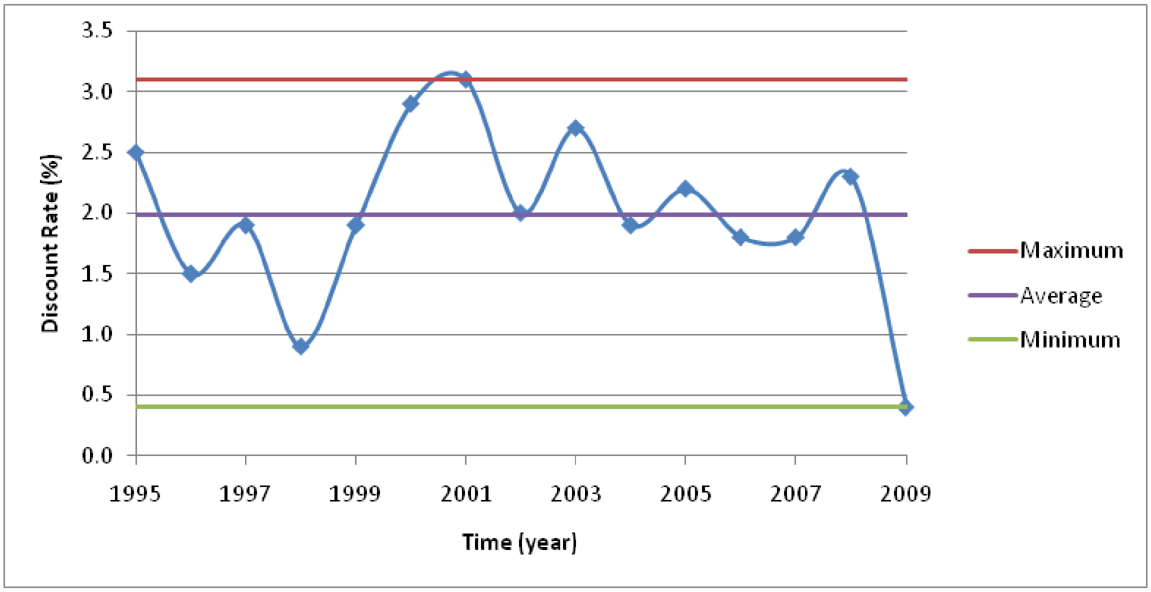


Figure 3-15: Discount rate vs. time (OMF, 2010)

3.8.3 Fuel price escalation rates for electricity, natural gas, and oil

Lastly, the price escalation rates for electricity, natural gas, and oil were estimated based on data obtained from various sources (National Energy Board [NEB], 2007; Statistics Canada, 2010; Statistics Canada, n.d.b).

As a result of the uncertainty in predicting future energy prices, difficulty arose when determining the escalation rates for the primary fuel sources that were considered. This could be attributed to various reasons, some of which have been identified in the study by Dong et al., (2005).

Therefore, the price escalation rates for electricity, natural gas, and oil were determined by taking the average of the historical and predicted future energy prices, and were identified as follows:

3.8.3.1 Price escalation rate for electricity

Based on the historical electricity prices from 1990 to 2008 (Statistics Canada, 2010), the average percent change of electricity price was determined to be 2.92%, as shown in Figure 3-16.

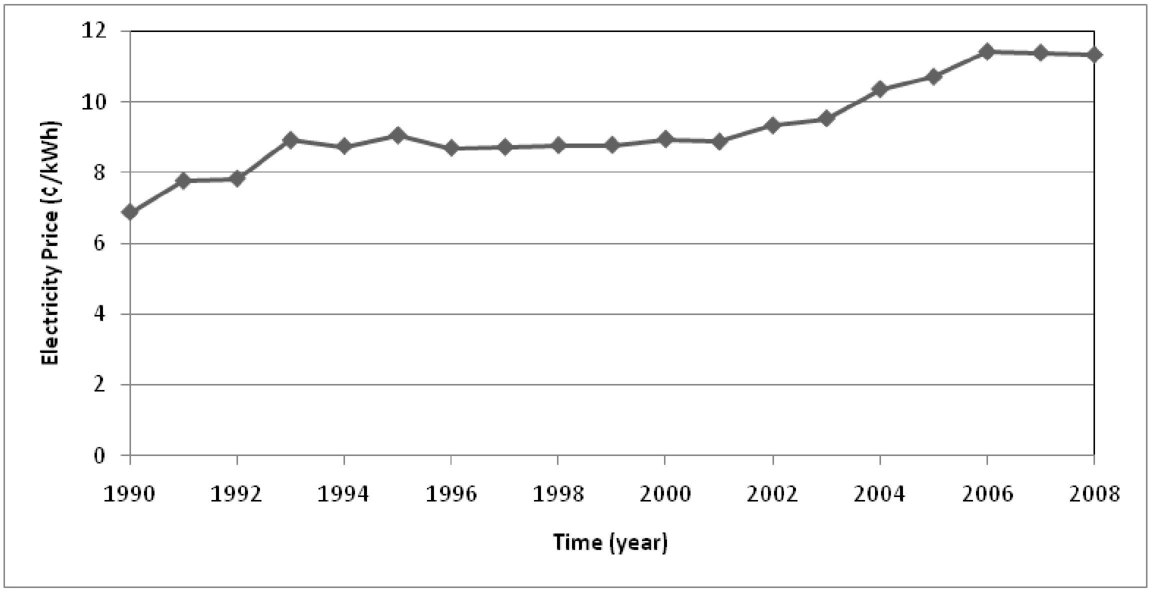


Figure 3-16: Electricity price vs. time for Ontario (Statistics Canada, 2010)

In addition to the historical prices, the electricity price forecast was obtained, which was the primary source used to determine the escalation rate. As Figure 3-17 indicates, the average percent change of electricity price, based on the predicted future electricity price from 2000 to 2030, was determined to be 4.16%.

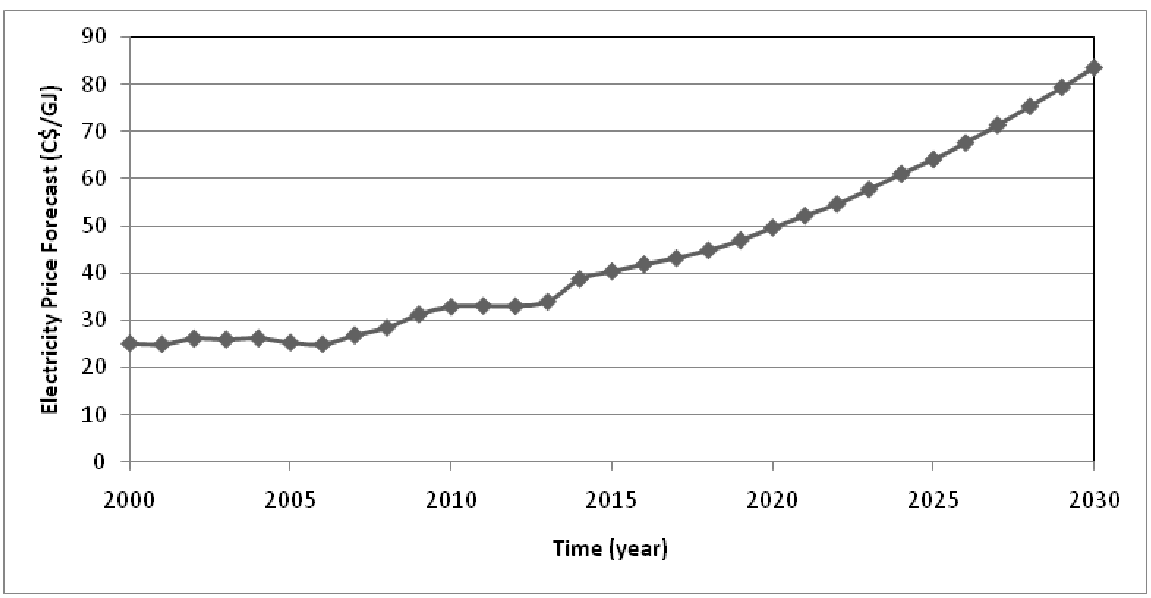


Figure 3-17: Electricity price forecast vs. time (NEB, 2007)

The Consumer Price Index (CPI) for electricity was also considered. It should be noted, the CPI does not provide the prices paid by the consumer; however, it provides a useful indication of the changes in prices with reference to the official base period, which, at present, is the year 2002 (Statistics Canada, n.d.b). Therefore, the average percent change of CPI for electricity from 1990 to 2008 was determined to be 4.92%, as shown in Figure 3-18.

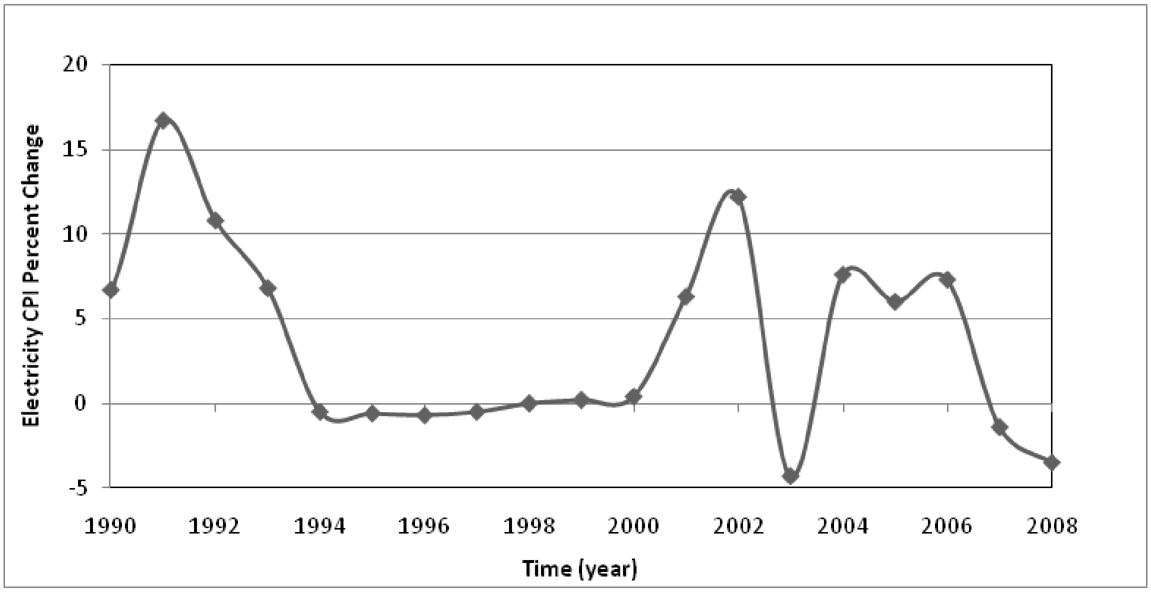


Figure 3-18: Percent change of CPI for electricity for Ontario (2002=100) vs. time (Statistics Canada, n.d.b)

The Ontario Ministry of Energy [OME] recently announced that the projected long-term electricity price increase of 3.50% annually for the next twenty years (OME, 2010). In order to apply this expected increase in the future price of electricity for Ontario, the 3.50% will be used as the identified electricity price escalation rate for the proposed methodology.

3.8.3.2 Price escalation rate for natural gas

Based on the historical natural gas prices from 1990 to 2008 (Statistics Canada, 2010), the average percent change of natural gas price was determined to be 5.11%, as shown in Figure 3-19.

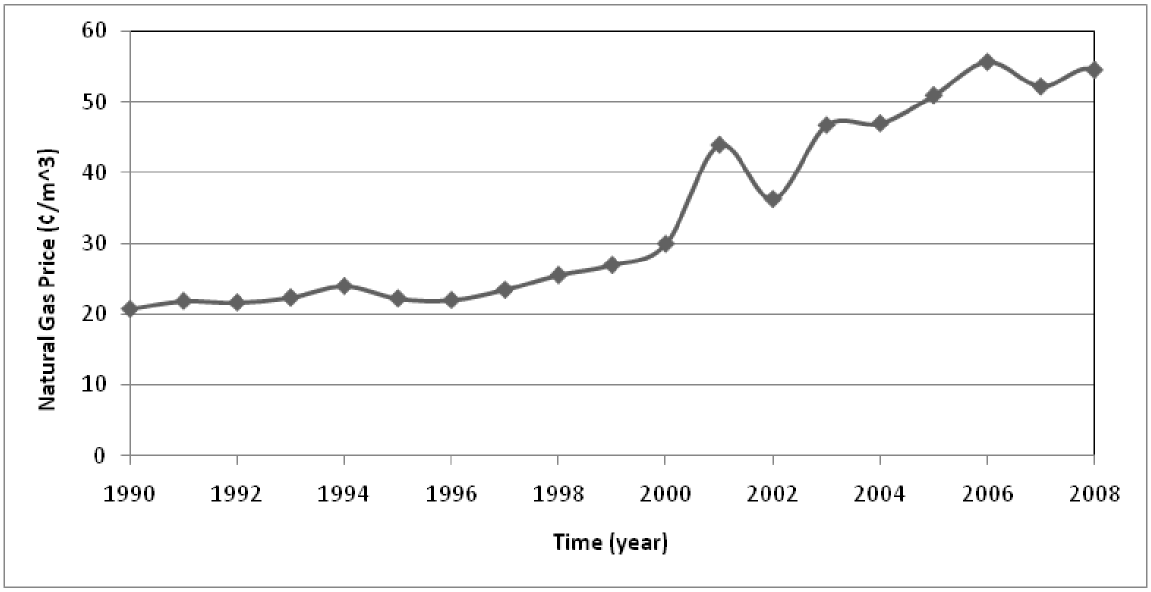


Figure 3-19: Natural gas price (tax excluded) vs. time (Statistics Canada, 2010)

In addition to the historical prices, the natural gas price forecast was obtained, which was the primary source used to determine the escalation rate. As Figure 3-20 indicates, the average percent change of natural gas price, based on the predicted future natural gas price from 2000 to 2030, was determined to be 3.02%.

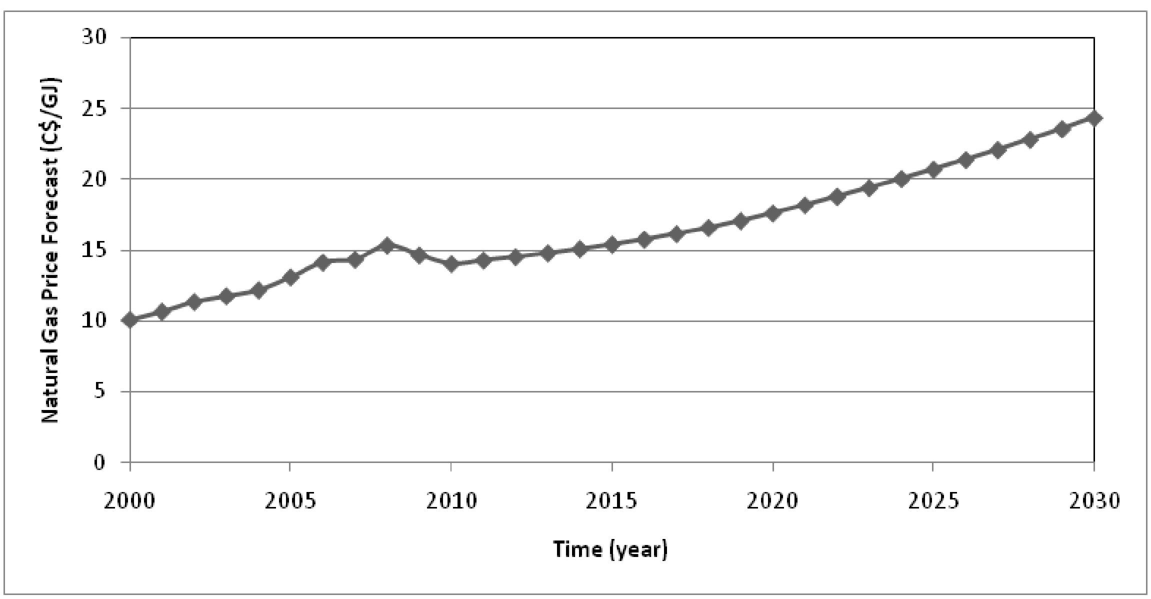


Figure 3-20: Natural gas price forecast vs. time (NEB, 2007)

The CPI for natural gas was also considered. It should be noted, the CPI does not provide the prices paid by the consumer; however, it provides a useful indication of the changes in prices with reference to the official base period, which, at present, is the year 2002 (Statistics Canada, n.d.b). Therefore, the average percent change of CPI for natural gas from 1990 to 2008 was determined to be 5.50%, as shown in Figure 3-21.

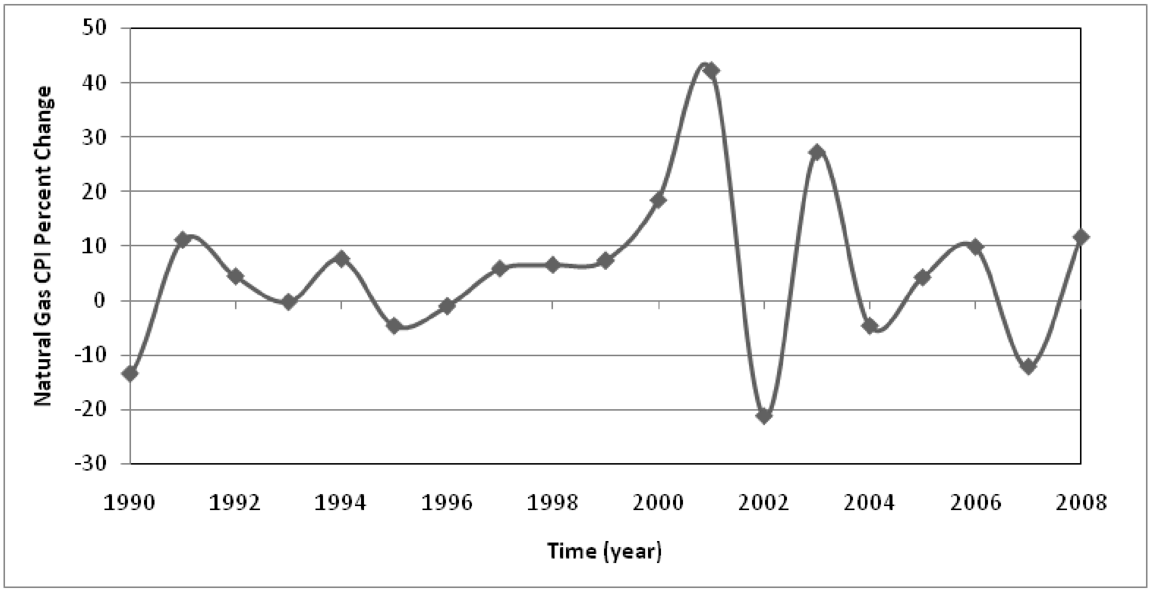


Figure 3-21: Percent change of CPI for natural gas (2002=100) vs. time (Statistics Canada, n.d.b)

3.8.3.3 Price escalation rate for oil

Based on the historical oil prices from 1990 to 2008 (Statistics Canada, 2010), the average percent change of oil price for Toronto was determined to be 5.45%, as shown in Figure 3-22.

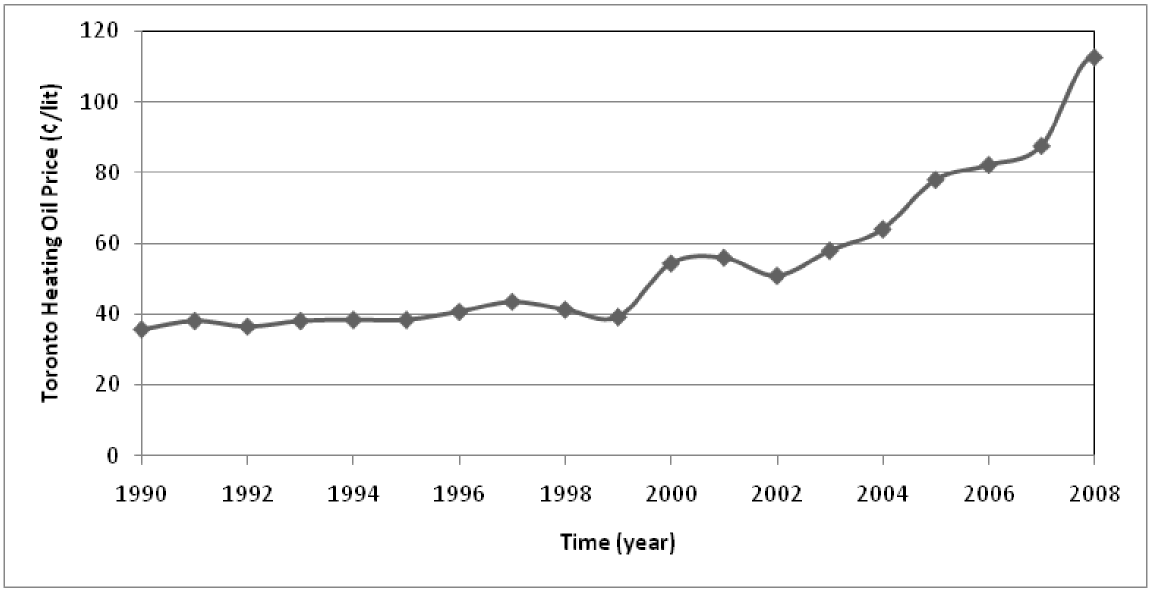


Figure 3-22: Oil price for Toronto (tax included) vs. time (Statistics Canada, 2010)

In addition to the historical prices, the oil price forecast was obtained, which was the primary source used to determine the escalation rate. As Figure 3-23 indicates, the average percent change of oil price, based on the predicted future oil price from 2000 to 2030, was determined to be 2.76%.

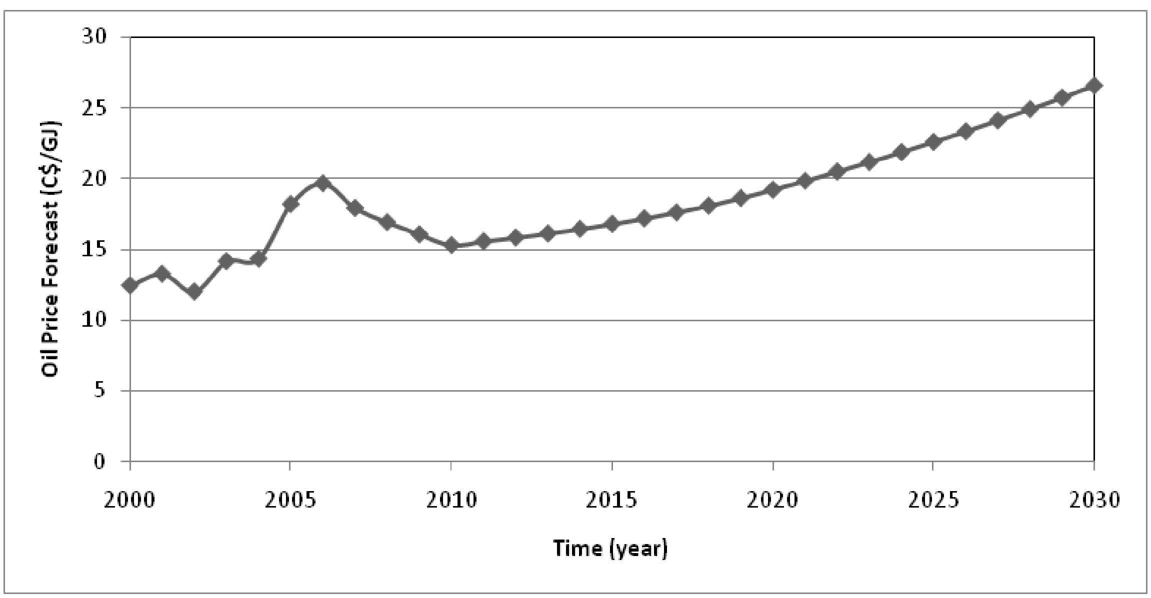


Figure 3-23: Oil price forecast vs. time (NEB, 2007)

The CPI for oil was also considered. It should be noted, the CPI does not provide the prices paid by the consumer; however, it provides a useful indication of the changes in prices with reference to the official base period, which, at present, is the year 2002 (Statistics Canada, n.d.b). Therefore, the average percent change of CPI for oil from 1990 to 2008 was determined to be 8.13%, as shown in Figure 3-24.

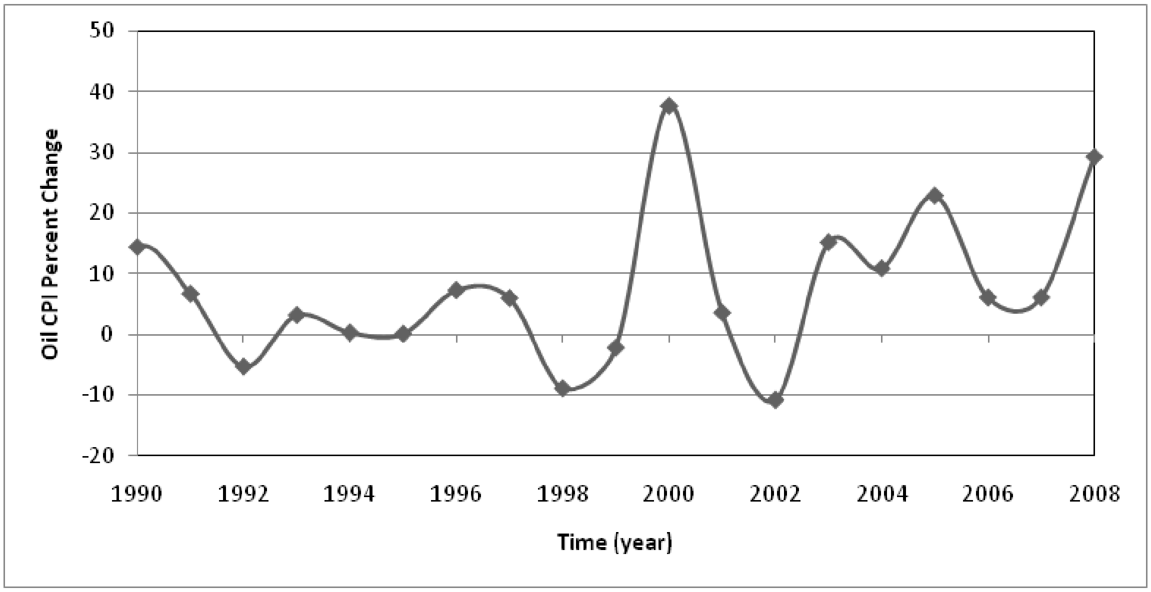


Figure 3-24: Percent change of CPI for oil (2002=100) vs. time (Statistics Canada, n.d.b)

In conclusion, the estimated price escalation rates for the primary fuel sources that were considered were as follows: 3.50% for electricity, 3.02% for natural gas, and 2.76% for oil, respectively.

Chapter 4

4 Sensitivity Analyses

4.1 Background

In Chapter 3, a set of parameters was determined based on the data obtained from various sources. In this chapter, sensitivity analysis of the identified parameters was conducted to determine a combination of eligible upgrades with the lowest total life cycle cost, and then to verify that the identified combination of upgrades was, in fact, the most cost-effective (or least cost) provided that some of the variables changed. The results will be discussed in Section 4.3.

Also in the previous chapter, appliances and lighting assumptions were made based on the standard operating conditions used in the HOT2000 program. In this chapter, additional assumptions were considered, and sensitivity analysis was conducted to evaluate the cost-effectiveness of the identified combination of upgrades after reducing the amount of energy required for running the appliances, lighting and hot water. The results will be discussed in Section 4.4.

Lastly, the extreme weather conditions for Toronto, ON, were determined based on the historical weather data obtained from the last 30 years to determine the combination of upgrades with the lowest total life cycle cost, and compare them against those that were identified using the long-term monthly weather data in the HOT2000 program. The results will be discussed in the last section of the chapter.

Once the most cost-effective (least cost) combination of upgrades was determined using the climatic conditions of Toronto, the same methodology was applied for other cities in Ontario. The results will be discussed in the next chapter.

4.2 Sensitivity Analysis of HOT2000 and TRNSYS

In this section of the chapter, a sensitivity analysis of two distinct energy simulation programs, HOT2000 and TRNSYS was performed not only to evaluate and compare both the similarities and differences in their capabilities as building energy simulation programs, but also, to determine the sensitivity of the results using the former by comparing it to those of a more advanced simulation program such as TRNSYS. The literature review, as well as the energy performance analysis of some of the potential upgrades using the selected programs was conducted as part of the analysis. Prior to conducting energy simulations using HOT2000 and TRNSYS, the following assumptions were made:

As briefly mentioned in Chapter 3, the building simulation model of the Reference House was created using HOT2000 based on the drawing set and the construction details obtained from the CCHT. The model was validated to the simulation model of the same house using TRNSYS, where the latter was used in the study conducted by Ouazia et al. (2009). The validated model, built in accordance with the current (2006) OBC specifications, was used as the baseline case for the analysis.

The set-point temperature of 21°C (69.8°F) for heating, and 25°C (77°F) for cooling was assumed for the analysis, respectively. Additional assumption was made to account for a setback temperature of 3°C (5.4°F) during the night time (from 0:00 to 7:00 AM). This assumption was made based on a similar approach taken by Guler et al. (2001; 2008). Therefore, the set-point temperature of 18°C (64.4°F) for heating was assumed, and entered in TRNSYS by creating a schedule to implement such assumption. In HOT2000, because it does not have a function to allow the user to create a schedule to specify the change in the set-point temperature, the daily average of 20.13°C (68.2°F), and 25.88°C (78.6°F) for heating and cooling, respectively was assumed using the following equation:

$$Daily\ average\ temperature(℃) = \frac{18℃ \times 7hr + 21℃ \times 17\ hr}{24hr} \qquad [\mathrm{Eq.}\ 3]$$

In order to determine and compare the peak energy demands for space heating and cooling, the assumption was made to exclude the HVAC systems. To implement such assumption in the selected programs, the input parameter was set to “unlimited heating and cooling” in TRNSYS, and specified electricity as a fuel source at 100% efficiency in HOT2000, respectively. Table 4-1 and 4-2 summarize the input parameters used for the sensitivity analysis of HOT2000 and TRNSYS.

Table 4-1: Summary of input parameters used in simulations

	HOT2000			TRNSYS		
Input Parameters	**Unit**	**Ottawa**	**Toronto**	**Unit**	**Ottawa**	**Toronto**
Annual Heating Degree Days (HDD) below 18°C)	HDD	4600	4200	HDD	4720	4192
Building Configuration/Geometry						
Floor area	m^2	Same as TRNSYS		m^2	346.63	
Volume	m^3	Same as TRNSYS		m^3	1198.10	
Set-Point Temperatures					**(Day/Night)**	
Heating	°C	20.13		°C	21/18	
Cooling	°C	25.88 26.00		°C	28/25 25/28	
Minimum Ventilation Requirements						
Occupancy Present in the house	- -	2 Adults and 2 Children 50% of the time		- -	Same as HOT2000 Same as HOT2000	
Mechanical ventilation	ACH	0.10		ACH	Same as HOT2000	
Air-tightness level	ACH at 50 Pa	3.57[1]		ACH at 50Pa	Not defined	
Natural ventilation	ACH	0.23		ACH	Same as HOT2000	
Total ventilation	ACH	0.33		ACH	Same as HOT2000	

Note

1. The air-tightness level of 3.57 ACH at 50 Pa was a value used in HOT2000 to represent the average air-tightness of newly built houses. It was reported in a study conducted by Parekh et al. (2007) that air-tightness of recently built (from 1991 to present) houses in Canada has improved historically, from about 8.1 ACH at 50 Pa pressure difference to 3.6 ACH, which was the value used in HOT2000.

Table 4-2: Summary of input parameters used in simulations (Cont.)

Thermal Resistance					
Ceiling below attic	RSI	7.00		U	0.14
Roof assembly w/o attic	RSI	4.93		U	0.20
Exterior walls	RSI	3.19		U	0.30
Basement walls	RSI	2.10		U	0.47
Main floors	RSI	4.70		U	0.23
Basement slab	RSI	1.76		U	0.57
Windows - South	U	1.87		U	1.69
- East	U	2.01		U	1.69
- North	U	1.90		U	1.69
- West	U	1.74		U	1.69
Average	**U**	**1.88**		**U**	**1.69**
Doors	RSI	0.70		U	1.42
HVAC System Efficiency					
Furnace Efficiency	AFUE (%)	100		-	Not defined
Output capacity (Calculated)	kW	15.50	13.50	-	Not defined
Air-conditioning unit	COP	1.00		-	Not defined
DHW heater Efficiency	EF	1.00		-	Not defined
Tank capacity (Calculated)	L	151.40		-	Not defined
Load	-	225 L/day at 55°C		-	Same as HOT2000
Appliances and Lighting Consumptions					
Interior lighting	kWh/day	3.0		kJ/h	450.0
Appliances	kWh/day	14.0		kJ/h	2548.8
Other appliances	kWh/day	3.0		kJ/h	
Exterior use	kWh/day	4.0		kJ/h	Not defined
Total base loads	**kWh/day**	**24.0**		**kJ/h**	**2998.8**

Based on the assumptions made, the simulation results of the baseline case using the selected programs were summarized in Table 4-3.

Table 4-3: Summary of simulation results for a baseline case

Output Parameters	Unit	HOT2000		TRNSYS		% of Difference	
		Ottawa	Toronto	Ottawa	Toronto	Ottawa	Toronto
Annual Heating Degree Days (HDD) below 18°C)	-	4600	4200	4720	4192	2.5	0.2
Space Heating Consumption	kWh	34,408.89	28,935.90	33,321.77	29,896.84	-3.3	3.2
Space Cooling Consumption	kWh	2,049.60	2,110.97	2,597.85	2,641.66	**21.1**	**20.1**
DHW Heating Consumption	kWh	4,472.56	4,357.83	4,379.28	4,379.23	2.1	0.5
Appliances[1]	kWh	8,760.00	8,760.00	8,760.00	8,760.00	-	-
Total Annual Energy Consumptions	**kWh**	**49,691.05**	**44,164.70**	**49,058.90**	**45,677.73**	**-1.3**	**3.3**

Note

1. The appliances and lighting consumption was based on the standard operating conditions used in the HOT2000 program. These values were then converted to match the specified inputs (in kJ/h) in TRNSYS.

As Table 4-3 indicates, the HOT2000's estimated annual space heating and DHW heating consumptions fell within the ±10% range (MacInnes, 1995) when compared against those of TRNSYS. However, the former's estimated annual space cooling consumption was outside the range, resulting in the difference of 21.1%, and 20.1% for Ottawa and Toronto, respectively. This could be attributed to the former's tendency to underestimate the annual space cooling consumption, and such observation was reported as one of the former's drawbacks in the study conducted by Haltrecht and Fraser (1997).

Table 4-4 summarizes the simulation results of the same baseline case as above, but with a setback temperature of 3°C (5.4°F) during the night time for heating (Case 1), as well a setup temperature of 3°C (5.4°F) during the day, night and entire day for cooling (Case 2).

Table 4-4: Summary of simulation results for a baseline case with a setback and setup temperatures

		HOT2000		TRNSYS		% of Difference	
Case 1 – Setback temperature (night)	**Unit**	**Ottawa**	**Toronto**	**Ottawa**	**Toronto**	**Ottawa**	**Toronto**
Space Heating Consumption	**kWh**	**32,345.95**	**26,687.18**	**26,495.32**	**23,208.88**	**-22.1**	**-15.0**
Space Cooling Consumption	kWh	1,991.01	2,053.20	4,858.05	4,930.10	59.0	58.4
DHW Heating Consumption	kWh	4,472.57	4,357.84	4,379.23	4,379.23	-2.1	0.5
Appliances	kWh	8,760.00	8,760.00	8,760.00	8,760.00	-	-
Total Annual Energy Consumptions	**kWh**	**47,569.53**	**41,858.22**	**44,492.60**	**41,278.21**	**-6.9**	**-1.4**
Case 2a – Setup temperature (day)							
Space Heating Consumption	kWh	34,522.63	28,746.06	28,596.71	25,252.55	-20.7	-13.8
Space Cooling Consumption	**kWh**	**1,578.92**	**1,608.71**	**4,048.31**	**4,134.91**	**61.0**	**61.1**
DHW Heating Consumption	kWh	4,472.56	4,357.83	4,379.23	4,379.23	-2.1	0.5
Appliances	kWh	8,760.00	8,760.00	8,760.00	8,760.00	-	-
Total Annual Energy Consumptions	**kWh**	**49,334.11**	**43,472.60**	**45,784.25**	**42,526.69**	**-7.8**	**-2.2**
Case 2b – Setup temperature (night)							
Space Heating Consumption	kWh	34,521.76	28,745.17	28,345.61	24,996.82	-21.8	-15.0
Space Cooling Consumption	**kWh**	**1,603.14**	**1,787.94**	**2,935.73**	**3,001.51**	**45.4**	**40.4**
DHW Heating Consumption	kWh	4,472.56	4,357.83	4,379.23	4,379.23	-2.1	0.5
Appliances	kWh	8,760.00	8,760.00	8,760.00	8,760.00	-	-
Total Annual Energy Consumptions	**kWh**	**49,357.46**	**43,650.94**	**44,420.57**	**41,137.56**	**-11.1**	**-6.1**
Case 2c – Setup temperature (entire day)							
Space Heating Consumption	kWh	34,532.25	28,756.08	28,279.88	24,923.99	-22.1	-15.4
Space Cooling Consumption	**kWh**	**844.73**	**908.29**	**2,559.16**	**2,593.75**	**67.0**	**65.0**
DHW Heating Consumption	kWh	4,472.56	4,357.83	4,379.23	4,379.23	-2.1	0.5
Appliances	kWh	8,760.00	8,760.00	8,760.00	8,760.00	-	-
Total Annual Energy Consumptions	**kWh**	**48,609.54**	**42,782.20**	**43,978.27**	**40,656.97**	**-10.5**	**-5.2**

As Table 4-4 indicates, with a setback temperature during the night time for heating, the HOT2000's estimated annual space heating consumption was outside of the range with a difference of more than 10% when compared against that of TRNSYS in both Toronto and Ottawa, where the latter resulted in a difference of more than 20%. Despite the fact that the HOT2000's estimated annual space heating was more than that of TRNSYS, overall, the space heating consumption, based on the simulation results using both programs, decreased as a result of a setback temperature during the night time for heating. As for the space cooling consumption, it was interesting to note that the HOT2000's estimated annual space cooling consumption was further off the range when compared against that of TRNSYS, resulting in differences of 59.0%, and 58.4% for Ottawa and Toronto, respectively. This could be attributed to the fact that the estimated space cooling consumption, determined based on the simulation result using the former, resulted in decrease in space cooling consumption when compared against that of the baseline case with no setback temperature during the night time for heating.

With a setup temperature for cooling, the HOT2000's estimated annual space cooling consumption was further off the range when compared against that of TRNSYS in both Toronto and Ottawa, with a difference of more than 60% for the cases during the day and entire day, while 40% for the case with a setup temperature during the night time for cooling. Despite the fact that the TRNSYS estimated space cooling consumption increased as a result of a setup temperature during the day[11] and night time for cooling, overall, the estimated space cooling, based on the simulation results using both programs, decreased as a result of a setup temperature for cooling, regardless of whether it was applied during the time of the day, night or the entire day. As for the space heating consumption, the HOT2000's estimated annual space heating consumption was outside of the range with a difference of more than 10% when compared against that of TRNSYS in both Toronto and Ottawa, where the latter resulted in a difference of

[11] Such trend was reported in a study conducted by Ugursal et al., (1992).

more than 20%. Despite the fact that the HOT2000's estimated annual space heating consumption was more than that of TRNSYS, overall, the space heating consumption, based on the simulation results using both programs, decreased as a result of a setup temperature for cooling, regardless of whether it was applied during the time of the day, night or the entire day. However, it should be noted that, for the case in Ottawa, the HOT2000's estimated annual space heating consumption was slightly higher than that of the baseline case without a setup temperature for cooling.

Despite the fact that there were discrepancies with respect to the estimation of both the space heating and cooling consumptions using the two simulation programs, the overall energy consumptions of the HOT2000 program fell within the ±10% range when compared against those of TRNSYS.

As mentioned previously, a few upgrade cases[12] were performed in addition to the baseline case, to further analyse and compare the differences in the simulation results of the selected programs. The results were identified as follows:

4.2.1 Increasing the thermal resistance of the building envelope (above-grade)

As shown in Figure 4-1, it was concluded, based on the simulation results, that HOT2000 underestimated the annual space cooling consumption by 23.5% when the thermal resistance of the ceiling increased by 51%, resulting from the increase in RSI from 7.00 to 10.57 (U 0.095). The annual space heating and DHW heating consumptions in HOT2000, on the other hand, were within the ±10% range of what was determined in TRNSYS.

[12] The analysis was for Toronto, ON, only.

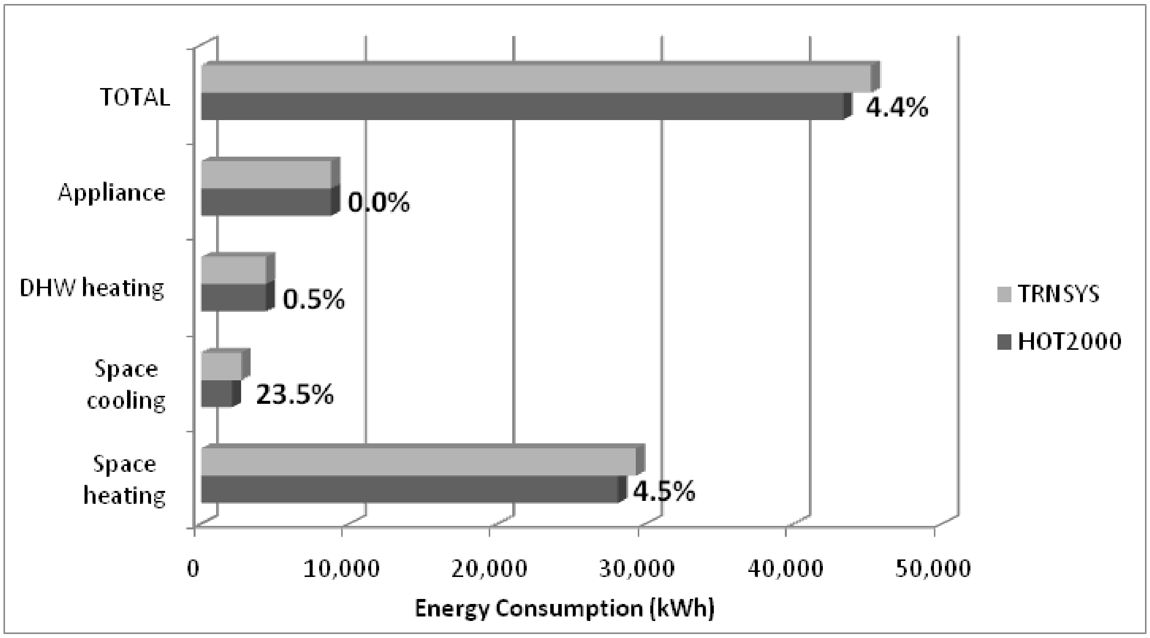


Figure 4-1: Increase to RSI 10.57 (R60) in the ceiling

When the thermal resistance of the exterior walls increased by 54%, resulting from the increase in RSI from 3.19 to 4.91(U 0.204), it was concluded, based on the simulation results, that HOT2000 underestimated the annual space cooling consumption by 27.9%, as shown in Figure 4-2. However, the annual space heating and DHW heating consumptions in HOT2000, on the other hand, were within the ±10% range of what was determined in TRNSYS.

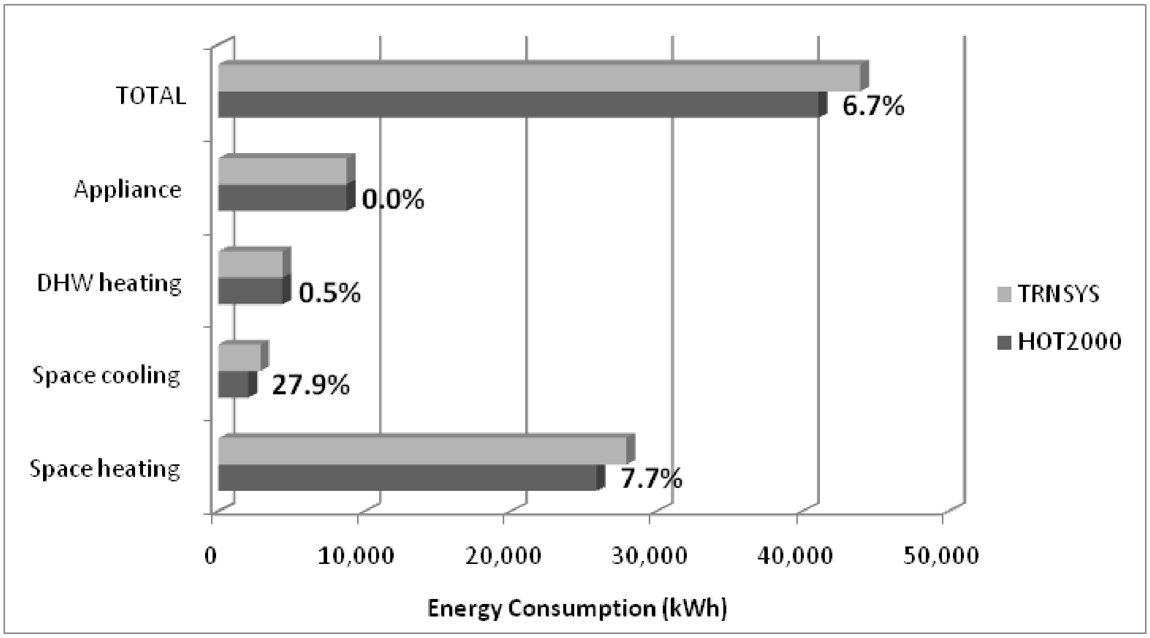


Figure 4-2: Increase to RSI 5.11 (R29) in the exterior walls, at 400 mm (16 in.) on-centre

The thermal resistance (RSI) of the exterior walls increased from 3.19 to 5.06 (U 0.198), resulting in increase by 59% from the baseline case. Based on the simulation results, it was concluded that HOT2000 underestimated the annual space cooling consumption by 27.7%. However, the annual space heating and DHW heating consumptions in HOT2000, on the other hand, were within the ±10% range of what was determined in TRNSYS. Figure 4-3 summarizes the results.

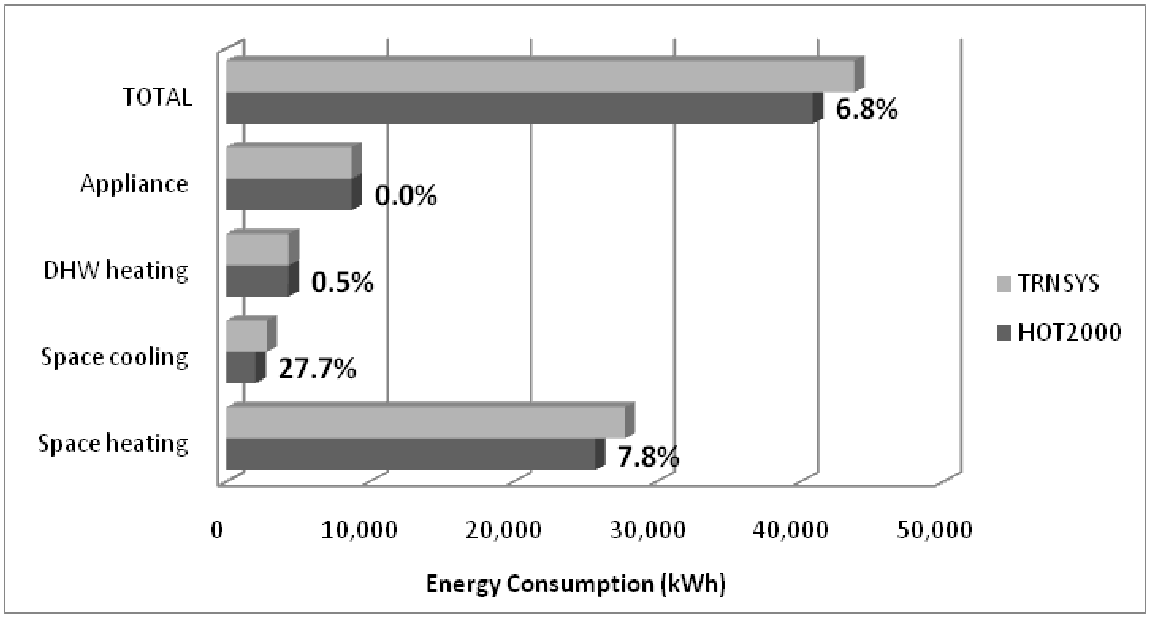


Figure 4-3: Increase to RSI 5.11 (R29) in the exterior walls, at 600 mm (24 in.) on-centre

When the thermal resistance of the floors increased by 16%, resulting from the increase in RSI from 4.70 to 5.46 (U 0.183), it was concluded, based on the simulation results, that HOT2000 underestimated the annual space cooling consumption by 20.9%, as shown in Figure 4-4. However, the annual space heating and DHW heating consumptions in HOT2000, on the other hand, were within the ±10% range of what was determined in TRNSYS.

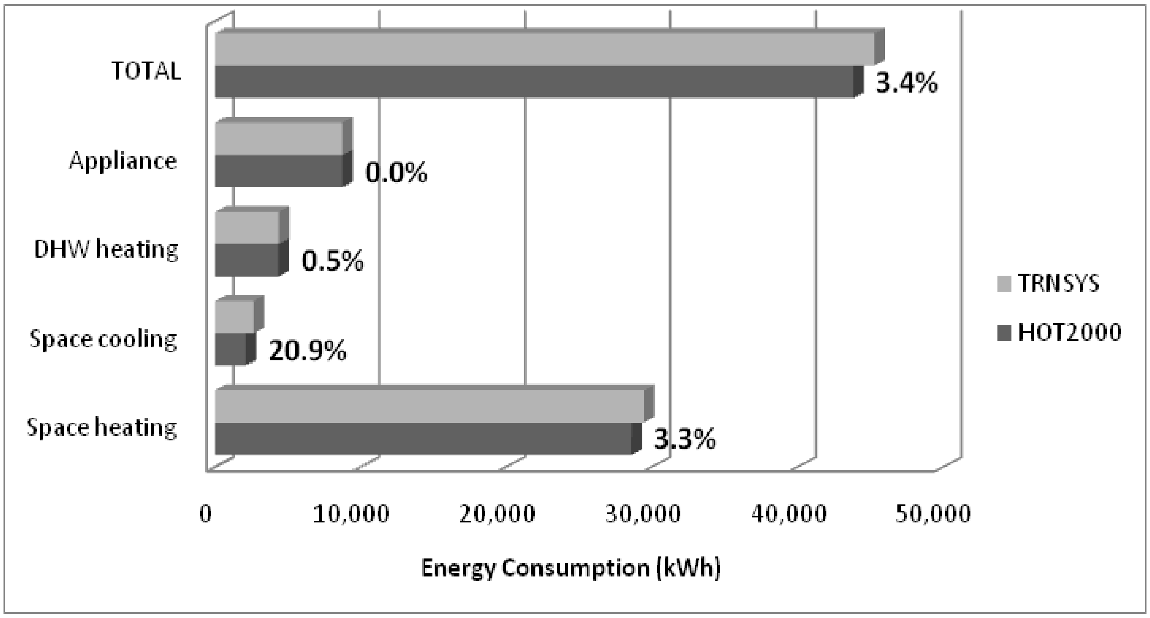


Figure 4-4: Increase to RSI 5.46 (R31) in the floors

4.2.2 Increasing the thermal resistance of the building envelope (below-grade)

As shown in Figure 4-5, it was concluded, based on the simulation results, that HOT2000 underestimated the annual space cooling consumption by 19.2% when the thermal resistance of the basement slab increased by 100%, resulting from the increase in RSI from 1.76 to 3.52 (U 0.284). The annual space heating and DHW heating consumptions in HOT2000, on the other hand, were within the ±10% range of what was determined in TRNSYS.

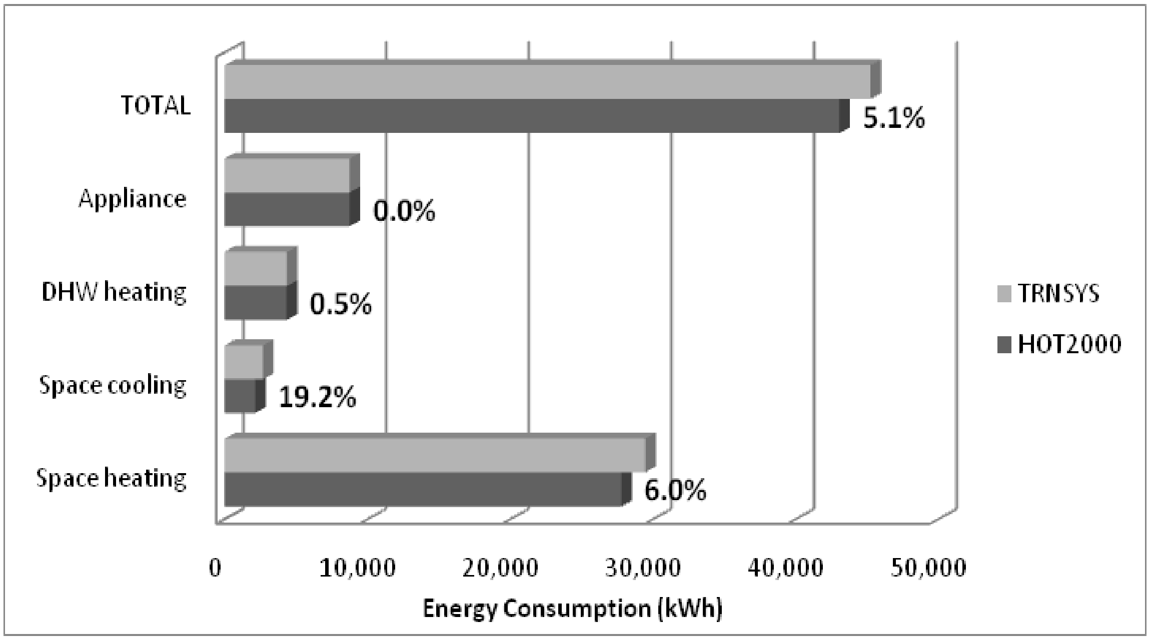


Figure 4-5: Increase to RSI 3.52 (R20) in the basement slab

When the thermal resistance of the basement walls increased by 110%, resulting from the increase RSI from 2.10 to 4.40 (U 0.227), the simulation results showed that HOT2000 underestimated the annual space cooling consumption by 60.7%. The annual space heating and DHW heating consumptions in HOT2000, on the other hand, were within the ±10% range of what was determined in TRNSYS. In fact, for the space heating, the difference was negative, which could imply that HOT2000 overestimated the annual space heating consumption by 8.3%. Figure 4-6 summarizes the results.

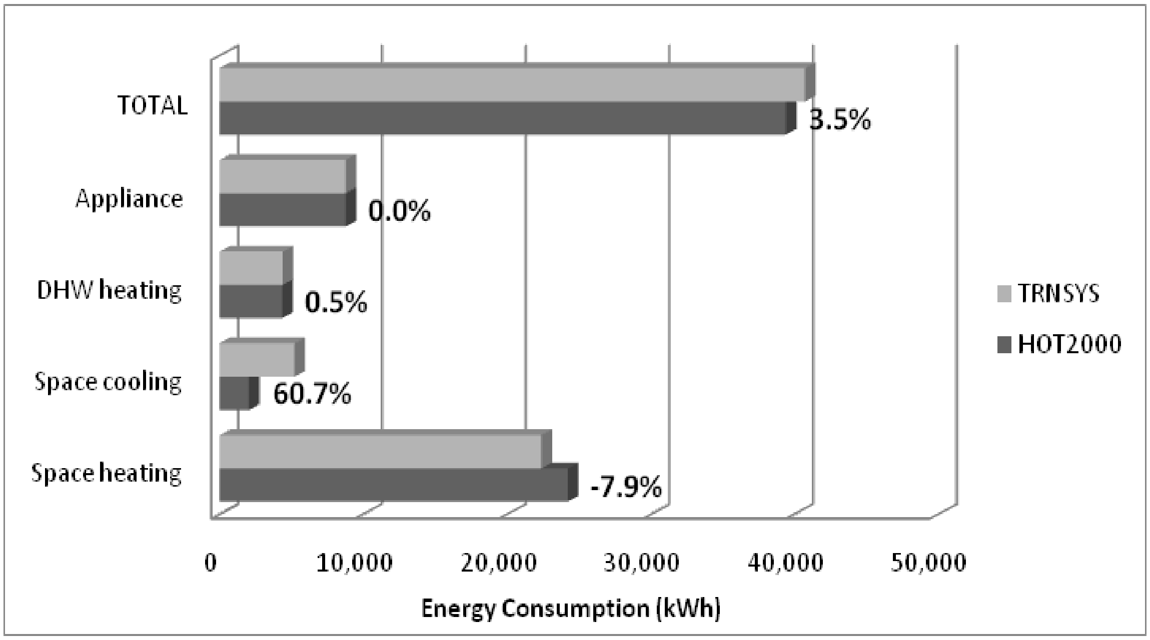


Figure 4-6: Increase to RSI 4.23 (R24) in the basement walls

This could be attributed to the difference in how the selected programs calculated heat loss from the basement. As mentioned previously in Chapter 2, the multiple studies (CHBA, 1991; Haltrecht and Fraser, 1997) reported that HOT2000 calculated heat loss from the basement by accounting for seasonal variation in soil temperatures, as well as the effect that the placement, and amount of insulation at various portions of the basement wall and slab floor have on heat loss; whereas TRNSYS used the undisturbed ground temperature to calculate heat loss from the basement, which was reported in the study by Kummert & Bernier (2008b).

4.2.3 Increasing the efficiency of the windows

As shown in Figure 4-7, it was concluded, based on the simulation results, that HOT2000 underestimated the annual space cooling consumption by 22.0% when the efficiency of the windows increased by 51% to U 1.26. However, the annual space heating and DHW heating consumptions in HOT2000, on the other hand, were within the ±10% range of what was determined in TRNSYS.

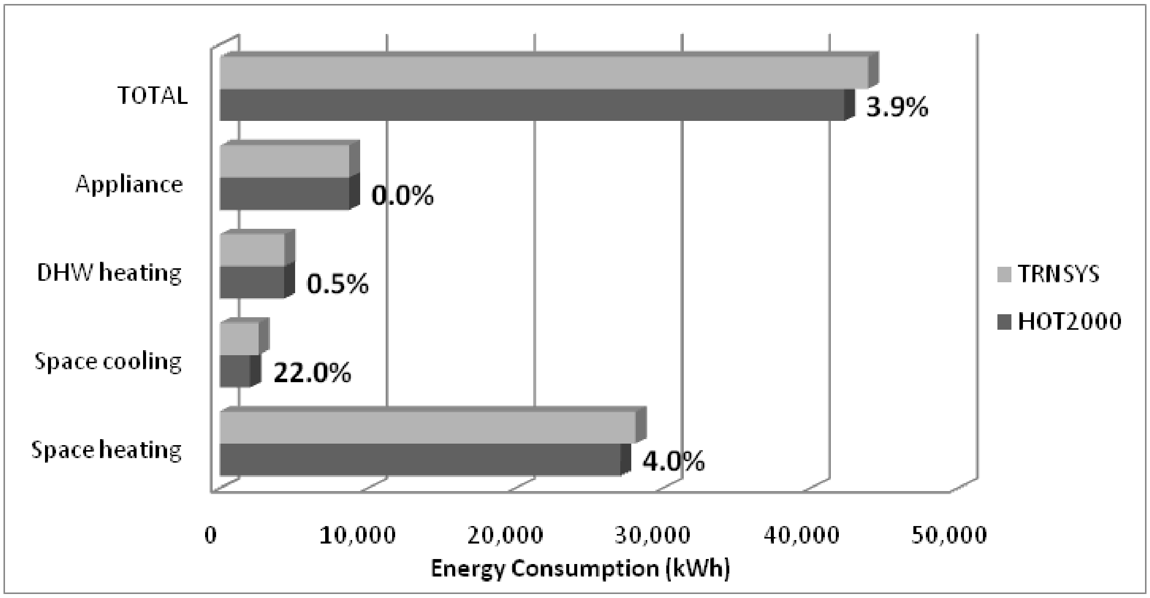


Figure 4-7: Increase to U1.26 in the windows

The efficiency of the windows increased further by 79% to U 1.06. The simulation results showed that the difference in the estimated annual space cooling consumption between HOT2000 and TRNSYS was negative, which could imply that HOT2000 overestimated the space cooling consumption by 5.8%. However, the annual space heating and DHW heating consumptions in HOT2000, on the other hand, were within the ±10% range of what was determined in TRNSYS. Figure 4-8 summarizes the results.

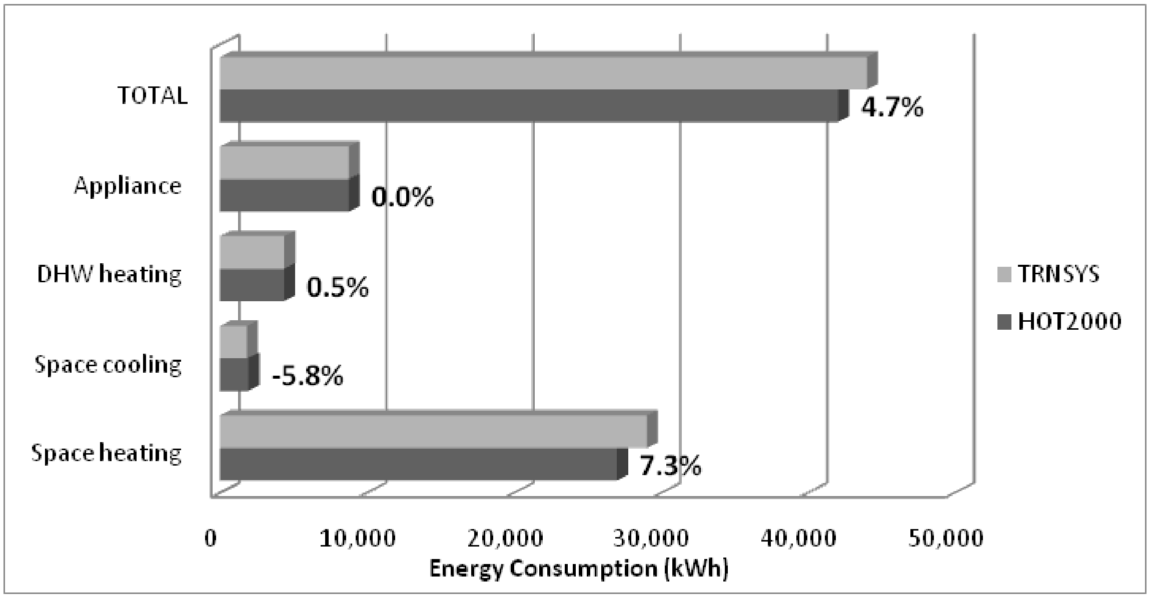


Figure 4-8: Increase to U1.06 in the windows

4.2.4 Increasing the thermal mass capacity of the building

As shown in Figure 4-9, it was concluded, based on the simulation results, that HOT2000 underestimated the annual space cooling consumption by 28.9% when the thermal mass capacity level changed from "Light, wood frame" to "Medium, wood frame" (refer to Section 2.5.3 in Chapter 2 for the descriptions of four different thermal mass capacity levels that are identified in HOT2000). The annual space heating and DHW heating consumptions in HOT2000 were within the ±10% range of what was determined in TRNSYS.

It should be noted that the identified thermal mass capacity level in HOT2000 was specified in TRNSYS as the change in the thermal resistance of the floors, achieved by increasing the thermal resistance of the floors by 11%, resulting from the increase in RSI from 4.70 to 5.24 (U 0.191).

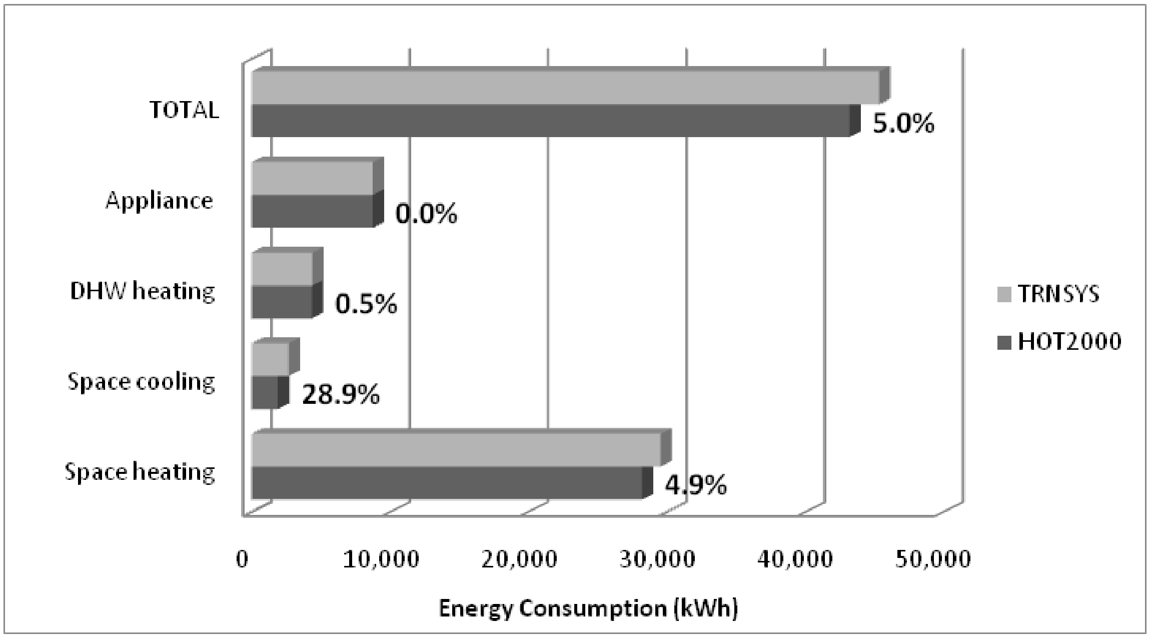


Figure 4-9: Increase the thermal mass capacity level from "Light" to "Medium"

When the thermal mass capacity level changed from "Light, wood frame" to "Heavy, masonry", the simulation results showed that HOT2000 underestimated the annual space cooling consumption by 50.1%, while the annual space heating and DHW heating consumptions were within the ±10% range of what was determined in TRNSYS.

It should also be noted that the identified thermal mass capacity level in HOT2000 was specified in TRNSYS as the change in the thermal resistances of the floors and the basement walls, respectively, where the latter was achieved by increasing the thermal resistance of the basement walls by 53%, resulting from the increase in RSI from 2.10 to 3.21 (U 0.312). Figure 4-10 summarizes the results.

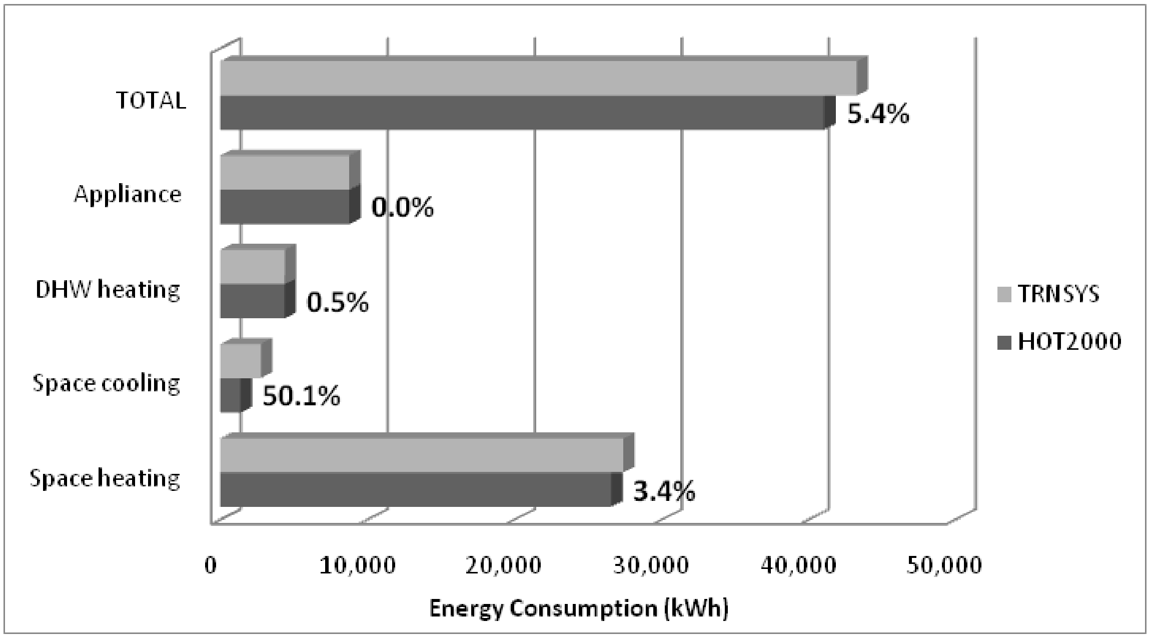


Figure 4-10: Increase a thermal mass capacity level from "Light" to "Heavy"

Based on the results of a literature review, as well as the energy performance analyses of some of the potential upgrades using the selected programs, it was concluded that, despite the program's tendency to underestimate the annual space cooling consumption, HOT2000 would be the appropriate tool for estimating the annual space heating and DHW heating consumptions.

4.3 Sensitivity analysis of the identified parameters

In the previous chapter, a set of parameters was determined based on the data obtained from various sources. In this section, sensitivity analysis of the identified parameters was conducted first, to determine a combination of eligible upgrades with the lowest total life cycle cost, and verify that the identified combination of upgrades was, in fact, the most cost-effective (or least cost) provided that some of the variables changed. Table 4-5 summarizes the parameters used for the sensitivity analysis.

Table 4-5: Summary of the identified parameters

Parameters	Minimum (%)	Maximum (%)		Average (%)
Discount rate	0.40	3.10		1.99
Fuel escalation rate for:				
-Electricity	2.92	4.92		3.92[1]
-Natural gas	3.02	5.50		4.26
-Oil	2.76	5.81		4.29
Electricity price (monthly):	**Description**	**$/kWh (before taxes)**		
-Less than 800 kWh (2.7×10^6 Btu)	-	0.1038		
-Greater than 800 kWh (2.7×10^6 Btu)	-	0.1138		
		$/m^3 (before taxes)		
Natural gas price (monthly):	**Description**	**Average**	**2006 Prices[2]**	**2008 Prices[2]**
-Distributor 1	First 30 m^3 (1059 ft^3)	0.2892	0.7053	0.5300
	Next 55 m^3 (1942ft^3)	0.2843	0.7053	0.5300
	Next 85 m^3 (3002ft^3)	0.2804	0.7053	0.5300
	Over 170 m^3 (6003ft^3)	0.2774	0.7053	0.5300
-Distributor 2	First 100 m^3 (3531 ft^3)	0.2573	0.7152	0.5379
	Next 150 m^3 (5297ft^3)	0.2550	0.7152	0.5379
	Next 250 m^3 (7063ft^3)	0.2496	0.7152	0.5379

Notes:

1. The OME recently announced that the projected long-term electricity price increase of 3.50% annually for the next twenty years (OME, 2010). Therefore, 3.50% will be used as the identified electricity escalation rate for the proposed methodology.
2. The commodity prices for natural gas in 2006 and 2008, respectively, were determined based on the historical data provided by the OEB (2008).

Several cases (6 cases in total) were performed for the sensitivity analysis, and the results are summarized as follows:

4.3.1 Case 1 - Average parameters

Based on the results using HOT2000, the combination of eligible upgrades with the lowest total life cycle cost was identified using the BFSS method, as shown in Figure 4-11. For a complete listing or glossary of the eligible upgrades, refer to Glossary.

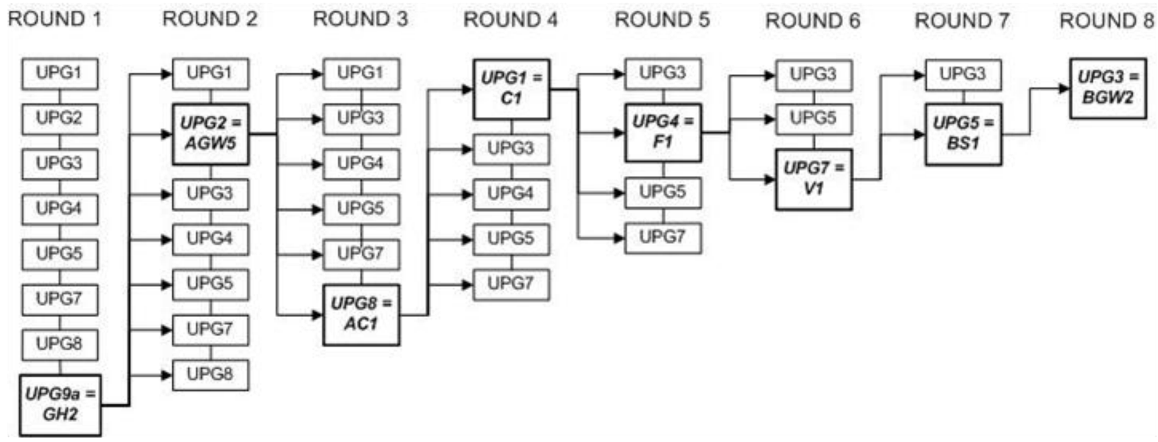


Figure 4-11: Least cost upgrade by round using the BFSS method

Table 4-6 summarizes the estimated total annual household energy consumption, percent savings per year, reductions of GHG emissions, and the total life cycle cost in NPV by round.

Table 4-6: Simulation results using HOT2000 for Toronto, using average parameters (Case 1)

Round	Description [Code]	Simulation Results			Total LCC[2] (NPV) ($)
		Energy Consumption (kWh/year; Btu/year)	% Savings (EGR)	GHG Emissions[1] (Tons/CO_2) and % Savings	
-	**Base case**	**32,610 (111x10^6)**	**N/A (78.4)**	**8.05 (N/A)**	**94,630**
1	Combo boiler with 0.85 EF [GH2]	29,728 (101x10^6)	9% (79.9)	7.51 (7%)	93,248
2	RSI 3.3 (R19) insulation at 600 mm (24 in.) on centre + RSI 0.9 (R5) exterior insulation board [AGW5]	27,408 (93.5x10^6)	16% (81.1)	7.10 (12%)	92,500
3	Air-conditioning unit at SEER 14 [AC1]	27,4408 (93.5x10^6)	16% (81.1)	7.09 (12%)	92,672
4	RSI 8.8 (R50) attic/ceiling insulation [C1]	26,966 (92.0x10^6)	17% (81.3)	7.01 (13%)	93,453
5	RSI 5.5 (R31) floor insulation [F1]	26,891 (91.8x10^6)	18% (81.3)	7.00 (13%)	94,265
6	HRV at 70% efficiency [V1]	24,865 (84.8x10^6)	24% (82.3)	6.67 (17%)	96,679
7	RSI 2.2 (R12) insulating board underneath the basement slab [BS1]	24,572 (83.8x10^6)	25% (82.5)	6.62 (18%)	100,218
8	RSI 3.5 (R20) basement wall insulation [BGW2]	24,359 (83.1x10^6)	25% (82.6)	5.59 (31%)	103,811
-	**Difference from the base case to the final combination of upgrades**	**8251 (28.2X10^6)**	**25% (82.6)**	**2.47 (31%)**	**- 9181**

Notes:

1. The GHG emission calculation was done using the carbon dioxide (CO_2) factors determined from the study by Fung & Gill (2011). In their study, 1.856 kg/m^3 equivalent CO_2 (NRCan, 2006) was used for natural gas, and the average emission factor for electricity was 226.35 tons CO_2/total gigawatt-hour (GWh) generation (Gordon & Fung, 2009).
2. The total life cycle cost (LCC) was determined based on the identified average mortgage rate of 7.87%, average discount rate of 1.99%, and the fuel escalation rates for electricity and natural gas of 3.50%, and 3.02%, respectively.

As shown in Table 4-6, the estimated total household energy consumption and GHG emissions of the baseline case decreased due to the outcome of the identified least cost upgrades, resulting in decrease in the total life cycle cost in NPV until the end of Round 5, although the EnerGuide Rating (EGR) was not sensitive, and remained at EGR of 81 at the end of Round 5 with a difference in percent savings of 2%.

4.3.2 Case 2 – Extreme parameters with the change in natural gas prices

For this case, the identified parameters were changed as follows: 30-year mortgage (same as the previous case) at a 5.05% mortgage rate (minimum) with 3.10% discount rate (maximum). As for the fuel price escalation rates for electricity and natural gas, 3.50% (same as the previous case) and 5.50% (maximum) were chosen, respectively.

Furthermore, different from the previous case was the change in the price of natural gas using the identified commodity prices in 2006 (Case 2a) and 2008 (Case 2b), respectively, where the prices were determined based on the historical data provided by the OEB (2008), as summarized in Table 4-5.

Based on the results using the BFSS method, the combination of eligible upgrades with the lowest total life cycle cost in NPV was the same as the one identified in the previous case; however, the HRV with 70% efficiency [V1] was the least cost upgrade solution at the end of Round 3, as shown in Figure 4-12.

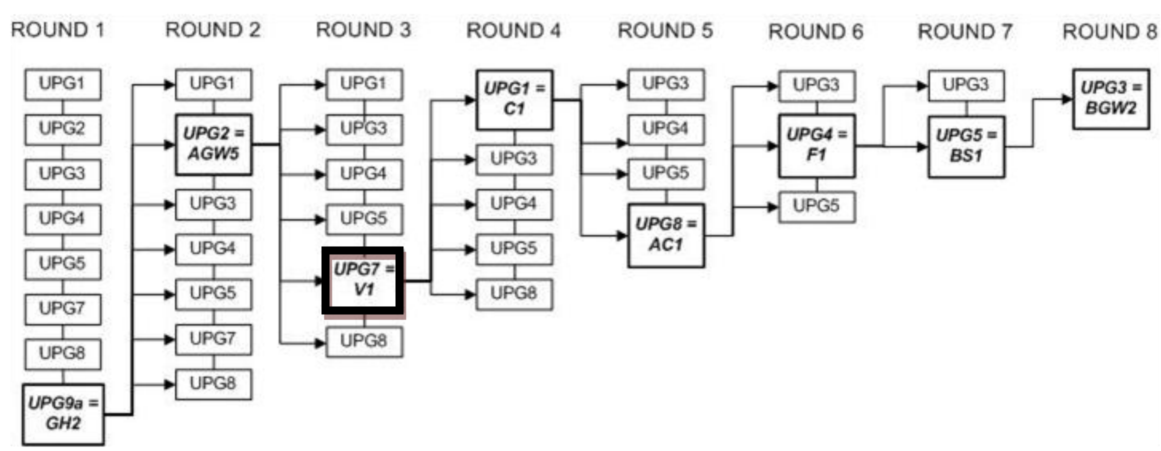


Figure 4-12: Least cost upgrade by round using the BFSS method (Case 2)

Table 4-7 summarizes the estimated total annual household energy consumption, percent savings per year, reductions of GHG emissions, and the total life cycle cost in NPV by round for Case 2a.

Table 4-7: Simulation results using HOT2000 for Toronto, ON (Case 2a)

Round	Description [Code]	Simulation Results			Total LCC[1] (NPV) ($)
		Energy Consumption (kWh/year; Btu/year)	% Savings (EGR)	GHG Emissions (Tons/CO_2) and % Savings	
-	**Base case**	**32,610 (111x10^6)**	**N/A (78.4)**	**8.05 (N/A)**	**158,258**
1	Combo boiler with 0.85 EF [GH2]	29,728 (101x10^6)	9% (79.9)	7.51 (7%)	150,781
2	RSI 3.3 (R19) insulation at 600 mm (24 in.) on centre + RSI 0.9 (R5) exterior insulation board [AGW5]	27,408 (93.5x10^6)	16% (81.1)	7.10 (12%)	144,306
3	HRV at 70% efficiency [V1]	25,374 (86.6x10^6)	22% (82.1)	6.77 (16%)	140,152
4	RSI 8.8 (R50) attic/ceiling insulation [C1]	24,937 (85.1x10^6)	24% (82.3)	6.69 (17%)	139,519
5	Air-conditioning unit at SEER 14 [AC1]	24,937 (85.1x10^6)	24% (82.3)	6.69 (17%)	139,628
6	RSI 5.5 (R31) floor insulation [F1]	24,866 (84.8x10^6)	24% (82.3)	6.67 (17%)	139,965
7	RSI 2.2 (R12) insulating board underneath the basement slab [BS1]	24,572 (83.8x10^6)	25% (82.5)	6.62 (18%)	141,471
8	RSI 3.5 (R20) basement wall insulation [BGW2]	24,359 (83.1x10^6)	25% (82.6)	6.58 (18%)	143,216
-	**Difference from the base case to the final combination of upgrades**	**8251 (28.2X10^6)**	**25% (82.6)**	**1.47 (18%)**	**15,042**

Note:

1. The total LCC was determined based on the identified minimum mortgage rate of 5.05%, maximum discount rate of 3.10%, and the fuel escalation rates for electricity and natural gas of 3.50%, and 5.50% (maximum), respectively. Furthermore, the commodity price in 2006 was used for natural gas.

Table 4-8 summarizes the estimated total annual household energy consumption, percent savings per year, reductions of GHG emissions, and the total life cycle cost in NPV by round for Case 2b.

Table 4-8: Simulation results using HOT2000 for Toronto, ON (Case 2b)

Round	Description [Code]	Simulation Results			Total LCC[1] (NPV) ($)
		Energy Consumption (kWh/year; Btu/year)	% Savings (EGR)	GHG Emissions (Tons/CO_2) and % Savings	
-	**Base case**	**32,610 (111x10^6)**	**N/A (78.4)**	**8.05 (N/A)**	**132,828**
1	Combo boiler with 0.85 EF [GH2]	29,728 (101x10^6)	9% (79.9)	7.10 (6%)	127,301
2	RSI 3.3 (R19) insulation at 600 mm (24 in.) on centre + RSI 0.9 (R5) exterior insulation board [AGW5]	27,408 (93.5x10^6)	16% (81.1)	6.77 (10%)	122,676
3	HRV at 70% efficiency [V1]	25,374 (86.6x10^6)	22% (82.1)	6.69 (11%)	120,460
4	RSI 8.8 (R50) attic/ceiling insulation [C1]	24,937 (85.1x10^6)	24% (82.3)	6.69 (11%)	120,176
5	Air-conditioning unit at SEER 14 [AC1]	24,937 (85.1x10^6)	24% (82.3)	6.67 (11%)	120,284
6	RSI 5.5 (R31) floor insulation [F1]	24,866 (84.8x10^6)	24% (82.3)	6.62 (12%)	120,678
7	RSI 2.2 (R12) insulating board underneath the basement slab [BS1]	24,572 (83.8x10^6)	25% (82.5)	6.58 (12%)	122,418
8	RSI 3.5 (R20) basement wall insulation [BGW2]	24,359 (83.1x10^6)	25% (82.6)	5.59 (26%)	124,333
-	**Difference from the base case to the final combination of upgrades**	**8251 (28.2X10^6)**	**25% (82.6)**	**2.47 (31%)**	**8494**

Note:

1. The total LCC was determined based on the identified minimum mortgage rate of 5.05%, maximum discount rate of 3.10%, and the fuel escalation rates for electricity and natural gas of 3.50%, and 5.50% (maximum), respectively. Furthermore, the commodity price in 2008 was used for natural gas.

As Tables 4-7 and 4-8 indicate, similar to the results of the previous case was the estimated energy consumption and GHG emissions of the baseline case in Cases 2a and 2b, which decreased due to the outcome of the identified least cost upgrades, resulting in decrease in the total life cycle cost in NPV, even at the end of Round 8, which was not the case in the previous scenario (Case 1). As for the EnerGuide Rating, it was not sensitive, and remained at EGR of 82 at the end of Round 8 with a difference in percent savings of 3%.

Figure 4-13 shows the total life cycle cost in NPV with respect to the increase in energy efficiency for the cases mentioned above.

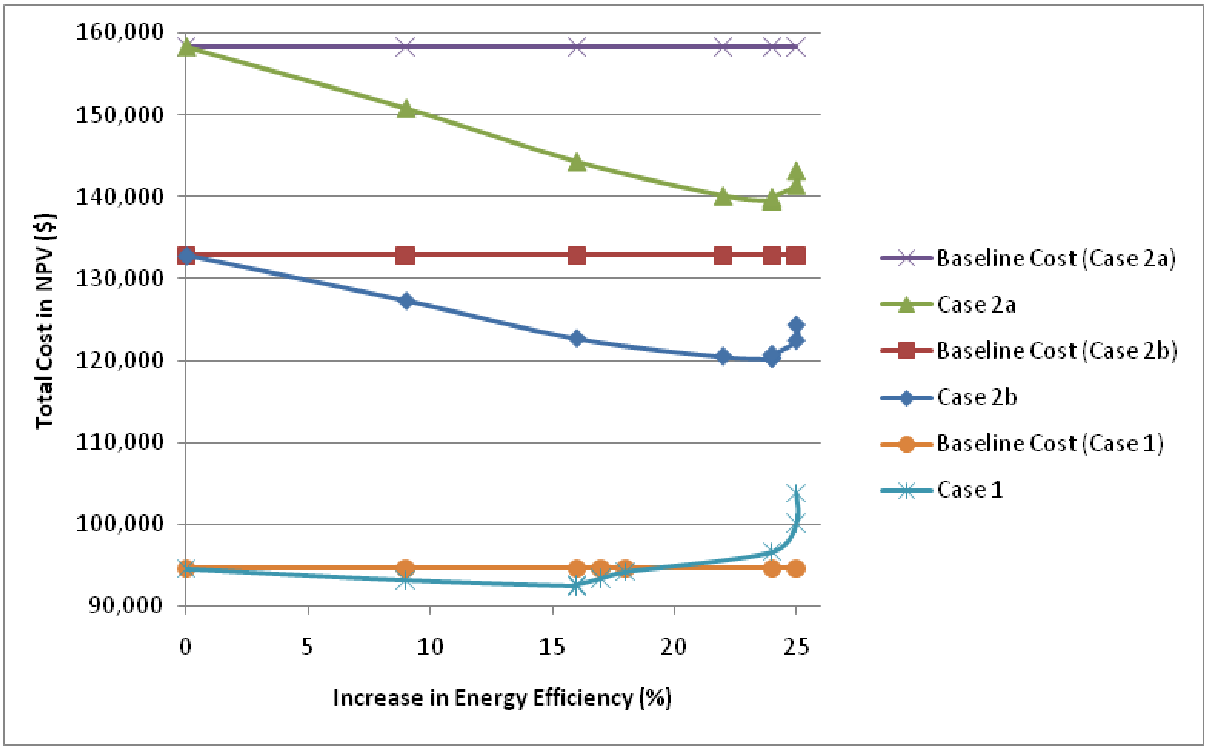


Figure 4-13: Total cost in NPV ($) vs. increase in energy efficiency (%)

4.4 Reduction in Appliances, Lighting and Hot Water Consumptions

Various appliances and lighting assumptions with reduction in the average hot water load were considered, and sensitivity analysis was conducted to evaluate the effectiveness of the eligible upgrades by reducing energy consumption with respect to appliances, lighting and hot water usage.

The assumptions were based on the study conducted by Tse et al., (2008). Based on their study, 40% reduction in major household appliances (refrigerator, stove, clothes washer and dryer, and dishwasher) was achieved by installing energy efficient devices. By installing Energy Star approved CFL bulbs, 75% reduction in lighting energy consumption was achieved (Tse et al., 2008).

4.4.1 Reduction in appliances and lighting consumption

Based on the results of the study referenced above, the reduced electricity consumption for appliances and lighting of 9.5 kWh (32,381 Btu) per day was assumed and entered in HOT2000. The result showed 42% reduction in the estimated annual electricity consumption in comparison to that of the previous cases. Table 4-9 summarizes the percent reduction in the appliances and lighting energy consumption between the two scenarios.

Table 4-9: Percent reduction in the energy consumption between the two scenarios

Breakdown of Baseloads:	Unit	Cases 1 and 2: Standard Operating Conditions	Case 3: Reduced Consumption[1]	% Reduction
Appliances	kWh/yr (Btu/yr)	5110 (17.44×10^6)	3066 (10.46×10^6)	40%
Lighting	kWh/yr (Btu/yr)	1095 (3.74×10^6)	274 (0.93×10^6)	75%
Other Electric Devices	kWh/yr (Btu/yr)	1095 (3.74×10^6)	1095 (3.74×10^6)	-
Exterior Use	kWh/yr (Btu/yr)	1460 (4.98×10^6)	675 (2.30×10^6)	54%
Total Baseloads Consumptions	**kWh/yr (Btu/yr)**	**8760 (29.89×10^6)**	**5110 (17.44×10^6)**	**42%**

Note:
1. The assumptions were based on the study conducted by Tse et al. **(2008)**

Table 4-10 summarizes the results of Cases 1 and 3, where the latter is the reduced electricity consumption for appliances and lighting.

Table 4-10: Difference in the energy consumption and the LCC between the two cases

Description	Unit	Case: 1 - Using the appliance and lighting consumption based on the standard operation conditions used in HOT2000	Case: 3 - Using reduced appliance and lighting consumption	Difference between the two cases
Space Heating	kWh/year	18,555	21,599	**-16%**
Space Cooling	kWh/year	885	755	**15%**
DHW Heating	kWh/year	5116	5119	**0%**
Baseloads (see Table 4-9)	kWh/year	8760	5110	**42%**
Total Energy Consumption	**kWh/year (Btu/year)**	**33,316 (113.68x10^6)**	**32,584 (111.18x10^6)**	**2%**
- % Savings	%/year	25%	24%	**1%**
EnerGuide Rating	-	82.6	83.8	**-**
Total LCC[1] (NPV)	$	103,811	83,173	**20%**

Note:

1. The life cycle cost (LCC) was determined based on the identified average mortgage rate of 7.87%, average discount rate of 1.99%, and the fuel escalation rates for electricity and natural gas of 3.50%, and 3.02%, respectively.

Based on the results of the reduced appliance and lighting consumption in Case 3, although the combination of eligible upgrades with the lowest total life cycle cost in NPV was the same as the one identified in the previous case (Case 1) using the standard operating conditions in HOT2000, the estimated total life cycle cost of the former decreased by 20% when compared against that of the previous case with no reduction in the appliance and lighting consumptions. The overall total energy consumption of the former also decreased by 2%, despite the fact that the estimated space heating consumption increased by 15%, while the estimated space cooling consumption was reduced by 16% as a result of the 42% reduction in the appliance and lighting consumptions.

For Cases 2a and 2b, it was interesting to note that the combo boiler with the 0.9 EF [GH3], and the exterior wall insulation with RSI 3.87 (R22) [AGW2] were the most cost-effective solutions than the same equipment with lower efficiency (0.85 EF) [GH2], and the insulation with higher thermal resistance (RSI 4.22 or R24) [AGW5], respectively, where the latter were identified as the most cost-effective solutions in the previous cases using the standard operating conditions in HOT2000 (refer to Figure 4-12). Figure 4-14 shows the identified combination of least cost upgrades for Case 3 using the BFSS method.

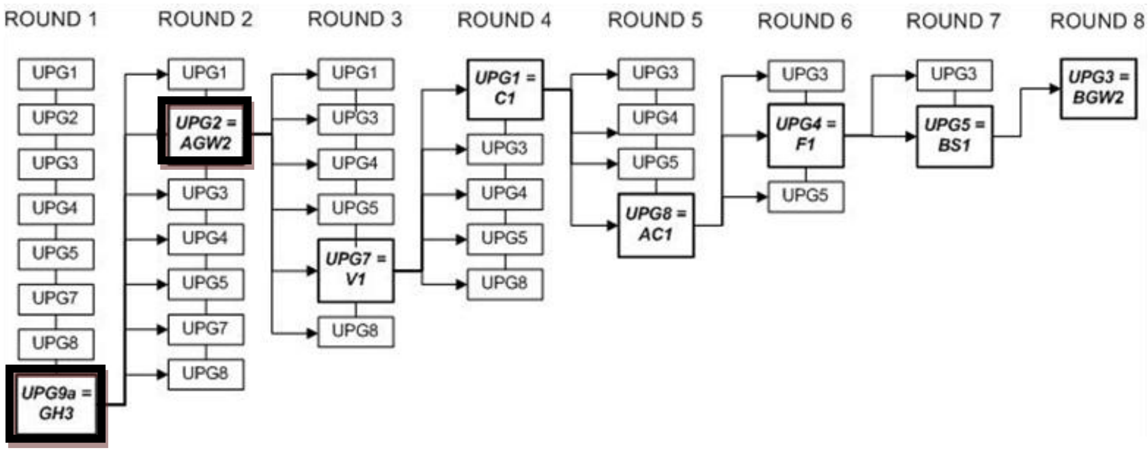


Figure 4-14: Least cost upgrade by round using the BFSS method (Case 3)

Table 4-11 summarizes the results for Case 2 with reduction in the appliance and lighting energy consumptions.

Table 4-11: Simulation results with reduction in the appliance and lighting consumptions (Case 2)

Round	Description [Code]	Simulation Results			Total LCC[1] (NPV)	
		Energy Consumption (kWh/year; Btu/year)	% Savings (EGR)	GHG Emissions (Tons/CO_2) and % Savings	With 2006 Gas Price ($)	With 2008 Gas Price ($)
-	**Base case**	**35,893 (122x10^6)**	**N/A (79.5)**	**7.42 (N/A)**	**149,102**	**121,099**
1	Combo boiler with 0.90 EF [GH3]	32,769 (112x10^6)	9% (81.1)	6.84 (8%)	141,494	115,587
2	RSI 4.2 (R22) insulation at 400 mm (16 in.) on centre [AGW2]	30,604 (104x10^6)	15% (82.2)	6.45 (13%)	135,527	111,348
3	HRV at 70% efficiency [V1]	28,481 (97.2x10^6)	21% (83.3)	6.10 (18%)	130,774	108,603
4	RSI 8.8 (R50) attic/ceiling insulation [C1]	28,036 (95.7x10^6)	22% (83.5)	6.02 (19%)	130,118	108,303
5	Air-conditioning unit at SEER 14 [AC1]	28,036 (95.7x10^6)	22% (83.5)	6.01 (19%)	130,249	108,433
6	RSI 5.5 (R31) floor insulation [F1]	27,960 (95.4x10^6)	22% (83.5)	6.00 (19%)	130,570	108,815
7	RSI 2.2 (R12) insulating board underneath the basement slab [BVS1]	27,644 (94.3x10^6)	23% (83.7)	5.94 (20%)	132,002	110,499
8	RSI 3.5 (R20) basement wall insulation [BGW2]	27,388 (93.5x10^6)	24% (83.8)	5.90 (21%)	133,608	112,309
-	**Difference from the base case to the final combination of upgrades**	**8504 (29.0X10^6)**	**24% (83.8)**	**1.52 (21%)**	**15,494**	**8790**

Note:

1. The total LCC was determined based on the identified minimum mortgage rate of 5.05%, maximum discount rate of 3.10%, and the fuel escalation rates for electricity and natural gas of 3.50%, and 5.50% (maximum), respectively.

As shown in Table 4-11, the estimated energy consumption and GHG emissions of the baseline case decreased due to the outcome of the identified least cost upgrades, resulting in decrease in the total life cycle cost in NPV, even at the end of Round 8, similar to the previous cases. As for the EnerGuide Rating, it was not sensitive, and remained at EGR of 83 at the end of Round 8 with a difference in percent savings of 3%.

Figure 4-15 shows the total life cycle cost in NPV with respect to the increase in energy efficiency for Case 3.

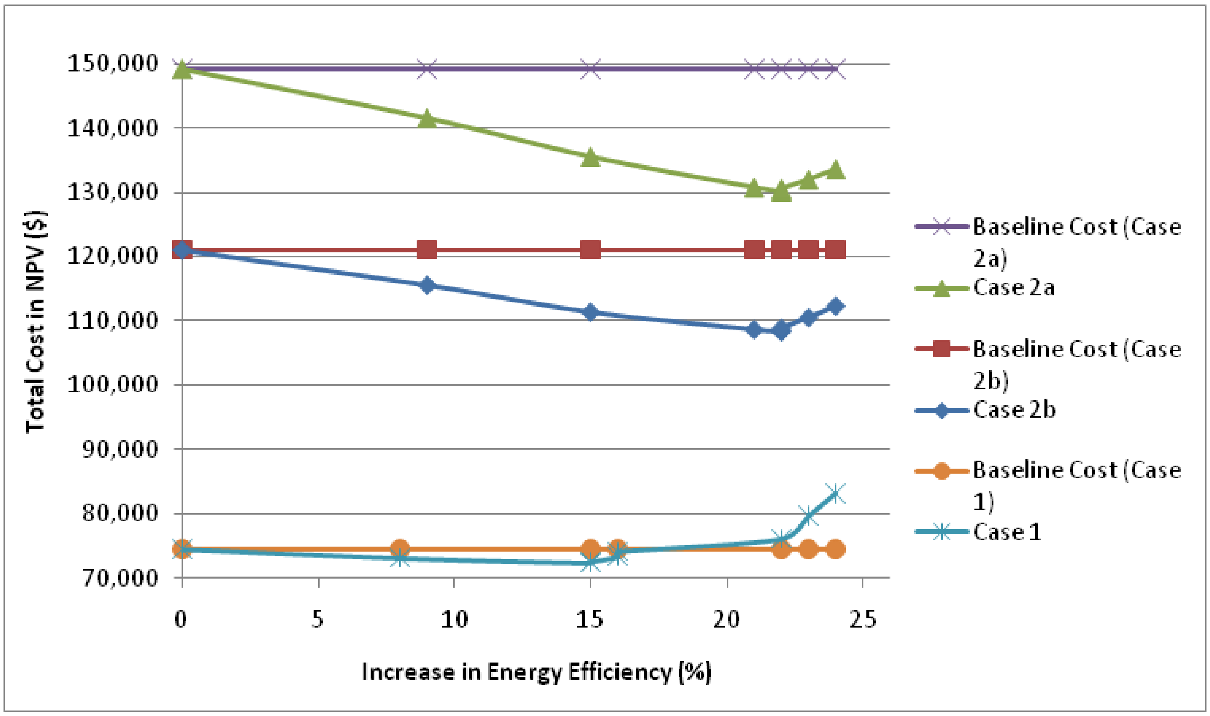


Figure 4-15: Total cost in NPV ($) vs. increase in energy efficiency (%) with reduction in the appliance and lighting consumptions

4.4.2 Reduction in average hot water load

In addition to reducing the amount of electricity used for lighting and appliances, the average hot water load of 100 L/day was assumed based on the study by Tse et al. (2008). As a result, 56% reduction was achieved in comparison to the HOT2000's average hot water load of 225 L/day.

Based on the results of the reduced appliance, lighting and hot water consumptions in Case 1, the combination of eligible upgrades with the lowest total life cycle cost in NPV was identical to the one identified in the previous case using the standard operating conditions in HOT2000, however, the exterior insulation with RSI 4.22 (R24) [AGW5] was the least cost upgrade solution at the end of Round 1, as shown in Figure 4-16.

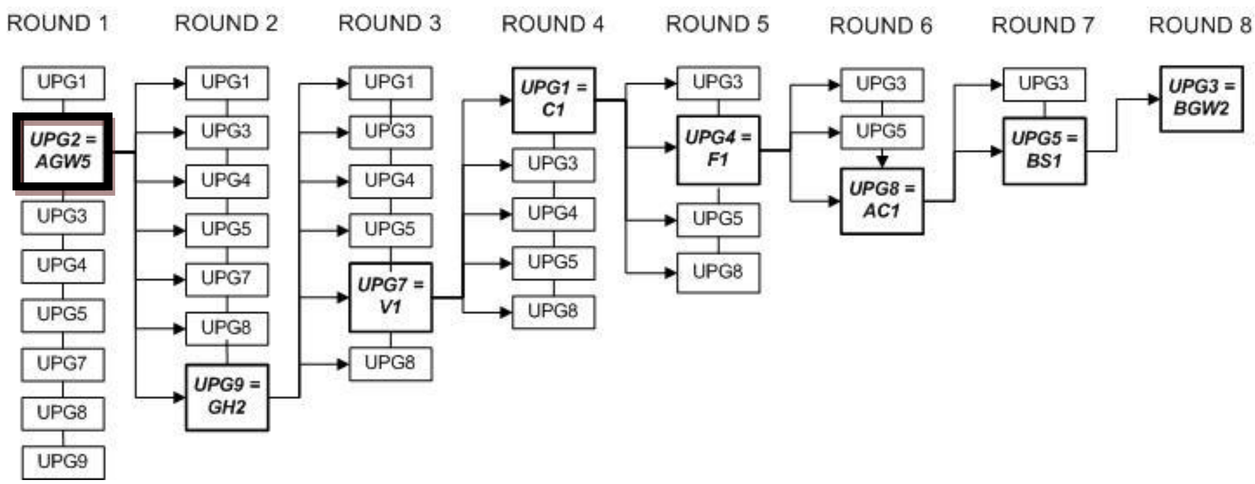


Figure 4-16: Least cost upgrade by round using the BFSS method (Case 4)

When compared against those identified in the previous cases using the standard operating conditions in HOT2000, the identified combination of eligible upgrades in this case (Case 4) resulted in decrease in the estimated net present value of the total life cycle cost in NPV by 22% and in the GHG emissions by 3%, despite the increase in the estimated energy consumption by 2%. Table 4-12 summarizes the result.

Table 4-12: Difference in the energy consumption, GHG emissions, and the LCC of the two cases

Case	Description	Simulation Results			Total LCC[1] (NPV) ($)
		Energy Consumption (kWh/year; Btu/year)	**% Savings (EGR)**	**GHG Emissions ($Tons/CO_2$) and % Savings**	
1	Using the appliance, lighting and hot water energy consumptions based on the standard operation conditions used in HOT2000	24,359 ($83.1x10^6$)	25% (82.6)	5.59 (31%)	103,811
4	Using reduced appliance, lighting and hot water energy consumptions	24,767 ($84.5x10^6$)	24% (85.2)	5.43 (20%)	80,553
-	**Difference between the two cases**	**-2%**	**-**	**3%**	**22%**

Note:

1. The total LCC was determined based on the identified average mortgage rate of 7.87%, average discount rate of 1.99%, and the fuel escalation rates for electricity and natural gas of 3.50%, and 3.02%, respectively.

Figure 4-17 shows the total life cycle cost in NPV with respect to the increase in energy efficiency for Case 4.

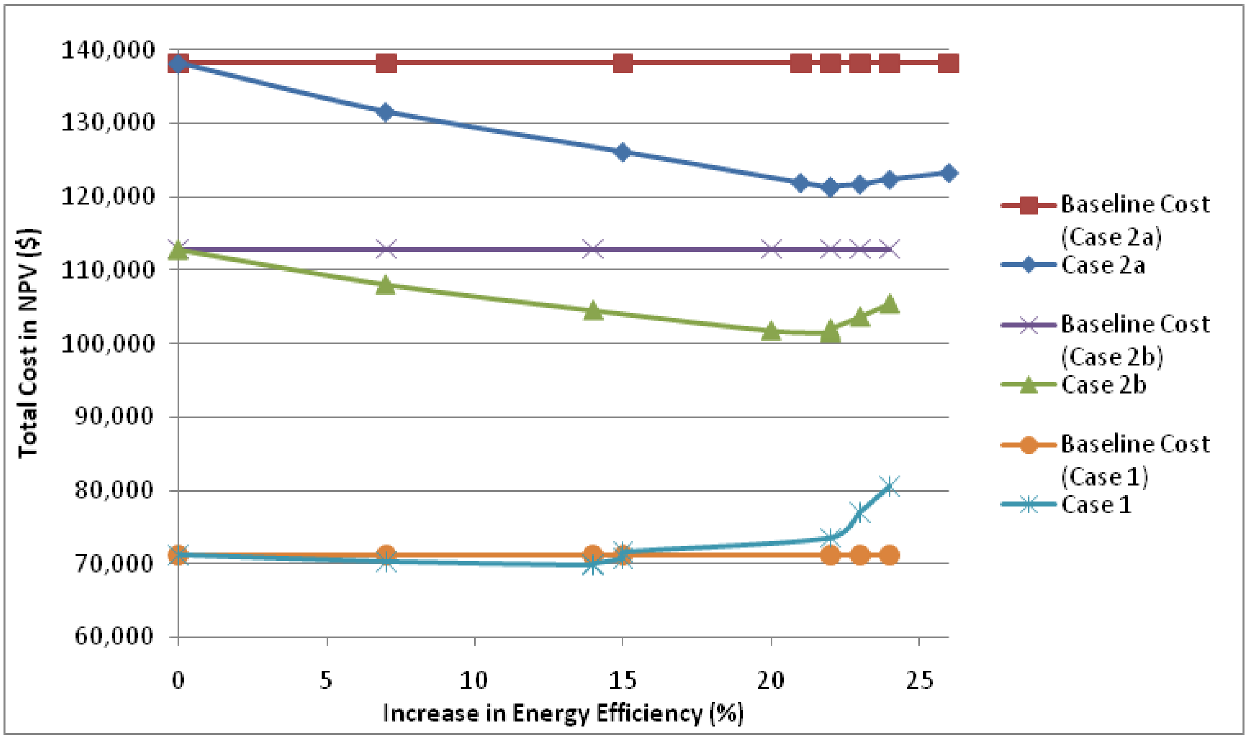


Figure 4-17: Total cost in NPV ($) vs. increase in energy Efficiency (%) with reduction in appliance, lighting and hot water consumptions

4.5 Sensitivity Analysis of the Upgrades with a Photovoltaic (PV) System

Additional analysis was conducted to determine the overall energy performance of the Reference House, after the installation of the identified combination of eligible upgrades with a PV system in Toronto.

For this analysis, NRCan's RETScreen® version 4 was used, because the PV system was not able to simulate using HOT2000. The input parameters used for the RETScreen simulation were derived based on data obtained from various sources, and are summarized in Table 4-13.

Table 4-13: Description of the input parameters for RETScreen simulation

	Unit	Value
1.Photovoltaic: - Collector area	m^2 (ft^2)	41.5 (446.7)[1]
- Collector slope (horizontal)	-	45.0°
- Collector orientation - Manufacturer and model - Panel area - Azimuth of PV array - Miscellaneous PV array losses	- - m^2 (ft^2) - %	South[1] Canadian Solar, CS5A-190M[2] 1.28 (13.78)[2] 0.0[3] 5.0[3]
2. Inverter:		
- Efficiency	%	90[1]
3. Results:		
- Number of panels required	-	32
- Estimated power capacity - Estimated efficiency - Estimated electricity exported to grid	kW (Btu/hr) % kWh (Btu)	6.08 (20,746) 16.9 7612 (25.97×10^6)
Notes: 1. The values for the solar collector were obtained from the study by Good et al. (2007) 2. Model and specifications for the solar collector were obtained from the Canadian Solar (n.d.) 3. Specified as default values in RETScreen (NRCan, 1995-2007; NRCan 1997-2000)		

Based on the results, the estimated electricity exported to grid was 7612 kWh per year, and with the introduction of Ontario's microFIT program, the price of $0.802 was applied for every kilowatt-hour of electricity generated by the PV (Ontario Power Authority [OPA], 2010).

Therefore, after subtracting the cost of installing a PV system (assumed $7/W for a total of $42,560) from the income, the net present value of the total profit for 20 years was estimated to be $57,359 for Case 1 and $47,430 for Cases 2a and 2b. Accounting for the electricity production from the PV system from 21 to 30 years, the difference in the net present value of the total electricity cost of what a homeowner would pay if the PV system were not installed (hence the savings) was estimated to be $12,679 for Case 1, and $9,612 for Cases 2a and 2b, resulting in total profits over the 30-year mortgage period of $70,038, and $57,043, respectively.

With the estimated 42% reduction in the appliance and lighting consumptions in Case 3, which resulted in 52% less electricity consumption than that generated by the PV system, the net present value of the total savings from 21 to 30 years was estimated to be $11,708 for Case 1, and $8,878 for Cases 2a and 2b, resulting in total profits of $69,067, and $56,309, respectively.

However, it should be noted that, with this particular case, the total savings after the termination of the micro FIT program was less than those of the previous cases without the reduction in the appliance and lighting consumptions. This could imply that reducing the appliance and lighting consumptions decreased the economic feasibility of the PV system. In other words, the higher the appliance and lighting consumptions, the more savings would be expected, allowing the homeowner to pay for the implementation of additional upgrade(s).

Despite the potential reduction in the economic feasibility of a residential PV system, the installation of such a system would result in the estimated total profit of up to $70,038 that could be achieved through Ontario's microFIT program, provided that such a program will continue onward.

4.6 Sensitivity Analysis of Extreme Weather Conditions for Toronto

Lastly, the extreme weather conditions for Toronto, ON, were determined based on the historical weather data to determine and compare the combination of eligible upgrades with the lowest total life cycle cost against those that were already identified in the previous five cases, using the long-term monthly weather data in the HOT2000 program.

Based on the historical weather data from 1940 to 2005, the coldest year was in 1972, and the warmest was in 1998, as summarized in Table 4-14.

Table 4-14: Summary of the historical weather data for Toronto, ON

Weather Conditions	Year	Heating-Degree Days	
Coldest	1972	4380	
Average	1955	3445	
Warmest	1998	2850	
HOT2000 (default)	**-**	**4200**	
Mean		3779	
Standard Deviation:		325	
-First Deviation	-	3454	4104
-Second Deviation		3129	4429
-Third Deviation		2804	4754

Figure 4-18 shows the average monthly temperature profile for the identified extreme weather conditions used in this analysis.

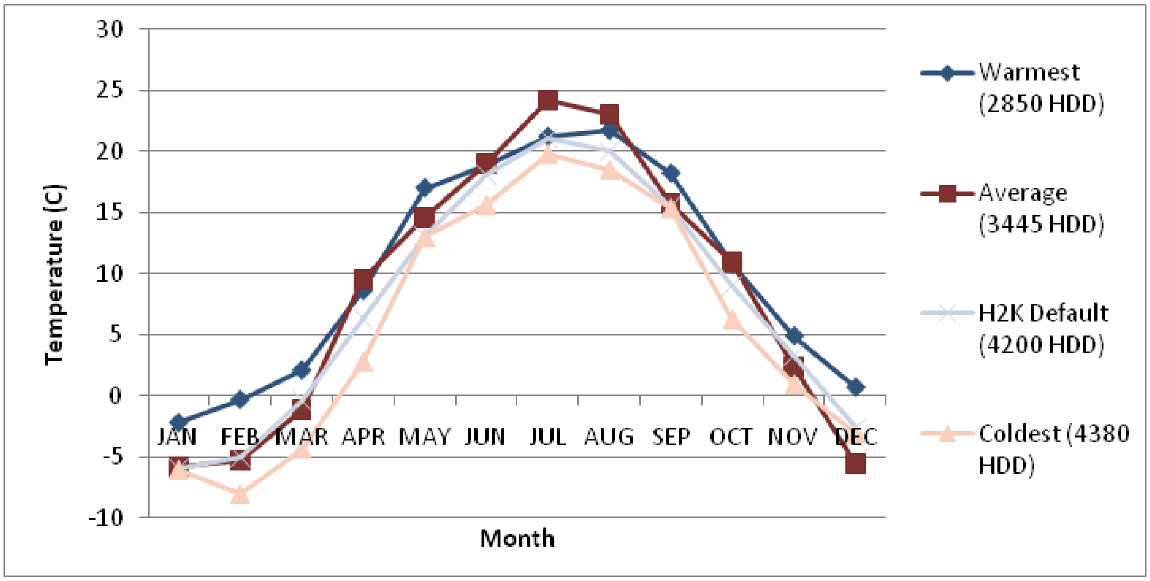


Figure 4-18: Average monthly temperature profiles for the identified extreme weather conditions

The average monthly temperature profile for each identified extreme weather condition was entered into HOT2000, and the energy and economic analyses were conducted using the identified parameters of Case 2b (see Section 4.3.2, p.102).

The combination of eligible upgrades with the lowest total life cycle cost in NPV for each of the extreme weather conditions was identified as follows:

4.6.1 Extreme weather condition 1 - Coldest winter (4380 HDD)

Based on the results, the combination of eligible upgrades with the lowest total life cycle cost was identical to the one already identified in the previous case (Case 2b) with no reduction in the appliance and lighting energy consumption. However, the basement wall insulation with RSI 3.50 (R20) [BGW2] was the least cost upgrade solution at the end of Round 7, as shown in Figure 4-19.

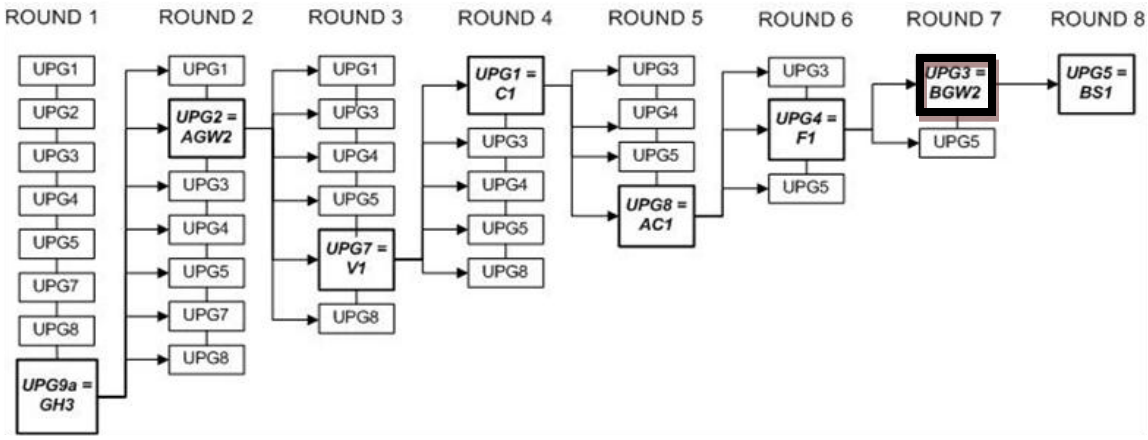


Figure 4-19: Least cost upgrade by round using the BFSS method (Case 6)

Table 4-15 summarizes the estimated total annual household energy consumption, percent savings per year, reductions of GHG emissions, and the total life cycle cost in NPV by round for the coldest winter condition.

Table 4-15: Simulation results for the identified coldest winter conditions for Toronto, ON

Round	Description [Code]	Simulation Results			Total LCC[1] (NPV) ($)
		Energy Consumption (kWh/year; Btu/year)	% Savings (EGR)	GHG Emissions (Tons/CO_2) and % Savings	
-	**Base case**	**36,523**	**N/A (76.5)**	**8.72 (N/A)**	**141,711**
1	Combo boiler with 0.90 EF [GH3]	33,385	9% (78.1)	8.13 (7%)	135,975
2	RSI 4.2 (R22) insulation at 400 mm (16 in.) on centre [AGW2]	31,014	15% (79.8)	7.70 (12%)	131,250
3	HRV at 70% efficiency [V1]	28,762	21% (80.9)	7.33 (16%)	128,305
4	RSI 8.8 (R50) attic/ceiling insulation [C1]	28,271	23% (81.2)	7.24 (17%)	127,901
5	Air-conditioning unit at SEER 14 [AC1]	28,270	23% (81.2)	7.24 (17%)	127,635
6	RSI 5.5 (R31) floor insulation [F1]	28,188	23% (81.2)	7.22 (17%)	128,402
7	RSI 3.5 (R20) basement wall insulation [BGW2]	27,586	24% (81.5)	7.11 (18%)	129,370
8	RSI 2.2 (R12) insulating board underneath the basement slab [BS1]	27,096	26% (81.8)	7.03 (19%)	130,635
-	**Difference from the base case to the final combination of upgrades**	**9426**	**26% (81.8)**	**1.69 (19%)**	**11,076**

Note:

1. The total LCC was determined based on the identified minimum mortgage rate of 5.05%, maximum discount rate of 3.10%, and the fuel escalation rates for electricity and natural gas of 3.50%, and 5.50% (maximum), respectively. Furthermore, the commodity price in 2008 was used for natural gas.

As shown in Table 4-15, the estimated energy consumption and the GHG emissions of the baseline case decreased due to the outcome of the identified lease cost upgrades, resulting in decrease in the total life cycle cost in NPV, even at the end of Round 8, which was also the case in the previous cases using the long-term monthly weather data in HOT2000. As for the EnerGuide Rating, it was not sensitive, and remained at EGR of 81 at the end of Round 8 with a difference in percent savings of 3%.

4.6.2 Extreme weather condition 2 – Average weather conditions (3445 HDD)

Table 4-16 summarizes the estimated total annual household energy consumption, percent savings per year, reductions of GHG emissions, and the total life cycle cost in NPV by round for the average weather conditions.

Table 4-16: Simulation results for the average weather conditions for Toronto, ON

Round	Description [Code]	Simulation Results			Total LCC (NPV) ($)
		Energy Consumption (kWh/year; Btu/year)	% Savings (EGR)	GHG Emissions (Tons/CO_2) and % Savings	
-	**Base case**	**32,555**	**N/A (75.7)**	**8.15 (N/A)**	**134,643**
1	Combo boiler with 0.90 EF [GH3]	29,442	10% (77.5)	7.58 (7%)	129,069
2	RSI 4.2 (R22) insulation at 400 mm (16 in.) on centre [AGW2]	27,370	16% (78.7)	7.20 (12%)	124,994
3	HRV at 70% efficiency [V1]	25,412	22% (79.7)	6.88 (16%)	122,898
4	RSI 8.8 (R50) attic/ceiling insulation [C1]	24,984	23% (80.0)	6.80 (17%)	122,612
5	Air-conditioning unit at SEER 14 [AC1]	24,983	23% (80.0)	6.80 (17%)	122,658
6	RSI 5.5 (R31) floor insulation [F1]	24,911	23% (80.0)	6.78 (17%)	123,050
7	RSI 3.5 (R20) basement wall insulation [BGW2]	24,366	25% (80.3)	6.69 (18%)	124,150
8	RSI 2.2 (R12) insulating board underneath the basement slab [BS1]	23,881	27% (80.6)	6.61 (19%)	125,607
-	**Difference from the base case to the final combination of upgrades**	**8674**	**27% (80.6)**	**1.54 (19%)**	**9035**

As shown in Table 4-16, the estimated energy consumption and the GHG emissions of the baseline case decreased due to the outcome of the identified least cost upgrades, resulting in decrease in the total life cycle cost in NPV, even at the end of Round 8, which was also the case in the previous weather condition. As for the EnerGuide Rating, it was not sensitive, and remained at EGR of 80 at the end of Round 8 with a difference in percent savings of 3%.

4.6.3 Extreme weather condition 3 – Warmest summer conditions (2850 HDD)

Lastly, Table 4-17 summarizes the estimated total annual household energy consumption, percent savings per year, reductions of GHG emissions, and the total life cycle cost in NPV by round for the warmest summer conditions.

Table 4-17: Simulation results for the warmest summer conditions for Toronto, ON

Round	Description [Code]	Simulation Results			Total LCC[1] (NPV) ($)
		Energy Consumption (kWh/year; Btu/year)	% Savings (EGR)	GHG Emissions (Tons/CO_2) and % Savings	
-	**Base case**	**27,358**	**N/A (76.7)**	**7.16 (N/A)**	**120,987**
1	Combo boiler with 0.90 EF [GH3]	24,310	11% (78.6)	6.60 (8%)	115,715
2	RSI 4.2 (R22) insulation at 400 mm (16 in.) on centre [AGW2]	22,578	17% (79.7)	6.28 (12%)	112,490
3	HRV at 70% efficiency [V1]	20,965	23% (80.7)	6.03 (16%)	111,191
4	RSI 8.8 (R50) attic/ceiling insulation [C1]	20,592	25% (80.9)	5.96 (17%)	111,051
5	Air-conditioning unit at SEER 14 [AC1]	20,591	25% (80.9)	5.96 (17%)	111,129
6	RSI 5.5 (R31) floor insulation [F1]	20,530	25% (81.0)	5.94 (17%)	111,547
7	RSI 3.5 (R20) basement wall insulation [BGW2]	20,091	27% (81.2)	5.87 (18%)	112,906
8	RSI 2.2 (R12) insulating board underneath the basement slab [BS1]	19,738	28% (81.5)	5.80 (19%)	114,512
-	**Difference from the base case to the final combination of upgrades**	**7619**	**28% (81.5)**	**1.36 (19%)**	**6475**

As shown in Table 4-17, the estimated energy consumption and the GHG emissions of the baseline case decreased due to the outcome of the identified least cost upgrades, resulting in decrease in the total life cycle cost in NPV, even at the end of Round 8, which was also the case in the previous weather conditions. As for the EnerGuide Rating, it was not sensitive, and remained at EGR of 81 at the end of Round 8 with a difference in percent savings of 3%.

Figure 4-20 shows the total life cycle cost in NPV versus the increase in energy efficiency curve for all the identified combinations of eligible upgrades using the weather data based on the historical data, in comparison to the long-term monthly weather data used in HOT2000.

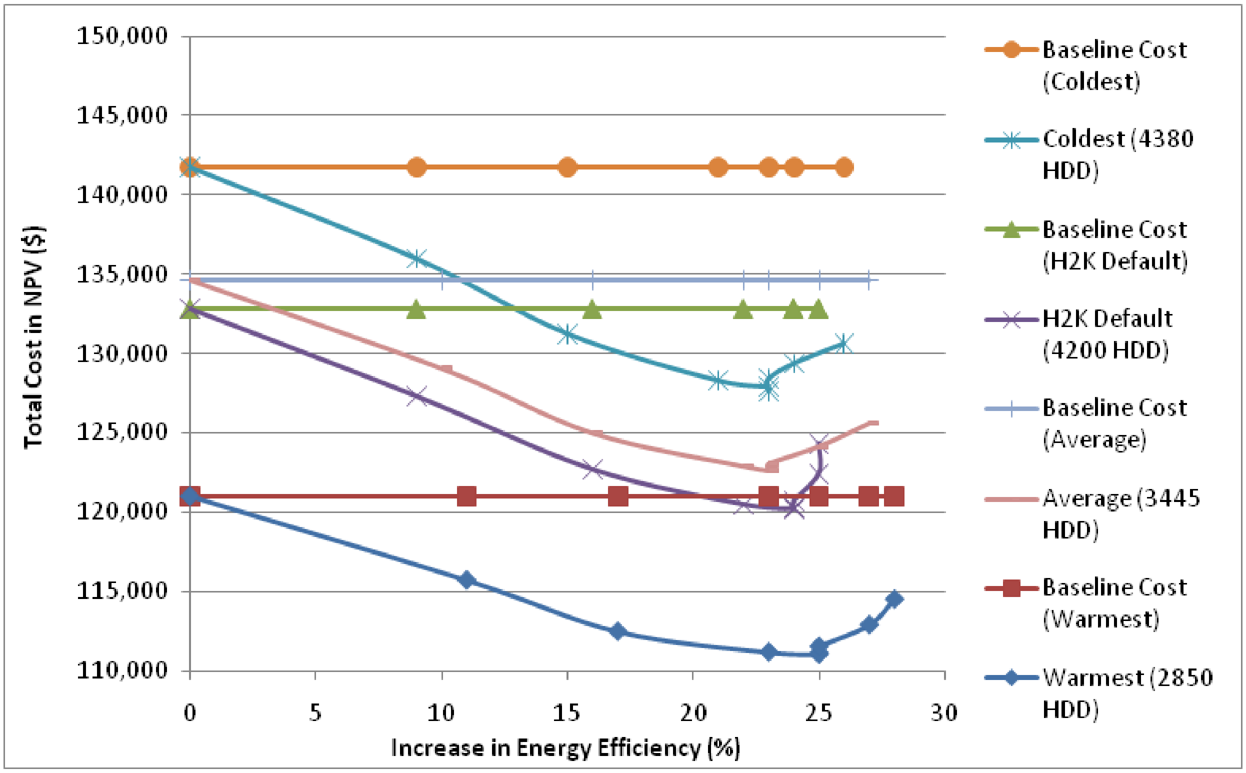


Figure 4-20: Total LCC in NPV ($) vs. increase in energy efficiency (%) for the extreme weather conditions in Toronto

Chapter 5

5 Least Cost Analysis for Ontario New Housing

5.1 Overview

In the previous chapter, the combination of the most cost-effective (least cost) upgrades was determined using the brute force sequential search (BFSS) method for the climatic condition of Toronto, ON. In this chapter, the same methodology was used to determine a set of least cost upgrades for other cities in Ontario, namely Ottawa, Windsor and Thunder Bay.

Both Ottawa and Thunder Bay have colder climatic conditions than Toronto with the estimated annual heating degree days (below 18°C) of 4602, and 5677, respectively; whereas Windsor, its climatic condition is warmer than that of Toronto with the estimated annual heating degree days (HDD) of 3525 (Environment Canada, n.d.). The results are discussed as follows:

5.2 Determination of the Eligible Upgrades

5.2.1 Case #1 - Average Parameters

Following the same methodology used in conducting sensitivity analyses (refer to Section 4.3 in the previous chapter), the identified parameters were as follows: 30-year mortgage at a 7.87% mortgage with 1.99% discount rate, and the fuel price escalation rates for electricity and natural gas of 3.50% and 4.26%, respectively.

Based on the results using HOT2000, the combination of eligible upgrades with the lowest total life cycle cost in NPV was identified using the BFSS method. Figures 5-1 to 5-3 show the determination of the eligible upgrade by round using the BFSS method for Ottawa, Windsor, and

Thunder Bay, respectively. For a complete listing or glossary of the eligible upgrades, refer to Glossary.

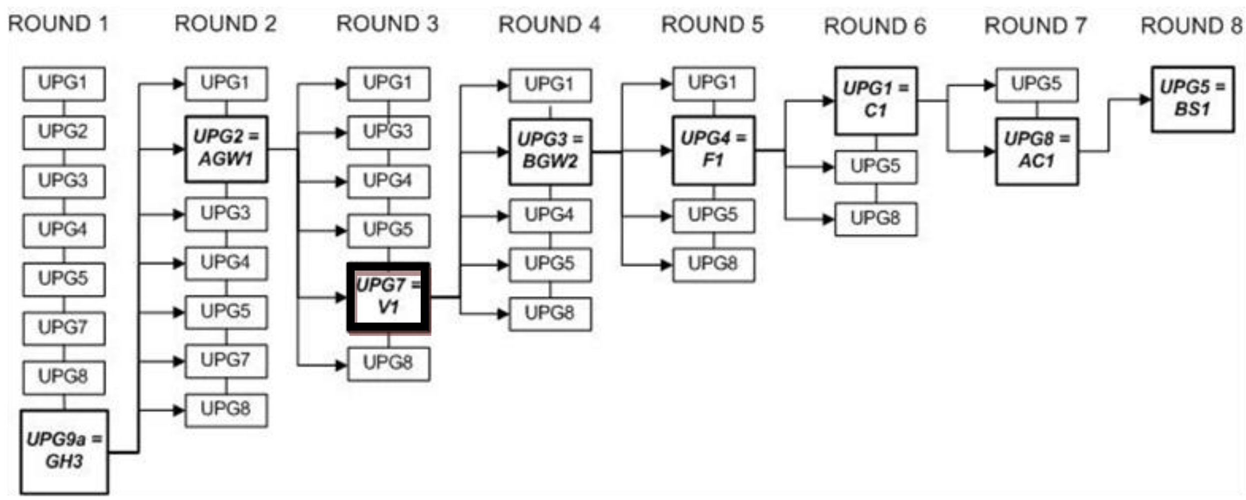


Figure 5-1: Least cost upgrade by round using the BFSS method for Ottawa

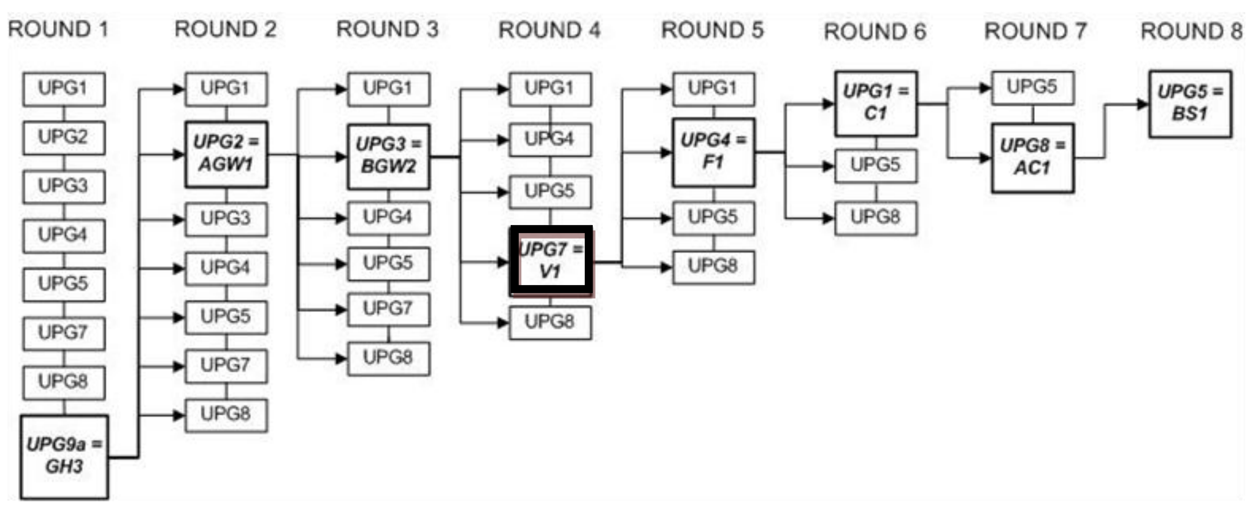


Figure 5-2: Least cost upgrade by round using the BFSS method for Windsor

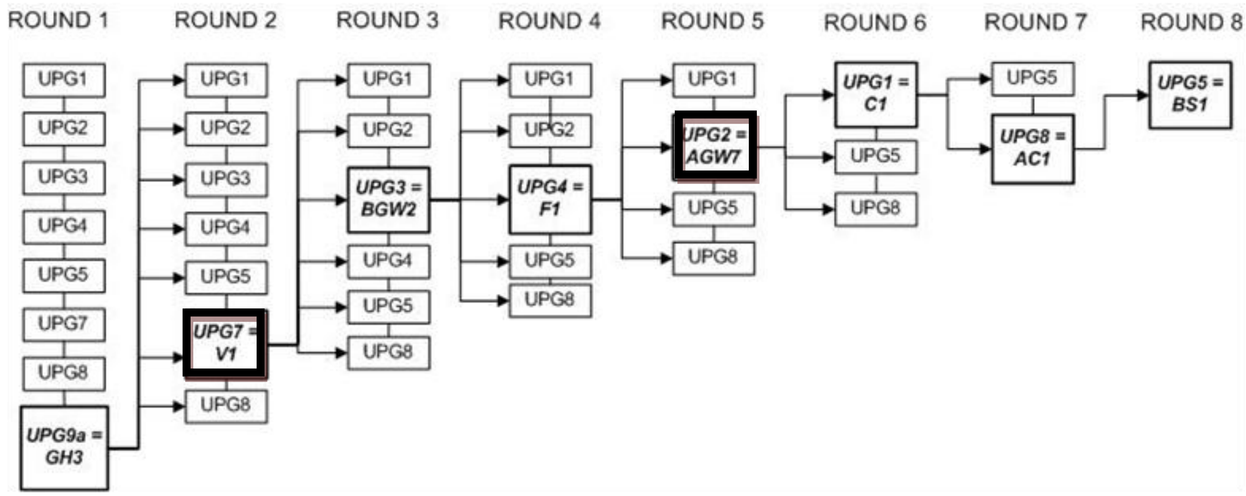


Figure 5-3: Least cost upgrade by round using the BFSS method for Thunder Bay

As shown in Figures 5-1 to 5-3, the identified combination of eligible upgrades was almost identical in all three cities, except for the HRV with 70% efficiency [V1], which was the least cost upgrade solution at the end of Round 2 in Thunder Bay, Round 3 in Ottawa, and Round 4 in Windsor, respectively. This could imply that the colder the weather the better the HRV as an upgrade.

Furthermore, for the case in Thunder Bay (Figure 5-3), the above-grade wall insulation of RSI 5.10 (R29), placed in between the studs at 600 mm (24 in.) on-centre [AGW7] was the least cost upgrade solution at the end of Round 5. It should be noted that some of the potential upgrades, in particular those with respect to the above-grade walls, were eliminated due to the baseline case having a higher thermal resistance (RSI) level (of 4.22) as mandated by the current 2006 OBC than the rest of the cities with their estimated annual HDD of 5000 or lower (i.e., Toronto, Ottawa, and Windsor). It should also be noted that the incremental costs for these upgrades were adjusted properly to account for such changes in the baseline case.

Tables 5-1 to 5-3 summarize the estimated total annual household energy consumption, percent savings per year, reductions of the GHG emissions, and the total life cycle cost in NPV by round for Ottawa, Windsor, and Thunder Bay, respectively, for Case 1.

Table 5-1: Simulation results for Ottawa, using the average parameters (Case 1)

Round	Description [Code]	Simulation Results: Energy Consumption (kWh/year; Btu/year)	% Savings (EGR)	GHG Emissions[1] (Tons/CO_2) and % Savings	Total LCC[2] (NPV) ($)
-	**Base case**	**37,264 ($127x10^6$)**	**N/A (77.4)**	**8.88 (N/A)**	**99,357**
1	Combo boiler with 0.90 EF [GH3]	33,956 ($116x10^6$)	9% (79.0)	8.27 (7%)	94,818
2	RSI 3.9 (R22) insulation [AGW1]	32,732 ($112x10^6$)	12% (79.6)	8.05 (9%)	93,922
3	HRV at 70% efficiency [V1]	30,476 ($104x10^6$)	18% (80.6)	7.67 (14%)	93,612
4	RSI 3.5 (R20) basement wall insulation [BGW2]	29,886 ($102x10^6$)	20% (80.9)	7.56 (15%)	93,539
5	RSI 5.5 (R31) floor insulation [F1]	29,802 ($102x10^6$)	20% (81.0)	7.55 (15%)	93,752
6	**RSI 8.8 (R50) attic/ceiling insulation [C1]**	**29,317 ($100x10^6$)**	**21% (81.2)**	**7.46 (16%)**	**95,260**
7	**Air-conditioning unit at SEER 14 [AC1]**	**29,317 ($100x10^6$)**	**21% (81.2)**	**7.46 (16%)**	**98,402**
8	RSI 2.2 (R12) insulating board underneath the basement slab [BS1]	29,302 ($100x10^6$)	21% (81.2)	7.45 (16%)	102,795
-	**Difference from the base case to the final combination of upgrades**	**7962 ($27X10^6$)**	**21% (81.2)**	**1.43 (16%)**	**- 3438**

Notes:

1. The GHG emission calculation was done using the carbon dioxide (CO_2) factors determined from the study by Fung & Gill (2011). In their study, 1.856 kg/m^3 equivalent CO_2 (NRCan, 2006) was used for natural gas, and the average emission factor for electricity was 226.35 tons CO_2/total gigawatt-hour (GWh) generation (Gordon & Fung, 2009).
2. The total LCC was determined based on the identified average mortgage rate of 7.87%, average discount rate of 1.99%, and the fuel escalation rates for electricity and natural gas of 3.50%, and 3.02%, respectively.

As shown in Table 5-1, for the case in Ottawa, the estimated total household energy consumption and the GHG emissions of the baseline case decreased due to the outcome of the identified least cost upgrades, resulting in decrease in the total life cycle cost in NPV until the end of Round 4, although the EnerGuide Rating was not sensitive, and remained at EGR of 81 at the end of Round 8 with a difference in percent savings of 1%.

Table 5-2: Simulation results for Windsor, using the average parameters (Case 1)

Round	Description [Code]	Simulation Results			Total LCC (NPV) ($)
		Energy Consumption (kWh/year; Btu/year)	% Savings (EGR)	GHG Emissions (Tons/CO_2) and % Savings	
-	**Base case**	**29,228 (100x10^6)**	**N/A (78.3)**	**7.51 (N/A)**	**92,466**
1	Combo boiler with 0.90 EF [GH3]	26,207 (89x10^6)	10% (80.0)	6.95 (7%)	88,692
2	RSI 3.9 (R22) insulation [AGW1]	25,251 (86x10^6)	14% (80.5)	6.78 (10%)	88,012
3	RSI 3.5 (R20) basement wall insulation [BGW2]	24,739 (84x10^6)	15% (80.8)	6.69 (11%)	87,989
4	HRV at 70% efficiency [V1]	22,957 (78x10^6)	21% (81.8)	6.40 (15%)	88,198
5	RSI 5.5 (R31) floor insulation [F1]	22,892 (78x10^6)	22% (81.8)	6.39 (15%)	88,413
6	**RSI 8.8 (R50) attic/ceiling insulation [C1]**	**22,512 (77x10^6)**	**23% (82.0)**	**6.32 (16%)**	**89,909**
7	**Air-conditioning unit at SEER 14 [AC1]**	**22,512 (77x10^6)**	**23% (82.0)**	**6.31 (16%)**	**92,997**
8	RSI 2.2 (R12) insulating board underneath the basement slab [BS1]	22,097 (75x10^6)	24% (82.3)	6.24 (17%)	96,787
-	**Difference from the base case to the final combination of upgrades**	**7131 (24X10^6)**	**24% (82.3)**	**1.27 (17%)**	**4320**

As shown in Table 5-2, for the case in Windsor, the estimated total household energy consumption and the GHG emissions of the baseline case decreased due to the outcome of the identified least cost upgrades, resulting in decrease in the total life cycle cost in NPV until the end of Round 4, although the EnerGuide Rating was not sensitive, and remained at EGR of 82 at the end of Round 8 with a difference in percent savings of 1%.

Table 5-3: Simulation results for Thunder Bay using the average parameters (Case 1)

Round	Description [Code]	Simulation Results			Total LCC (NPV) ($)
		Energy Consumption (kWh/year; Btu/year)	% Savings (EGR)	GHG Emissions (Tons/CO_2) and % Savings	
-	**Base case**	**40,521 (138x10^6)**	**N/A (78.8)**	**9.41 (N/A)**	**101,486**
1	Combo boiler with 0.90 EF [GH3]	36,910 (126x10^6)	9% (80.3)	8.73 (7%)	96,462
2	HRV at 70% efficiency [V1]	34,242 (117x10^6)	15% (81.5)	8.28 (12%)	95,704
3	RSI 3.5 (R20) basement wall insulation [BGW2]	33,597 (115x10^6)	17% (81.7)	8.16 (13%)	95,560
4	RSI 5.5 (R31) floor insulation [F1]	33,497 (114x10^6)	17% (81.8)	8.15 (13%)	95,743
5	RSI 5.1 (R29) insulation, placed in between the studs spaced at 600 mm (24 in.) on-centre [AGW7]	32,545 (111x10^6)	20% (82.2)	7.97 (15%)	96,651
6	**RSI 8.8 (R50) attic/ceiling insulation [C1]**	**31,972 (109x10^6)**	**21% (82.4)**	**7.87 (16%)**	**97,996**
7	**Air-conditioning unit at SEER 14 [AC1]**	**31,972 (109x10^6)**	**21% (82.4)**	**7.87 (16%)**	**101,180**
8	RSI 2.2 (R12) insulating board underneath the basement slab [BS1]	31,378 (107x10^6)	23% (82.7)	7.76 (17%)	104,796
-	**Difference from the base case to the final combination of upgrades**	**9142 (31X10^6)**	**23% (82.7)**	**1.64 (17%)**	**92**

As shown in Table 5-3, for the case in Thunder Bay, the estimated total household energy consumption and the GHG emissions of the baseline case decreased due to the outcome of the identified least cost upgrades, resulting in decrease in the total life cycle cost in NPV until the end of Round 3, although the EnerGuide Rating was not sensitive, and remained at EGR of 82 at the end of Round 8 with a difference in percent savings of 3%.

It is interesting to note that the estimated annual total household energy consumption for all three cities did not change after the installation of an AC unit at SEER 14 (from Round 6 to Round 7). This could imply that the effectiveness of the change in the efficiency of the unit (from SEER 13 to 14) was very minimal, while increased the total life cycle cost by 3%. This could be due to the increase in the installation cost associated with the replacement of the unit as a result of its life expectancy of 12 years. Therefore, it was concluded that this upgrade was eliminated from the identified least cost upgrades.

Figure 5-4 shows the total life cycle cost in NPV with respect to the increase in energy efficiency for the selected four cities (Toronto, Ottawa, Windsor, and Thunder Bay) in Ontario.

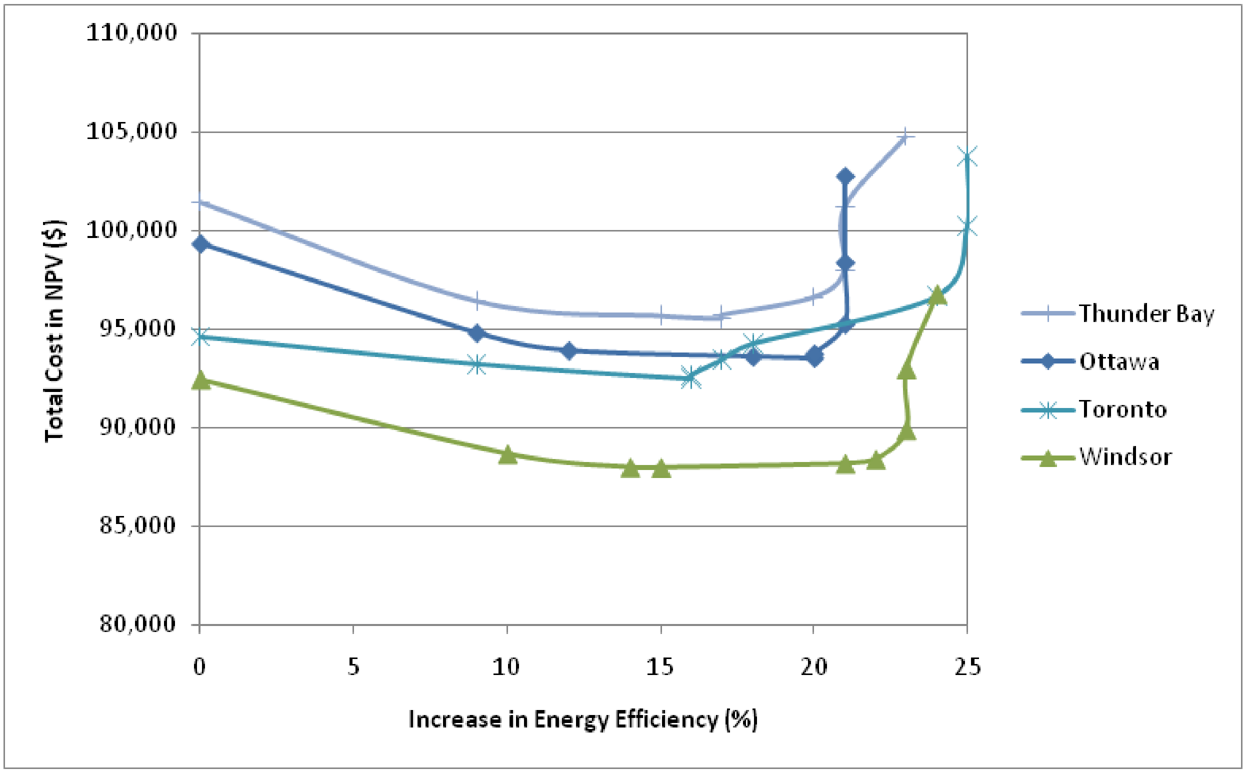


Figure 5-4: Total cost in NPV ($) vs. increase in energy efficiency (%) for the selected cities in Ontario (Case 1)

5.2.2 Case #2 - Extreme parameters with the change in natural gas prices

For this analysis, the identified parameters were changed as follows: 30-year mortgage (same as the previous case) at a 5.05% mortgage rate (minimum) with 3.10% discount rate (maximum). As for the fuel price escalation rates for electricity and natural gas, 3.50% (same as the previous case) and 5.50% (maximum) were chosen, respectively. Furthermore, different from the previous case was the change in the price of natural gas using the identified commodity prices in 2006 (Case 2a) and 2008 (Case 2b), respectively.

Based on the results using the BFSS method, the combination of eligible upgrades with the lowest total life cycle cost in NPV was almost identical for the cases in Ottawa and Thunder Bay, except for the case in Windsor, as shown in Figures 5-5 and 5-6, respectively.

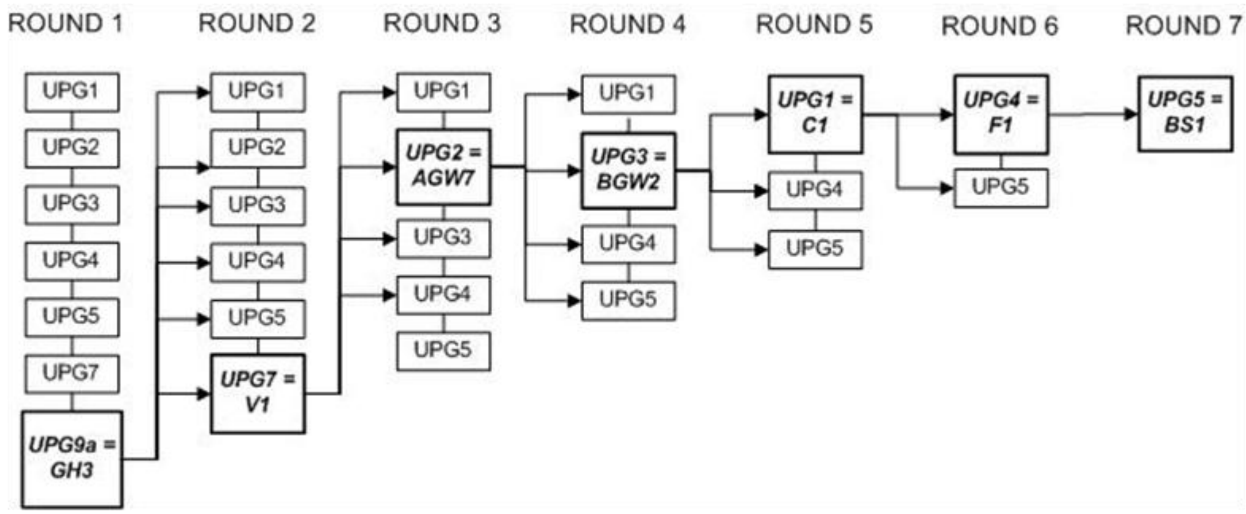


Figure 5-5: Least cost upgrade by round using the BFSS method for Ottawa and Thunder Bay (Case 2a)

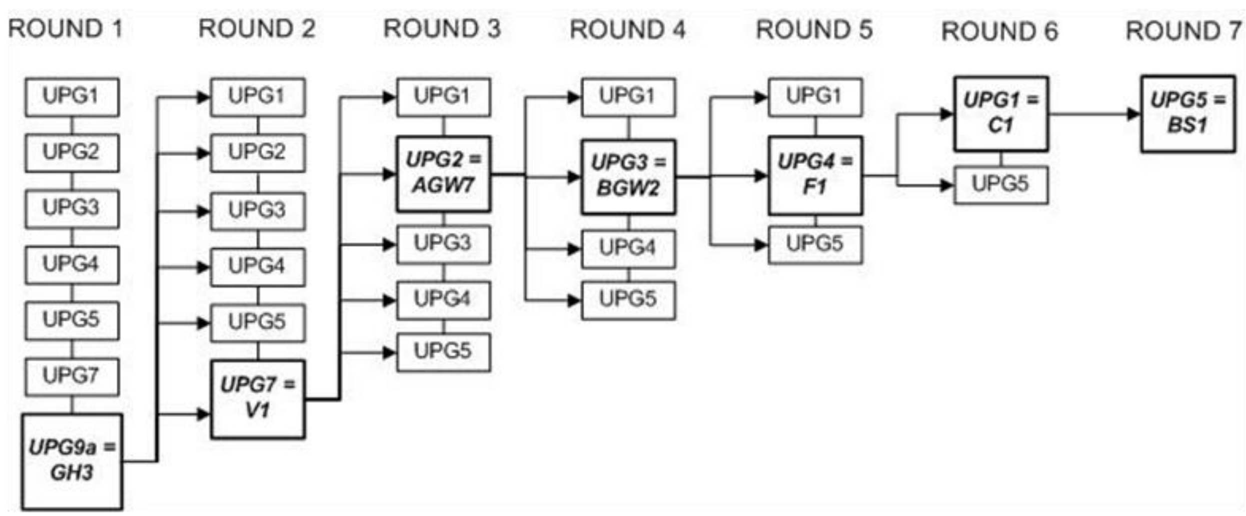


Figure 5-6: Least cost upgrade by round using the BFSS method for Windsor (Case 2a)

Tables 5-4 to 5-6 summarize the estimated total annual household energy consumption, percent savings per year, reductions of the GHG emissions, and the total life cycle cost in NPV by round for Ottawa, Windsor, and Thunder Bay, respectively, for Case 2a.

Table 5-4: Simulation results for Ottawa, using the extreme parameters (Case 2a)

Round	Description [Code]	Simulation Results: Energy Consumption (kWh/year; Btu/year)	Simulation Results: % Savings (EGR)	Simulation Results: GHG Emissions (Tons/CO_2) and % Savings	LCC[1] (NPV) ($)
-	**Base case**	**37,264 (127x10^6)**	**N/A (77.4)**	**8.88 (N/A)**	**173,144**
1	Combo boiler with 0.90 EF [GH3]	33,956 (116x10^6)	9% (79.0)	8.27 (7%)	162,568
2	HRV at 70% efficiency [V1]	31,689 (108x10^6)	15% (80.1)	7.89 (11%)	155,910
3	RSI 5.1 (R29) insulation, placed in between the studs spaced at 600 mm (24 in.) on-centre [AGW7]	27,784 (95x10^6)	25% (82.0)	7.18 (19%)	149,623
4	RSI 3.5 (R20) basement wall insulation [BGW2]	27,211 (93x10^6)	27% (82.2)	7.08 (20%)	148,110
5	RSI 8.8 (R50) attic/ceiling insulation [C1]	26,727 (91x10^6)	28% (82.5)	6.99 (21%)	147,822
6	RSI 5.5 (R31) floor insulation [F1]	26,644 (91x10^6)	28% (82.5)	6.98 (21%)	147,745
7	RSI 2.2 (R12) insulating board underneath the basement slab [BS1]	26,172 (89x10^6)	30% (82.7)	6.89 (22%)	149,056
-	**Difference from the base case to the final combination of upgrades**	**10,634 (36X10^6)**	**30% (82.7)**	**1.99 (22%)**	**20,381**

Note:

1. The LCC was determined based on the identified minimum mortgage rate of 5.05%, maximum discount rate of 3.10%, and the fuel escalation rates for electricity and natural gas of 3.50%, and 5.50% (maximum), respectively. Furthermore, the commodity price in 2008 was used for natural gas.

Table 5-5: Simulation results for Windsor, using the extreme parameters (Case 2a)

Round	Description [Code]	Simulation Results: Energy Consumption (kWh/year; Btu/year)	Simulation Results: % Savings (EGR)	Simulation Results: GHG Emissions (Tons/CO_2) and % Savings	LCC (NPV) ($)
-	**Base case**	**29,228 (100x10^6)**	**N/A (78.3)**	**7.51 (N/A)**	**148,555**
1	Combo boiler with 0.90 EF [GH3]	26,207 (89x10^6)	10% (80.0)	6.95 (7%)	138,997
2	HRV at 70% efficiency [V1]	24,415 (83x10^6)	16% (81.0)	6.67 (11%)	133,965
3	RSI 5.1 (R29) insulation, placed in between the studs spaced at 600 mm (24 in.) on-centre [AGW7]	21,368 (73x10^6)	27% (82.7)	6.11 (19%)	130,052
4	RSI 3.5 (R20) basement wall insulation [BGW2]	20,873 (71x10^6)	29% (82.9)	6.02 (20%)	128,773
5	RSI 5.5 (R31) floor insulation [F1]	20,808 (71x10^6)	29% (83.0)	6.01 (20%)	128,742
6	RSI 8.8 (R50) attic/ceiling insulation [C1]	20,431 (70x10^6)	30% (83.2)	5.94 (21%)	128,718
7	RSI 2.2 (R12) insulating board underneath the basement slab [BS1]	20,032 (68x10^6)	31% (83.4)	5.87 (22%)	128,905
-	**Difference from the base case to the final combination of upgrades**	**8810(30X10^6)**	**31% (83.4)**	**1.58 (22%)**	**16,227**

Table 5-6: Simulation results for Thunder Bay, using the extreme parameters (Case 2a)

Round	Description [Code]	Simulation Results			LCC (NPV) ($)
		Energy Consumption (kWh/year; Btu/year)	% Savings (EGR)	GHG Emissions (Tons/CO_2) and % Savings	
-	**Base case**	**40,521 (138x10^6)**	**N/A (78.8)**	**9.41 (N/A)**	**182,547**
1	Combo boiler with 0.90 EF [GH3]	36,910 (126x10^6)	9% (80.3)	8.73 (7%)	170,964
2	HRV at 70% efficiency [V1]	34,242 (117x10^6)	15% (81.5)	8.28 (12%)	162,918
3	RSI 5.1 (R29) insulation, placed in between the studs spaced at 600 mm (24 in.) on-centre [AGW7]	33,284 (114x10^6)	18% (81.9)	8.16 (13%)	161,015
4	RSI 3.5 (R20) basement wall insulation [BGW2]	32,645 (111x10^6)	19% (82.1)	7.99 (15%)	159,276
5	RSI 8.8 (R50) attic/ceiling insulation [C1]	32,072 (109x10^6)	21% (82.4)	7.89 (16%)	158,650
6	RSI 5.5 (R31) floor insulation [F1]	31,972 (109x10^6)	21% (82.4)	7.87 (16%)	158,509
7	RSI 2.2 (R12) insulating board underneath the basement slab [BS1]	31,378 (107x10^6)	23% (82.7)	7.76 (17%)	159,286
-	**Difference from the base case to the final combination of upgrades**	**8565 (29X10^6)**	**23% (82.7)**	**1.64 (17%)**	**19,127**

As Tables 5-4 to 5-6 indicate, similar to the results of the previous case was the estimated energy consumption and the GHG emissions of the baseline case in all three cities, which decreased due to the outcome of the identified least cost upgrades, resulting in decrease in the life cycle cost in NPV, even at the end of Round 8, which was not the case in the previous scenario (Case 1). As for the EnerGuide Rating, it was not sensitive, and remained at EGR of 82 at the end of Round 7 with a difference in percent savings of 5% in Ottawa, and 4% in Thunder Bay, respectively, while remained at EGR of 83 at the end of Round 7 with a difference in percent savings of 2% in Windsor. Figure 5-7 shows the life cycle cost in NPV with respect to the increase in energy efficiency for the selected four cities in Ontario.

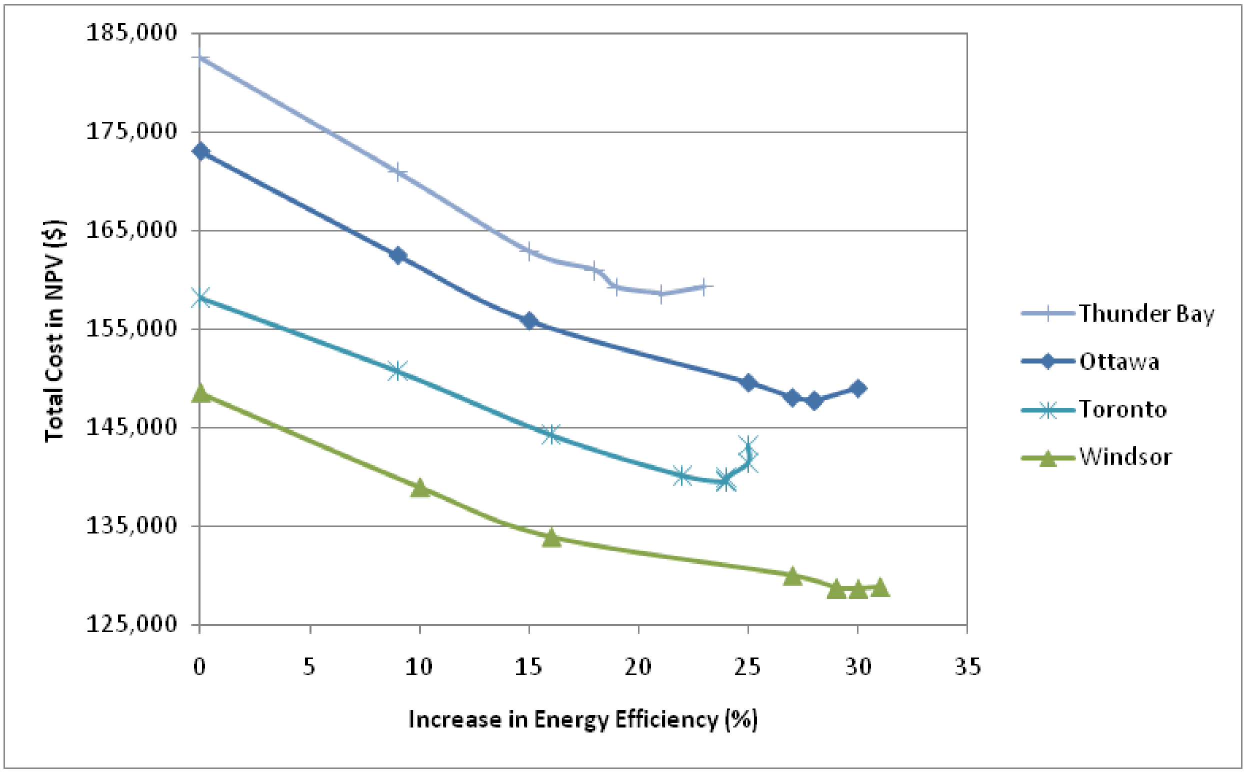


Figure 5-7: Total cost in NPV ($) vs. increase in energy efficiency (%) for the selected four cities in Ontario (Case 2a)

5.2.3 Using the 2008 price of natural gas (Case 2b)

Based on the results using the BFSS method, the combination of eligible upgrades with the lowest total life cycle cost was the same for the cases in Ottawa and Thunder Bay, except for the case in Windsor, as shown in Figures 5-8 and 5-9, respectively.

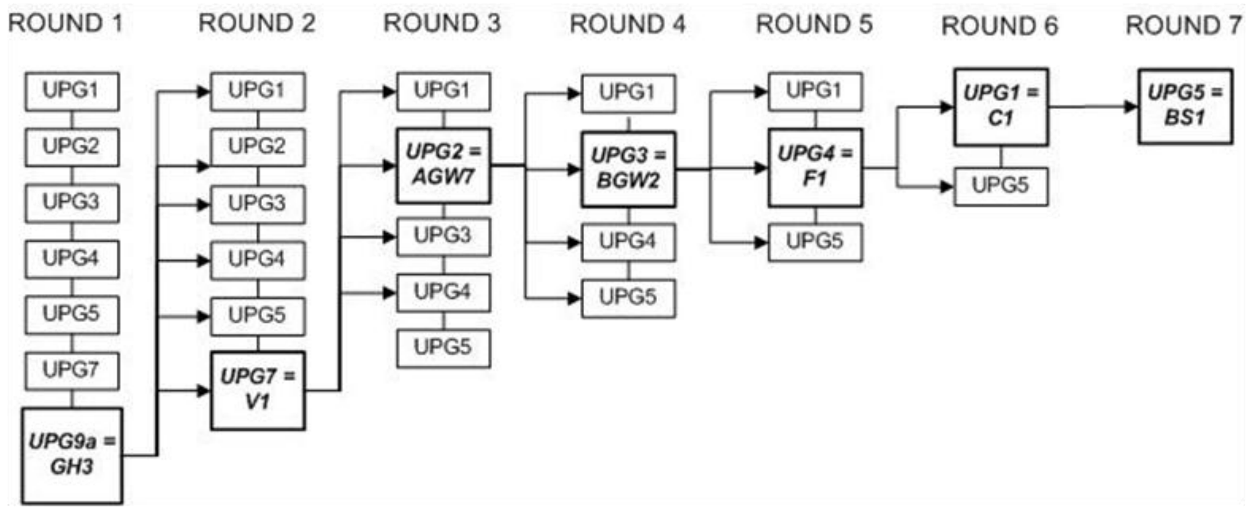


Figure 5-8: Least cost upgrade by round using the BFSS method for Ottawa and Windsor[13] (Case 2b)

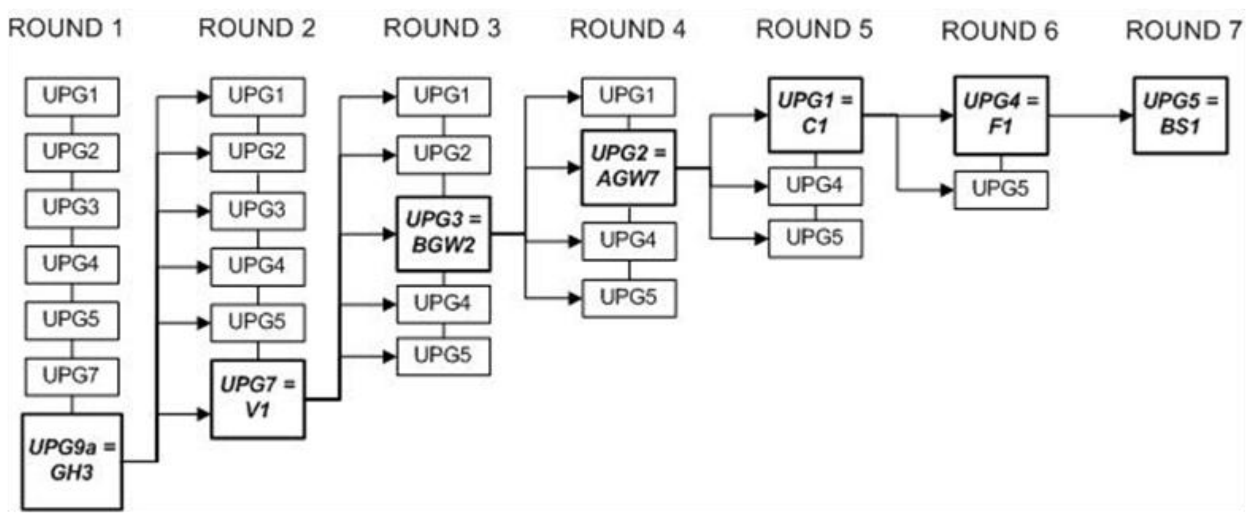


Figure 5-9: Least cost upgrade by round using the BFSS method for Thunder Bay (Case 2b)

[13] RSI 3.9 (R22) above-grade wall insulation [AGW1] was the most cost-effective solution for the case in Windsor.

Tables 5-7 to 5-9 summarize the estimated total annual household energy consumption, percent savings per year, reductions of the GHG emissions, and the total life cycle cost in NPV by round for Ottawa, Windsor, and Thunder Bay, respectively, for Case 2b.

Table 5-7: Simulation results using HOT2000 for Ottawa, using the extreme parameters (Case 2b)

Round	Description [Code]	Simulation Results			Total LCC[1] (NPV) ($)
		Energy Consumption (kWh/year; Btu/year)	% Savings (EGR)	GHG Emissions (Tons/CO_2) and % Savings	
-	**Base case**	**37,264 (127x10^6)**	**N/A (77.4)**	**8.88 (N/A)**	**144,067**
1	Combo boiler with 0.90 EF [GH3]	33,956 (116x10^6)	9% (79.0)	8.27 (7%)	135,716
2	HRV at 70% efficiency [V1]	31,689 (108x10^6)	15% (80.1)	7.89 (11%)	131,186
3	RSI 5.1 (R29) insulation, placed in between the studs spaced at 600 mm (24 in.) on-centre [AGW7]	27,784 (95x10^6)	25% (82.0)	7.18 (19%)	128,015
4	RSI 3.5 (R20) basement wall insulation [BGW2]	27,211 (93x10^6)	27% (82.2)	7.08 (20%)	126,959
5	RSI 5.5 (R31) floor insulation [F1]	27,128 (93x10^6)	27% (82.3)	6.99 (21%)	126,947
6	RSI 8.8 (R50) attic/ceiling insulation [C1]	26,664 (91x10^6)	28% (82.5)	6.98 (21%)	127,045
7	RSI 2.2 (R12) insulating board underneath the basement slab [BS1]	26,172 (89x10^6)	30% (82.7)	6.89 (22%)	128,733
-	**Difference from the base case to the final combination of upgrades**	**11,092 (38X10^6)**	**30% (82.7)**	**1.99 (22%)**	**15,334**

Note:

1. The total LCC was determined based on the identified minimum mortgage rate of 5.05%, maximum discount rate of 3.10%, and the fuel escalation rates for electricity and natural gas of 3.50%, and 5.50% (maximum), respectively. Furthermore, the commodity price in 2008 was used for natural gas.

Table 5-8: Simulation results using HOT2000 for Windsor, using the extreme parameters (Case 2b)

Round	Description [Code]	Simulation Results			Total LCC (NPV) ($)
		Energy Consumption (kWh/year; Btu/year)	% Savings (EGR)	GHG Emissions (Tons/CO_2) and % Savings	
-	**Base case**	**29,228 ($100x10^6$)**	**N/A (78.3)**	**7.51 (N/A)**	**125,766**
1	Combo boiler with 0.90 EF [GH3]	26,207 ($89x10^6$)	10% (80.0)	6.95 (7%)	118,316
2	HRV at 70% efficiency [V1]	24,415 ($83x10^6$)	16% (81.0)	6.67 (11%)	115,016
3	RSI 3.9 (R22) insulation [AGW1]	23,468 ($80x10^6$)	20% (81.5)	6.49 (14%)	112,891
4	RSI 3.5 (R20) basement wall insulation [BGW2]	22,957 ($78x10^6$)	21% (81.8)	6.40 (15%)	111,965
5	RSI 5.5 (R31) floor insulation [F1]	22,892 ($78x10^6$)	22% (81.8)	6.39 (15%)	111,985
6	RSI 8.8 (R50) attic/ceiling insulation [C1]	22,512 ($77x10^6$)	23% (82.0)	6.32 (16%)	112,256
7	RSI 2.2 (R12) insulating board underneath the basement slab [BS1]	22,097 ($75x10^6$)	24% (82.2)	6.25 (17%)	113,943
-	**Difference from the base case to the final combination of upgrades**	**6729 ($23X10^6$)**	**24% (82.2)**	**1.27 (17%)**	**8670**

Table 5-9: Simulation results using HOT2000 for Thunder Bay, using the extreme parameters (Case 2b)

Round	Description [Code]	Simulation Results			Total LCC (NPV) ($)
		Energy Consumption (kWh/year; Btu/year)	% Savings (EGR)	GHG Emissions (Tons/CO_2) and % Savings	
-	**Base case**	**40,521 (138x106)**	**N/A (78.8)**	**9.41 (N/A)**	**150,926**
1	Combo boiler with 0.90 EF [GH3]	36,910 ($126x10^6$)	9% (80.3)	8.73 (7%)	141,769
2	HRV at 70% efficiency [V1]	34,242 ($117x10^6$)	15% (81.5)	8.28 (12%)	136,188
3	RSI 3.5 (R20) basement wall insulation [BGW2]	33,597 ($115x10^6$)	17% (81.7)	8.16 (13%)	134,942
4	RSI 5.1 (R29) insulation, placed in between the studs spaced at 600 mm (24 in.) on-centre [AGW7]	32,645 ($111x10^6$)	19% (82.1)	7.99 (15%)	133,819
5	RSI 8.8 (R50) attic/ceiling insulation [C1]	32,072 ($109x10^6$)	21% (82.4)	7.89 (16%)	133,651
6	RSI 5.5 (R31) floor insulation [F1]	31,972 ($109x10^6$)	21% (82.4)	7.87 (16%)	133,589
7	RSI 2.2 (R12) insulating board underneath the basement slab [BS1]	31,378 ($107x10^6$)	23% (82.7)	7.76 (17%)	134,840
-	**Difference from the base case to the final combination of upgrades**	**8565 ($29X10^6$)**	**23% (82.7)**	**1.64 (17%)**	**12,413**

As Tables 5-7 to 5-9 indicate, similar to the results of the previous cases were the estimated energy consumption of the baseline case in all three cities, which decreased due to the outcome of the identified least cost upgrades, resulting in decrease in the total life cycle cost in NPV, even at the end of Round 8. As for the EnerGuide Rating, it was not sensitive, and remained at EGR of 82 at the end of Round 7 with a difference in percent savings of 5% in Ottawa, 1% in Windsor, and 4% in Thunder Bay, respectively.

It was interesting to note that RSI 5.11 (R29) exterior wall insulation was identified as the least cost upgrades not only in Thunder Bay, but also, Ottawa and Windsor, particularly in the case of using the extreme parameters (i.e., maximum discount rate, and natural gas price escalation rate). However, this particular upgrade was not considered for implementation by the local homebuilders in Ontario based on the results of the survey. In fact, none of the participant builders considered the implementation of any insulation material with nominal RSI of 4.75 (R27) or higher into their current building practices, unless otherwise required by the building code and/or the existing energy efficiency labelling programs such as the ESNH and/or LEED.

Figure 5-10 shows the total life cycle cost in NPV with respect to the increase in energy efficiency for the selected four cities in Ontario.

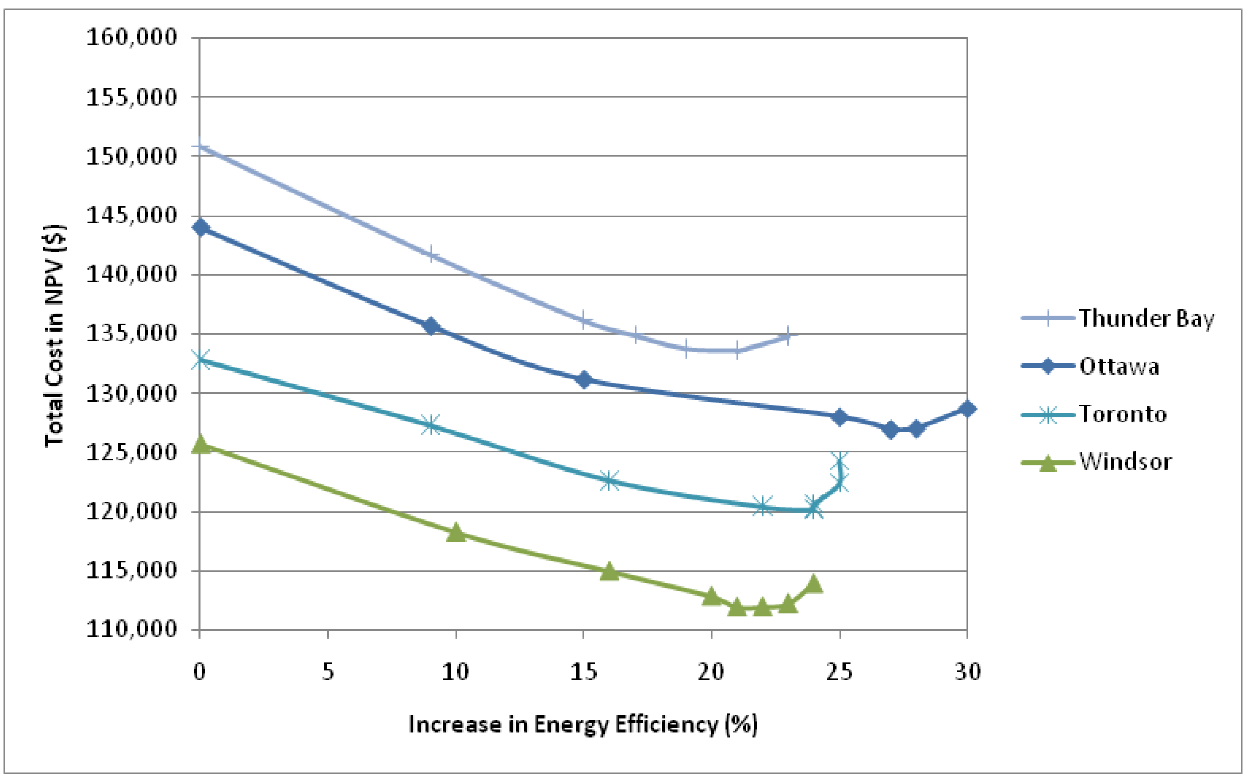


Figure 5-10: Total cost in NPV ($) vs. increase in energy efficiency (%) for the selected four cities in Ontario (Case 2b)

Additional cases with the reduction in the appliance, lighting and hot water consumptions were conducted and their results are summarized in Appendix C.

5.3 Eligible Upgrades with the Installation of a PV System

Additional analysis was conducted to determine the overall energy performance of the Reference House, after the installation of the identified combination of least cost upgrades with a photovoltaic (PV) system in Ottawa, Windsor, and Thunder Bay, respectively. For this analysis, NRCan's RETScreen® version 4 was used, because the PV system was not able to simulate using HOT2000.

Based on the results, the estimated electricity exported to grid for the cases in Ottawa, Windsor, and Thunder Bay was 7667 kWh, 8317 kWh, and 8901 kWh per year, respectively.

With the introduction of Ontario's microFIT program, the price of $0.802 was applied for every kilowatt-hour of electricity generated by the PV.

After subtracting the cost of installing a PV system (assumed $7/W for a total of $42,560) from the income, the net present value of the total income for 20 years was estimated to be $58,081 for Ottawa, $66,613 for Windsor, and $74,279 for Thunder Bay.

Accounting for the electricity production from the PV system from 21 to 30 years, the difference in the net present value of the total electricity cost of what a homeowner would pay if the PV system were not installed (hence the savings) was estimated to be $12,760 for Ottawa, $13,883 for Windsor, and $14,756 for Thunder Bay.

Therefore, with the installation of the PV system, the total profits, over the 30-year mortgage period, were estimated to be $70,841 for Ottawa, $80,496 for Windsor, and $89,035 for Thunder Bay, which would allow a homeowner to pay for the implementation of additional upgrade(s).

Table 5-10 summarizes the estimated total profit as a result of installing a PV system in each of the selected cities (Ottawa, Windsor, and Thunder Bay) using Ontario’s microFIT program, assuming such a program will continue onward.

Table 5-10: Summary of estimated total PV profit (NPV) over 30 years for Ottawa, Windsor, and Thunder Bay

Results	Unit	Location		
		Ottawa	Windsor	Thunder Bay
Estimated electricity exported to grid	kWh/yr	7667	8317	8901
Case 1: Using the average parameters				
Total income for 20 years	$	58,081	66,613	74,279
Total savings from 21 to 30 years	$	12,760	13,883	14,756
Total PV profit after 30 years (mortgage period)	**$**	**70,841**	**80,496**	**89,035**
Case 2: Using the extreme parameters				
Total income for 20 years	$	48,081	55,765	62,669
Total savings from 21 to 30 years	$	9,672	10,525	11,187
Total PV profit after 30 years (mortgage period)	**$**	**57,753**	**66,290**	**73,856**

Chapter 6

6 Conclusion and Recommendations

6.1 Conclusion

With an escalated awareness for limited energy resources, the urgent need to reduce energy consumption in the residential sector in Canada has been brought to the forefront. One of the immediate solutions is to develop potential energy efficiency upgrades that can be implemented into the currently practiced new housing constructions to achieve significant energy savings.

It can be concluded based on numerous studies that most currently practiced new housing constructions in Canada are not as close to the optimal levels in terms of energy performance for the same overall cost to the homeowners over the lifetime of the ownership or mortgage period. For the construction of a new home, some of the commonly practiced retrofit solutions considered for the existing residential buildings may not apply and, therefore, there is a need to develop energy efficiency solutions specifically for the new housing constructions that combine both innovative designs and the use of renewable energy systems to not only cost-effectively increase overall product value and quality of a home, but also, significantly reduce energy consumption and use of raw materials, especially when new homes are built on a mass-production basis.

The objective of this thesis was to present the methodology developed to identify the most cost-effective (or least cost) energy efficiency upgrade solutions that could meet various levels of thermal performance while considering the use of local materials and resources, ease of construction, and most importantly, adoption by the Canadian housing industry through the optimization in energy related costs using a brute force sequential search (BFSS) method.

Potential energy efficiency upgrade solutions considered in this thesis were identified as either implemented or considered for implementation by the local homebuilders in Ontario into their current practices of building new homes, as it was evidenced by the results of the survey. A total of 28 upgrade solutions comprised of improved thermal resistance in the building envelope components, and installation of the most efficient HVAC systems were identified as the least cost upgrades based on the determination of the additional/incremental cost to implement each upgrade using the RSMeans cost data publications, and obtaining the average construction costs from the local homebuilders in Ontario by conducting a survey. The majority of the upgrade costs determined based on the comparison of the two sources were within a difference of 10%; however, for some of the upgrades (e.g., windows, and air-tightness level), the agreement could not be reached due to the fact that the installation cost of those upgrades was not readily available at the time of the survey and, therefore, they were eliminated from the potential least cost upgrades considered in this thesis. Furthermore, an upgrade with the large incremental cost was eliminated by the BFSS method, despite the fact that such an upgrade had the most reduction potentials in the overall energy consumption and/or the GHG emissions. Such an upgrade was the improvement in the exterior wall insulation by using the structural insulated panels (SIPs), the insulated concrete forms for the basement wall, high-efficiency boiler and solar-assisted domestic hot water (DHW) heater for both the space and DHW heating. This raises a need for the government to support their local homebuilders and manufacturers in a form of financial incentives and rebates to offset the high initial (material and installation) costs associated with the implementation of new or unconventionally used technologies. With the support of the financial incentives and rebates, this will not only allow the homebuilders and manufacturers adapt to the implementation of these technologies into their current practices without the burden to pay for the additional expenses, but also, potentially reduce the overall costs down as the adaption by the local homebuilders and manufacturers becomes the norm in constructing new houses that are far more energy efficient than the recently built houses, leading to the successful reduction in the overall energy consumption and the GHG emissions from the residential sector in Canada.

With approximately 7,500 possible combinations of upgrades, HOT2000 was chosen over TRNSYS as the appropriate tool for conducting building energy simulation analyses for this thesis, because of its capability to conduct such analyses in a most time-efficient manner, although numerous studies have reported the program's limitations as a simulation tool.

The results showed that, based on the life cycle cost analysis of 30 years, all of the identified combinations of least cost upgrades for the selected four cities in Ontario resulted in up to 31% reduction in both the estimated annual energy consumption and the GHG emissions against the baseline case, while achieving the EnerGuide Rating of 82, thereby meeting the requirements of the 2012 OBC. Some of the results to highlight are as follows:

- Annual space and DHW energy consumption of ranging from 21,409 kWh ($107x10^6$ Btu) to 31,378 kWh ($73x10^6$ Btu) was determined for Windsor, Toronto, Ottawa, and Thunder Bay, resulting in up to 31% reduction against the baseline case.
- Annual GHG emissions of ranging from 5.92 tons/CO_2 to 7.76 tons/CO_2 were determined for Toronto, Windsor, Ottawa, and Thunder Bay, resulting in up to 31% reduction against the baseline case.
- The estimated savings in the total life cycle cost (LCC) of up to $20,381 could be achieved with the implementation of the identified combinations of the upgrades.
- With the installation of a residential PV system, the estimated total profit of up to $89,035 could be achieved through Ontario's microFIT program, allowing a homeowner to pay for the implementation of additional upgrade(s) to further improve the energy efficiency of a home.

This thesis used the proposed prescriptive-based specifications of the 2012 OBC as the energy performance target against the existing 2006 OBC as the baseline case for comparison purposes. Despite the fact that the official release of the 2012 OBC was not available at the start of this thesis as it was released in the beginning of year 2010 (MMAH, 2010), the identified combination of optimal (or least cost) upgrades have met or, in some cases, exceeded the minimum efficiency level as prescribed by the building code. Table 6-1 summarizes the efficiency level with respect to the thermal resistance (RSI) of the building envelope components, and of the HVAC systems of the identified least cost upgrades against the minimum efficiency level as prescribed by the 2012 OBC.

Table 6-1: Comparison of the proposed least cost upgrades against the 2012 OBC

Component	Zone 1 (*Less than 5000 Degree-Days*[1])				Zone 2 (*5000 or More Degree-Days*[2])	
	2012 OBC[3]		Current Study		2012 OBC[4]	Current Study
	Compliance Package (A)	Compliance Package (I)	Upgrade Package (1)	Upgrade Package (2)	Compliance Package (A)	Upgrade Package (1)
Ceiling Attic Space Minimum RSI (R)-Value	8.81 (R50)	8.81 (R50)	8.81 (R50)	8.81 (R50)	8.81 (R50)	8.81 (R50)
Exposed Floor Minimum RSI (R)-Value	5.46 (R31)	5.46 (R31)	5.46 (R31)	5.46 (R31)	5.46 (R31)	5.46 (R31)
Walls Above Grade Minimum RSI (R)-Value	4.23 (R24)	3.87 (R22)	4.23 (R24)	3.87 (R22)	5.11 (R29)	5.11 (R29)
Basement Walls Minimum RSI (R)-Value	3.52 (R20)	**3.87 (R22)**	3.52 (R20)	**3.52 (R20)**	3.52 (R20)	3.52 (R20)
Below Grade Slab Entire surface > 600 mm below grade Minimum RSI (R)-Value	**0.88 (R5)**	**-**	**2.11 (R12)**	**2.11 (R12)**	**0.88 (R5)**	**2.11 (R12)**
Edge of Below Grade Slab ≤ 600 mm below grade Minimum RSI (R)-Value	-	1.76 (R10)	-	-	-	-
Windows and Sliding Glass Doors Maximum U-Value	1.6	**1.8**	1.6	**1.6**	1.6	1.6
Space-Heating Equipment Minimum AFUE	90%	**92%**	90%	**90%**	90%	90%
HRV Minimum Efficiency	**-**	**55%**	**70%**	**70%**	**-**	**70%**
DHW Heater Minimum EF	**0.57**	**0.62**	**0.85**	**0.90**	**0.57**	**0.90**

Notes:
1. Weather condition for Toronto, ON, was used.
2. Weather condition for Thunder Bay, ON, was used.
3. Refer to the Table 2.1.1.2.A (MMAH, 2010)
4. Refer to the Table 2.1.1.3.A (MMAH, 2010)

It was concluded in Section 3.2.2 of the thesis that the energy performance level of the CCHT Reference House, built in accordance with the existing 2006 OBC was equivalent to the EnerGuide Rating of 78 using the HOT2000 simulation program. In order to meet the proposed requirements of the 2012 OBC (the EnerGuide 80), the implementation of additional energy efficiency measures was mandatory for the same house to achieve, at minimum, two additional points on the EnerGuide scale, or 12% reduction in the total annual energy consumption. As it was the intent of the thesis to determine the most cost-effective solutions that could be adapted by the large-volume builders in Canada, the outcome of the thesis was the indication that the energy efficiency level of the proposed 2012 OBC could well be achieved by using the existing conventional new housing construction practices, and thereby expecting a savings in return with the implementation of the additional upgrades over the lifetime of the ownership of the home or the mortgage period.

Based on the analysis, how to meet the net zero energy target with 100% increase in energy efficiency in the most cost-effective manner, while using the existing conventional new housing constructions in Canada would require further investigation. Anderson et al. (2006) have done a similar study in the U.S., where they have investigated, out of numerous possible energy efficiency measures available in the U.S., which one would be the most cost-effective for a new home to achieve the net zero energy level over the life cycle of 30 years. The distinct differences between their study from this thesis were the economic parameters (mortgage interest rate, inflation rate, discount rate, and fuel price escalation rate) used, and also, in their study, the optimization in cost using the brute force sequential search method was done automatically using the software called the BEopt; whereas, in this thesis, the process was done manually using the HOT2000 simulation program. The results of the study by Anderson et al. (2006) have shown that the studied house has achieved between 27% and 39% energy savings with the corresponding investment in net present value of $1337 to $3899, where the variances in the energy savings, as well as the estimated total investment were due to the differences in the climatic conditions and the economic parameters of the five cities in the U.S. that were selected for the analysis. Furthermore, the energy performance target used in the study by Anderson et al. (2006) was the net zero energy with 100% energy savings. The results have shown that with a residential PV system, all of the selected five cities in the U.S. have achieved the net zero energy ; however, the estimated additional cost needed to reach such a level was in the range of $42,808 to $71,874 in Chicago with cold weather conditions (Anderson et al., 2006).

If the energy performance target for this thesis were to change from the EnerGuide 80, the proposed requirements of the 2012 OBC to the net zero energy, it is expected that, based on the outcome of the thesis, a typical, single-family dwelling built using the existing conventional new housing practices could achieve the net zero energy level with 100% energy savings, as shown in

Figure 6-1, provided that some sort of renewable energy systems such as photovoltaic panels be installed onsite.

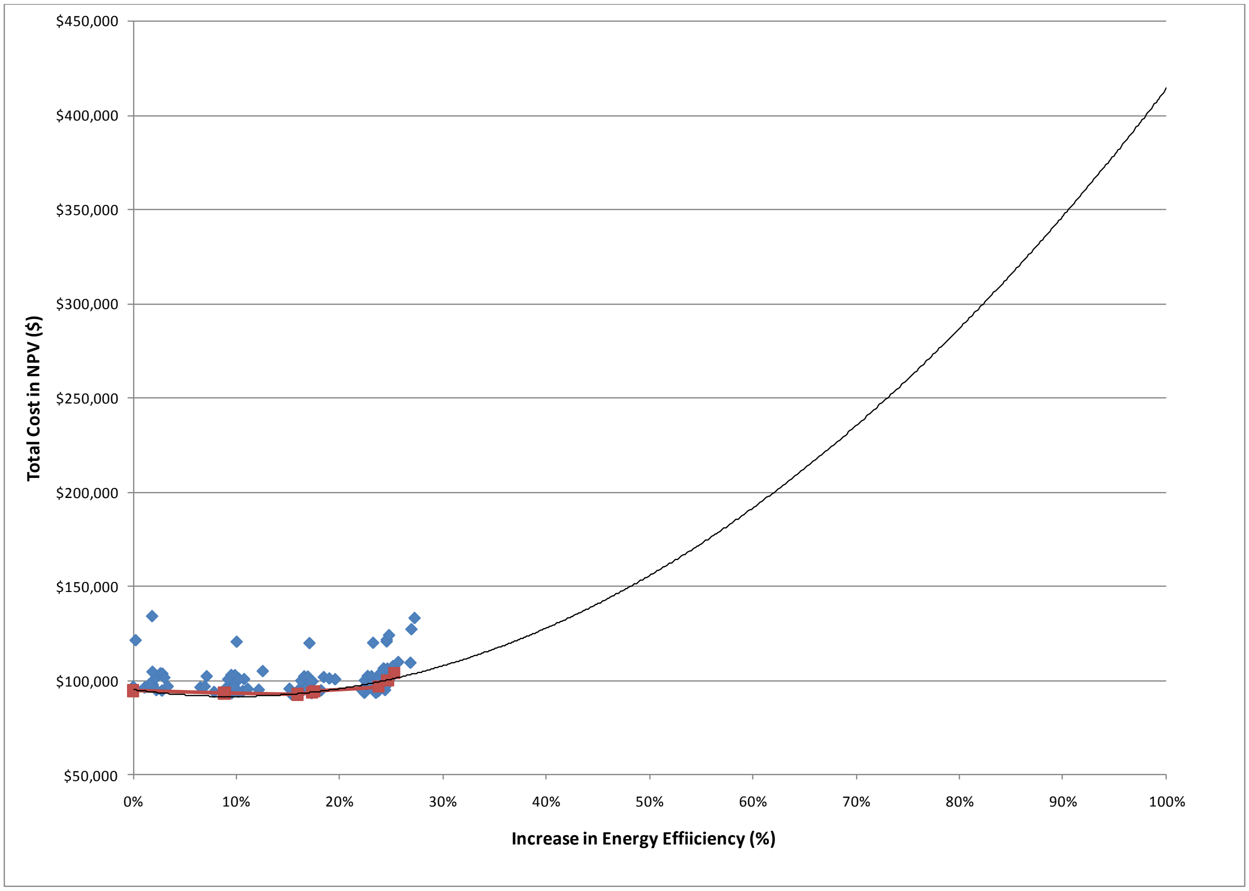


Figure 6-1: Total cost in NPV ($) vs. increase in energy efficiency (%) reaching the net zero energy (Case in Toronto)

With the benefit of Ontario's microFIT program, it was concluded that the estimated total profit of up to $89,035 (for the case in Toronto, it was estimated to be around $70,038) could be achieved with the installation of a residential PV system. Based on the results of the study by Anderson et al. (2006), if the additional cost to reach the net zero energy level were to be around $71,000, the estimated total profit generated from the installation of the PV system would allow a homeowner not only to pay for the implementation of additional upgrade(s) to further improve the energy efficiency of a home, but also to achieve the net zero energy level cost-effectively.

6.2 Recommendations and Future Work

This thesis was limited to the investigation of potential upgrades that could be implemented by the local homebuilders into their currently practiced new housing constructions as the most cost-effective (least cost) solutions to achieve improved energy efficiency standards. The survey was conducted as part of the thesis to determine the suitability and economic feasibility of these upgrades based on the responses received by the participant builders in Ontario.

Furthermore, this thesis used the proposed requirements of the 2012 OBC as the energy performance target against the existing building code for comparison purposes. However, as the requirements of both the national and provincial building codes continue to change, some of the identified least cost upgrades considered in this thesis may have very minimal effect on the overall reductions in the energy consumption and/or the GHG emissions; for instance, RSI 5.11 (R29) exterior wall insulation was identified as the least cost upgrade in Thunder Bay, Ottawa and Windsor, but not in Toronto, although based on the results of the survey, none of the participant builders considered the implementation of any insulation material with nominal RSI of 4.75 (R27) or higher into their current building practices, unless otherwise required by the building code and/or the existing energy efficiency labelling programs in near future.

With over 7,500 possible combinations of the identified least cost upgrades, the HOT2000 building energy simulation program was employed as an assessment tool for conducting the energy performance analyses of these upgrades, because of its capability to conduct such analyses in a most time-efficient manner, although numerous studies have reported the program's limitations as a simulation tool. Therefore, in order to properly assess the economic feasibility and suitability of the some of the advanced renewable energy systems, another simulation program like TRNSYS or EnergyPlus would be the recommended tool to use because of its capability to simulate the performance of such building integrated renewable energy systems on an hourly basis, rather than a monthly or annual basis.

It is recommended for future work, that further investigations/analyses would be needed in order to properly assess the implications of the changes in the building code and/or the third-party energy efficiency standards on the currently practiced new housing constructions in Canada. Some of the recommended studies include:

- Multi-unit, both low- and high-rise, residential buildings for the understanding and improvement of the technical, economic, and environmental aspects of housing as a whole provided that the required data were available.
- Assessment of new building construction techniques/materials/equipment and/or renewable energy resources based systems (solar, wind, and geothermal) for buildings with highly dynamic thermal and electrical demand conditions, especially if those buildings were designed to reach net zero energy, which would require much higher thermal resistance level in the building envelope in order to reduce the energy demand for heating and cooling.
- Using an advanced building energy simulation program such as TRNSYS with an ability to write a program to perform batch processing or simulations would be recommended in order to speed up the overall process. This would be particularly important if a future work/analysis were being conducted for more than one province in Canada.

As the recommended future studies above indicate, it was the objective of this thesis to develop a methodology that would be flexible enough to be applied for not only the future impact analysis on new and emerging energy systems, but also, on the integrated building upgrade potentials in other jurisdictions in Canada for policy making and optimal deployment decisions on such energy sources. The outcome of this thesis, while being original in nature, provided an immediate solution to the current state of rapid renewable energy development in the integrated building upgrade potentials in the residential sector in Canada, while laying out the groundwork for future work in meeting the nation's commitment to the Kyoto Protocol.

Appendix A

A. Architectural Drawings of the CCHT Reference House

A-1 Basement Floor Plan

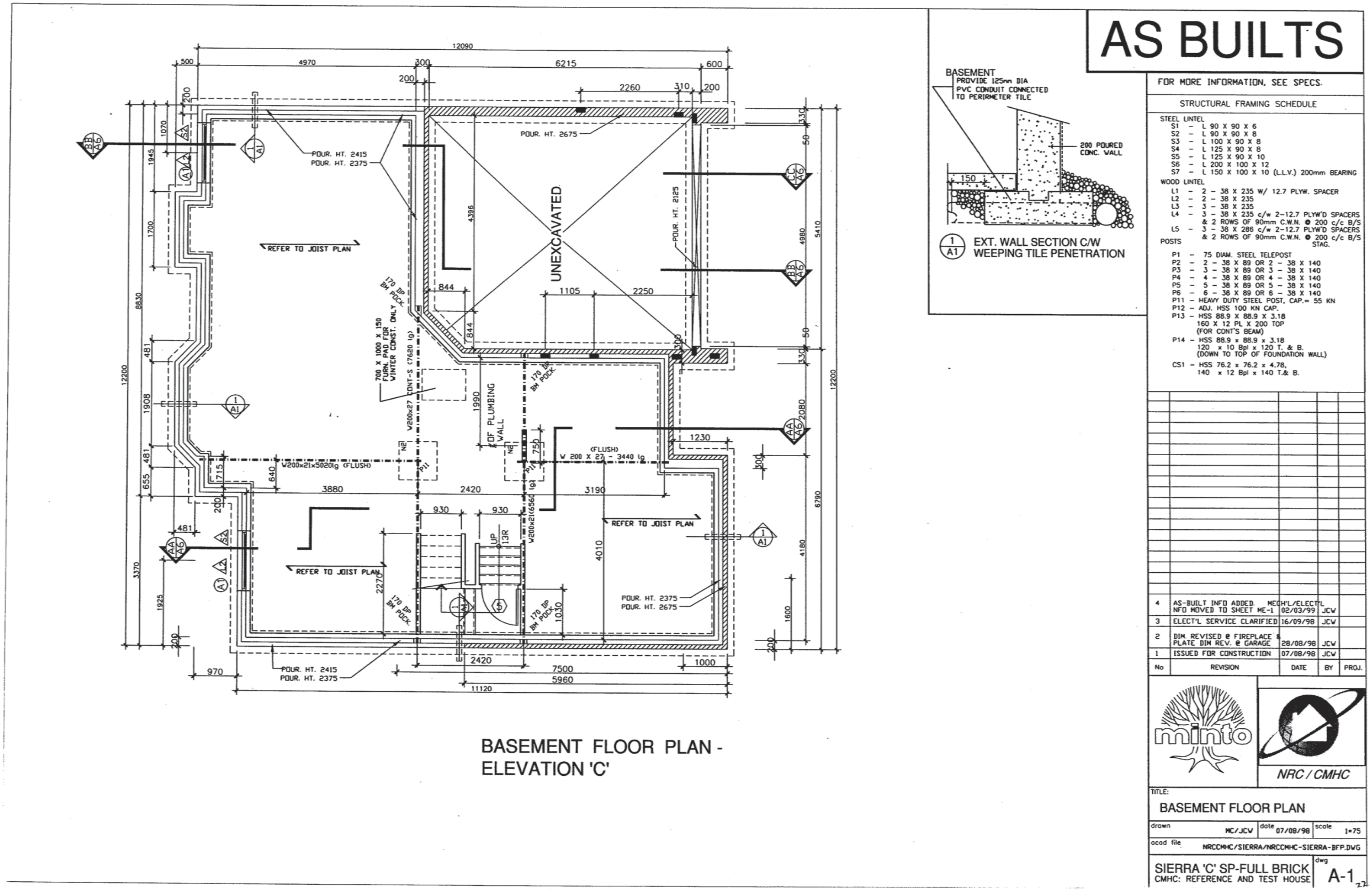
A-2 Ground Floor Plan

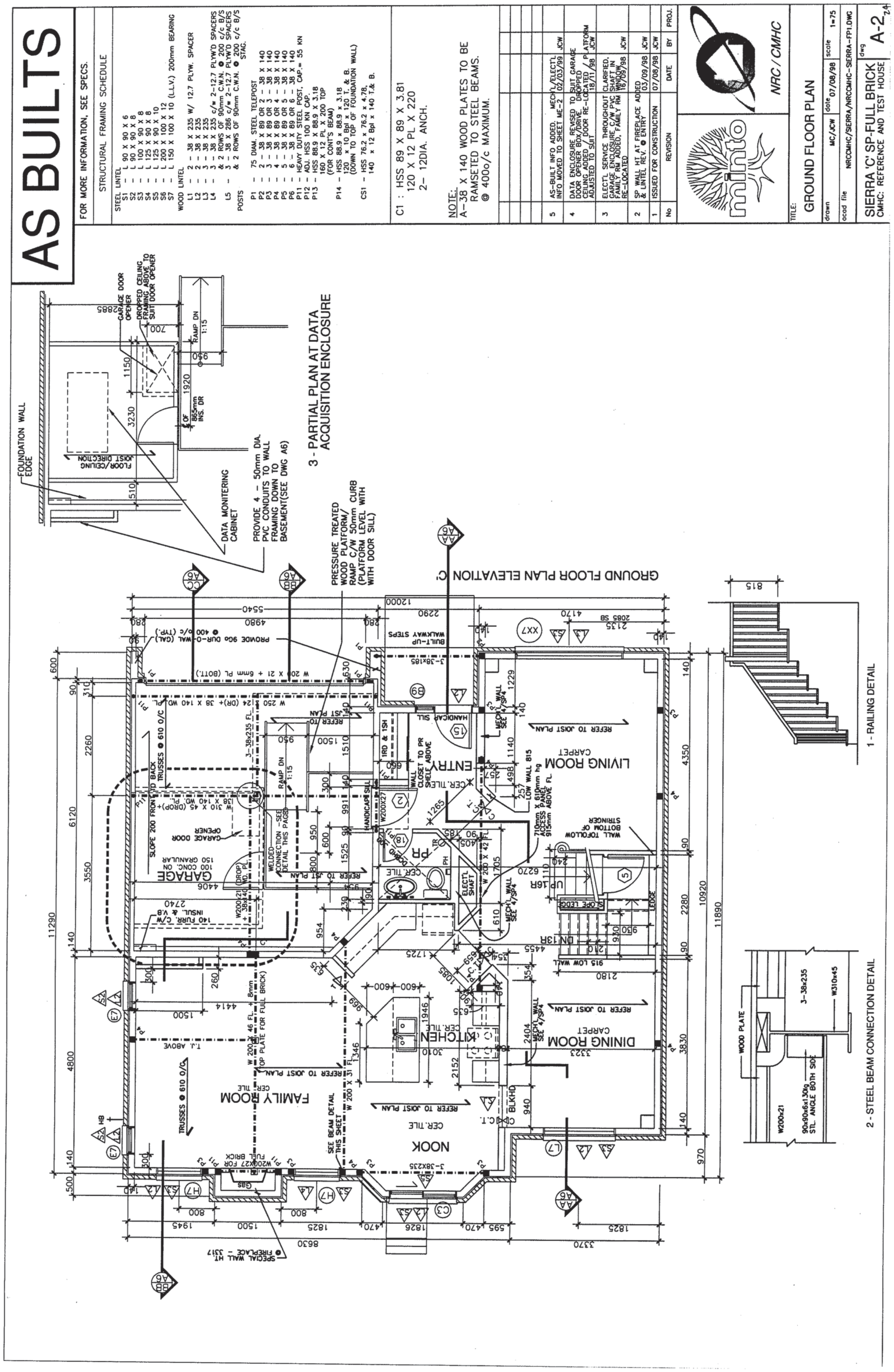
A-3 Second Floor Plan

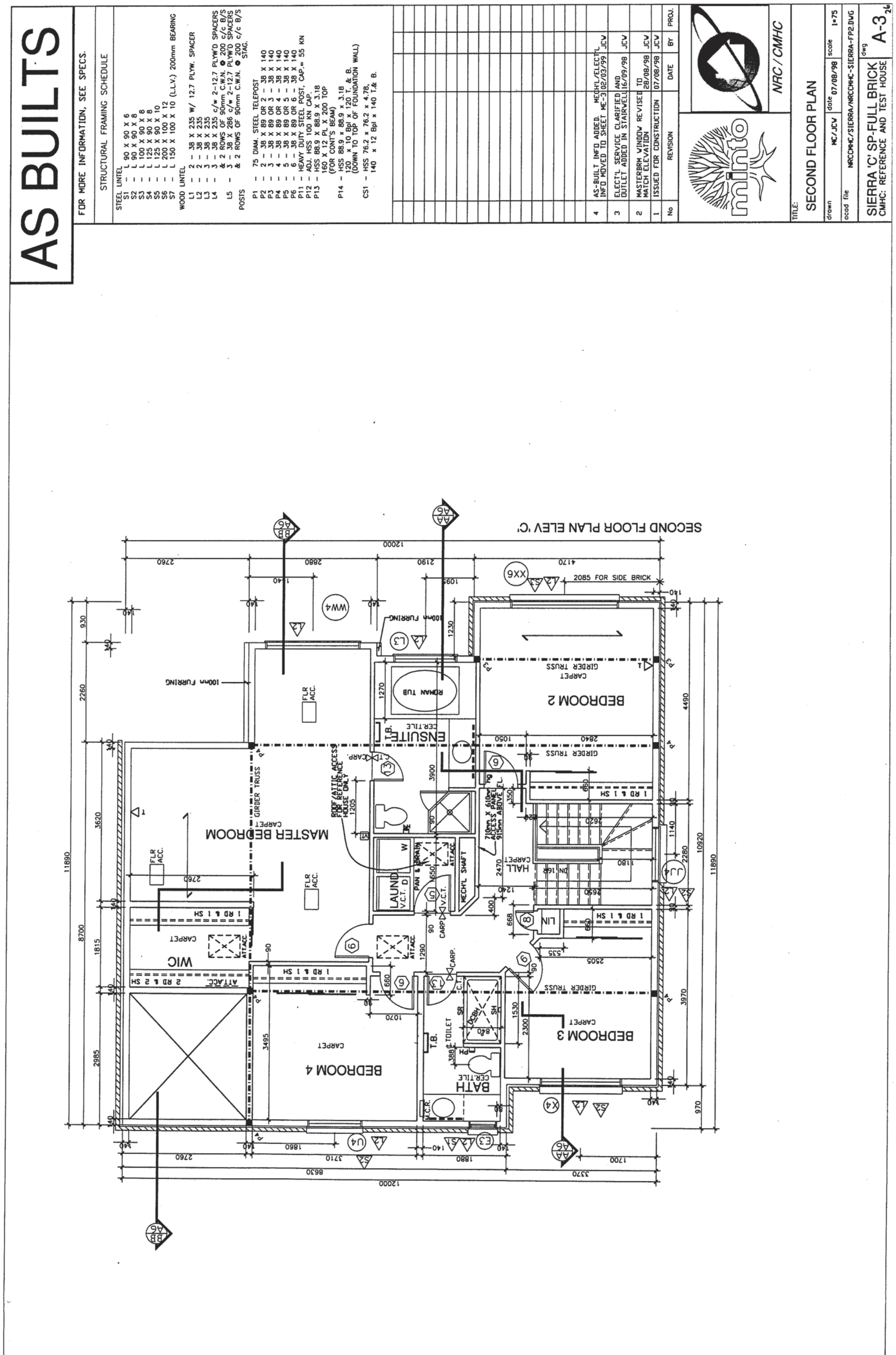
A-4 Front and Right Side Elevations

A-5 Rear and Left Side Elevations

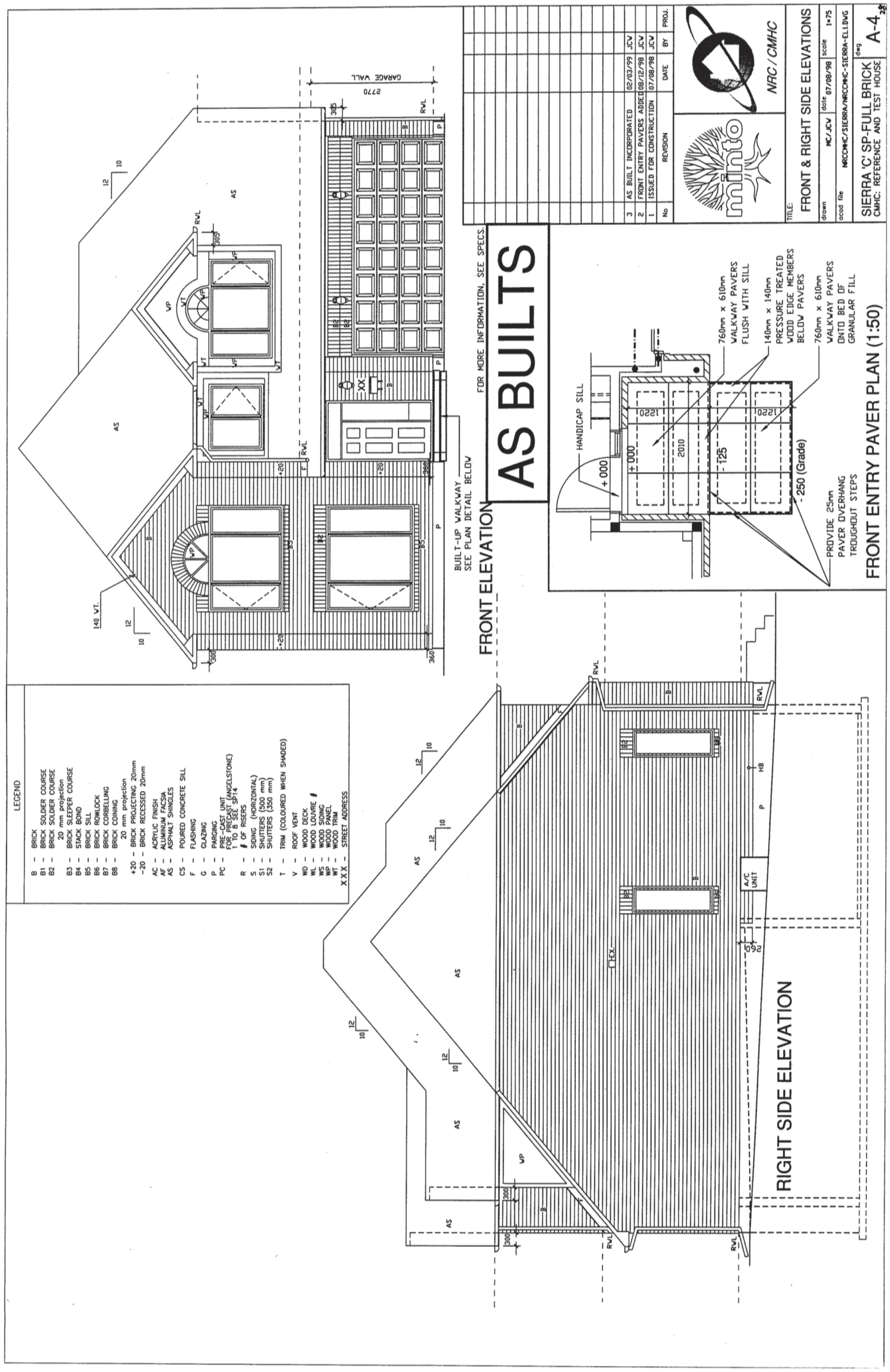
A-6 Building Cross Section


AS BUILTS
FOR MORE INFORMATION, SEE SPECS.
STRUCTURAL FRAMING SCHEDULE
STEEL LINTEL
S1 - L 90 X 90 X 6
S2 - L 90 X 90 X 8
S3 - L 100 X 90 X 8
S4 - L 125 X 90 X 8
S5 - L 125 X 90 X 10
S6 - L 200 X 100 X 12
S7 - L 150 X 100 X 10 (L.L.V.) 200mm BEARING
WOOD LINTEL
L1 - 2 - 38 X 235 W/ 12.7 PLYW. SPACER
L2 - 2 - 38 X 235
L3 - 3 - 38 X 235
L4 - 3 - 38 X 235 c/w 2-12.7 PLYW'D SPACERS & 2 ROWS OF 90mm C.W.N. @ 200 c/c B/S
L5 - 3 - 38 X 286 c/w 2-12.7 PLYW'D SPACERS & 2 ROWS OF 90mm C.W.N. @ 200 c/c B/S STAG.
POSTS
P1 - 75 DIAM. STEEL TELEPOST
P2 - 2 - 38 X 89 OR 2 - 38 X 140
P3 - 3 - 38 X 89 OR 3 - 38 X 140
P4 - 4 - 38 X 89 OR 4 - 38 X 140
P5 - 5 - 38 X 89 OR 5 - 38 X 140
P6 - 6 - 38 X 89 OR 6 - 38 X 140
P11 - HEAVY DUTY STEEL POST, CAP.= 55 KN
P12 - ADJ. HSS 100 KN CAP.
P13 - HSS 88.9 X 88.9 X 3.18 160 X 12 PL X 200 TOP (FOR CONT'S BEAM)
P14 - HSS 88.9 x 88.9 x 3.18 120 x 10 Bpl x 120 T. & B. (DOWN TO TOP OF FOUNDATION WALL)
CS1 - HSS 76.2 x 76.2 x 4.78, 140 x 12 Bpl x 140 T.& B.
BASEMENT
PROVIDE 125mm DIA PVC CONDUIT CONNECTED TO PERIMETER TILE
200 POURED CONC. WALL
EXT. WALL SECTION C/W WEEPING TILE PENETRATION
4 AS-BUILT INFO ADDED. MECH'L/ELECT'L INFO MOVED TO SHEET ME-1 02/03/99 JCV
3 ELECT'L SERVICE CLARIFIED 16/09/98 JCV
2 DIM. REVISED @ FIREPLACE & PLATE DIM REV. @ GARAGE 28/08/98 JCV
1 ISSUED FOR CONSTRUCTION 07/08/98 JCV
No REVISION DATE BY PROJ.
minto
NRC / CMHC
TITLE:
BASEMENT FLOOR PLAN
drawn MC/JCV date 07/08/98 scale 1:75
acad file NRCCMHC/SIERRA/NRCCMHC-SIERRA-BFP.DWG
SIERRA 'C' SP-FULL BRICK
CMHC: REFERENCE AND TEST HOUSE
dwg A-1
UNEXCAVATED
REFER TO JOIST PLAN
POUR. HT. 2415
POUR. HT. 2375
POUR. HT. 2675
POUR. HT. 2125
700 X 1000 X 150 FURN. PAD FOR WINTER CONST. ONLY
170 BP BM POCK.
W200x27 CONT-S (7620 lg)
W200x21x5020lg (FLUSH)
V 200 X 27 - 3440 lg (FLUSH)
W200x21(6560 lg)
℄ OF PLUMBING WALL
UP 13R
BASEMENT FLOOR PLAN - ELEVATION 'C'

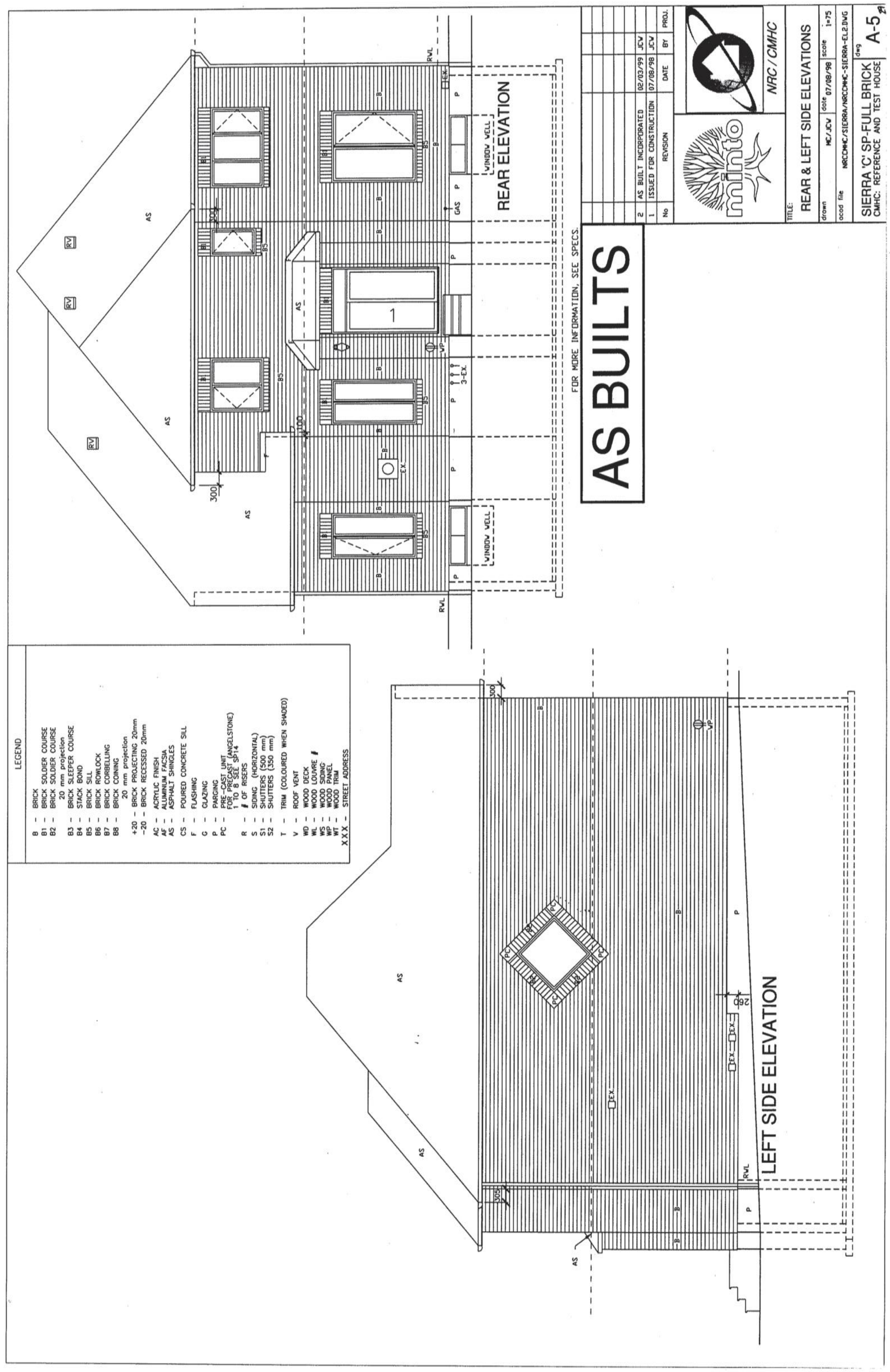

AS BUILTS
GROUND FLOOR PLAN
SIERRA 'C' SP-FULL BRICK
CMHC: REFERENCE AND TEST HOUSE
A-2
NRC / CMHC
3 - PARTIAL PLAN AT DATA ACQUISITION ENCLOSURE
1 - RAILING DETAIL
2 - STEEL BEAM CONNECTION DETAIL
GARAGE
FAMILY ROOM
NOOK
KITCHEN
DINING ROOM
LIVING ROOM
ENTRY
PR



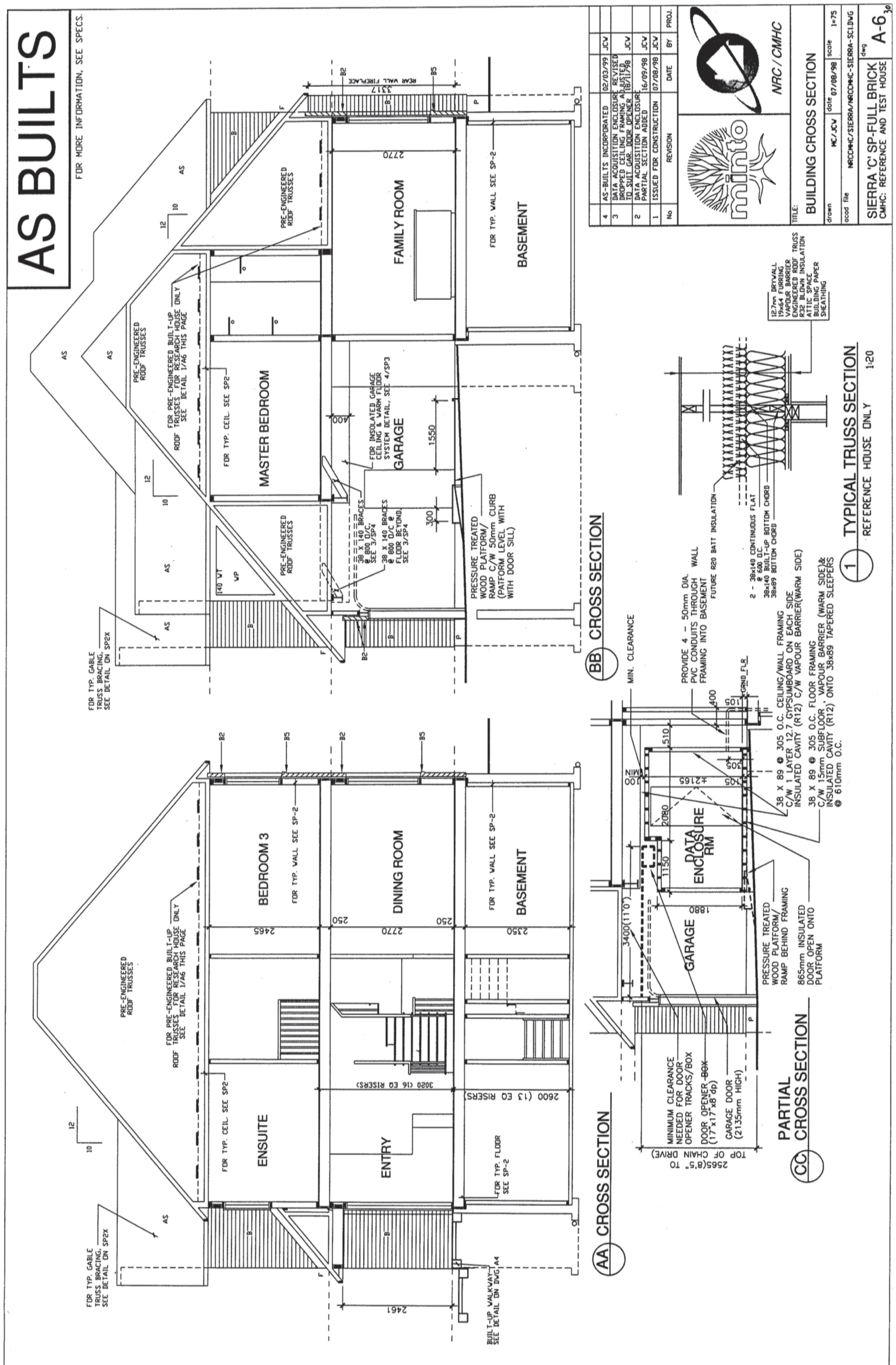
AS BUILTS
FOR MORE INFORMATION, SEE SPECS.
STRUCTURAL FRAMING SCHEDULE
STEEL LINTEL
S1 - L 90 X 90 X 6
S2 - L 90 X 90 X 8
S3 - L 100 X 90 X 8
S4 - L 125 X 90 X 8
S5 - L 125 X 90 X 10
S6 - L 200 X 100 X 12
S7 - L 150 X 100 X 10 (L.L.V.) 200mm BEARING
WOOD LINTEL
L1 - 2 - 38 X 235 W/ 12.7 PLYW. SPACER
L2 - 2 - 38 X 235
L3 - 3 - 38 X 235
L4 - 3 - 38 X 235 c/w 2-12.7 PLYW'D SPACERS & 2 ROWS OF 90mm C.W.N. @ 200 c/c B/S
L5 - 3 - 38 X 286 c/w 2-12.7 PLYW'D SPACERS & 2 ROWS OF 90mm C.W.N. @ 200 c/c B/S STAG.
POSTS
P1 - 75 DIAM. STEEL TELEPOST
P2 - 2 - 38 X 89 OR 2 - 38 X 140
P3 - 3 - 38 X 89 OR 3 - 38 X 140
P4 - 4 - 38 X 89 OR 4 - 38 X 140
P5 - 5 - 38 X 89 OR 5 - 38 X 140
P6 - 6 - 38 X 89 OR 6 - 38 X 140
P11 - HEAVY DUTY STEEL POST, CAP.= 55 KN
P12 - ADJ. HSS 100 KN CAP.
P13 - HSS 88.9 X 88.9 X 3.18 160 X 12 PL X 200 TOP (FOR CONT'S BEAM)
P14 - HSS 88.9 x 88.9 x 3.18 120 x 10 Bpl x 120 T. & B. (DOWN TO TOP OF FOUNDATION WALL)
CS1 - HSS 76.2 x 76.2 x 4.78, 140 x 12 Bpl x 140 T.& B.
4 AS-BUILT INFO ADDED. MECH'L/ELECT'L INFO MOVED TO SHEET ME-3 02/03/99 JCV
3 ELECT'L SERVICE CLARIFIED AND OUTLET ADDED IN STAIRWELL 16/09/98 JCV
2 MASTERBRM WINDOW REVISED TO MATCH ELEVATION 28/08/98 JCV
1 ISSUED FOR CONSTRUCTION 07/08/98 JCV
No REVISION DATE BY PROJ.
minto
NRC / CMHC
TITLE:
SECOND FLOOR PLAN
drawn MC/JCV date 07/08/98 scale 1=75
acad file NRCCMHC/SIERRA/NRCCMHC-SIERRA-FP2.DWG
SIERRA 'C' SP-FULL BRICK
CMHC: REFERENCE AND TEST HOUSE
dwg A-3
SECOND FLOOR PLAN ELEV 'C'
MASTER BEDROOM
BEDROOM 2
BEDROOM 3
BEDROOM 4
WIC
ENSUITE
BATH
HALL
LAUND
MECH'L SHAFT
ROMAN TUB



AS BUILTS
FRONT ELEVATION
RIGHT SIDE ELEVATION
FRONT ENTRY PAVER PLAN (1:50)
FOR MORE INFORMATION, SEE SPECS.
BUILT-UP WALKWAY SEE PLAN DETAIL BELOW
HANDICAP SILL
760mm x 610mm WALKWAY PAVERS FLUSH WITH SILL
140mm x 140mm PRESSURE TREATED WOOD EDGE MEMBERS BELOW PAVERS
760mm x 610mm WALKWAY PAVERS ONTO BED OF GRANULAR FILL
PROVIDE 25mm PAVER OVERHANG TROUGHOUT STEPS
-250 (Grade)
LEGEND
3 AS BUILT INCORPORATED 02/03/99 JCV
2 FRONT ENTRY PAVERS ADDED 08/12/98 JCV
1 ISSUED FOR CONSTRUCTION 07/08/98 JCV
No REVISION DATE BY PROJ.
NRC/CMHC
TITLE: FRONT & RIGHT SIDE ELEVATIONS
drawn MC/JCV date 07/08/98 scale 1:75
SIERRA 'C' SP-FULL BRICK
CMHC: REFERENCE AND TEST HOUSE
dwg A-4



REAR ELEVATION
WINDOW WELL
LEFT SIDE ELEVATION
AS BUILTS
FOR MORE INFORMATION, SEE SPECS.
LEGEND
B - BRICK
B1 - BRICK SOLDIER COURSE
B2 - BRICK SOLDIER COURSE 20 mm projection
B3 - BRICK SLEEPER COURSE
B4 - STACK BOND
B5 - BRICK SILL
B6 - BRICK ROWLOCK
B7 - BRICK CORBELLING
B8 - BRICK CORNING 20 mm projection
+20 - BRICK PROJECTING 20mm
-20 - BRICK RECESSED 20mm
AC - ACRYLIC FINISH
AF - ALUMINUM FACSIA
AS - ASPHALT SHINGLES
CS - POURED CONCRETE SILL
F - FLASHING
G - GLAZING
P - PARGING
PC - PRE-CAST UNIT FOR PRECAST (ANGELSTONE)
R - # OF RISERS
S - SIDING (HORIZONTAL)
S1 - SHUTTERS (500 mm)
S2 - SHUTTERS (350 mm)
T - TRIM (COLOURED WHEN SHADED)
V - ROOF VENT
WD - WOOD DECK
WL - WOOD LOUVRE
WS - WOOD SIDING
WP - WOOD PANEL
WT - WOOD TRIM
XXX - STREET ADDRESS
2 AS BUILT INCORPORATED 02/03/99 JCV
1 ISSUED FOR CONSTRUCTION 07/08/98 JCV
No REVISION DATE BY PROJ.
minto
NRC / CMHC
TITLE:
REAR & LEFT SIDE ELEVATIONS
drawn MC/JCV
date 07/08/98
scale 1=75
acad file NRCCMHC/SIERRA/NRCCMHC-SIERRA-EL2.DWG
SIERRA 'C' SP-FULL BRICK
CMHC: REFERENCE AND TEST HOUSE
dwg A-5


AS BUILTS
FOR MORE INFORMATION, SEE SPECS.
BB CROSS SECTION
AA CROSS SECTION
PARTIAL
CC CROSS SECTION
TYPICAL TRUSS SECTION
REFERENCE HOUSE ONLY
MASTER BEDROOM
FAMILY ROOM
GARAGE
BASEMENT
BEDROOM 3
DINING ROOM
ENSUITE
ENTRY
DATA ENCLOSURE RM
PRE-ENGINEERED ROOF TRUSSES
NRC / CMHC
BUILDING CROSS SECTION
SIERRA 'C' SP-FULL BRICK
CMHC: REFERENCE AND TEST HOUSE
A-6

Appendix B

B. Builder Survey

As mentioned in Chapter 3, a survey was developed to conduct a detailed review of the suitability of potential least cost upgrade solutions, and to determine accurate estimations of the cost to implement such upgrades into the currently practiced new housing constructions to achieve improved energy efficiency standards. The results were summarized as follows:

A total of 43% of the participant builders built over 300 houses a year, as shown in Figure B-1

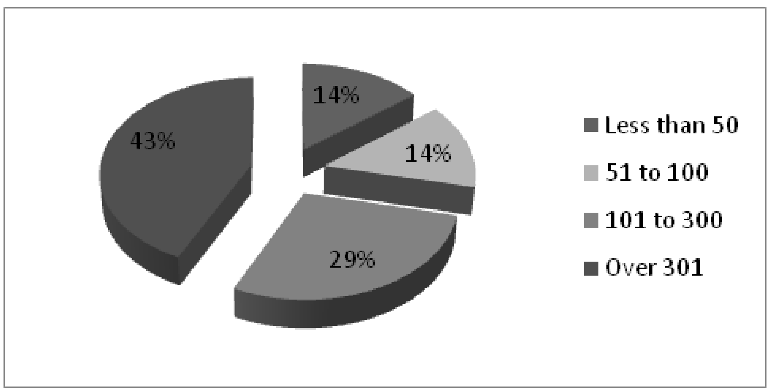


Figure B-1: Number of houses built over a year in Ontario

A total of 71% of the houses built were single-detached, and the remaining 29% were the low-rise multi-residential (21%), single-attached (6%), and the high-rise multi-residential buildings (2%), as shown in Figure B-2.

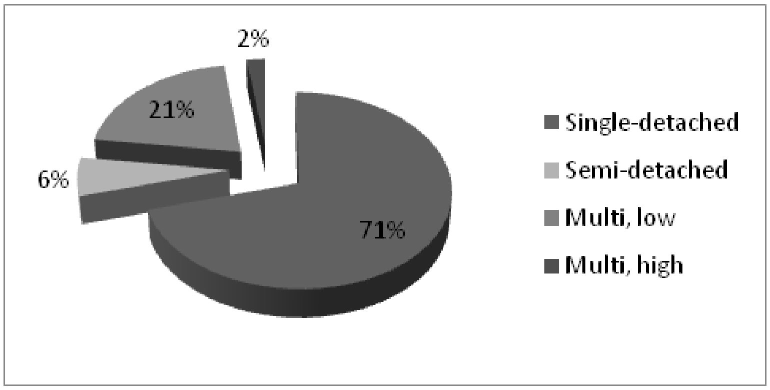


Figure B-2: Breakdown of housing types in Ontario

The majority (57%) of the houses built were in a range of 186 to 232m^2 (2001 to 2500 sq. ft.) of area. It was interesting to note that the remaining 43% of the houses built had an overall area of either less than 186m^2 (29%), or more than 232m^2 (14%), respectively.

All participant builders have responded that they were involved in the energy efficiency labelling program known as the ENERGY STAR for New Homes (ESNH), a commonly adopted energy efficiency standard in Canada, developed based on the U.S. DOE and the Environmental Protection Agency (EPA)'s ENERGY STAR program. In addition to the ESNH program, a few builders have participated in other labelling programs such as the NRCan's EnerGuide for New Houses (EGNH) program, EnerQuality Corporation's GreenHouse Certified Construction (GHCC) program, and the Canada Green Building Council (CaGBC)'s LEED Canada for Homes (LEEDH), where the latter is another commonly adopted energy efficiency standard in Canada, developed based on the U.S. Green Building Council (USGBC)'s LEED for Homes program, and modified to suit the nature and practices of the residential sector in Canada.

Figure B-3 summarizes the breakdown of the various labelling programs involved in by the participant builders in Ontario.

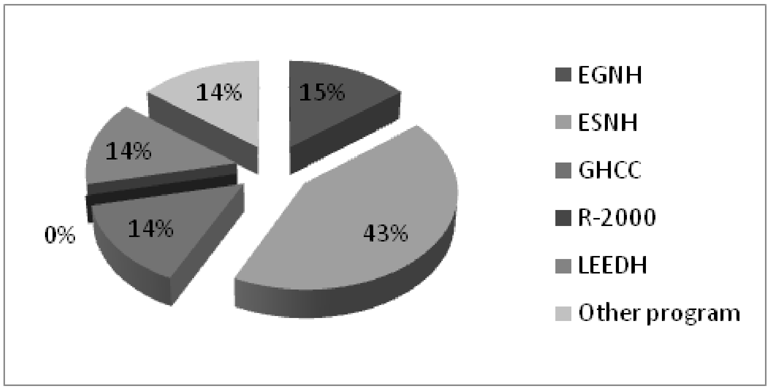


Figure B-3: Breakdown of labeling programs in Ontario

As Figure B-3 indicates, it was interesting to note that none of the participant builders responded that they were involved in the R-2000 program, which was created by the NRCan in partnership with the Canadian Home Builders' Association (CHBA) in 1981, and became the basis for many of the commonly adopted energy efficiency standards such as the ESNH, EGNH and LEEDH in Canada.

This could be attributed to the program's targeted air-tightness level of 1.5 ACH at 50 Pa, as evidenced by the responses received from the survey, which indicated that none of the houses built by the participant builders achieved the air-tightness level of 1.5 ACH at 50 Pa or lower. Figure B-4 summarizes the breakdown of varying levels of air-tightness achieved by the participant builders in Ontario.

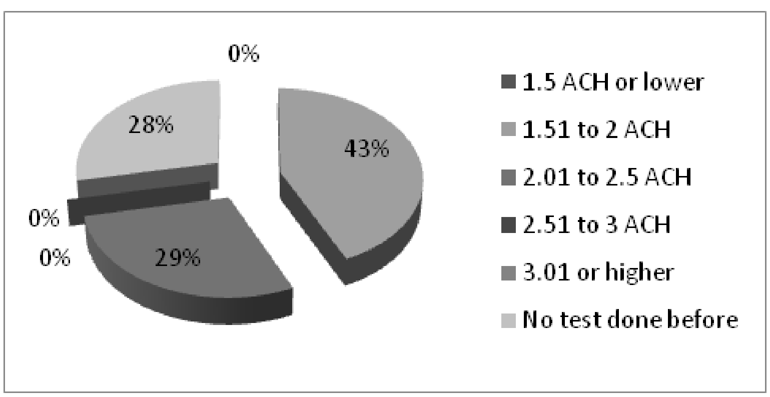


Figure B-4: Breakdown of air-tightness level

As Figure B-4 indicates, the majority of the houses built by the participant builders achieved an air-tightness level, ranging from 1.51 to 2 ACH at 50 Pa (43%), and from 2.01 to 2.5 ACH at 50 Pa (29%), respectively. It was also interesting to note that 28% of the houses built have not been subjected to the depressurization test (also known as the blower door test) to evaluate the air-tightness level of the house. This could be attributed to the targeted air-tightness level as well as the program requirements as specified by each labelling program in which the participant builders were involved.

Prior to conducting the survey, it was important to understand the requirements of the commonly adopted energy efficiency standards as referenced above, because these standards, although not mandated by the federal/provincial governments in Canada, have been practiced by the local homebuilders, thereby forming the basis of today's commonly practiced new housing constructions. Based on the results of the survey, it was apparent that all participant builders who have responded to the survey were building their homes to the current (2006) OBC and/or the ESNH Standard.

Further analysing the results in detail, 43% of the participant builders responded that their current exterior wall construction practices use timber-framed construction, where the studs are spaced at 400mm (16 in.) on-centre, with RSI 3.34 (R19) wall insulation placed in between the studs. Out of these, 29% were considering upgrading the existing wall insulation to RSI 3.87 (R22), and the remaining 14% were considering upgrading it to RSI 4.23 (R24) (comprising of installing RSI 3.34 (R19) interior wall insulation, and RSI 0.90 (R5) exterior wall insulation) in the near future.

The remaining 57% of the participant builders on the other hand, responded that they have began to construct the exterior walls by using the same timber-framed construction, but with studs spaced at 600mm (24in.) on-centre, and with higher levels of insulation than RSI 4.23 (R24). Out of these, 43% had no intention of upgrading the existing wall insulation in the near future, although the remaining 14% were considering using advanced framing technologies such as prefabricated panels. Figure B-5 summarizes the result.

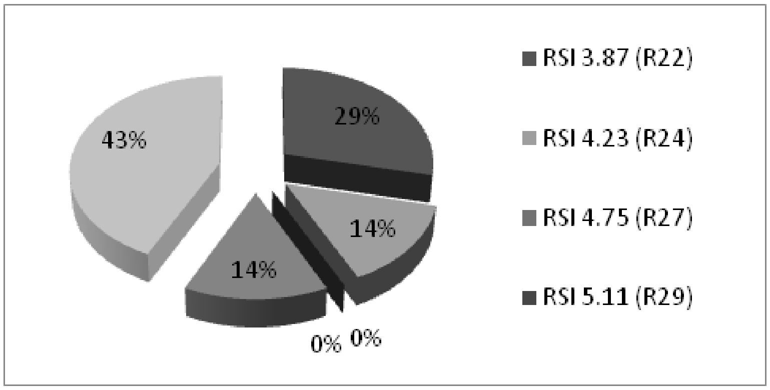


Figure B-5: Breakdown of exterior wall insulation level

For the attic construction, it was interesting to note that 43% of the participant builders were considering upgrading their existing attic/ceiling insulation of RSI 7.00 (R40) to RSI 8.80 (R50) in the near future, while the remaining 57% were reluctant to upgrade their current attic/ceiling construction practices by installing an insulation of RSI 8.80 (R50) or higher, as shown in Figure B-6.

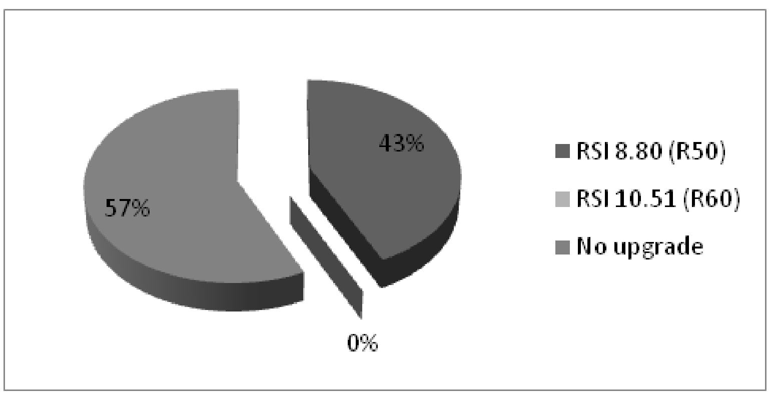


Figure B-6: Breakdown of attic/ceiling insulation level

This could be attributed to the fact that such an upgrade is neither required by the homeowners and, therefore, no benefit to the builders, nor specified by the current (2006) OBC or the ESNH Standard at this point.

The same conclusion was made with respect to the participant builders' views on upgrading the current basement wall construction practices, as was evidenced by the responses received from the survey, which indicated that upgrading the basement wall insulation from RSI 2.11 (R12) to RSI 3.52 (R20) or higher would not be considered a viable option, because such an upgrade is, at present, required neither by the current (2006) OBC nor by the ESNH Standard, and also there is no market demand.

For the construction of floors, 43% of the participant builders responded that their existing floor insulation level was RSI 4.40 (R25), and out of these, 29% were considering upgrading it to RSI 5.46 (R31). 57% of the participant builders on the other hand, have begun constructing the floors by using higher insulation levels than RSI 5.46 (R31) and, therefore, had no intention of upgrading their existing floor insulation in the near future, unless required by the OBC and/or the ESNH Standard. Figure B-7 summarizes the results.

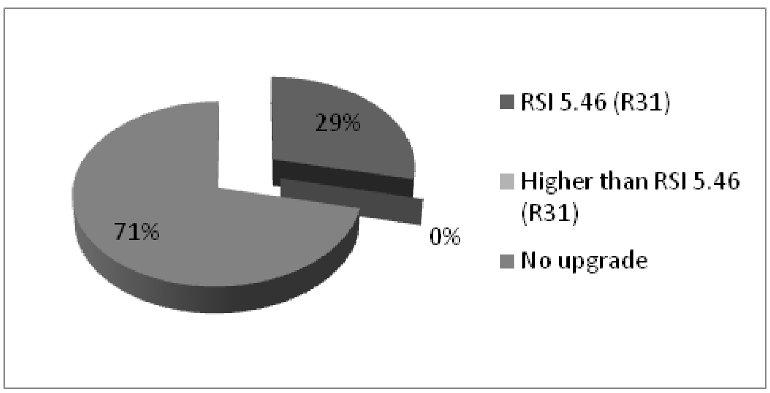


Figure B-7: Breakdown of floor insulation level

With respect to the basement slab insulation, 43% of the participant builders responded that they currently use RSI 1.41 (R8), installed around the perimeter of the slab, and out of these, 14% were considering upgrading it to RSI 1.76 (R10), and another 14% were considering upgrading it to RSI 2.11 (R12), both installed around the perimeter of the slab. A total of 14% of the participant builders on the other hand, responded that they have begun to use RSI 1.76 (R10) insulation for the entire surface of the slab and, therefore, were not considering upgrading it to higher levels of insulation in the near future, unless required by the OBC and/or the ESNH

Standard. It should be noted that, consensus could not be achieved with regard to this question due to the fact that the remaining 43% of the participant builders had no response. This could imply that the majority of the houses built had no basement slab insulation as a result of lack of demand by the homeowner. Figure B-8 summarizes the results.

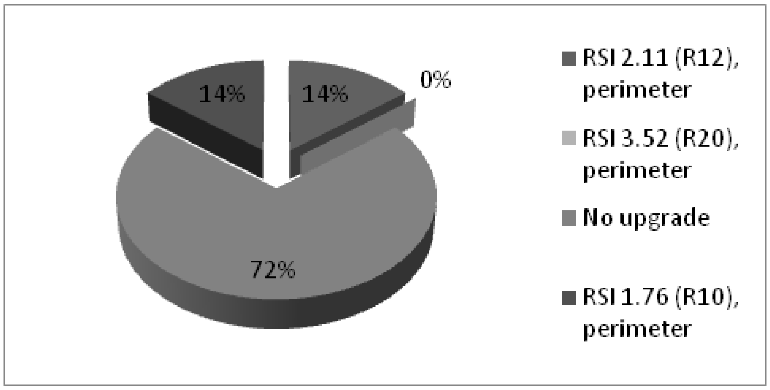


Figure B-8: Breakdown of slab insulation level

Lastly, with respect to windows, all participant builders responded that most of the houses built have double-glazed, low-E, argon filled windows installed, as per the requirements of the ESNH Standard. Out of these, all participant builders responded that they were considering upgrading their current windows to those with U-value of 1.6 (RSI 3.5) (29%), 1.8 (RSI 3.1) (43%), or 2.0 (RSI 2.8) (14%), respectively. It should be noted that consensus could not be achieved with respect to this question due to the fact that the remaining 14% of the participant builders had no response, which could imply that they had no intention of upgrading their current windows in the near future.

For the HVAC systems, it was evidenced by the responses received from the survey that a furnace with ECM was the most commonly used system for space heating (with 46%), followed by the combination or combo boiler (39%), DHW heater (8%), and other systems including a high-efficiency furnace without the ECM (8%), as shown in Figure B-9.

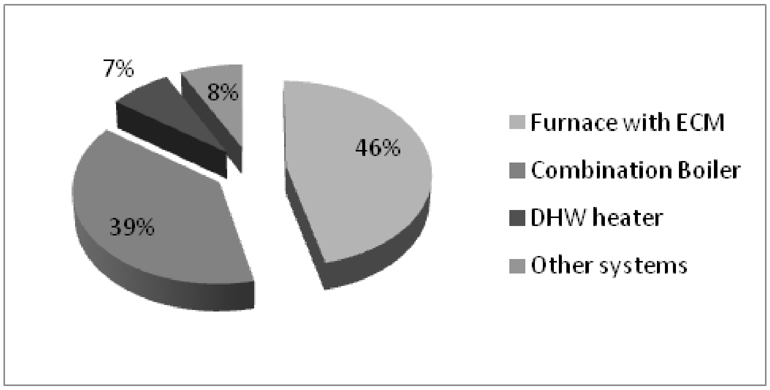


Figure B-9: Breakdown of space-heating systems used in Ontario

A total of 43% of the participant builders responded that they were installing a furnace with 90% AFUE as per the current (2006) OBC and/or the ESNH Standard, while another 43% were installing the same system with AFUE of 92 or higher, as shown in Figure B-10.

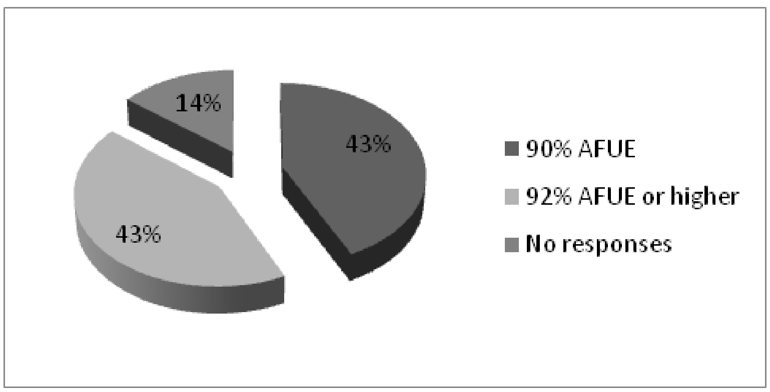


Figure B-10: Breakdown of furnace efficiency level, present

Out of these, almost all of the participant builders responded that they were considering upgrading their existing furnace to one with higher AFUE of 92%, 94% and 95%, respectively in the near future, as shown in Figure B-11.

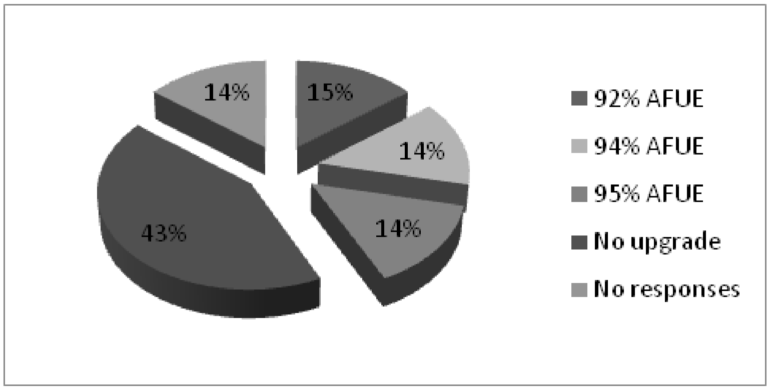


Figure B-11: Breakdown of furnace efficiency level, future

It should be noted that, as shown in Figure B-10 and B-11, consensus could not be achieved with regard to these questions due to the fact that the remaining 14% of the participant builders had no response. This could imply that these houses were built with no furnace installed or such equipment was on lease.

As for the DHW heater, 57% of the participant builders were installing the system with 0.57 EF or higher, and out of these, 14% were considering upgrading it to 0.80 EF, although the remaining 86% were not considering upgrading their existing systems unless such an upgrade were to be required by the future OBC or the ESNH Standard, as shown in Figure B-12.

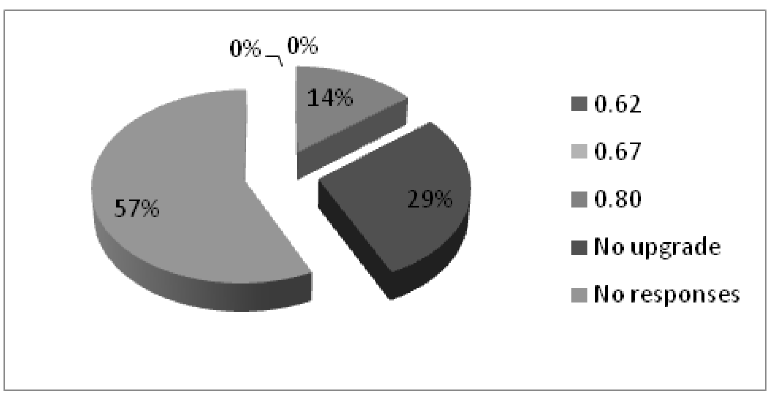


Figure B-12: Breakdown of DHW heater efficiency level

A total of 43% of the participant builders were installing the HRV system with 55% efficiency, and out of these, 29% were considering upgrading it to 70% efficiency, although the remaining

71% were not considering upgrading their existing systems to higher efficiency due to the lack of market demand at this point, unless otherwise required by the future OBC or the ESNH Standard, as shown in Figure B-13.

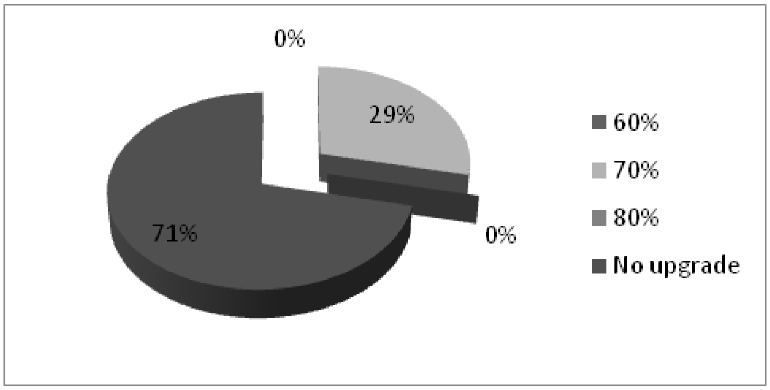


Figure B-13: Breakdown of HRV efficiency level

Builder Survey

Hello, my name is Aya Dembo. I am currently enrolled in the Masters of Building Science Program (M.A.Sc.) at Ryerson University. Under the supervision of Dr. Alan S. Fung, I am conducting a research for my thesis entitled, “Least Cost Analysis for Canadian New Housing”. The objective is to identify the most cost effective specifications to achieve improved energy efficiency standards for new housing, for example, the EnerGuide 80 (2012 requirements of the Ontario Building Code) and beyond. We are seeking to obtain the average construction costs and other information from local homebuilders, such as you.

Your cooperation in answering the following questions would help us conduct the detailed review of the suitability of different upgrade scenarios that we are proposing for the research. Please be advised that the information we obtained from this survey will be used for this study only, and will remain confidential.

Thank you very much.

1. General

1. How many homes/units does your company build a year?

☐ Less than 50 ☐ 51 to 100 ☐ 101 to 300 ☐ Over 301

2. What percentage of homes/units built fall into the following housing types?

(%) Single detached (%) Semi detached

(%) Multi-residential, low-rise (%) Multi-residential, high-rise

3. What is the square footage (square meter) of the home/unit that you specified in Question #2? **NB:** If there are multiple housing types that you specified, please select the one with the most percentage.

Housing type that you specified in Question #2 is: ________________________________

☐ Less than 1,500 sq. ft. (139 m^2) ☐ 1,501 to 2,000 sq. ft. (139 to 186 m^2)

☐ 2,001 to 2,500 sq. ft. (186 to 232 m^2) ☐ 2,501 sq. ft. (232 m^2) or more

4. Is a “green label” included in your point of sale materials? If **yes**, which of the following labels/programs does your company participate? (**Select all that apply**)

☐ EnerGuide for New Houses

☐ ENERGY STAR for New Homes

☐ GreenHouse Certified Construction

☐ LEED Canada for Homes

☐ R-2000

☐ Other program (**Please specify**): ______

☐ If **no**, please specify the reason: ____

2. Building Envelope

5. What is the insulation level (R-value) of your attic construction?

☐ R40 (RSI 7.00)

☐ Others, with R (or RSI) (**Please specify**) ____

6. Does your company consider of improving the attic construction methods in near future? If **yes**, which of the following improvements will it be?

☐ R50 (RSI 8.80)

☐ R60 (RSI 10.51)

☐ If **no**, please specify the reason: ____ ________

7. What percentage of homes/units built that have the following exterior wall constructions?

(%) 2x6 inches (38x140 mm) wood studs at 16 inches (400 mm) on-centre

(%) 2x6 inches (38x140 mm) wood studs at 24 inches (610 mm) on-centre

(%) Advanced framing using SIPs or other systems (**Please specify**)

8. What is the insulation level (R-value) of your above-grade wall construction?

☐ R19 (RSI 3.34)

☐ Others, with R (or RSI) (**Please specify**) ____

9. Does your company consider of improving the above-grade wall construction methods in near future? If **yes**, which of the following improvements will it be?

   - ☐ R22 (RSI 3.87)
   - ☐ R24 (RSI 4.23)
   - ☐ R27 (RSI 4.75)
   - ☐ R29 (RSI 5.11)
   - ☐ Advanced framing using SIPs or other systems (**Please specify**) ____________________________
   - ☐ If **no**, please specify the reason: ____

10. What is the insulation level (R-value) of your below-grade wall construction?

    - ☐ R12 (RSI 2.11), down to 15 inches (380mm) above the basement floor
    - ☐ R12 (RSI 2.11), full-height

11. Does your company consider of improving the below-grade wall construction methods in near future? If **yes**, which of the following improvements will it be?

    - ☐ R20 (RSI 3.52)
    - ☐ R22 (RSI 3.87)
    - ☐ R24 (RSI 4.23)
    - ☐ Advanced framing using ICFs or other systems (**Please specify**) ____________________________
    - ☐ If **no**, please specify the reason: ____

12. What is the insulation level (R-value) of your exposed floor (i.e., a floor above garage or unheated basement) construction?

    - ☐ R25 (RSI 4.40)
    - ☐ Others, with R (or RSI) (**Please specify**) ____

13. Does your company consider of improving the exposed floor construction methods in near future? If **yes**, which of the following improvements will it be?

☐ R31 (RSI 5.46)

☐ Others, with R (or RSI)(**Please specify**) ____________________

☐ If **no**, please specify the reason: ____________________

14. What is the insulation level (R-value) of your basement slab construction?

☐ R8 (RSI 1.41), covering just the perimeter of the slab

☐ R8 (RSI 1.41), entire surface

☐ R10 (RSI 1.76), covering just the perimeter of the slab

☐ R10 (RSI 1.76), entire surface

15. Does your company consider of improving the basement slab construction methods in near future? If **yes**, which of the following improvements will it be?

☐ R12 (RSI 2.11) → ☐ just the perimeter of the slab, **or** entire surface

☐ R20 (RSI 3.52) → ☐ just the perimeter of the slab, **or** ☐ entire surface

☐ If **no**, please specify the reason: ____________________

16. What percentage of homes/units built that have the following window types?

(%) Single-glazing (%) Double-glazing

(%) Double-glazing with low-E, argon-fill, or insulated spacer (%) Triple-glazing

17. What is the efficiency level (U-value) of the window that you specified in Question #16? **NB:** If there are multiple window types that you specified, please select the one with the most percentage.

☐ 1.6 (ER 25 – Operable, Energy Rating [ER] 35 – Fixed)

☐ 1.8 (ER 21 – Operable, ER 31 – Fixed)

☐ 2.0 (ER 17 – Operable, ER 27 – Fixed)

18. What is the air-tightness level of your home/unit?

☐ 1.5 ACH @ 50 Pa or lower ☐ 1.51 to 2 ACH @ 50 Pa

☐ 2.01 to 2.5 ACH @ 50 Pa ☐ 2.51 to 3 ACH @ 50 Pa

☐ 3.01 ACH @ 50 Pa or higher ☐ Have not done the test on a home/unit before

3. HVAC

19. Which of the following space heating equipments is installed in your home/unit? (**Select all that apply**)

☐ Boiler ☐ Furnace with ECM motor

☐ Combination ("combo") system ☐ Hot-water heater

☐ Other systems (**Please specify**) ____

20. What percentage of homes/units built that have the specified space heating equipment(s) in Question #19?

(%) Hot-water heater → **Proceed to Question #21**

(%) Boiler → **Proceed to Question #23**

(%) Furnace with ECM motor → **Proceed to Question #23**

(%) Combination ("combo") system → **Proceed to Question #23**

21. What is the efficiency (Energy factor) of a hot-water heater that is installed in your home/unit?

☐ 0.57

☐ Others, with efficiency (EF) of (**Please specify**) ________________________________

22. Does your company consider of improving the hot-water heater in near future? If **yes**, which of the following improvements will it be?

- ☐ 0.62
- ☐ 0.67
- ☐ 0.80
- ☐ If **no**, please specify the reason: ____________________

23. What is the efficiency of the boiler/furnace/combo system that is installed in your home/unit?

- ☐ 90% AFUE
- ☐ Others, with efficiency (%) of (**Please specify**) ____________________

24. Does your company consider of improving the boiler/furnace/combo system in near future? If **yes**, which of the following improvements will it be?

- ☐ 92% AFUE
- ☐ 94% AFUE
- ☐ 95% AFUE
- ☐ If **no**, please specify the reason: ____________________

25. Is your home/unit equipped with an HRV or ERV? If **yes**, what is the efficiency of the unit?

- ☐ 55%
- ☐ Others, with efficiency (%) of (**Please specify**) ____________________

26. Does your company consider of improving the (sensible recovery) efficiency of the HRV/ERV in near future? If **yes**, which of the following improvements will it be?

- ☐ 60%
- ☐ 70%
- ☐ 80%

☐ If **no**, please specify the reason: ____

27. Does your company include "green features" in a home/unit? If yes, what percentage of homes/units that have the following renewable energy system(s)?

(%) Air-source heat pump (%) Ground-source heat pump

(%) Drain water/grey water heat recovery (%) Solar-thermal hot-water heater

(%) Photovoltaic panels (%) Solar-wall/air-heater

(%) Other systems (**Please specify**) ____

This completes the first part of the survey. If you are interested in participating in the second part of the survey, please contact me by email for more information.

Thank you very much for your cooperation

Builder Survey – Part 2

Hello, my name is Aya Dembo. I am currently enrolled in the Masters of Building Science Program (M.A.Sc.) at Ryerson University. Under the supervision of Dr. Alan S. Fung, I am conducting a research for my thesis entitled, “Least Cost Analysis for the Canadian New Housing”. The objective is to identify the most cost effective specifications to achieve improved energy efficiency standards for new housing, for instance the EnerGuide 80 (2012 requirements of the Ontario Building Code) and beyond. We are seeking to obtain the average construction costs and other information from local production homebuilders.

Your cooperation in answering the following questions would help us determine the accurate estimation of different upgrade costs that we are proposing for the research. Please be advised that the information we obtained from this survey will be used for this study only, and will remain confidential.

Thank you very much.

1. Building Envelope

1. If you were to insulate the attic/ceiling with R50 (RSI 8.8) insulation as opposed to R40 (RSI 7.0), what would be the incremental cost* (including material and labour) associated with the former type of construction?

   *Cost is based on 1,536.87 sq. ft. (142.78m^2) of total attic/ceiling area:

   ☐ \$496, or less ☐ \$496.01 to \$552 ☐ \$552.01 to \$607

   ☐ \$607.01, or more ☐ Unit price of \$ ______ per sq. ft. (or m^2)

2. Similar to Question #1, what would be the incremental cost of installing R60 (RSI 10.5) insulation as opposed to R40 (RSI 7.0) in the attic?

   ☐ \$1,257, or less ☐ \$1,257.01 to \$1,397 ☐ \$1,397.01 to \$1,536

   ☐ \$1,536.01, or more ☐ Unit price of \$ ______ per sq. ft. (or m^2)

3. If you were to build the exterior walls using studs at 24 inches (610 mm) on-centre instead of 16 inches (400 mm) on-centre, what would be the incremental cost* (including material and labour) associated with the former type of construction?

   *Cost is based on 2,764.71 sq. ft. (256.85m2) of total above-grade wall area:

   ☐ \$649, or less ☐ \$649.01 to \$721 ☐ \$721.01 to \$793

   ☐ \$793.01, or more ☐ Unit price of \$ ______ per sq. ft. (or m^2)

4. If you were to insulate the above-grade walls with R22 (RSI 3.9) as opposed to R19 (RSI 3.3), what would be the incremental cost associated with the former type of construction?

☐ $1,189, or less ☐ $1,189.01 to $1,321 ☐ $1,321.01 to $1,453

☐ $1,453.01, or more ☐ Unit price of $ ______ per sq. ft. (or m²)

5. Similar to Question #4, what would be the incremental cost of installing R24 (RSI 4.2) insulation as opposed to R19 (RSI 3.3) in the above-grade walls?

☐ $649, or less ☐ $649.01 to $721 ☐ $721.01 to $793

☐ $793.01, or more ☐ Unit price of $ ______ per sq. ft. (or m²)

6. Similar to Question #5, what would be the incremental cost of installing R27 (RSI 4.8) insulation as opposed to R19 (RSI 3.3) in the above-grade walls?

☐ $3,744, or less ☐ $3,744.01 to $4,161 ☐ $4,161.01 to $4,577

☐ $4,577.01, or more ☐ Unit price of $ ______ per sq. ft. (or m²)

7. Similar to Question #6, what would be the incremental cost of installing R29 (RSI 5.1) insulation as opposed to R19 (RSI 3.3) in the above-grade walls?

☐ $4,480, or less ☐ $4,480.01 to $4,978 ☐ $4,978.01 to $5,475

☐ $5,475.01, or more ☐ Unit price of $ ______ per sq. ft. (or m²)

8. If you were to build the above-grade walls using advanced framing including Structural Insulated Panels (SIPs) as opposed to using conventional framing methods, what would be the incremental cost (including material and labour) associated with the former type of construction?

☐ $18,331 or less ☐ $18,331.01 to $20,367 ☐ $20,367.01 to $22,404

☐ $22,404.01, or more ☐ Unit price of $ ______ per sq. ft. (or m²)

9. If you were to insulate the below-grade walls with R20 (RSI 3.5) as opposed to R12 (RSI 2.1) full-height insulation, what would be the incremental cost* (including material and labour) associated with the former type of construction?

*Cost is based on 1,179.26 sq. ft. (109.56m²) of total below-grade wall area:

☐ $1,513, or less ☐ $1,513.01 to $1,681 ☐ $1,681.01 to $1,849

☐ $1,849.01, or more ☐ Unit price of $ ______ per sq. ft. (or m²)

10. Similar to Question #9, what would be the incremental cost of insulating the below-grade walls with R22 (RSI 3.9) as opposed to R12 (RSI 2.1), full-height insulation?

☐ $3,053, or less ☐ $3,053.01 to $3,392 ☐ $3,392.01 to $3,731

☐ $3,731.01, or more ☐ Unit price of $ ______ per sq. ft. (or m^2)

11. Similar to Question #10, what would be the incremental cost of insulating the below-grade walls with R24 (RSI 4.2) as opposed to R12 (RSI 2.1), full-height insulation?

☐ $2,603, or less ☐ $2,603.01 to $2,893 ☐ $2,893.01 to $3,182

☐ $3,182.01, or more ☐ Unit price of $ ______ per sq. ft. (or m^2)

12. If you were to build the below-grade walls using advanced constructions including Insulated Concrete Forms (ICFs) as opposed to using conventional methods, what would be the incremental cost (including material and labour) associated with the former type of construction?

☐ $11,021, or less ☐ $11,021.01 to $12,245 ☐ $12,245.01 to $13,470

☐ $13,470.01, or more ☐ Unit price of $ ______ per sq. ft. (or m^2)

13. If you were to insulate the exposed floor (i.e., a floor above garage or unheated basement) with R31 (RSI 5.5) as opposed to R25 (RSI 4.4), what would be the incremental cost* (including material and labour) associated with the former type of construction?

*Cost is based on 271.90 sq. ft. (25.26m2) of total exposed floor area:

☐ $355, or less ☐ $355.01 to $394 ☐ $394.01 to $433

☐ $433.01, or more ☐ Unit price of $ ______ per sq. ft. (or m^2)

14. If you were to insulate the basement slab with R12 (RSI 2.1) full slab insulation as opposed to R10 (RSI 1.8) or lower, what would be the incremental cost* (including material and labour) associated with the former type of construction?

*Cost is based on 960.68 sq. ft. (89.25m2) of total basement floor area:

☐ $1,525, or less ☐ $1,525.01 to 1,694 ☐ $1,694.01 to $1,864

☐ $1,864.01, or more ☐ Unit price of $ ______ per sq. ft. (or m^2)

15. Similar to Question #14, what would be the incremental cost of installing R20 (RSI 3.5) full slab insulation as opposed to R10 (RSI 1.8) or lower?

- ☐ $2,965, or less
- ☐ $2,965.01 to $3,295
- ☐ $3,295.01 to $3,624
- ☐ $3,624.01, or more
- ☐ Unit price of $ ______ per sq. ft. (or m^2)

16. If you were to install a double-glazed window with Low-E coating as opposed to installing the same type of window without Low-E, what would be the incremental cost* (including material and labour) associated with the former type of construction?

*Cost is based on 24 x 40 inches (609 x 1,016mm) double-glazed, argon-filled with insulating spacer window:

- ☐ $78, or less
- ☐ $78.01 to $87
- ☐ $87.01 to $96
- ☐ $96.01 or more
- ☐ Unit price of $ ______ per window

2. HVAC

17. What would be the incremental cost (including material and labour) of installing a 92% or higher AFUE furnace with ECM motor as opposed to installing the same one with 90% efficiency?

- ☐ $424, or less
- ☐ $424.01 to $472
- ☐ $472.01 to $519
- ☐ $519.01, or more
- ☐ Unit price of $ ______ per unit

18. What would be the incremental cost (including material and labour) of installing a 0.92 or higher efficiency boiler as opposed to installing the same one with lower efficiency?

- ☐ $788, or less
- ☐ $788.01 to $875
- ☐ $875.01 to $963
- ☐ $963.01, or more
- ☐ Unit price of $ ______ per unit

19. What would be the incremental cost (including material and labour) of installing a higher efficiency combination ("combo") system as opposed to installing the furnace/boiler with 90% efficiency?

- ☐ $1,581, or less
- ☐ $1,581.01 to $1,757
- ☐ $1,757.01 to $1,932
- ☐ $1,932.01, or more
- ☐ Unit price of $ ______ per unit

20. What would be the incremental cost (including material and labour) of installing an HRV with 80% efficiency as opposed to installing the same one with 55% efficiency?

- ☐ $752, or less
- ☐ $752.01 to $835
- ☐ $835.01 to $919
- ☐ $919.01, or more
- ☐ Unit price of $ ______ per unit

21. What would be the incremental cost (including material and labour) of installing an air-conditioning unit with SEER 14 as opposed to installing the same one with SEER 13 or lower?

- ☐ $59, or less
- ☐ $59.01 to $65
- ☐ $65.01 to $72
- ☐ $72.01, or more
- ☐ Unit price of $ ______ per unit

22. What would be the incremental cost (including material and labour) of installing an air-source heat pump (ASHP) as opposed to installing the furnace (90% AFUE) with air-conditioning unit (SEER 13 or lower)?

- ☐ $12,096, or less
- ☐ $12,096.01 to $13,440
- ☐ $13,440.01 to $14,784
- ☐ $14,784.01, or more
- ☐ Unit price of $ ______ per unit

23. What would be the incremental cost (including material and labour) of installing a ground-source heat pump (GSHP) as opposed to installing the furnace (90% AFUE) with air-conditioning unit (SEER 13 or lower)?

- ☐ $16,326, or less
- ☐ $16,326.01 to $18,140
- ☐ $18,140.01 to $19,953
- ☐ $19,953.01, or more
- ☐ Unit price of $ ______ per unit

24. What would be the additional cost (including material and labour) to install a drain water heat-recovery system?

- ☐ $871, or less
- ☐ $871.01 to $968
- ☐ $968.01 to $1,064
- ☐ $1,064.01, or more
- ☐ Unit price of $ ______ per unit

25. What would be the incremental cost (including material and labour) of installing a solar-assisted DHW heater as opposed to installing the same one with 0.57 EF or higher, but no solar (PV) panels?

- ☐ $3,645, or less
- ☐ $3,645.01 to $4,050
- ☐ $4,050.01 to $5,111

☐ $5,111.01, or more ☐ Unit price of $ ______ per unit

Thank you for your cooperation

Appendix C

C. Additional Cases for the Other Cities in Ontario

As previously mentioned in Chapter 5, additional cases with reduction in the appliance, lighting and hot water consumptions were conducted for Ottawa, Windsor and Thunder Bay, respectively, and their results are summarized as follows:

C.1 Reduction in the Appliance and Lighting Consumptions

Following the same methodology used in conducting sensitivity analysis of reduction in the appliance, lighting and hot water consumptions[14], the assumptions were based on the study conducted by Tse et al., (2008). The identified parameters used for this analysis were the same as Case 1, which are summarized in Section 4.3 of Chapter 4.

Based on the results of the reduced appliance and lighting consumption in Case 1, the combination of eligible upgrades with the lowest total life cycle cost in NPV was identified using the BFSS method, which was almost identical to the one identified in the previous case using the standard operating conditions in HOT2000 for all three cities.

Tables D-1 to D-3 summarize the estimated total annual household energy consumption, percent savings per year, reductions of the GHG emissions, and the total life cycle cost in NPV by round for Ottawa, Windsor, and Thunder Bay, respectively.

---

[14] Refer to Section 4.4 in Chapter 4.

Table C-1: Simulation results for Ottawa, using reduced appliance and lighting consumption

Round	Description [Code]	Simulation Results: Energy Consumption (kWh/year; Btu/year)	% Savings (EGR)	GHG Emissions[1] (Tons/CO_2) and % Savings	Total LCC[2] (NPV) ($)
-	**Base case**	**40,589 ($138x10^6$)**	**N/A (78.3)**	**8.26 (N/A)**	**79,249**
1	Combo boiler with 0.90 EF [GH3]	37,260 ($127x10^6$)	8% (79.9)	7.64 (8%)	74,709
2	RSI 3.9 (R22) insulation [AGW1]	36,020 ($123x10^6$)	11% (80.5)	7.41 (10%)	73,801
3	HRV at 70% efficiency [V1]	33,699 ($115x10^6$)	17% (81.6)	7.03 (15%)	73,250
4	RSI 5.5 (R31) floor insulation [F1]	33,614 ($115x10^6$)	17% (81.6)	7.01 (15%)	73,462
5	RSI 3.5 (R20) basement wall insulation [BGW2]	33,517 ($114x10^6$)	17% (81.7)	6.99 (15%)	73,885
6	RSI 8.8 (R50) attic/ceiling insulation [C1]	32.497 ($111x10^6$)	20% (82.2)	6.81 (18%)	74,871
7	**Air-conditioning unit at SEER 14 [AC1]**	**32.497 ($111x10^6$)**	**20% (82.2)**	**6.81 (18%)**	**76,020**
8	RSI 2.2 (R12) insulating board underneath the basement slab [BS1]	31,958 ($109x10^6$)	21% (82.5)	6.71 (19%)	79,908
-	**Difference from the base case to the final combination of upgrades**	**8631 ($29X10^6$)**	**21% (82.5)**	**1.55 (19%)**	**- 659**

Notes:

1. The GHG emission calculation was done using the carbon dioxide (CO_2) factors determined from the study by Fung & Gill (2011). In their study, 1.856 kg/m^3 equivalent CO_2 (NRCan, 2006) was used for natural gas, and the average emission factor for electricity was 226.35 tons CO_2/total gigawatt-hour (GWh) generation (Gordon & Fung, 2009).
2. The total LCC was determined based on the identified average mortgage rate of 7.87%, average discount rate of 1.99%, and the fuel escalation rates for electricity and natural gas of 3.50%, and 3.02%, respectively.

As shown in Table C-1, for the case in Ottawa, the estimated total household energy consumption and the GHG emissions of the baseline case decreased due to the outcome of the identified least cost upgrades, resulting in decrease in the total life cycle cost in NPV until the end of Round 3, while the EnerGuide Rating was not sensitive, and remained at EGR of 82 at the end of Round 8 with a difference in percent savings of 1%.

Despite the fact that the estimated total household energy consumption decreased at the end of each round, it was interesting to note that the overall household consumption increased by 9% when compared it against that of the previous case without the reduction in the appliance and lighting consumptions, while the total life cycle cost in NPV decreased by 20%. This could imply that the effectiveness of the reduction in the appliance and lighting consumptions by 42%

resulted in decrease in the energy required for space cooling, but not for space heating purposes, where the latter accounted for the heat gains from the appliances and lighting.

It was also interesting to note that, as similar to the previous case without the reduction in the appliance and lighting consumptions, the estimated total household energy consumption did not change after the installation of an AC unit at SEER 14 (from Round 6 to Round 7). This could imply that the effectiveness of the change in the efficiency of the unit (from SEER 13 to 14) was very minimal in terms of reducing the overall household energy consumption, while increased the total life cycle cost by 2%.

Table C-2: Simulation results for Windsor, using reduced appliance and lighting consumption

Round	Description [Code]	Simulation Results			Total LCC (NPV) ($)
		Energy Consumption (kWh/year; Btu/year)	% Savings (EGR)	GHG Emissions (Tons/CO_2) and % Savings	
-	**Base case**	**32,245 ($110x10^6$)**	**N/A (79.7)**	**7.51 (N/A)**	**71,714**
1	Combo boiler with 0.90 EF [GH3]	29,220 ($100x10^6$)	9% (81.4)	6.26 (17%)	67,923
2	RSI 3.9 (R22) insulation [AGW1]	28,245 ($96x10^6$)	12% (81.9)	6.08 (19%)	67,230
3	HRV at 70% efficiency [V1]	26,375 ($90x10^6$)	18% (82.9)	5.78 (23%)	67,158
4	RSI 3.5 (R20) basement wall insulation [BGW2]	25,828 ($88x10^6$)	20% (83.2)	5.68 (24%)	67,101
5	RSI 5.5 (R31) floor insulation [F1]	25,760 ($88x10^6$)	20% (83.2)	5.67 (25%)	67,314
6	RSI 8.8 (R50) attic/ceiling insulation [C1]	25,376 ($87x10^6$)	21% (83.5)	5.60 (25%)	68,807
7	**Air-conditioning unit at SEER 14 [AC1]**	**25,376 ($87x10^6$)**	**21% (83.5)**	**5.59 (26%)**	**71,931**
8	RSI 2.2 (R12) insulating board underneath the basement slab [BS1]	24,916 ($85x10^6$)	23% (83.7)	5.51 (27%)	75,668
-	**Difference from the base case to the final combination of upgrades**	**7329 ($25X10^6$)**	**23% (83.7)**	**2.00 (27%)**	**- 3954**

As shown in Table C-2, for the case in Windsor, the estimated total household energy consumption and the GHG emissions of the baseline case decreased due to the outcome of the identified least cost upgrades, resulting in decrease in the total life cycle cost in NPV until the end of Round 4, while the EnerGuide Rating was not sensitive, and remained at EGR of 83 at the end of Round 8 with a difference in percent savings of 3%.

Similar to the case in Ottawa, despite the fact that the estimated total household energy consumption decreased at the end of each round, it was interesting to note that the overall household consumption increased by 10% when compared it against that of the previous case without the reduction in the appliance and lighting consumptions, while the total life cycle cost in NPV decreased by 22%. This could imply that the effectiveness of the reduction in the appliance and lighting consumptions by 42% resulted in decrease in the energy required for space cooling, but not for space heating purposes, where the latter accounted for the heat gains from the appliances and lighting.

It was also interesting to note that, as similar to the case in Ottawa, the estimated total household energy consumption did not change after the installation of an AC unit at SEER 14 (from Round 6 to Round 7). This could imply that the effectiveness of the change in the efficiency of the unit (from SEER 13 to 14) was very minimal in terms of reducing the overall household energy consumption, while increased the total life cycle cost by 5%.

Table C-3: Simulation results for Thunder Bay using reduced appliance and lighting consumption

Round	Description [Code]	Simulation Results			Total LCC (NPV) ($)
		Energy Consumption (kWh/year; Btu/year)	% Savings (EGR)	GHG Emissions (Tons/CO_2) and % Savings	
-	**Base case**	**44,321 (151x10^6)**	**N/A (79.5)**	**8.88 (N/A)**	**82,212**
1	Combo boiler with 0.90 EF [GH3]	40,669 (139x10^6)	8% (81.0)	8.20 (8%)	77,157
2	HRV at 70% efficiency [V1]	37,856 (129x10^6)	15% (82.2)	7.72 (13%)	76,077
3	RSI 3.5 (R20) basement wall insulation [BGW2]	37,176 (127x10^6)	16% (82.5)	7.60 (14%)	75,898
4	RSI 5.5 (R31) floor insulation [F1]	37,072 (126x10^6)	16% (82.5)	7.58 (15%)	76,077
5	RSI 5.1 (R29) insulation, placed in between the studs spaced at 600 mm (24 in.) on-centre [AGW7]	36,092 (123x10^6)	19% (83.0)	7.40 (17%)	76,960
6	RSI 8.8 (R50) attic/ceiling insulation [C1]	35,514 (121x10^6)	20% (83.2)	7.30 (18%)	78,300
7	**Air-conditioning unit at SEER 14 [AC1]**	**35,514 (121x10^6)**	**20% (83.2)**	**7.30 (18%)**	**81,494**
8	RSI 2.2 (R12) insulating board underneath the basement slab [BS1]	34,849 (119x10^6)	21% (83.5)	7.18 (19%)	85,041
-	**Difference from the base case to the final combination of upgrades**	**9471 (32X10^6)**	**21% (83.5)**	**1.71 (19%)**	**- 2829**

As shown in Table C-3, for the case in Thunder Bay, the estimated total household energy consumption and the GHG emissions of the baseline case decreased due to the outcome of the identified least cost upgrades, resulting in decrease in the total life cycle cost in NPV until the end of Round 3, while the EnerGuide Rating was not sensitive, and remained at EGR of 83 at the end of Round 8 with a difference in percent savings of 2%.

Similar to the cases in Ottawa and Windsor, despite the fact that the estimated total household energy consumption decreased at the end of each round, it was interesting to note that the overall household consumption increased by 9% when compared it against that of the previous case without the reduction in the appliance and lighting consumptions, while the total life cycle cost in NPV decreased by 19%. This could imply that the effectiveness of the reduction in the appliance and lighting consumptions by 42% resulted in decrease in the energy required for space cooling, but not for space heating purposes, where the latter accounted for the heat gains from the appliances and lighting.

It was also interesting to note that, as similar to the case in Ottawa, the estimated total household energy consumption did not change after the installation of an AC unit at SEER 14 (from Round 6 to Round 7). This could imply that the effectiveness of the change in the efficiency of the unit (from SEER 13 to 14) was very minimal in terms of reducing the overall household energy consumption, while increased the total life cycle cost by 4%.

Figure C-1 shows the total life cycle cost in NPV, after the reduction in the appliance and lighting consumptions, with respect to the increase in energy efficiency for the selected four cities (Thunder Bay, Ottawa, Toronto, and Windsor) in Ontario.

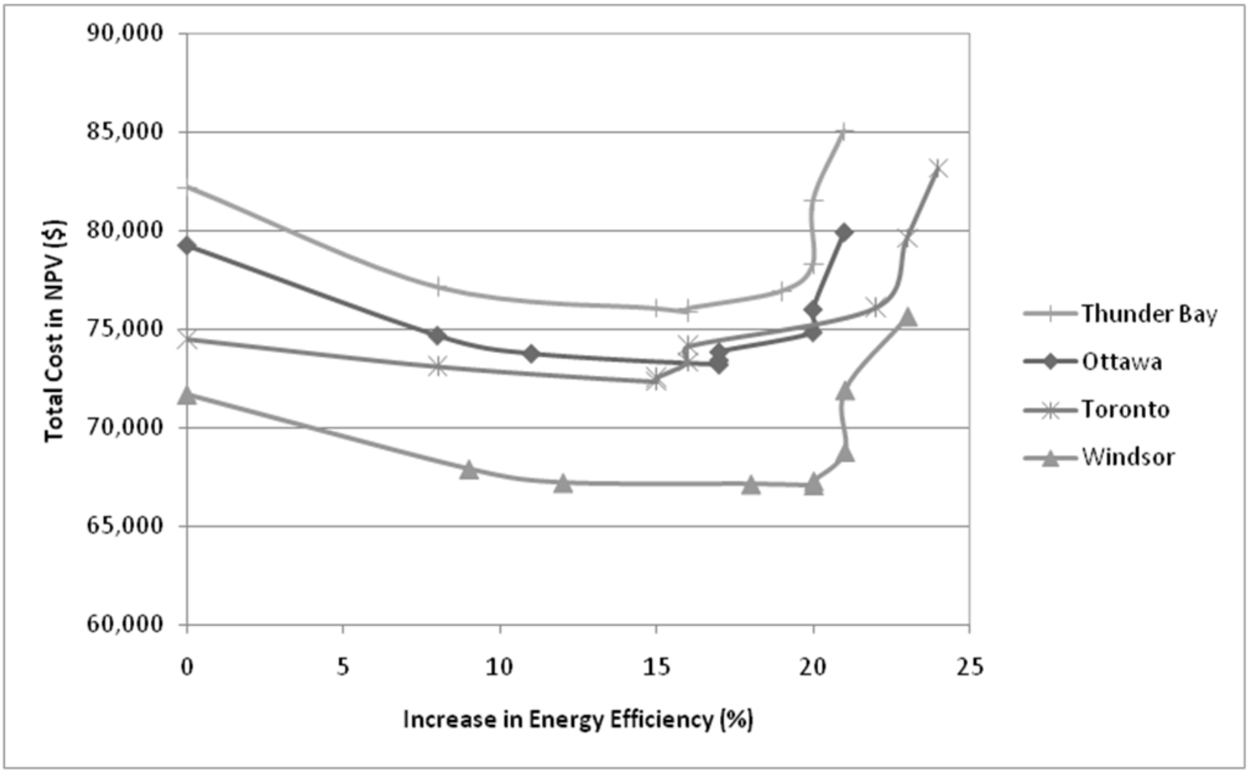


Figure C-1: Total cost in NPV ($) vs. increase in energy efficiency (%) for the selected cities in Ontario, after the reduction in the appliance and lighting consumptions

C.2 Reduction in Average Hot Water Load

In addition to reducing the amount of electricity used for appliances and lighting, the average hot water load was reduced from 225L/day to 100L/day based on the assumption used in the study by Tse et al. (2008).

Based on the results of the reduced appliance, lighting and hot water consumptions in Case 1, the combination of eligible upgrades with the lowest total life cycle cost in NPV was identified using the BFSS method, which was almost identical to the one identified in the previous case using the standard operating conditions in HOT2000 for all three cities.

Tables C-4 to C-6 summarize the estimated total annual household energy consumption, percent savings per year, reductions of the GHG emissions, and the total life cycle cost in NPV by round for Ottawa, Windsor, and Thunder Bay, respectively.

Table C-4: Simulation results for Ottawa, using reduced appliances lighting and hot water consumptions

Round	Description [Code]	Simulation Results			LCC (NPV) ($)
		Energy Consumption (kWh/year; Btu/year)	% Savings (EGR)	GHG Emissions (Tons/CO_2) and % Savings	
-	**Base case**	**37,098 (127x10^6)**	**N/A (80.0)**	**7.63 (N/A)**	**75,813**
1	**Combo boiler with 0.85 EF [GH2]**	**34,612 (118x10^6)**	**7% (81.2)**	**7.16 (6%)**	**72,018**
2	RSI 3.9 (R22) insulation [AGW1]	33,553 (114x10^6)	10% (81.7)	6.97 (9%)	71,287
3	HRV at 70% efficiency [V1]	31,217 (107x10^6)	16% (82.8)	6.58 (14%)	70,716
4	RSI 3.5 (R20) basement wall insulation [BGW2]	30,588 (104x10^6)	18% (83.1)	6.47 (15%)	70,606
5	RSI 5.5 (R31) floor insulation [F1]	30,504 (104x10^6)	18% (83.2)	6.45 (15%)	70,818
6	RSI 8.8 (R50) attic/ceiling insulation [C1]	30,014 (102x10^6)	19% (83.4)	6.36 (17%)	72,325
7	**Air-conditioning unit at SEER 14 [AC1]**	**30,013 (102x10^6)**	**19% (83.4)**	**6.36 (17%)**	**73,472**
8	RSI 2.2 (R12) insulating board underneath the basement slab [BS1]	29,468 (101x10^6)	21% (83.7)	6.26 (18%)	77,349
-	**Difference from the base case to the final combination of upgrades**	**7630 (26X10^6)**	**21% (83.7)**	**1.37 (18%)**	**- 1536**

Table C-5: Simulation results for Windsor, using reduced appliance, lighting and hot water consumptions

Round	Description [Code]	Simulation Results			LCC (NPV) ($)
		Energy Consumption (kWh/year; Btu/year)	% Savings (EGR)	GHG Emissions (Tons/CO_2) and % Savings	
-	**Base case**	**28,862 (98x10^6)**	**N/A (81.6)**	**6.21 (N/A)**	**68,355**
1	**Combo boiler with 0.85 EF [GH2]**	**26,652 (91x10^6)**	**9% (82.8)**	**5.80 (7%)**	**65,284**
2	RSI 3.9 (R22) insulation [AGW1]	25,854 (88x10^6)	12% (83.2)	5.65 (9%)	64,767
3	HRV at 70% efficiency [V1]	23,976 (82x10^6)	18% (84.2)	5.35 (14%)	64,687
4	RSI 3.5 (R20) basement wall insulation [BGW2]	23,426 (80x10^6)	20% (84.5)	5.25 (15%)	64,628
5	RSI 5.5 (R31) floor insulation [F1]	23,359 (80x10^6)	20% (84.6)	5.24 (16%)	64,841
6	RSI 8.8 (R50) attic/ceiling insulation [C1]	22,977 (78x10^6)	22% (84.8)	5.17 (17%)	66,335
7	**Air-conditioning unit at SEER 14 [AC1]**	**22,976 (78x10^6)**	**22% (84.8)**	**5.16 (17%)**	**69,458**
8	RSI 2.2 (R12) insulating board underneath the basement slab [BS1]	22,507 (77x10^6)	23% (85.1)	5.08 (18%)	73,187
-	**Difference from the base case to the final combination of upgrades**	**6355 (22X10^6)**	**23% (85.1)**	**1.13 (18%)**	**- 4832**

Table C-6: Simulation results for Thunder Bay, using reduced appliance, lighting and hot water consumptions

Round	Description [Code]	Simulation Results - Annual: Energy Consumption (kWh/year; Btu/year)	% Savings (EGR)	GHG Emissions (Tons/CO_2) and % Savings	LCC (NPV) ($)
-	**Base case**	**40,687(139x10^6)**	**N/A (81.0)**	**8.23 (N/A)**	**78,635**
1	Combo boiler with 0.90 EF [GH3]	37,914 (129x10^6)	7% (82.2)	7.70 (6%)	74,449
2	HRV at 70% efficiency [V1]	35,096 (120x10^6)	14% (83.4)	7.22 (12%)	73,364
3	RSI 3.5 (R20) basement wall insulation [BGW2]	34,413 (117x10^6)	15% (83.7)	7.10 (14%)	73,183
4	RSI 5.5 (R31) floor insulation [F1]	34,310 (117x10^6)	16% (83.7)	7.08 (14%)	73,363
5	RSI 5.1 (R29) insulation, placed in between the studs spaced at 600 mm (24 in.) on-centre [AGW7]	33,331 (114x10^6)	18% (84.1)	6.91 (16%)	74,246
6	RSI 8.8 (R50) attic/ceiling insulation [C1]	32,753 (112x10^6)	20% (84.4)	6.80 (17%)	75,586
7	**Air-conditioning unit at SEER 14 [AC1]**	**32,753 (112x10^6)**	**20% (84.4)**	**6.80 (17%)**	**78,781**
8	RSI 2.2 (R12) insulating board underneath the basement slab [BS1]	32,085 (109x10^6)	21% (84.7)	6.68 (19%)	82,324
-	**Difference from the base case to the final combination of upgrades**	**8602 (29X10^6)**	**21% (84.7)**	**1.55 (19%)**	**- 3689**

As Tables C-4 to C-6 indicate, similar to the results of the previous case with the reduction in the appliance and lighting consumptions were the estimated energy consumption and the GHG emissions of the baseline case in all three cities, which decreased due to the outcome of the identified least cost upgrades, resulting in decrease in the life cycle cost in NPV until the end of Round 4 in both Ottawa and Windsor, and Round 3 in Thunder Bay. As for the EnerGuide Rating, it was not sensitive, and remained at EGR of 83 at the end of Round 8 with a difference percent savings of 3% in Ottawa, EGR of 84 at the end of Round 7 with a difference in percent savings of 4% in Windsor, and also EGR of 84 at the end of Round 8 with a difference in percent savings of 3% in Thunder Bay, respectively.

For the cases in Ottawa and Windsor, it was interesting to note that, with the reduction in the average hot water load, the combo boiler with 0.85 EF was the most cost-effective solution (at the end of Round 1) than the same system with higher efficiency (of 0.9 EF), where the latter was identified as the most cost-effective solution in the previous case without the reduction. This could imply that with 56% reduction in the average hot water load, the combo boiler with lower efficiency would be sufficient when a significant amount of hot water load was reduced.

It was also interesting to note that, as similar to the previous case with the reduction in the appliance and lighting consumptions, the estimated total household energy consumption did not change after the installation of an AC unit at SEER 14 (from Round 6 to Round 7). This could imply that the effectiveness of the change in the efficiency of the unit (from SEER 13 to 14) was very minimal in terms of reducing the overall household energy consumption, while increased the total life cycle cost by 2% in Ottawa, 5% in Windsor, and 4% in Thunder Bay, respectively.

Figure C-2 shows the life cycle cost in NPV, after the reduction in the appliance, lighting and hot water consumptions, with respect to the increase in energy efficiency for the selected four cities in Ontario.

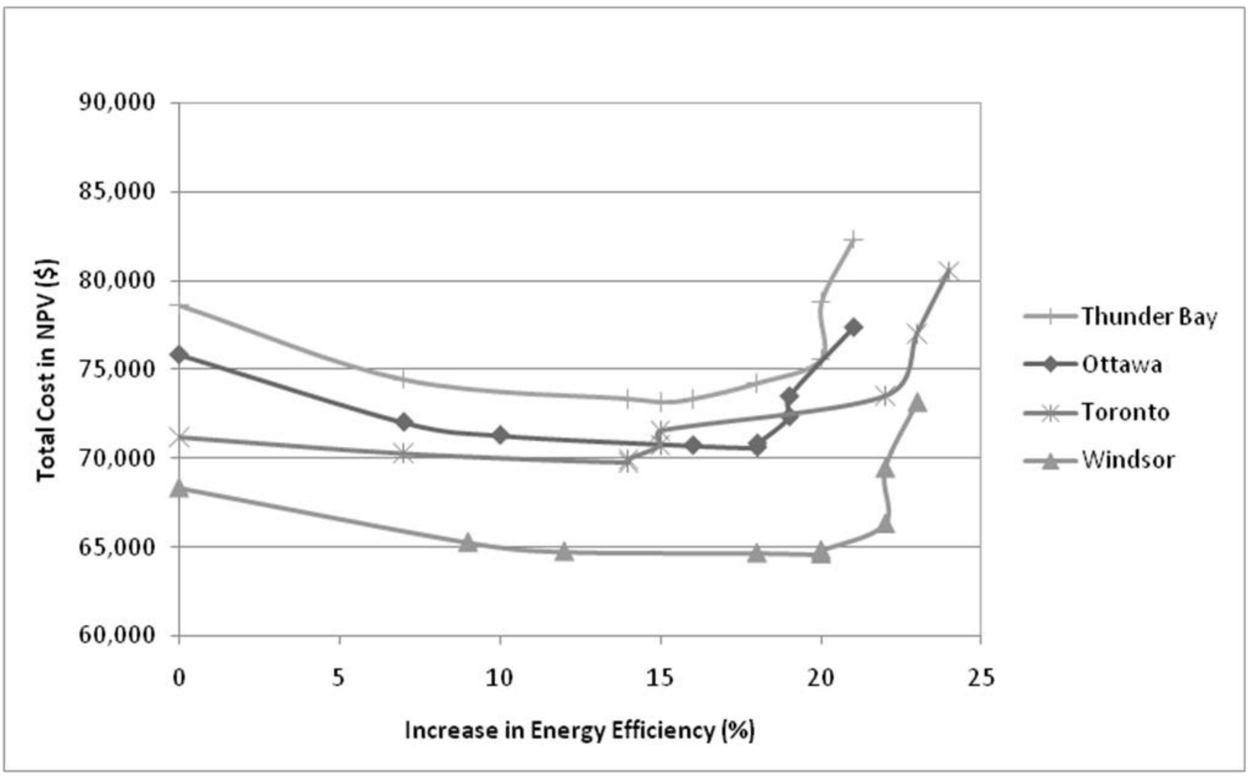


Figure C-2: Total cost in NPV ($) vs. increase in energy efficiency (%) for the selected four cities in Ontario, after the reduction in the appliance, lighting and hot water consumptions

C.3 Reduced Consumption with the Installation of a PV System

The overall energy performance of the Reference House, after the installation of the identified combination of least cost upgrades with a photovoltaic (PV) system, was re-evaluated to account for the reduction in the appliance, lighting and hot water consumptions.

Based on the results using RETScreen, the estimated electricity exported to grid was the same as the previous cases without the reduction for all three cities. However, the net present value of the total income for 20 years, after subtracting the cost of installing a PV system from the income, was slightly less than that of the previous cases without the reduction, where the former was estimated to be $58,081 for Ottawa, $66,613 for Windsor, and $74,279 for Thunder Bay, respectively.

Furthermore, the difference in the net present value of the total electricity cost of what a homeowner would pay if the PV system were not installed (hence the savings), while accounting for the electricity production from the PV system from 21 to 30 years, was slightly less than that of the previous cases without the reduction, where the former was estimated to be $11,656 for Ottawa, $12,075 for Windsor, and $11,330 for Thunder Bay, respectively.

Therefore, with the installation of the PV system, the total profits, over the 30-year mortgage period, were estimated to be slightly less than those of the previous cases without the reduction, where the former were $69,737 for Ottawa, $878,688 for Windsor, and $85,609 for Thunder Bay, respectively.

Table C-7 summarizes the estimated total profit as a result of installing a PV system, after the reduction in the appliance, lighting and hot water consumptions for the selected cities (Ottawa, Windsor, and Thunder Bay) in Ontario using its micro FIT program.

Table C-7: Summary of estimated total PV profit (NPV) over 30 years for Ottawa, Windsor, and Thunder Bay

Results	Unit	Location		
		Ottawa	Windsor	Thunder Bay
Estimated electricity exported to grid	kWh/yr	7667	8317	8901
Total income for 20 years	$	58,081	66,613	74,279
Total savings from 21 to 30 years	$	11,656	12,075	11,330
Total PV profit after 30 years (mortgage period)	**$**	**69,737**	**78,688**	**85,609**
Percent decrease from the previous cases without the reduction	**-**	**2%**	**2%**	**4%**

As Table C-7 indicates, despite the decrease in the estimated total profit after the reduction in the appliance, lighting and hot water consumptions, the overall profit after the installation of the PV system would still allow a homeowner to pay for the implementation of additional upgrade(s).

References

Anderson, R., Christensen, C., & Horowitz, S. (2006). Analysis of Residential System Strategies Targeting Least-Cost Solutions Leading to New Zero Energy Homes. *ASHRAE 2006 Annual Meeting Session: How Low Can You Go? Low-Energy Buildings through Integrated Design*, (pp. 1-19). Quebec City, Canada.

Anderson, R., Christensen, C., & Horowitz, S. (2006). Analysis of Residential System Strategies Targeting Least-Cost Solutions Leading to New Zero Energy Homes. *ASHRAE 2006 Annual Meeting Session: How Low Can You Go? Low-Energy Buildings through Integrated Design*, (pp. 1-6). Quebec City, Canada.

ANSI/ASHRAE Standard 140-2004. (2004). *Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs.* Atlanta, GA: American Society of Heating, Refriderating and Air-Conditioning Engineers Inc.

ASHRAE. (1985). Energy Estimating Methods. In *ASHRAE Handbook - Fundamentals* (SI ed., Vol. 1, pp. 28.9-28.17). Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASHRAE. (2005). Ventilation and Infiltration. In R. a.-C. American Society of Heating, *Handbook - Fundamentals* (p. 27.22). Atlanta, GA, USA.

Barry, C. J., & Elmahdy, A. H. (2007). Selection of optimum low-e coated glass type for residential glazing in heating dominated climates. *Glass Performance Days 07 Proceedings*, (pp. 1-13). Tampere, Finland.

Beausoleil-Morrison, I., & Mitalas, G. (1997). BASESIMP: A Residential-Foundation Heat-Loss Algorithm for Incorporating into Whole-Building Energy-Analysis Programs. *Proceedings of the Building Simulation '97. 2*, pp. 1-8. Prague, Czech Republic: International Building Performance Simulation Association.

Bolling, A. L., & Mathias, J. A. (2008). Investigation of Optimal Heating and Cooling Systems in Residential Buildings. *ASHRAE Transactions* , 128-139.

Bradley, B. (1993). *Implementation of the AIM-2 Infiltration Model in HOT2000.* report prepared by Unies Ltd., Winnipeg, Manitoba, for Energy, Mines and Resources Canada.

Bradley, D. E., Kummert, M., & McDowell, T. P. (2004a). CONVERGING ON A RECOMMENDED SET OF INTERPRETATIONS AND ASSUMPTIONS IN APPLYING STANDARD TESTS TO ENRGY ANALYSIS TOOLS. *SimBuild 2004 Conference.* Boulder, Colorado.

Bradley, D. E., Kummert, M., & McDowell, T. P. (2004b). EXPERIENCES WITH AND INTERPRETATION OF STANDARD TEST METHODS OF BUILDING ENERGY ANALYSIS TOOLS. *e Sim 2004 Canadian conference on building energy simulation.* Vancouver, Canada.

Brunklaus, B., Thormark, C., & Baumann, H. (2010). Illustrating limitations of energy studies of buildings with LCA and actor analysis. *BUILDING RESEARCH & INFORMATION , 38* (3), 265-279.

Canada Mortgage and Housing Corporation [CMHC]. (2008). Analysis of Renewable Energy Potential in the Residential Sector Through High-Resolution Building-Energy Simulation. *Technical Series* (08-106).

Canada Mortgage and Housing Corporation [CMHC]. (2005). *Effects of ECPM Furnace Motors on Electricity and Gas Use.* Ottawa, ON: Canada Mortgage and Housing Corporation.

Canadian Centre for Housing Technology [CCHT]. (n.d.). *Selected Characteristics of the CCHT Houses*. Retrieved July 21, 2009, from Canadian Centre for Housing Technology: http://www.ccht-cctr.gc.ca/main_e.html

Canadian Home Builders' Association (CHBA). (1991). *HOT2000 Version 6.00 TECHNICAL MANUAL for DOS and Macintosh computers.* Ottawa, ON.

Canadian Solar Solutions Inc. (n.d.). *Product Datasheet for CS5A.* Retrieved December 16, 2010, from Products & Applications: http://www.canadian-solar.com/upload/datasheets/CS5A-M_en.pdf

Christensen, C., Horowitz, S., Givler, T., Courtney, A., & Barker, G. (2005). BEopt: Software for Identifying Optimal Building Designs on the Path to Zero Net Energy. *ISES 2005 Solar World Congress,* (pp. 1-6). Orlando, Florida.

Christensen, C., Horowitz, S., Givler, T., Courtney, A., & Barker, G. (2005). BEopt: Software for Identifying Optimal Building Designs on the Path to Zero Net Energy. *ISES Solar World Congress 2005,* (pp. 1-6). Orlando, Florida.

CMHC. (2011, August). *Housing Now - Greater Toronto Area (previously Toronto).* Retrieved September 9, 2011, from Publications and Reports: https://www03.cmhc-schl.gc.ca/catalog/productDetail.cfm?lang=en&cat=70&itm=41&fr=1315582512906

Crawley, D. B., Hand, J. W., Kummert, M., & Griffith, B. T. (2008). Contrasting the capabilities of building energy performance simulation programs. *Building and Environment , 43* (4), 661-673.

Dembo, A., Ng, K. L., Pyrka, A., & Fung, A. S. (2010). The Archetype Sustainable House: Investigating its potentials to achieving the net-zero energy status based on the results of a detailed energy audit. *International High Performance Buildings Conference*, (pp. 1-8). West Lafayette, IN.

Dembo, A., Zhou, J., & Fung, A. S. (2009). Summary of Detailed Audit and Building Simulation on Archetype Sustainable House, Woodbridge ON. *CANCAM 2009 Conference.* Halifax, NS.

Department of Finance Canada. (2011, January 17). *Backgrounder: Supporting the long-term stability of Canada's housing market*. Retrieved January 26, 2011, from Publications and reports: http://www.fin.gc.ca/n11/data/11-003_1-eng.asp

Dong, B., Kennedy, C., & Pressnail, K. (2005). Comparing life cycle implications of building of retrofit and replacement options. *Can. J. Civ. Eng. , 32*, 1051-1063.

Dong, B., Kennedy, C., & Pressnail, K. (2005). Comparing life cycle implications of building of retrofit and replacement options. *Can. J. Civ. Eng.* (32), 1051-1063.

Dupuis, S. (2009, August 29). Green standards must be uniform in province. *Toronto Star, Homes & Condos* , p. H16.

EnerQuality Corporation. (2009, October 19). *4TH ANNUAL ENERQUALITY SURVEY SHOWS IMPORTANCE OF ENERGY EFFICIENCY AMONG HOME BUYERS, DESPITE RECESSION.* Retrieved November 30, 2009, from NEWS RELEASE: http://www.enerquality.ca/site/enerquality/assets/pdf/October_News_Release_-_Survey_Results_-_October_19,_2009.pdf

EnerQuality Corporation. (2009). *4TH ANNUAL ENERQUALITY SURVEY SHOWS IMPORTANCE OF ENERGY EFFICIENCY AMONG HOME BUYERS, DESPITE RECESSION.* Retrieved November 30, 2009, from NEWS RELEASE: http://www.enerquality.ca/site/enerquality/assets/pdf/October_News_Release_-_Survey_Results_-_October_19,_2009.pdf

Entchev, E., Gusdorf, J., Swinton, M., Bell, M., Szadlkhowski, F., Kalbfleisch, W., et al. (2004). Micro-generation technology assessment at the Canadian Centre for Housing Technology. *Energy and Buildings , 36* (9), 925-931.

Entchev, E., Gusdorf, J., Swinton, M., Bell, M., Szadlkhowski, F., Kalbfleisch, W., et al. (2004). Micro-generation technology assessment at the Canadian Centre for Housing Technology. *Energy and Buildings , 36* (9), 925-931.

Environment Canada. (n.d.). *Canadian Climate Normals or Average 1971-2000*. Retrieved March 1, 2010, from Environment Canada: http://climate.weatheroffice.gc.ca/climate_normals/index_e.html

Farahbakhsk, H., Ugursal, I. V., & Fung, A. S. (1998). A residential end-use energy consumption model for Canada. *Int. J. Energy Research , 22*, 1133-1143.

Farahbakhsk, H., Ugursal, V. I., & Fung, A. S. (1998). A residential end-use energy consumption model for Canada. *Int. J. Energy Research , 22*, 1133-1143.

Feist, W. (1997). *LIFE-CYCLE ENERGY ANALYSIS: COMPARISON OF LOW-ENERGY HOUSE, PASSIVE HOUSE, SELF-SUFFICIENT HOUSE.* Passive House Institute.

Fung, A. S., & Gill, G. S. (2011). Energy and Environmental Analysis of Residential Hot Water Systems: A Study for Ontario, Canada. *2011 Montreal Annual Conference.* Montreal, QC.

Fung, A. S., Dembo, A., & Zhou, J. (2008, October 30). *Least Cost Analysis for the Canadian New Housing.* A proposal submitted to the CMHC External Research Program Application for Housing Research Grant, Ryerson Univeristy, Toronto, ON.

Fung, A. S., Farahbakhsh, H., & Ugursal, I. (1997). *Household Energy Consumption Benchmarks for 1994 Newly Constructed Houses and its Associated Potential Energy Savings for both National Energy Code for Housing (NECH) and R-2000 Upgrades.* Dalhousie University, Department of Mechanical Engineering, Halifax, NS.

Fung, A. S., Farahbakhsh, H., & Ugursal, I. V. (1997). *Household Energy Consumption Benchmarks for 1994 Newly Constructed Houses and its Associated Potential Energy Savings for both National Energy Code for Housing (NECH) and R-2000 Upgrades.* Dalhousie University, Department of Mechanical Engineering, Halifax, NS.

Fung, A. S., Guler, B., Aydinalp, M., & Ugursal, I. V. (2000). *Development of Canadian Residential Energy End-use and Emission Model (CREEM).* Dalhousie University, Canadian Residential Energy End-use Data and Analysis Centre (CREEDAC), Halifax, NS.

Fung, A. S., Guler, B., Aydinalp, M., & Ugursal, V. I. (2000). *Development of Canadian Residential Energy End-use and Emission Model (CREEM).* Dalhousie University, Canadian Residential Energy End-use Data and Analysis Centre (CREEDAC), Halifax, NS.

Fung, A., Ng, K. R., Rad, F. M., & Tse, H. (2009). Analysis of Different Mechanical Systems for Ontario's Housing Market Using Hot2000 and RETScreen. *22nd Canadian Congress of Applied Mechanics [CANCAM]*, (pp. 97-98). Halifax, N.S.

Fung, A., Ng, K. R., Rad, F. M., & Tse, H. (2009). Analysis of Different Mechanical Systems for Ontario's Housing Market Using Hot2000 and RETScreen. *22nd Canadian Congress of Applied Mechanics [CANCAM]*, (pp. 97-98). Halifax, N.S.

Good, J. T., Ugursal, V. I., & Fung, A. S. (2007). Modelling and Technical Feasibility Analysis of a Low-Emission Residential Energy System. *International Journal of Green Energy* , 27-43.

Goodman Company Canada. (2007). *List Price.*

Gordon, C., & Fung, A. S. (2009). Hourly emission factors from the electricity generation sector - A tool for analyzing the impact of renewable technologies in Ontario. *CSME Transactions , 33* (1), 105-18.

Gorgolewski, M. (1995). Optimising Renovation Strategies for Energy Conservation in Housing. *Building and Environment , 30* (4), pp. 583-589.

Gorgolewski, M., Grindley, P. C., & Probert, S. D. (1996). Energy-Efficient Renovation of High-Rise Housing. *Applied Energy* (53), 1-18.

Guler, B. (2000). *Impact of Energy Efficiency Retrofits on Residential Energy Consumption and Associated Carbon Dioxide Emissions.* MASc Thesis, Dalhousie University, Department of Mechanical Engineering, Halifax, Canada.

Guler, B., Fung, A. S., Aydinalp, M., & Ugursal, I. V. (2001). Impact of energy efficiency upgrade retrofits on the residential energy consumption in Canada. *Int. J. Energy Research , 25*, 785-792.

Guler, B., Fung, A. S., Aydinalp, M., & Ugursal, V. I. (2001). Impact of energy efficiency upgrade retrofits on the residential energy consumption in Canada. *Int. J. Energy Research* , *25*, 785-792.

Guler, B., Ugursal, I. V., Fung, A. S., & Aydinalp-Koksal, M. (2008). Impact of energy efficiency upgrade retrofits on the residential energy consumption and Greenhouse Gas emissions in Canada. *Int. J. Environmental Technology and Management , 9* (4), 434-444.

Guler, B., Ugursal, V. I., Fung, A. S., & Aydinalp-Koksal, M. (2008). Impact of energy efficiency upgrade retrofits on the residential energy consumption and Greenhouse Gas emissions in Canada. *Int. J. Environmental Technology and Management , 9* (4), 434-444.

Gustafsson, S. I. (2000). Optimisation of insulation measures on existing buildings. *Energy and Building , 33*, 49-55.

Haddad, K., Ouazia, B., & Barhoun, H. (2008). Simulations of a desiccant-evaporative cooling system for residential buildings. *3rd Canadian Solar Buildings Conference*, (pp. 1-8). Fredericton, N.B.

Haltrecht, D., & Fraser, K. (1997). VALIDATION OF HOT2000™ USING HERS BESTEST. *Fifth International IBPSA Conference Building Simulation 1997.* Prague, Czech Republic.

Hendron, R. (2005). *Building America Research Benchmark Definition, Version 3.1, Updated July 14, 2004.* Technical Report.

Hermelink, A. H. (2009). *HOW DEEP TO GO: REMARKS ON HOW TO FIND THE COST-OPTIMAL LEVEL FOR BUILDING RENOVATION.* Koln, Germany: ECOFYS.

Jaggs, M., & Palmer, J. (2000). Energy performance indoor environmental quality retrofit - a European disgnosis and decision making method for building refurbishment. *Energy and Buildings , 31* (2), 97-101.

Judkoff, R. D., & Neymark, J. S. (1995a). A Procedure for Testing the Ability of Whole Building Energy Simulation Programs to Thermally Model the Building Fabric. *Journal of Solar Energy Engineering , 117*, 7-15.

Judkoff, R. e. (1983). *A Methodology for Validating Building Energy Analysis Simulations.* Golden, CO: Solar Energy Research Institute (now known as National Renewable Energy Laboratory).

Judkoff, R., & Neymark, J. (1995b). *Home Energy Rating System Building Energy Simulation Test (HERS BESTEST), NREL/TP-472-7332.* Golden, CO: National Renewable Energy Laboratory.

Judkoff, R., & Neymark, J. (1995c). *International Energy Agency Building Energy Simulation Test (BESTEST) and Diagnostic Method, NREL/TP-472-6231.* Golden, CO: National Renewable Energy Laboratory.

Judkoff, R., & Neymark, J. (2006). Model Validation and Testing: The Methodological Foundation of ASHRAE Standard 140. *ASHRAE 2006 Annual Meeting*, (pp. 1-12). Quebec City.

Judkoff, R., Wortman, D., O'Doherty, B., & Burch, J. (2008). *A Methodology for Validating Building Energy Analysis Simulations.* Golden, CO: National Renewable Energy Laboratory.

Karlsson, F., Rohdin, P., & Persson, M.-L. (2007). Measured and predicted energy demand of a low energy building: important aspects when using Building Energy Simulation. *Building Serv. Eng. Res. Technol. , 28, 3*, 223-235.

Kummert, M., & Bernier, M. (2008a). Analysis of a combined photovoltaic-geothermal gas-fired absorption heat pump system in a Canadian climate. *Journal of Building Performance Simulation , 1* (4), 245-256.

Kummert, M., & Bernier, M. (2008b). Sub-hourly simulation of residential ground coupled heat pump systems. *Building Serv. Eng. Res. Technol.* (29.1), 27-44.

Kummert, M., Andre, P., & Argiriou, A. A. (2006). Comparing Control Strategies Using Experimental and Simulation Results: Methodology and Application to Heating Control of Passive Solar Buildings. *HVAC&R RESEARCH SPECIAL ISSUE , 12* (3a), 715-737.

Kummert, M., Bradley, D. E., & McDowell, T. P. (2004). COMBINING DIFFERENT VALIDATION TECHNIQUES FOR CONTINUOUS SOFTWARE IMPROVEMENT - IMPLICATION IN THE DEVELOPMENT OF TRNSYS 16. *The Canadian conference on building energy simulation.* Vancouver.

Kummert, M., Dempster, W., & McLean, K. (2009). THERMAL ANALYSIS OF A DATA CENTRE COOLING SYSTEM UNDER FAULT CONDITIONS. *Eleventh International IBPSA Conference Building Simulation 2009.* Glasgow, Scotland.

Lutz, J., Lekox, A., Chan, P., Dunham Whitehead, C., Meyers, S., & McMahon, J. (2006). Life-cycle cost analysis of energy efficiency design options for residential furnaces and boilers. *Energy* (31), 311-329.

MacInnes, C. (1995). *Flair Energy Demo Project: Energy Monitoring Program and Validation of HOT2000 version 6.0.* Ottawa, ON: CANMET.

Manning, M. M., Elmahdy, A. H., Swinton, M. C., Parekh, A., Szadkowski, F., & Barry, C. (2008). Summer and winter field monitoring of high and low solar heat gain glazing at a Canadian twin house facility. *ASHRAE Transactions*, (pp. 1-17). Salk Lake City, Utah.

Manning, M. M., Swinton, M. C., Szadkowski, F., Gusdorf, J., & Ruest, K. (2007). The Effects of thermostat setting on seasonal energy consumption at the CCHT Twin House Facility. *ASHRAE Transactions , 113* (1), 1-12.

McQuinston, F. C., Parker, J. D., & Spitler, J. D. (2005). *Heating, Ventilating and Air Conditioning, Analysis and Design* (6th Edition ed.). John Wiley & Sons.

Ministry of Energy [MIE]. (2010). *Ontario's Long-Term Energy Plan.* Queen's Printer for Ontario.

Ministry of Municipal Affairs and Housing [MMAH]. (2008). *2006 Building Code Compendium.* Toronto, Ontario: Queen's Printer for Ontario.

Ministry of Municipal Affairs and Housing [MMAH]. (2010, January 1 Update). Acceptable Solutions for Energy Efficiency Compliance. In M. o. [MMAH], *2006 Building Code Compendium* (Vol. 1, pp. 8-17). Queen's Printer for Ontario.

Ministry of Municipal Affairs and Housing [MMAH]. (2008b). Enclosed Unheated Space. In *2006 Building Code Compendium* (Vol. 1). Toronto, ON: Queen's Printer for Ontario.

Ministry of Municipal Affairs and Housing [MMAH]. (2008f). Energy Efficiency Design After December 31,2011. In *2006 Building Code Compendium* (Vol. 1, p. 4). Toronto, ON: Queen's Printer for Ontario.

Ministry of Municipal Affairs and Housing [MMAH]. (2008). *Energy Efficiency in the 2006 Building Code.* Retrieved June 24, 2009, from Ontario Ministry of Municipal Affairs and Housing: http://www.mah.gov.on.ca/Page681.aspx

Ministry of Municipal Affairs and Housing [MMAH]. (n.d.a). *Energy Efficiency in the 2006 Building Code.* Retrieved June 24, 2009, from Newsroom: http://www.mah.gov.on.ca/Page681.aspx

Ministry of Municipal Affairs and Housing [MMAH]. (2008d). Equipment Efficiency for Buildings of Residential Occupancy. In *2006 Building Code Compendium* (Vol. 1, p. 5). Toronto, ON: Queen's Printer for Ontario.

Ministry of Municipal Affairs and Housing [MMAH]. (2008g). Indoor Design Temperatures. In *2006 Building Code Compendium* (Vol. 1, p. 231). Toronto, Ontario, Canada: Queen's Printer for Ontario.

Ministry of Municipal Affairs and Housing [MMAH]. (2008a). Minimum Thermal Resistance of Insulation to be Installed based on Degree Day Zones. In *2006 Building Code Compendium* (Vol. 1, p. 6). Toronto, ON: Queen's Printer for Ontario.

Ministry of Municipal Affairs and Housing [MMAH]. (2006). Questions and Answers. *Introduction of the 2006 Building Code* . Retrieved June 24, 2009, from http://www.obc.mah.gov.on.ca/site4.aspx

Ministry of Municipal Affairs and Housing [MMAH]. (1998b). Required Insulation. In *Ontario Building Code 1997* (p. 108). Toronto, ON.

Ministry of Municipal Affairs and Housing [MMAH]. (2008c). Thermal Resistance of Windows. In *2006 Building Code Compendium* (Vol. 1, p. 7). Toronto, ON: Queen's Printer for Ontario.

Ministry of Municipal Affairs and Housing. (2008d). Energy Efficiency Design After December 31, 2011. In *2006 Building Code Compendium* (Vol. 1, p. 4). Toronto, ON: Queen's Printer for Ontario.

Ministry of Municipal Affairs and Housing. (2008c). Insulation of Foundation Walls. In *2006 Building Code Compendium* (Vol. 1, p. 7). Toronto, ON: Queen's Printer for Ontario.

Ministry of Municipal Affairs and Housing. (2008e). Insulation of Foundation Walls. In *2006 Building Code Compendium* (Vol. 1, p. 7). Toronto, ON: Queen's Printer for Ontario.

Ministry of Municipal Affairs and Housing. (1998a). Minimum Thermal Resistance of Insulation to be Installed based on Degree Day Zones. In *Ontario Building Code 1997* (p. 108). Toronto, ON.

Ministry of Municipal Affairs and Housing. (1998a). Minimum Thermal Resistance of Insulation to be Installed based on Degree Day Zones. In *Ontario Building Code 1997* (p. 108). Toronto, ON.

Ministry of Municipal Affairs and Housing. (2008a). Minimum Thermal Resistance of Insulation to be Installed based on Degree Day Zones. In *2006 Building Code Compendium* (Vol. 1, p. 6). Toronto, ON: Queen's Printer for Ontario.

Ministry of Municipal Affairs and Housing. (2008a). Minimum Thermal Resistance of Insulation to be Installed based on Degree Day Zones. In *2006 Building Code Compendium* (Vol. 1, p. 6). Toronto, ON: Queen's Printer for Ontario.

Ministry of Municipal Affairs and Housing. (n.d.b). *Questions and Answers*. Retrieved June 24, 2009, from Introduction of the 2006 Building Code: http://www.obc.mah.gov.on.ca/site4.aspx

Ministry of Municipal Affairs and Housing. (1998b). Required Insulation. In *Ontario Building Code 1997* (p. 108). Toronto, ON.

Ministry of Municipal Affairs and Housing. (2008b). Thermal Resistance of Windows. In *2006 Building Code Compendium* (Vol. 1, p. 7). Toronto, ON: Queen's Printer for Ontario.

Ministry of Municipal Affairs and Housing. (n.d.c). *What You Should Know About the 2006 Building Code*. Retrieved June 24, 2009, from Ministry of Municipal Affairs and Housing: http://www.mah.gov.on.ca/Page683.aspx

Mitalas, G. P. (1982). *Basement Heat Loss Studies at DBR/NRC.* DBR Paper No. 1045, NRCC 20416, National Research Council of Canada, Division of Building Research, Ottawa.

National Association of Home Builders [NAHB]. (2007, February). *Study of Life Expectancy of Home Components.* Retrieved January 26, 2011, from http://www.nahb.org/fileUpload_details.aspx?contentID=99359

National Energy Board. (2007). *Canada's Energy Future: Reference Case and Senarios to 2030.* Quebec.

National Research Council of Canada [NRCC]. (2009). *Model Code Adoption Across Canada*. Retrieved March 8, 2010, from National Research Council of Canada: http://www.nationalcodes.ca/ncd_model-code_e.shtml

Natural Resources Canada [NRCan]. (1994). *200-House Audit Project.* Natural Resources Canada, Ottawa, Canada.

Natural Resources Canada [NRCan]. (2011). *Energy Efficiency Trends in Canada 1990 to 2008.* Ottawa, ON: Her Majesty the Queen in Right of Canada.

Natural Resources Canada [NRCan]. (2010). *Energy Use Data Handbook.* Ottawa, ON: Her Majesty the Queen in Right of Canada.

Natural Resources Canada [NRCan]. (2005). *R-2000 Standard (2005 Edition)*. Retrieved July 28, 2009, from http://oee.nrcan.gc.ca/residential/personal/new-homes/r-2000/standard/current/purpose.cfm?attr=4

Natural Resources Canada [NRCan]. (n.d.a). *Residential Sector Canada Table 2: Secondary Energy Use and GHG Emissions by End-Use*. Retrieved January 20, 2010, from Office of Energy Efficiency: http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/tablestrends2/res_ca_2_e_4.cfm?attr=0

Natural Resources Canada [NRCan]. (2010b). *Survey of Household Energy Use 2007. Detailed Statistical Report.* Ottawa, ON: Her Majesty the Queen in Right of Canada.

Natural Resources Canada [NRCan]. (2010a). *Survey of Household Energy Use 2007. Summary Report.* Ottawa, ON: Her Majesty the Queen in Right of Canada.

Natural Resources Canada [NRCan]. (n.d.a). *Table 2: Secondary Energy Use and GHG Emissions by End-Use*. Retrieved January 20, 2010, from Comprehensive Energy Use Database Tables. Residential Sector - Canada.: http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/tablestrends2/res_ca_2_e_4.cfm?attr=0

Natural Resources Canada. (2010a). Dwelling Type. In *Survey of Household Energy Use 2007. Summary Report.* Ottawa, ON: Energy Publications.

Natural Resources Canada. (2010c). Energy source for heating. In *Survey of Household Energy Use 2007. Summary Report.* Ottawa, ON: Energy Publications.

Natural Resources Canada. (2010b). General Characteristics. In *Survey of Household Energy Use 2007. Detailed Statistical Report.* . Ottawa, ON: Energy Publications.

Natural Resources Canada. (2010d). Main heating system. In *Survey of Household Energy Use 2007. Detailed Statistical Report.* Ottawa, ON: Energy Publications.

Natural Resources Canada. (n.d.e). *Space HeatingTable 13: Secondary Energy Use and GHG Emissions by Region - Excluding Electricity-Related Emissions*. Retrieved January 20, 2010, from Comprehensive Energy Use Database Tables. Residential Sector - Canada: http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/tablestrends2/res_ca_13_e_4.cfm?attr=0

Natural Resources Canada. (n.d.c). *Table 1: Total End-Use - Energy Use Analysis*. Retrieved April 22, 2010, from Energy Efficiency Trends Analysis Tables (Canada) Total End-Use Sector: http://www.oee.nrcan.gc.ca/corporate/statistics/neud/dpa/tablesanalysis2/aaa_ca_1_e_4.cfm?attr=0

Natural Resources Canada. (n.d.b). *Table 20: Total Households by Building Type and Principal Heating Energy Source*. Retrieved January 20, 2010 , from Comprehensive Energy Use Database Tables. Residential Sector - Canada: http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/tablestrends2/res_ca_20_e_4.cfm?attr=0

Natural Resources Canada. (n.d.d). *Table 7: Space Heating Secondary Energy Use and GHG Emissions by Energy Source*. Retrieved January 20, 2010, from Comprehensive Energy Use Database Tables. Residential Sector - Canada: http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/tablestrends2/res_ca_7_e_4.cfm?attr=0

Norton, P., & Christensen, C. (2006). A Cold-Climate Case Study for Affordable Zero Energy Homes. *Solar 2006 Conference*, (pp. 1-6). Denver, Colorado.

NRCan. (2007a). *2007 Survey of Household Energy Use (SHEU-2007) - Data Tables*. Retrieved 2010 йил 2-November from Office of Energy Efficiency: http://www.oee.nrcan.gc.ca/corporate/statistics/neud/dpa/data_e/sheu07/sheu_008_1.cfm

NRCan. (1994). *200-House Audit Project.* Natural Resources Canada, Ottawa, Canada.

NRCan. (2006). *Energy Use Data Handbook, 1990 and 1998 to 2004.* Ottawa, ON: Office of Energy Efficiency, Natural Resources Canada.

NRCan. (2010). *HOT2000 Procedures Manual.*

NRCan. (2010). *HOT2000 Procedures Manual.*

NRCan. (2010). *HOT2000 Procedures Manual.* Retrieved Janaury 26, 2011, from http://www.enerquality.ca/site/enerquality/assets/pdf/A_-_HOT2000_Procedures_Manual_March_2010.pdf

NRCan. (1995). *HOT2000 V.7.10 User's Manual for DOS for Macintosh computers.* CANMET/EAETB, Ottawa, Canada.

NRCan. (2007b). *Keeping the heat in.* Ottawa, ON: Natural Resources Canada.

NRCan. (2005). *R-2000 Standard (2005 Edition)*. Retrieved 2009 йил 28-July from http://oee.nrcan.gc.ca/residential/personal/new-homes/r-2000/standard/current/purpose.cfm?attr=4

NRCan. (1997-2005). RETScreen® Software Online User Manual. Canada: Minister of Natural Resources Canada.

NRCan. (1997-2000). Utility Peak Load Shaving / Ontario, Canada. Photovoltaic Project. Teacher's Note 01. Canada: Minister of Natural Resources Canada.

Ontario Energy Board (OEB). (2008). *Natural Gas Rates - Historical*. Retrieved May 29, 2010, from http://www.oeb.gov.on.ca/OEB/Consumers/Natural+Gas/Natural+Gas+Rates/Natural+Gas+Rates+-+Historica

Ontario Ministry of Energy [OME]. (2010). *Ontario's Long-Term Energy Plan.* Queen's Printer for Ontario.

Ontario Ministry of Finance [OMF]. (2010). Public Accounts of Ontario 2008-2009. Queen's Printer for Ontario. Retrieved May 29, 2010, from Ministry of Finance / Ministère des Finances: http://www.fin.gov.on.ca/en/budget/paccts/2009/

Ontario Power Authority [OPA]. (2010). *microFIT pricing*. Retrieved December 16 2010, 2010, from Renewable energy micro feed-in tariff program: http://microfit.powerauthority.on.ca/microFIT-Rules/microFIT-Program-pricing/index.php

Ouazia, B., Barhoun, H., Haddad, K., Armstrong, M., Marchand, R., & Szadkowski, F. (2009). DESICCANT EVAPORATIVE COOLING SYSTEM FOR RESIDENTIAL BUILDINGS. *12th Canadian Conference on Building Science and Technology*, (pp. 1-12). Montreal, Quebec.

Parekh, A., Roux, L., & Gallant, P. (2007). Thermal and Air Leakage Characteristics of Canadian Housing. *11th Canadian Conference on Building Science and Technology*. Banff, AB.

Parker, D. S. (2008). *Very Low Energy Homes in the United States: Perspectives on Performance from Measured Data.* Cocoa, Florida: Florida Solar Energy Center/University of Central Florida.

RSMeans. (2010). *Building Construction Cost Data* (68th Annual ed.). Kingston, MA: Construction Publishers & Consultants.

Ruegg, R. T., & Marshall, H. E. (1990). *Building Economics - Theory and Practice.* New York: Van Nostrand Reinhold.

Sambou, V., Lartigue, B., Monchoux, F., & Adj, M. (2009). Thermal optimization of multilayered walls using genetic algorithms. *Energy and Buildings , 41*, 1031-1036.

Scanada. (1992). *Statistically Representative Housing Stock.* Final Report, Submitted to Canada Mortgage and Housing Corporation, Ottawa, Canada.

Statistic Canada. (2011). *Annual Demographic Estimates: Subprovincial Areas 2005 to 2010.* Ottawa, ON: Minister of Industry.

Statistic Canada. (2010). *Estimates of Population by Age and Sex for Canada, Provinces and Territories.* Ottawa, ON: Minister of Industry.

Statistic Canada. (n.d.b). *Population by year, by province and territory (Number)*. Retrieved January 20, 2010, from Statistic Canada: http://www40.statcan.gc.ca/l01/cst01/demo02a-eng.htm

Statistics Canada. (2010). *Energy Statistics Handbook.* Ottawa: Minister of Industry.

Statistics Canada. (2011). *Estimates of Population by Age and Sex for Census Divisions, Census Metropolitan Areas and Economic Regions (Component Method).* Ottawa, ON: Minister of Industry.

Statistics Canada. (n.d.a). *Household size, by province and territory (2006 Census) (New Brunswick, Quebec, Ontario) Summary Tables. Last updated October 3, 2007*. Retrieved August 29, 2010, from http://www40.statcan.gc.ca/l01/cst01/famil53b-eng.htm

Statistics Canada. (2007). *Households and the Environment: Energy Use.* Ottawa, ON: Minister of Industry.

Statistics Canada. (n.d.a). *Population of census metropolitan areas (2006 Census boundaries)*. Retrieved January 19, 2010, from Statistics Canada: http://www40.statcan.gc.ca/l01/cst01/demo05a-eng.htm?sdi=population

Statistics Canada. (2007). Population, Occupied Private Dwellings, Private Households, Average Number of Persons per Private Household, Collective Dwellings and Population in Collective Dwellings of Canada, Provinces and Territories, 1971 to 2006 Censuses - 100% Data. Retrieved August 29, 2010, from http://www.statcan.gc.ca/bsolc/olc-cel/olc-cel?catno=97-554-XWE2006036&lang=eng#formatdisp

Statistics Canada. (n.d.b). *Table 027-0015 Canada Mortgage and Housing Corporation, conventional mortgage lending rate, 5-year term, monthly (percent). CANSIM. Using E-STAT. Last updated June 2010*. Retrieved July 13, 2010, from http://estat.statcan.gc.ca/cgi-win/cnsmcgi.pgm?Lang=EESTAT/&C2DB=EST&ArrayId=270015&Array_Pick=1&Detail=1&ResultTemplate=ESTAT/CII___

Statistics Canada. (n.d.a). *Table 027-0015*. Retrieved July 13, 2010, from CANSIM: http://estat.statcan.gc.ca/cgi-win/cnsmcgi.pgm?Lang=EESTAT/&C2DB=EST&ArrayId=270015&Array_Pick=1&Detail=1&ResultTemplate=ESTAT/CII___

Statistics Canada. (n.d.c). *Table 326-0021 Consumer Price Index (CPI), 2005 Basket Content, Annual. CANSIM. Using E-STAT. Last updated March 2010*. Retrieved July 16, 2010, from http://estat.statcan.gc.ca/cgi-win/cnsmcgi.pgm?Lang=E&ArrayId=3260021&Array_Pick=1&Detail=1&ResultTemplate=ESTAT/CII___&RootDir=ESTAT/

Statistics Canada. (n.d.b). *Table 326-0021*. Retrieved July 16, 2010, from http://estat.statcan.gc.ca/cgi-win/cnsmcgi.pgm?Lang=E&ArrayId=3260021&Array_Pick=1&Detail=1&ResultTemplate=ESTAT/CII___&RootDir=ESTAT/

Statistics Canada. (1993). *The Survey of Household Energy Use, Microdata User's Guide.* Ottawa, Canada.

Stein, J. R., & Meier, A. (2000). Accuracy of home energy rating systems. *Energy 25* , 339-354.

Swinton, M. C., Manning, M. M., Elmahdy, A. H., Parekh, A., Barry, C., & Szadkowski, F. (2007). Field assessment of the effect of different spectrally selective low emissivity glass coatings on the energy consumption in residential application in cold climates. *11th Canadian Building Science and Technology Conference*, (pp. 1-16). Banff, Alberta.

Torcellini, P. A., & Crawley, D. B. (2006 йил September). Understanding Zero-Energy Buildings. *ASHRAE Journal* , 63-69.

Torcellini, P. A., Hayter, S. J., & Judkoff, R. (1999). Low-Energy Building Design - the Process and a Case Study. *ASHRAE Transactions: Symposia , 105*, 802-810.

Torcellini, P., Pless, M., Deru, M., & Crawley, D. (2006). Zero Energy Buildings: A Critical Look at the Definition; Preprint. *ACEEE Summer Study*, (p. 12). Pacific Grove, CA.

Tse, H., Siddiqui, O., Fung, A. S., & Masoumi Rad, F. (2008). Simulation and Analysis of a Net-Zero Energy Townhome in Toronto. *3rd Canadian Solar Buildings Conference.* Fredericton, NB, August 20-22, 2008.

Tse, H., Siddiqui, O., Fung, A. S., & Masoumi Rad, F. (2008). Simulation and Analysis of a Net-Zero Energy Townhome in Toronto. *3rd Canadian Solar Buildings Conference.* Fredericton, NB, August 20-22, 2008.

U.S. Energy Information Administration [EIA]. (2005). *Table US9. Average Consumption by Fuels Used, 2005 Million British Units (Btu) per Household*. Retrieved 2010 йил 16-August from 2005 Residential Energy Consumption Survey--Detailed Tables: http://www.eia.doe.gov/emeu/recs/recs2005/c&e/summary/pdf/tableus9.pdf

Ugursal, I. V., & Fung, A. S. (1996). Impact of appliance efficiency and fuel substitution on residential end-use energy consumption in Canada. *Energy and Buildings , 24* (2), 137-146.

Ugursal, I. V., & Fung, A. S. (1996). Impact of appliance efficiency and fuel substitution on residential end-use energy consumption in Canada. *Energy and Buildings , 24* (2), 137-146.

Ugursal, V. I., Ma, B., & Li, C. (1992). Thermal performance and economic feasibility of a low energy house equipped with an air-source heat pump. *Annual Meeting of the American Society of Mechanical Engineers*, *28*, pp. 111-117. New York, NY.

Van der Veken, J., Saelens, D., Verbeeck, G., & Hens, H. (2004). Comparison of Steady-State and Dynamic Building Energy Simulation Programs. *ASHRAE Transactions* , 1-11.

Verbeeck, G., & Hens, H. (2007). Life Cycle Optimization of Extremely Low Energy Dwellings. *Journal of Building Physics , 31* (2), 143-177.

Walker, I. S., & Wilson, D. J. (1990). *The Alberta Air Infiltration Model, AIM-2*. Report 71, University of Alberta, Department of Mechanical Engineering.

Walker, I., & Wilson, D. (1998). Field validation of algebraic equations for stack and wind driven air infiltration calculations. *HVAC&R* , 119-139.

Witte, M. J., Henninger, R. H., Glazer, J., & Crawley, D. B. (2001). TESTING AND VALIDATION OF A NEW BUILDING ENERGY SIMULATION PROGRAM. *Seventh International IBPSA Conference*, (pp. 353-360). Rio de Janeiro.

Wojdyga, K. (2009). An investigation into the heat consumption in a low-energy building. *Renewable Energy* , 1-5.

Zheng, M., & Pan, S. (2007). Application as Commissioning Tool of Various HVAC Simulation Programs and Visual Tools. *Tenth International IBPSA Building Simulation Conference 2007*, (pp. 1975-1982). Beijing, China.

Zmeureanu, R., Fazio, P., DePani, S., & Calla, R. (1999). Development of an energy rating system for existing houses. *Energy and Buildings* (29), 107-119.

Glossary

C	Ceiling
C1	RSI 8.81 (R50) Insulation
C2	RSI 10.57 (R60) Insulation
AGW	Above Grade Walls
AGW1	RSI 3.87 (R22) Insulation
AGW2	RSI 4.22 (R24) Insulation
AGW3	RSI 4.75 (R27) Insulation
AGW4	RSI 5.10 (R29) Insulation
AGW5	RSI 4.22 (R24) Insulation @ 600 mm (24 in.) o/c
AGW6	RSI 4.57 (R26) Insulation @ 600 mm (24 in.) o/c
AGW7	RSI 5.10 (R29) Insulation @ 600 mm (24 in.) o/c
AGW8	RSI 7.00 (R40) Insulation
BGW	Below Grade Walls
BGW1	RSI 2.11 (R12) Insulation, Exterior
BGW2	RSI 3.5 (R20) Insulation
BGW3	RSI 3.5 (R20) Insulation, Exterior
BGW4	RSI 3.87 (R22) Insulation
BGW5	RSI 4.22 (R24) Insulation
BGW6	RSI 4.22 (R24) Insulation (ICFs)
EF	Exposed Floor
EF1	RSI 5.45 (R31) Insulation
EF2	RSI 5.10 (R29) Insulation
BS	Basement Slab
BS1	RSI 2.11 (R12) Insulation
BS2	RSI 3.5 (R20) Insulation
W	Windows
W1	U1.6
W2	U1.8
W3	U2.0
V	Ventilation
V1	HRV @ 70% Efficiency
AC	Cooling
AC1	SEER of 14
GH	Gas Heating
GH1	Furnace w/ ECM @ 90% AFUE
GH2	DHW Heater @ 85% AFUE
GH3	DHW Heater @ 90% AFUE
GH4	Solar-Assisted DHW @ 85% AFUE
GH5	Solar-Assisted DHW @ 90% AFUE

GH6	Drain Water Heat Recovery @ 55% Efficiency
EH	Electrical Heating
EH1	Ground Source Heat Pump @ COP 3.2/4.32 (Heating/Cooling)
EH2	Air Source Heat Pump, 1-Stage, SEER of 14
EH3	Air Source Heat Pump, 2-Stage
EH4	Solar-Assisted DHW w/ Electric Backup @ 100% Efficiency (CSIA Rating: 10400 MJ/year)
EH5	Solar-Assisted DHW w/ Electric Backup @ 100% Efficiency (CSIA Rating: 13600 MJ/year)
EH6	Drain Water Heat Recovery @ 55% Efficiency