A METHODOLOGY FOR CODE-COMPLIANT DESIGN BASED ON LIFECYCLE ANALYSIS FOR HOUSING IN COLD CLIMATES

by

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Abstract

Well-designed walls and windows play a major role in reducing heating energy usage in the home in cold climates. There are also different design options to improve home energy efficiency which have different cost impacts. This study presents a methodology to determine code-compliant energy-efficient window design (type and sizing), wall insulations, and house designs with the least lifecycle cost for homes in Edmonton, Alberta. Window types and wall insulations are selected according to code prescriptive requirements, and designs are selected according to code energy performance requirements. Literature has shown that a more-energy-efficient mechanical system (space heating system, heat recovery ventilation and domestic hot water heating system), improved building envelope (wall, window, attic and exposed floor), and installation of a PV system are solutions commonly considered in house designs. A sensitivity analysis on the cost effectiveness of these design options is thus conducted in this research using a case study. With the cost scheme predicted based on historical data, the results show a 16% decrease in the window lifecycle cost by using double-pane window with one heat mirror film between the panes rather than triple-pane window, and a 30% reduction in the wall lifecycle cost by using fibreglass batt and rigid foam insulations rather than polyurethane spray foam insulation. The forced-air space heating system using natural gas furnace is found to be the most economical heating system when compared with boiler, electric baseboard, and air-source heat pump. Design using the natural gas furnace heating system, hot water heater, and ventilation, as well as minor envelope upgrades from the base design case results in the least lifecycle cost to achieve the desired improved energy performance. Two other cost schemes are also considered in the sensitivity analysis.

Acknowledgements

My deepest gratitude goes to my supervisors, Dr. Mohamed Al-Hussein and Dr. Yuxiang Chen at the University of Alberta. It has been a real pleasure and learning experience working under their continual guidance and support throughout this study.

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Nomenclature

ABC	Alberta Building Code
ABS	Absorption Air Conditioner System
AC	Air Conditioner
ACH	Air Changes Per Hour
AFUE	Annual Fuel Utilization Efficiency
BIM	Building Information Modelling
CCBFC	Canadian Commission of Building and Fire Codes
CMHC	Canada Mortgage and Housing Corporation
CPEI	Cumulative Primary Energy Input
CPI	Consumer Price Index
DG	Double Glazing
DHW	Domestic Hot Water
DOE	U.S. Department of Energy
EPS	Expanded Polystyrene
EF	Energy Factor
ER	Energy Rating

EGH	EnerGuide rating for Houses
GHG	Greenhouse Gas
GSHP	Ground Source Heat Pumps
HDD	Heating Degree Days
HM	Heat Mirror
HRV	Heat Recovery Ventilator
HSPF	Heating Season Performance Factor, in watt-hours
HVAC	Heating, Ventilation, and Air Conditioning
LCCA	Lifecycle Cost Analysis
LCC	Lifecycle Cost
NAC	Normalized Annual Energy Consumption
NBCC	National Building Code of Canada
NBIMS	U.S. National Building Information Modeling Standard
NRC	National Research Council of Canada
NRCan	Natural Resources Canada
OBC	Ontario Building Code
PV	Photovoltaic

SHGC	Solar Heat Gain Coefficient
SRE	Sensible Heat Recovery Efficiency
TDHP	Thermal Driven Heat Pumps
TG	Triple Glazing
WWR	Window-to-Wall ratio
XTPS	Extruded Polystyrene

CHAPTER 1: INTRODUCTION

The residential building sector is one of the major energy consumers in North America. It accounts for 17% of energy used in Canada, resulting in 70 megatons (Mt) of annual greenhouse gas (GHG) emissions (Canada Mortgage and Housing Corporation (CMHC) 2008). According to Natural Resources Canada (NRCan 2010a), 65% of residential energy consumption is attributed to space heating by means of the primary fuel types, natural gas and electricity (Statistics Canada 2007).

Due to the importance of reducing energy consumption from limited energy sources and minimizing environmental impacts, a number of energy-efficiency measures have emerged for Canadian residential buildings in recent years. Provincial and national building energy codes have been modified and many programs have been initiated concerning the minimum building energy performance level.

Building energy codes set the minimum requirements that must be satisfied in order to achieve high energy efficiency for new and renovated buildings (DOE 2016) and have a significant impact in terms of reducing energy demand and GHG emissions. For instance, it is estimated that $126 billion energy cost and 841 million metric tons (MMt) CO_2 emissions (equivalent to 245 coal power plants) reductions would be achieved for U.S. homes and commercial buildings over 30 years by following building energy codes (DOE 2016). As a result, in recent years stringent energy codes have begun to be enforced in many countries including Canada for the residential and commercial sectors (Young 2014).

Although energy codes are provided for designers, there are still several challenges such as different material, technique and building product choices which are not addressed in energy codes and must be taken in to account. For instance, the minimum effective R-value of building envelope is prescribed in the codes; thus, home designers can easily determine how much insulation is needed in a building, but the decision is left to the designer to determine whether to select the minimum insulation level to meet building code, or to invest more in building envelope materials with better thermal performance and operational energy savings.

Since cost is a major concern in construction projects, there are several studies which evaluate different design parameters such as wall construction, window types and sizes and HVAC system to determine the best design solutions that minimize the lifecycle cost while complying with the energy code requirements (Bichiou and Krarti 2011). In this regard, Hamelin and Zmeureanu (2014) conducted a lifecycle cost analysis (LCCA) in a single-family home in Québec; they presented the optimum thermal resistance value of building envelope that achieved the minimum lifecycle cost. The insulation level of recommended design in their study was much higher than code requirements. This is due to the fact that the lifespan of an actual house is quite long, which provides a substantial energy savings from better insulation and would have offset the additional initial cost in this case.

Given that cost is an important consideration in construction, this thesis aims to identify energy-efficient code-compliant solutions for cold climates from a cost efficiency point of view.

1.1 Energy Consumption in Canadian Residential Sector

According to NRCan (2010c), there are four types of dwellings in Canada: single detached home (56%), apartment (31%), single attached home (11%), and mobile home (2%). Figure 1-1 illustrates that residential buildings are the third largest energy users in Canada after the industrial and transportation sectors, and that the residential sector is also responsible for 17% of the total consumed energy (NRCan 2008b).

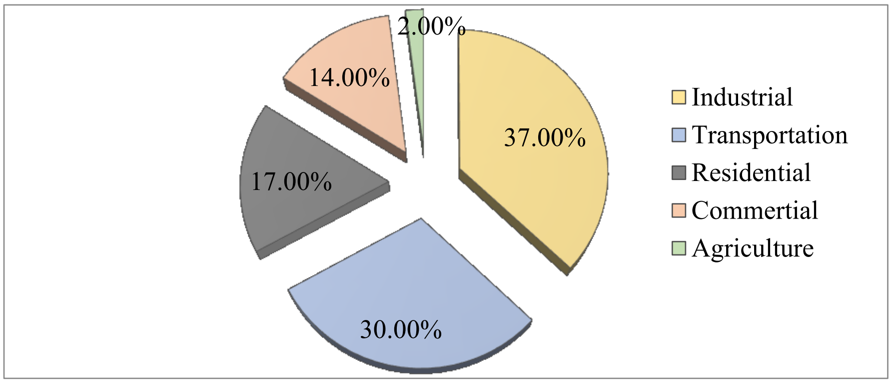

Figure 1-1: Breakdown of Energy use by sector in Canada (NRCan 2008b)

Most regions in Canada feature an extremely cold climate and a long winter, thus almost two thirds of the energy used in residential buildings is attributed to heating indoor spaces; the remaining energy is used for water heating (17%), appliances (14%), lighting (4%), and space cooling (2%) (NRCan 2010a). In addition, a large amount of heat is lost due to transfer from interior to exterior through various building components; this lost heat has to be replaced by the heating system, thereby causing further energy consumption in buildings (NRCan 2007a). As stated by NRCan (2007a), most heat loss in buildings occurs through air leakage, windows, exterior walls, and basements. Figure 1-2 indicates the distribution of annual heat loss by different components in a home (NRCan 2007a).

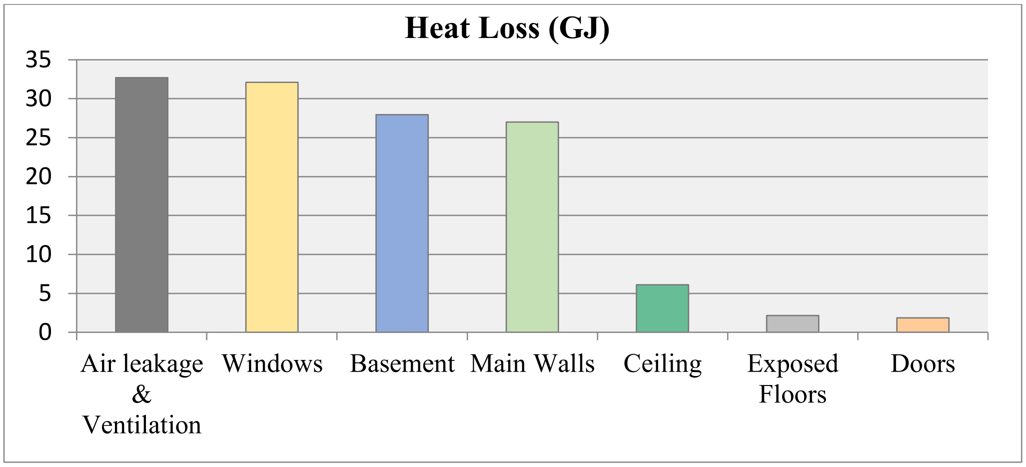

Figure 1-2: Annual heat loss distribution by different components (NRCan 2007a)

Canadians have different options available for their heating energy sources, such as electricity, propane, natural gas, oil, wood, and solar energy; some even use more than one fuel type for space heating (NRCan 2010a). As can be seen in Figure 1-3, natural gas and electricity are major fuel types used for household space heating in Canada; however, their distribution varies in different regions. For instance, in Alberta, ~81% of households consume natural gas as their main energy source, while only 12% are heated with electricity. In contrast, 76% of homes in Québec are heated with electricity, though most of its western regions use natural gas for space heating (NRCan 2007b). Figure 1-4 illustrates the average household energy consumption of all fuel types in the more populous provinces of Canada.

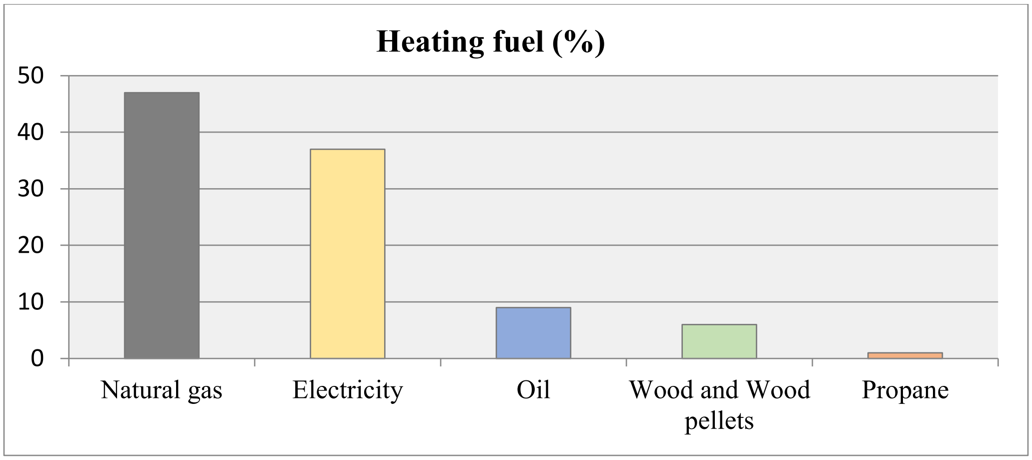

Figure 1-3: Main heating fuel types used in Canada (Statistics Canada 2007)

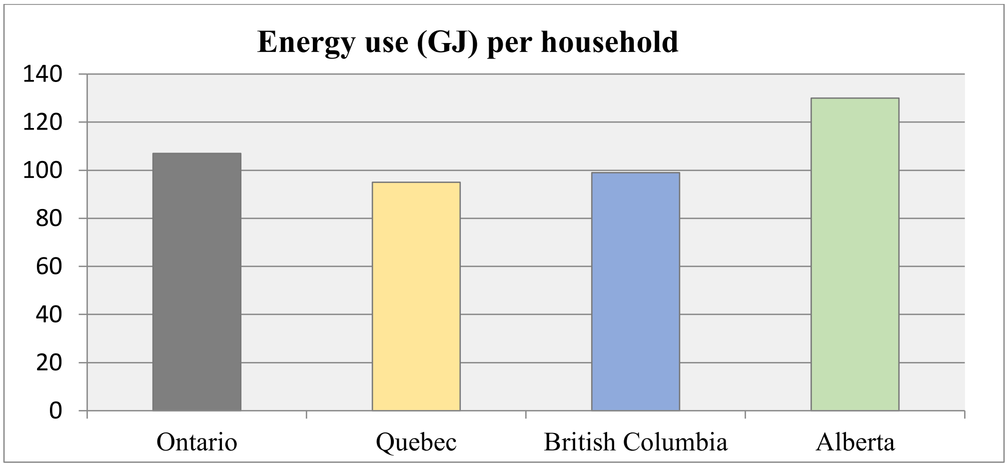

Figure 1-4: Average household energy consumption in Canada (Statistics Canada 2011)

1.2 Research Objectives and Scope

The overall objective of this thesis is to present a methodology to determine code-compliant energy-efficient solutions with the least lifecycle cost (LCC) for homes in Edmonton, Alberta, considering the initial cost and 30-year operation cost. This evaluation will be presented in three parts:

a. Window design, including window type, style, and size.
b. Insulation type within above- and below-grade wood-framed wall assemblies.
a. House upgrade approaches, focusing on space heating system, heat recovery ventilation (HRV), building envelope, domestic hot water heating system (DHW), and solar photovoltaic (PV) system.

1.3 Thesis Organization

The dissertation is organized as follows:

Chapter 2: Literature review, which will discuss the following areas of research: (1) national and Alberta building codes, (2) new approaches in high-performance housing and studies regarding energy-efficient houses; (3) research methodologies for the evaluation of building upgrades; and (4) common energy simulation tools and their capabilities.

Chapter 3: Research Methodology, where the selected house type and necessary information for LCCA are summarized. In addition, key selection criteria for window types, wall insulations, and house upgrade approaches are presented, followed by potential designs and methods of LCC estimations.

Chapter 4: Presentation of results and discussion.

Chapter 5: Conclusions and recommendations for future work.

CHAPTER 2: LITERATURE REVIEW

The literature review provides a background on the Alberta Building Code (ABC) 2014 and a survey of studies conducted to improve building energy performance. A number of new approaches are presented in this chapter which are in contrast to traditional approaches to high-performance housing. Finally, common research methodologies are discussed in order to evaluate building upgrades and energy simulation tools for the purpose of finding an appropriate approach for this study.

2.1 National and Alberta Building Codes

A code, by definition, is "*a collection of requirements, policies, and rules pertaining to a specific subject or activity, to set standards which pertain to that subject or activity*" ((Ontario Building Official Association 2009). Building code, then, is a standard guideline which involves the review of technical concerns and safety codes for new and existing building construction that has to be followed by designers, engineers, architects, and all other participants in construction projects.

The first National Building Code of Canada (NBCC) was developed by Canadian Commission of Building and Fire Codes (CCBFC) and published in 1941 by National Research Council of Canada (NRC). In general, the codes address the following subjects (NRCan 2015):

- National Building Code
- National Fire Code
- National Plumbing Code
- National Farm Building Code

- National Energy Code

However, since Canada has different climate conditions from one region to another, some municipalities in this country have established their own building regulations based on the concept of the NBCC (Table 2-1) and others have followed the National Building Code (NBC) with further modifications (Table 2-2). As a result, building codes vary from one province to another (NRCan 2011c).

Table 2-1: Provinces that published their own building codes

Alberta and British Columbia	Building, Fire, and Plumbing Codes are consistent with National Building Codes with some modifications.
Ontario	Building and Plumbing Codes are based on National Building Codes with substantial variations. The Ontario Fire code is different from National Fire Code. In addition, Ontario refers to the National Energy Code in their Energy Codes.
Québec	Building and Plumbing Codes are consistent with National Building Code and Plumbing Code with some modifications. The National Fire Codes are adopted by major municipalities.

Source: (NRCan 2011c)

Table 2-2: Provinces that adopted the National Building Codes

New Brunswick, Nova Scotia, Manitoba, and Saskatchewan	The National Building Code, National Fire Code, and National Plumbing Code are adopted with some modifications.
Newfoundland and Labrador	The National Fire Code and Building Code are adopted except for regulations concerning the means of egress and one- and two-family dwellings of group C in part 9. Plumbing Codes are not adopted.
Northwest, Territories, Nunavut, and Yukon	The National Building Code and National Fire Code are adopted with some additional modifications. Yukon follows the National Plumbing Code.
Prince Edward Island	The National Plumbing Codes are adopted. Main municipalities adopt the National Building Code but The National Fire Codes are not followed.

Source: (NRCan 2011c)

Both national and provincial codes have been changed in recent years to meet the increasing demand to reduce residential energy consumption (Kraljevska 2014). According to the Ministry of Municipal Affairs and Housing (2010), the improvement of codes for buildings constructed after 2011 has resulted in a 35% increase in building energy performance compared with those built before 2006.

In general, Canada is divided into climate zones ranging from 3,000 to 8,000 heating degree days (HDD), and each zone contains areas with the same climate condition and heating demands

(NRCan 2011a). The province of Alberta is committed to deploy the National Building Code as a baseline to publish its own regulations based on the corresponding climate zone and HDD. This thesis, in particular, considers the Alberta climate zone for the city of Edmonton (5,000 < HDD < 5,999), which, as indicated by a gold star on the map in Figure 2-1, is located in zone 7A.

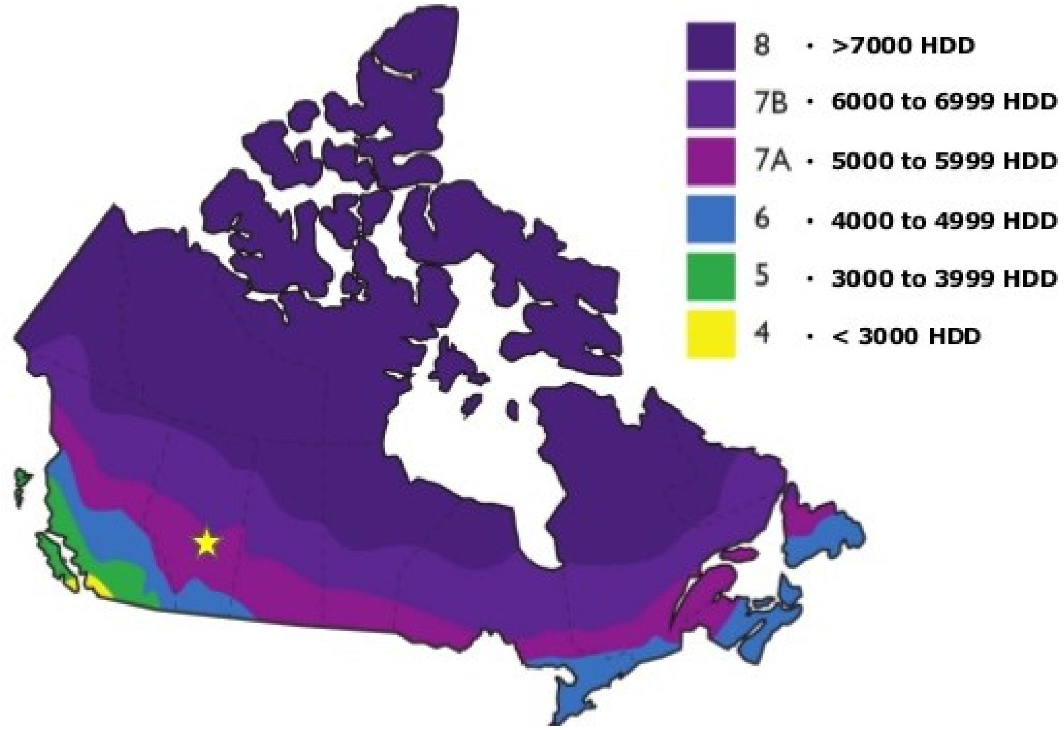

Figure 2-1: Average heating degree days (HDD) in Canada (Graham Finch 2013)

The Alberta Building Code (ABC) includes technical rules for new buildings as well as the retrofit of existing buildings to address the following areas (ABC 2014e):

- health and safety;
- structural and fire protection of building;
- environment;

- ease of access for persons with disabilities.

There are three pathways to code compliance for residential buildings, which include:

1. **Prescriptive path**: The prescriptive pathway is the simplest method of code compliance. It is basically a check-list containing all building requirements for a specific climate zone (Thermal wise Co. 2016).
2. **Trade-off path**: The trade-off path follows the prescriptive path but agrees to trade between building elements. It allows more flexibility to designers, for instance, if the design requires more windows than required by the code, it will be made possible by improving the insulation of walls. Trade-off path only applies to above-grade building envelopes and does not consider the HVAC system or hot water heater in calculations (NRCan 2014).
3. **Performance path**: The performance path is a method that demonstrates that a building is as efficient as the one built in accordance with the prescriptive path. The performance path provides the opportunity to design a building with more flexibility but further complexity. According to building codes, the following building types and sizes qualify for the performance pathway (ABC 2014a):
    - Houses with or without a secondary suite
    - Buildings containing only residential units with common spaces ≤ 20% of total floor area

The ABC prescriptive codes are concerned with the energy consumption of buildings as a result of:

a) Designing the building envelope,
b) Designing equipment for:
    i. heating, ventilation and air conditioning (HVAC) system, and
    ii. hot water system.

Building envelope refers to *"components or assemblies of the building that separate conditioned space from unconditioned space, the exterior air or the ground"*. In general, the building envelope is divided into three parts, including (ABC 2014c):

- above ground opaque building assembly;
- fenestration, doors and skylights;
- building assemblies below-grade or in contact with ground.

However, the requirements of the ABC are more concerned with the thermal characteristics of building envelope assemblies such as the amount of heat transfer and air leakage that may occur based on the material used (ABC 2014c). The thermal resistance of building envelope is determined through calculation and computer programs and must comply with minimum ABC 2014 requirements, which are provided in the Appendix. Additionally, reducing the air leakage of building envelope is an essential factor in designing low-energy homes and should be controlled to meet the code requirements.

Although improving the air tightness of buildings provides many benefits, it should be pointed out that this may also lead to reduced air movement. As a result, mechanical ventilation is needed to control indoor air quality. The heat recovery ventilator (HRV) is a ventilation system deployed to control air humidity, reduce pollutants, and improve fresh air circulation within a building (NRcan 2016).

2.2 Energy-efficient Housing

Energy efficiency plays a significant role in public policies in developed countries. Patterson (1996) defines energy efficiency as "*using less energy to produce the same amount of services or useful output*". Energy conservation measures are usually developed for existing buildings that need to be refurbished or new building construction. As a consequence, buildings will lead to a significant reduction in energy consumption but additional construction costs (Chwieduk 2003).

In Canada, many efforts have been put forth in the development of low-energy homes. For example, the government of Canada has invested $195 million toward studies and research in low-energy homes to improve the energy performance of buildings (Government of Canada 2013). In addition, the Office of Energy Efficiency (OFF) has developed a number of programs, such as R-2000, EnerGuide, and ecoEnergy (OEE 2011), for the purpose of encouraging Canadians to consider energy efficiency in housing design. As stated in the report published by Natural Resources Canada (NRCan), the ecoEnergy program provides motivation for Canadian homeowners, and has led to $400 million in savings on their annual energy bills over five years

(NRCan 2007a). Table 2-3 lists a number of prominent energy efficiency programs and their year of initiation for housing in Canada.

Table 2-3: List of energy efficiency programs for houses in Canada

Initiated year	Program
1982	R-2000
1998	EnerGuide for houses
1999	Novoclimat
2001	Energy Star program
2003	BuiltGreen^{TM} in Alberta
2005	EQuilibrium™ in Québec
2007	LEED for homes
2007	ecoEnergy

Source: (Choudhary 2014; NRCan 2016b; NRCan 2016d)

Similar to Canada, the U.S. department of energy (DOE) of residential buildings has initiated a research approach aiming to reduce 90% of residential energy use by 2025 (Anderson et al. 2006). A key factor in this program is finding the affordable energy saving solutions among all possible practices (Lutz et al. 2006). Furthermore, according to the literature, a large number of studies have been reported in Europe to reduce the energy consumption of residential sectors in an economical way (Verbeeck and Hens 2005; Feist 1998). In general, there are a number of primary concerns in designing an energy-efficient building, which include the following (HPO 2014):

- building envelope (insulation levels and windows);
- space heating, cooling, and heat recovery system;
- hot water heating system;
- renewable energy system;
- lighting and electrical system.

Thermal insulation is a practical step toward energy-efficient building design (Al-Homoud 2005). Deploying insulation in building envelope components enhances the thermal resistance and reduces the conduction heat loss (Asadi 2012). Therefore, proper use of insulation level and insulation material within the building envelope is a strong solution to achieve low-energy design. Generally, improving insulation results in two economic consequences: (1) additional upfront cost, and (2) less energy consumption and operation costs. There are various studies which compare the lifetime cost savings in buildings with the additional upfront cost due to insulation improvement in order to determine whether better insulation is economically worthwhile. In this regard, the U.S. DOE provides a guideline to recommend the level of insulation required for new or existing buildings based on LCCA in different climate conditions in the United States (Ornl 2002).

In general, the thermal resistance (R-value) of insulation is dependent upon level of thickness and material type (Ornl 2002). A number of common insulation types are described in more detail below:

- Spray foam insulation is usually made of polyurethane that is sprayed into the wall or attic cavity or directly on to the wall surface. It has higher R-value than fibreglass, cellulose, and mineral wool insulation types and also provides greater protection against air leakage (Green Building Advisor 2014).
- The most common insulation type available on the market is blanket insulation that can be in the form of batts or rolls. Blanket insulations are made from mineral wool, fiber (i.e., cotton, sheep's wool) and most commonly fibreglass, and are available in various widths and thermal resistance levels (U.S. DOE).
- Blown-in or loose-fill insulating is a technique that blows insulation into any space where it is difficult to use other types of insulation. The most common materials used for this are cellulose and fibreglass made from recycled wastes such as newsprint (U.S. DOE). Although this technique is more common in attic insulation, it is also used within wall cavities through some innovative methods (Aderholdt 2011).
- Rigid insulation is a thin foam board which is applicable for exterior and basement walls and provides almost two times better thermal resistance than other insulations of the same thickness. Polyisocyanurate, extruded polystyrene (XTPS), and expanded polystyrene (EPS) are common materials used to fabricate rigid foams (Asadi 2012). EPS and XTPS are made from the same materials, but undergo different manufacturing processes. In addition, XTPS features better R-value and moisture resistance (Owens Corning Co. 2014).

Window design also plays an important role in building energy performance (Susorova et al. 2013). Selecting the proper window for a specific home is more complicated than wall system selection because window performance depends on two variables, R-value and solar heat gain coefficient (SHGC), which usually move inversely (when the R-value increases, the SHGC decreases), whereas it is usually desired to have a window with both high SHGC and thermal resistance in cold climates. On the other hand, the performance of a wall system depends on one variable (R-value). In addition, windows are 3 to 7 times more expensive than wall systems with the same area (Proskiw 2010).

As shown in Figure 2-2, window configuration consists of different zones, and all zones have a direct effect on the total thermal performance of a window. The key zone in a window is the glazing zone, which consists of single, double (DG), triple (TG) or rarely quadruple glass sheets separated by spaces.

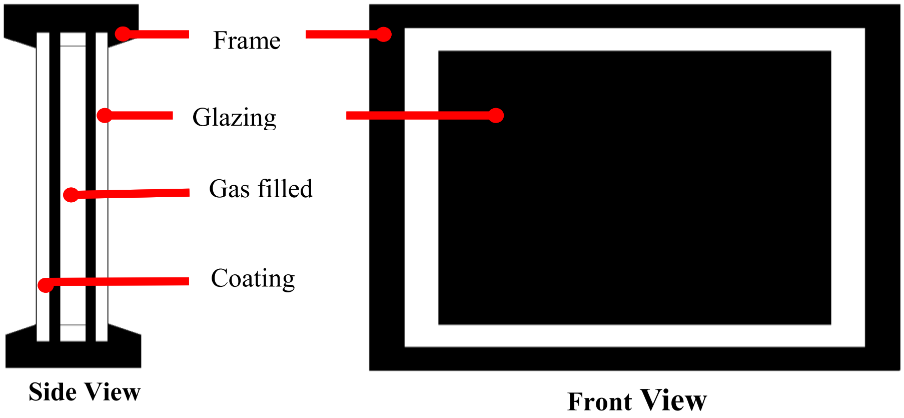

Figure 2-2: Window properties (Karlsson 2001)

Adding heat mirror (HM) films within double-pane glazing is an advanced strategy to improve the U-value of windows. As a result, the double-pane window with one layer of HM film in between performs as well as one which is triple-pane with the benefit of weighing almost equal as a double-pane window.

Table 2-4 presents the advantage of HM film over glazing (Albo Co. 2001). There are various types of HM films with different reflectance and light transmittance on the market such as HM 88, 66, and 55 (West Island Glass 2016). Heat mirror with a greater number features higher visible light transmission and solar heat gain (Albo Co. 2001).

Table 2-4: Comparison between DG, DG+HM, and TG

Window type	Thickness (mm)	Weight (Kg/m^2)	U-value (W/m^2•K)
Low-e double-pane glazing, argon-filled	24.5	20	1.14
Low-e double-pane glazing with one film in between (TC88), argon-filled	32.5	20	0.78
Low-e triple-pane glazing, argon-filled	32.5	30	0.82

Source: (Albo Co. 2001)

Filling the window cavity with a type of heavy gas (i.e., argon, krypton) reduces convection loss and heat transfer (Bülow-Hübe 2001). In addition, the spacing distance between panes affects the U-value of windows. Karlsson (2001) found that, for double-pane windows filled with argon or krypton gas, the optimum spacing distance with the lowest U-value is somewhere between 10 mm to 15 mm.

Applying low emissivity (low-e) coating to the glazing has considerable impact on reducing the U-factor of windows. Emissivity value of coatings is the ratio of heat emitted compared to a black body (Wikipedia 2016b). Low-e coatings are classified into two types: soft (silver), and hard (tin-oxide) (Karlsson 2001). The soft type has lower emissivity and heat loss compared to the hard type, whereas, hard low-e coating is more durable and allows more sunlight to enter (BuildingGreen Inc. 2012). Generally, windows are measured based on the value outlined below:

- U-factor ($W/m^2 \bullet K$), which is a parameter related to the amount of heat loss through the window per m^2 and the temperature difference between interior surface and exterior surface (Karlsson 2001). A low U-factor results from a well-insulated window (EnerGlaze 2013). Thermal resistance (R-value) is the inverse of U-factor, and effective thermal resistance indicates the overall thermal performance of a window accounting for all window assemblies (Armstrong et al. 2008).
- Energy rating (ER), which is a value that measures the overall thermal performance of a window based on the heat loss and solar heat gain through it (Armstrong et al. 2008). The higher the ER value, the more effective the low-energy window (NRCan 2016e).

Heating, cooling, and hot water heater systems also consume a great amount of energy in a house (Bolling and Mathias 2008). Lutz et al. (2006) showed that furnaces or boilers are responsible for 30% of the total primary energy consumption in residential buildings, and Harvey (2009) stated that a well-designed HVAC system may result in a 30% to 75% building energy savings. There are several heating system types which have different effects on initial and long-term building costs as described below:

- Forced-air furnace is the most common type of heating systems in Canada (mostly in the Prairie provinces, Ontario, and British Columbia). As stated by Statistics Canada (2010), 56% of Canadian households used this system as their main heating system in 2011. The forced-air furnace system consists of a furnace as heating unit, ducts to distribute air, and a fan to circulate air in the house (Lutz et al. 2006).
- Air-source heat pump is designed to absorb and transfer heat from outdoor to indoor or vice versa. It is more common than the ground-source heat pump due to less initial and installation costs. This system includes an air-source heat pump as heating unit and other components similar to forced-air furnace system (SmartHouse 2015).
- Hydronic boiler system is less common in Canada, and, according to Statistics Canada (2010), 5% of Canadian households (mostly in Prince Edward Island) used this system to heat their homes in 2011. The main components of the boiler heating system include a boiler to heat water, pipes to distribute water, and a pump to circulate water throughout the house (SmartHouse 2015).
- After forced-air furnace, electric baseboard heating is very common in Canada. According to Statistics Canada (2010) 27% of Canadian houses (mostly in Québec, Newfoundland and Labrador, and New Brunswick) use electric baseboard heating in 2011. The electric baseboard space heater converts electricity into heat in a similar method to a clothes iron, and the only component of this system is the baseboard heater itself. Therefore, its initial cost is lower than other heating types, but the associated energy cost is excessively high (SmartHouse 2015).

Implementing solar technology for space and water heating, space cooling, and power generation is another strategy in low-energy buildings (Nikoofard 2012). Photovoltaic (PV) is a well-known solar energy system to generate electricity from the sun. As technology advances, the market of solar PV panels has expanded by 30% to 45% worldwide (Zahedi 2006), but, since installing this system is costly, many studies have been conducted to evaluate the cost effectiveness of this technology in reducing household energy use.

Additionally, as mentioned in Chapter 1, ~18% of building energy consumption is attributable to appliances and lightings (NRCan 2010a), and therefore these energy consumers need to be considered in efforts to achieve energy-efficient design. Norton and Christensen (2006) mentioned the importance of using proper appliances and lighting in net zero home design and recommended using compact fluorescent lighting throughout the house as well as Energy Star rated appliances to reduce electricity consumption.

Further to the key factors previously mentioned, it is also required to take different approaches in designing high-performance buildings beyond what is common in conventional design (Aksamija 2013). In recent years, building information modelling (BIM) technology has offered the potential to empower construction processes, which leads to more energy-efficient buildings (Rowe 2015). In traditional approaches, evaluation of the energy efficiency of buildings is narrow and is usually conducted after the architectural design stage (Moakher and Pimplikar 2012). However, it is crucial to determine all energy related requirements at an early design stage, which is one important role of BIM (Krygiel and Nies 2008). In the following section, the impacts of the BIM approach to developing high-performance housing are described in more detail.

2.2.1 BIM in high-performance housing

In simple terms, building information modelling (BIM) is a technology for managing data to enhance the performance of a building during its lifetime (WBDG 2014). Traditionally, information and project documents from each stage are independent (not linked) of one another (Meadati 2009). According to National Institute of Standard and Technology (NIST 2004), there was an estimated $15.8 billion annual cost burden in the capital segment of the American construction industry due to inadequate interoperability among different stakeholders in 2002. Therefore, deficiencies in coordination and retrieval of information have significant impact on productivity reduction and inaccuracy of large projects. In the early 2000s, BIM was introduced to the industry in order to facilitate data exchange by creating a well-structured shared repository among all project participants. Furthermore, it provided the design team an opportunity to develop a virtual model of a building prior to the construction phase in order to address any serious errors at the early stages of the project (U.S GSA 2007). In the last two decades, BIM has developed beyond 2D and 3D modelling and has expanded to 4D (time) and 5D (cost), supporting the whole building lifecycle (Wikipedia 2016a).

In general, BIM is a process to assist in the stages of planning and design, construction and monitoring, and operation and maintenance (Meadati 2009). In the design phase, many important decisions are made which have remarkable impact on the end result of a project (Tempelmans Plat and Deiman 1993). Thus, building energy analysis must be conducted in the early design phase (Stumpf et al. April, 2009). Therefore, this stage is critical, and the effective communication between the design team and other stakeholders is the key strength of BIM. During the construction phase, BIM helps to improve the project management and avoid constructability issues. Real-time monitoring is an important benefit of BIM in this phase (Hergunsel 2011). Furthermore, a number of studies focus on BIM integration into the operation phase for the purpose of developing high-performance housing, some of which are presented as follows:

- Hallberg and Tarandi (2011) proposed a BIM-based methodology to improve the dynamic visualization of building components during the operation phase. This approach can assist the project team to easily receive performance feedback, which in turn makes the building performance more efficient.
- Ham and Golparvar-Fard (2015) presented an automated BIM-based system to map the actual thermal properties of a building during its lifecycle. This proposed method is being updated over time and is reliable to calculate long-term thermal loads and energy performance of a building.
- Chen and Wang (2009) developed a system to visualize the real-time state of mechanical equipment based on the application of BIM. This study assists the project team in decision making and quality control during the building lifetime, which has significant impact on efficient operation of equipment.
- McGinley and Fong (2015) described a method to map occupant behaviour into the BIM model. This navigation system could be beneficial in decisions made during the operation phase based on actual occupant needs.

Although there are a number of scientific studies motivated to implement BIM into the building lifecycle, it is evident that BIM applications in current practices are more focused on preconstruction phases. In conclusion, it is derived from the literature that integration of BIM into the building lifecycle processes from the earliest stages is useful to successfully produce high-performance housing. However, there are still a number of challenges and associated risks (i.e., training and transition costs) that have impact on the involvement of BIM in projects (Azhar 2011).

2.2.2 Upgrade energy efficiency of building envelope design

Optimizing envelope design to consume minimal energy sources during the building lifecycle has been a subject of interest in many scientific studies. For example, Hamelin and Zmeureanu (2014) focused on the feasible insulation configuration for wood-framed walls aiming to minimize the LCC and environmental impacts of Canadian houses. The authors stated that an optimum R-value of insulation should be greater than what is prescribed in any codes, even from an LCC point of view. Moreover, a combination of fibreglass batt insulation for the wall's cavity and polyisocyanurate insulation as a continuous insulation are found to be the best choice with the lowest LCC compared with other current practices such as sprayed polyurethane, mineral fiber, blown-in cellulose, and extruded polystyrene. Similarly, Hasan et al. (2008) also attempted to minimize the LCC of a detached house built in accordance with the Finnish National Building Code of 2003 considering the improvement of wall, roof, and floor insulation as well as the U-value of windows. The results of this study show a reduction of 23% to 49% of the space heating energy by optimizing the envelope design.

As discussed in Chapter 1, a considerable amount of heat loss occurs through the basement. Therefore, substantial energy savings can be achieved by improving the basement envelope. In addition, basements are more commonly being used as liveable spaces and thus need to perform at the same level as above-grade spaces of the house. For this reason, the Canada Mortgage and Housing Corporation (CMHC) is interested in seeking cost-effective solutions to improve basement energy performance, and building code agencies are eager to upgrade the minimum basement insulation level (Kesik and Eng 2007).

In a study funded by CMHC different basement envelope assemblies were evaluated for Canadian houses (Kesik and Eng 2007). This study revealed that having full height insulation is always more cost-effective than partial height insulation. In addition, internal insulation of a basement is more effective per unit of thermal resistance than external insulation.

As mentioned previously, determining an optimal window design is another factor that has major impact on building energy performance. In this regard, Karlsson et al. (2001) developed a model to evaluate the cost efficiency and thermal performance of different advanced windows in the Swedish climate. The proposed model of this study can be deployed as a tool for window energy rating or in the selection of appropriate windows.

In addition to the window configuration, building performance is also influenced by a number of window-related design factors such as orientation and size. Pursuing the energy saving target in cold climate, some researchers have made an effort to find an optimum window-to-wall ratio for different building orientations. Window-to-wall ratio (WWR) is the percentage of window area to the exterior wall area (RDH Inc. 2016). Generally in the northern hemisphere, south-orientated windows allow the maximum solar radiation to enter compared with other orientations (Nikoofard et al. 2012) which assists in reducing space heating energy consumption in cold climates.

Thalfeldt et al. (2013) concluded that a 25% WWR for triple-pane argon-filled windows and 200 mm insulation thickness for walls is the most energy-efficient and cost-optimal façade solution over a 30-year lifespan in the cold climate of Estonia. Susorova et al. (2013) also studied the effect of fenestration design on building energy performance and concluded that in cold climates a WWR of 30% on south and 20% on other orientations are optimal window sizes for the least annual energy consumption.

Retrofit of building envelope is a strategy which leads to operational energy savings for existing buildings. Maleki (2012) conducted an economic analysis on potential retrofit options for existing high-rise buildings in Toronto. This study aimed to improve insulation and air tightness of building envelope through over-cladding methods and window replacement. The author considered the LCCs and associated energy savings to compare different scenarios. As a result, by replacing single-glazed windows with low-e triple-glazed (argon-filled) windows, 42% savings in peak heat load and 12% infiltration reduction is achieved with a payback period of 4 years; thus it is considered a cost-effective retrofit option. However, this conclusion is in contrast with a research declaring that window replacement is not a cost-effective retrofit solution in cold climates with only 2% to 5% savings on normalized annual energy consumption (NAC), whereas 12% to 21% savings on NAC can be achieved by insulating ceiling and walls (Cohen et al. 1991).

Dong et al. (2005) posed the question in their study of whether, considering the environmental impacts, retrofitting an old house or demolish and rebuilding a new house is the optimal solution. To answer this, a typical single-detached house located in Toronto was studied using Net Present Value (NPV) lifecycle analysis. The retrofit options considered were improving the attic and basement insulation, and reducing air leakage. It was stated that retrofitting the basement results in more lifecycle energy savings than retrofitting the attic. In addition, the authors asserted that there was a trade-off negative environmental impact resulting from both options. By retrofitting an old house, material waste and associated pollutants from their production were avoided, whereas the total lifecycle energy, global warming, and air pollution were less by rebuilding the house (including demolition and new materials). Similar to the study by Dong et al., Verbeeck and Hens (2005) evaluated the impact of different retrofits on energy consumption, CO_2 emissions, and associated costs for new buildings in Belgium. This study found that improving the roof insulation is the most economical and energy-efficient retrofit option because it has a high impact on the heating load but lower incremental costs compared with other building envelopes. The authors also recommended that between a better heating system and more insulation, it is better to invest in the insulation first because it has a longer lifespan.

2.2.3 Upgrade energy efficiency of whole house design

As discussed earlier, there are several measures that can be considered to improve the energy efficiency of buildings. Many studies have been carried out in this regard all over the world, and, their general approaches are more or less the same, including improving building envelopes, increasing the efficiency of mechanical system (heating, cooling, ventilation, and hot water heater), and reducing air leakage. A number of studies in this regard are summarized in more detail.

Lutz et al. (2006) carried out an analysis to compare the cost effectiveness of conventional furnace and boiler design with more energy-efficient options for residential houses in the United States. In this study, additional initial cost due to improvement of equipment units and any associated energy savings over their total lifecycle were considered as the main factors of comparison. As a result, the analysis of six different product alternatives indicates that operation savings by means of a more energy-efficient furnace or boiler heating system serves to offset the additional initial cost of the products.

Another similar study was conducted by Bolling and Mathias (2008) on different heating and cooling systems in climate conditions in the United States for the purpose of finding the optimal system. The analysis was carried out for high-efficiency condensing furnace and air conditioner (AC) units, ground source heat pumps (GSHP), absorption air conditioner system (ABS), and direct heating and thermal driven heat pumps (TDHP). The ABS and TDHP systems used solar thermal collectors to obtain their required energy. Bolling and Mathias (2008) concluded that the GSHP is an economically feasible option with the shortest payback period (between 4-15 years) in all climate zones compared to condensing furnace and AC. In addition, due to the large initial cost of solar collector systems, they did not consider them to be an economically feasible option compared with GSHP. Zogou and Stamatelos (1998) also argued that the performance of the GSHP is superior to that of an air source heat pump in all climate conditions.

The U.S. department of energy (DOE) had set a target to develop affordable net-zero homes by 2020. To support this target, Norton and Christensen (2006) carried out an investigation in cold climates to determine the method of designing net-zero homes that could achieve the highest energy savings during operation, thereby allowing owners with limited economic resources to afford mortgage payments and operation costs. To achieve this, the design of building envelope, equipment, lighting, and electric appliances were carefully considered in this study. In addition, the house was equipped with the grid-connected PV system, which stores excess energy in the grid during hot seasons and make use of it when more energy is required. The grid-connected PV panel does not require battery storage and thereby decreases costs. As a result, the proposed design recommended direct-vent natural gas furnace (in living room) and electric baseboard heaters (in bedrooms) for space heating because of their lower initial and installation costs compared to costs of ground coupled heat pumps and the associated duct system or hydronic system.

The energy-efficiency related targets of the DOE have been a major contributing factor in initiating other research and programs. This approach is deployed in a study carried out by Anderson et al. (2006) to determine cost-effective ways of improving the energy performance of existing buildings, integration of energy system innovations, and deploying renewable energy systems in place of conventional techniques for the U.S. residential sector. As the authors asserted, determining the trade-off relationships among design variables consisting of building envelope, appliances and lighting, hot water system, space conditioning system, and renewable energy system was an important factor to investigate in this study. Anderson et al. (2006) stated that the method of analysis presented was limited to the initial costs, annual costs, and energy savings through various possible options over a 30-year lifecycle. However, the impacts of other factors such as durability, installation difficulties, reliability, and warranty were not considered.

A similar approach was taken in another study (Dembo 2011) conducted in Canada in order to find the least-cost scenarios to reduce building energy consumption and associated GHG emissions. This study aimed to improve the baseline model, built in accordance with the 2006 Ontario Building Code (OBC), to meet the 2012 OBC while keeping incremental upgrade costs to a minimum. As a result, by improving the building envelope and energy efficiency of the HVAC system, a 31% reduction was achieved for energy consumption and associated GHG emissions (Dembo 2011). Following this, Yip and Richman (2015) also developed a framework that achieved a 50% reduction in space heating over the baseline case, a house built in accordance with 2012 OBC. The variables considered for improvement in this study were building envelope, furnace efficiency, air tightness, and HRV efficiency, and the payback period to return the incremental cost of such upgrades was estimated to be ~15 years. Guler et al. (2008) stated that replacing heating systems with units that are more energy-efficient provides the most energy savings in residential buildings in Canada.

As previously explained, improvement measures in a building have many consequences such as additional upfront cost, reduction in operation costs, and decreasing environmental impacts over its lifecycle. Based on the literature, lifecycle analysis is a suitable method to evaluate the feasibility of different upgrade options for a building from the time they are implemented to when the building is demolished. In the following section, different types of lifecycle analysis are described in detail.

2.3 Lifecycle Analysis Methodology

Lifecycle Analysis (LCCA) is a common technique in various studies (Anderson et al. 2006; Brunklaus et al. 2010; Dembo and Khaddad 2013; Dong et al. 2005; Gorgolewski et al. 1996; Verbeeck and Hens 2005) used to evaluate impacts of any alternative designs on energy, economic, or environmental performance of a building throughout its life-time (Figure 2-3) (Dembo 2011).

Lifecycle energy analysis is a useful method to assess the impacts of any approaches on the overall building energy consumption. For example, Stephan et al. (2013) deployed this methodology to compare embodied energy and overall energy demand of a passive house with other typical Belgian houses over a 50- and 100-years building lifecycle. Feist (1997) also conducted a study using the same methodology on various energy-efficient and passive houses in Germany to compare cumulative primary energy input (CPEI) during building lifecycle.

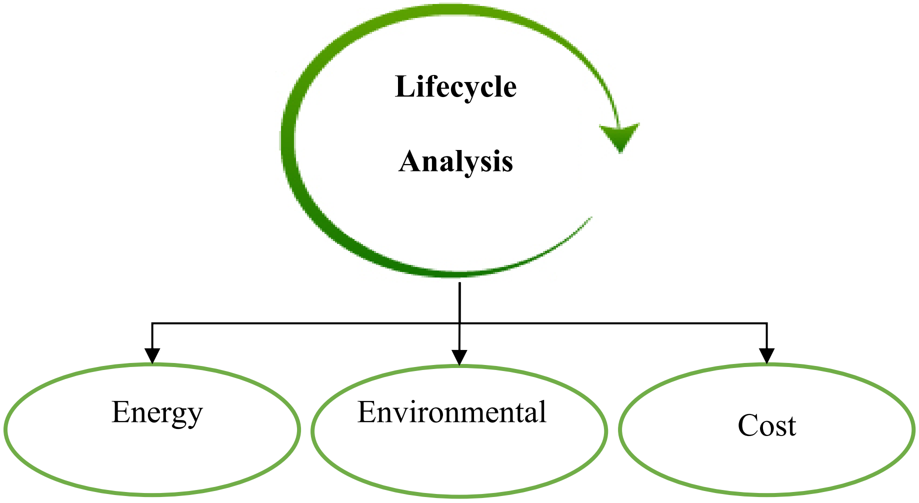

Figure 2-3: Lifecycle analysis methodology (Dembo 2011)

Lifecycle environmental analysis is another tool to evaluate the environmental impacts of different designs (Ramesh et al. 2010). There are numerous studies using this tool targeting to decrease environmental impacts of the construction (Frenette et al. 2010; Peuportier 2001). For instance, in a study conducted in New Zealand, CO_2 emissions from building construction using concrete, steel, and wood construction were compared for residential and office buildings and concluded that using wood construction results in less CO_2 emissions (Buchanan and Honey 1994). Seo and Hwang (2001) also used Lifecycle environmental analysis to estimate the CO_2 emissions over the life time of residential buildings.

The importance of cost control in the construction industry has led many studies to consider cost effectiveness in evaluation of building design improvements. Lifecycle cost analysis (LCCA) is a method of assessing the economic performance of different design approaches over the lifespan of a building (Dembo 2011). Anderson et al. (2006) and Dembo and Khaddad (2013) conducted studies to determine the least-cost path of reducing energy use in buildings using this methodology. Both of these studies evaluated eligible upgrades considering the capital cost and operations cost over a 30-year lifecycle. In addition, Lutz et al. (2006) used LCCA methodology to identify the cost effectiveness of upgrading different boiler and furnace designs for a house in the United States.

2.4 Building Energy Simulation Tools

There is a wide variety of simulation tools to model energy performance of buildings. Some are designed to focus on specific components of a building and others are able to simulate the entire building (Hanam 2010). Crawley et al. (2008) conducted a detailed study to compare major building energy simulation tools based on their capabilities and features. A number of common tools are reviewed below.

DOE-2 is a thermal simulation engine, ASHRAE qualified (Diamond and Hunn 1981), developed by Hirsch and Berkely with the financial support of the U.S. Department of Energy (NRCan 2008a). This program is able to predict the hourly energy consumption and associated building costs (Birdsall et al. 1990) and has been used for more than 25 years (NRCan 2008a) in various building design studies (Anderson et al. 2006; Ang Co 2013; Chua and Chou 2010). In addition, eQuest (Hirsch 2010), EE4 (DOE 2010), and many other user interfaces have been created based on the DOE-2 engine. DOE-2 has the capability of simulating thermal performance and heating loads such as solar heat gain, lighting, and equipment loads (Birdsall et al. 1990). In a study conducted by Maile et al. (2007), several limitations of this program were argued, such as some hidden errors in the DOE-2 engine code, which make this software less accurate. Cho and Haberl (2006) also mentioned the incapability of this program in simulating some HVAC systems.

The TRSYS program was developed in 1975 at the solar energy laboratory (SEL) of Wisconsin University–Madison. This program allows users to access the library and add more building components using programming languages. Although TRSYS is more complicated than DOE-2 based programs, the users have complete control over the building model in TRSYS (SEL 2006). TRSYS is also able to simulate renewable energy systems such as a solar energy system (Kummert et al. 2004). In a study conducted by Judkoff and Neymark (1995), TRSYS is considered as the most advanced and accurate program sponsored by the DOE for active solar energy system simulation. Dembo (2011) also showed that the use of TRSYS has positive effects on the design of advanced HVAC systems. Although TRSYS is more accurate and has greater capabilities than DOE-2, this program is less common due to its cost, while many DOE-2 based programs are free of charge (SEL 2006).

HOT2000 is a simple open-source energy analysis program developed by NRCan to calculate the monthly or annual amount of building energy consumption for residential buildings. It is also able to evaluate the performance of household heating and cooling systems and the thermal efficiency of different designs (U.S DOE 2011). HOT2000 is well-known software throughout Canada to support regulations, building codes, and different energy efficiency related programs (NRCan 2016f).

The EnerGuide for Houses (EGH) rating system is a scale for builders or owners to evaluate the energy efficiency of residential houses with a rating from 0 to 100. An increase of one EGH rating number represents a 10% improvement in the overall energy consumption of a building; the higher the rating, the more energy-efficient the home. An EGH of 80 and higher is accepted in some Canadian provinces as an energy performance target in a house (Buchan 2007). Table 2-5 depicts how EGH measures the energy performance of new houses across Canada (NRCan 2016c).

Table 2-5: EGH rating of new houses in Canada

House Characteristics	EGH

New house built in accordance with building codes and energy requirements	77 to 80
Energy-efficient new house	81 to 85
High performance, energy-efficient new house	86 to 99
Net-zero house	100

Source: (NRCan 2016c)

Further to the EGH rating, HOT2000 also supports Energy Star (ESNH), R-2000 programs (NRCan 2016f), and several building design studies in Canada (Guler et al. 2008; Kikuchi et al. 2009; Dembo 2011; Fung et al. 2009; Dong et al. 2005).

2.5 Conclusion

In this chapter, several scientific studies, including dissertations, journals, and conference papers, are collected to understand the need of low-energy housing and uncover any approaches that may be applied to new or existing buildings to achieve this objective. The application of BIM from the design to operation stage of high-performance buildings is one of the innovative approaches in this regard.

The lifetime energy savings of a building, and any associated upgrade costs, is the primary focus of this study. Consequently, different lifecycle analysis methods and simulation programs are evaluated in this chapter. In addition, as this study is conducted in Canada (Edmonton), a detailed literature review is conducted concerning the Alberta energy code requirements.

Based on the literature, to achieve energy savings in a building, various improvements are commonly used, including improving the building envelope, more energy-efficient units for HVAC system, increasing the air tightness, upgrading the hot water heating system, and using a renewable energy system. However, since envelope and heating system have dramatic impact on building energy savings, optimizing their design is the greatest concern of energy-efficient solutions.

Base on the literature, it can be concluded that the 30-year LCCA is a suitable methodology to evaluate the cost effectiveness of energy-efficient solutions. Furthermore, HOT2000 software is an appropriate program option to predict the building energy performance due to its reliability in Canada, and also its capability to shape building code and determine EGH rating.

CHAPTER 3: METHODOLOGY

3.1 Research methodology

The primary purpose of this study is to present a methodology to determine the code-compliant energy-efficient solutions with the lowest LCC for houses. The National Building Code 2011, adopted in Alberta in 2014 as the Alberta Building Code (ABC), together with case study houses in Edmonton, Alberta, is used to develop and illustrate the methodology.

Research indicates that, in Canada, a large amount of interior heat is lost through exterior walls, basement walls, and windows, such that improved design of these elements will have a significant impact on building energy performance. Additionally, there are alternative upgrade options to improve overall energy efficiency, and each has different cost impacts. Accordingly, this study aims to evaluate and determine cost effectiveness of window designs (type and sizing), wall thermal insulations, and house upgrade solutions.

A series of window and wall thermal insulations are selected based on ABC requirements according to the prescriptive path. Then, these types are ranked based on their LCC (initial and operation costs) per unit area. The initial cost data are collected from quotations by local suppliers and RSMeans cost data (RSMeans 2016). The operation costs are based on HOT2000 (NRCan 1987) simulated energy consumption converted to dollar values using the present natural gas price.

An investigation of is conducted of upgrades to a base house design with an energy performance rating of EGH 71 (calculated by HOT2000). The first approach, which follows the prescriptive code requirements, achieves an EGH rating of 82. As required by the ABC performance path, an

EGH of 82 generated from prescriptive design is used as the reference value for alternative house designs in this study. Seven other upgrade approaches, which can be applied on the base house design and each result in an EGH of 82, are investigated and compared based on their LCC. According to the literature, improvements to building envelope, more-efficient units for HVAC system and hot water heating system, and the use of a renewable energy system are common measures implemented to achieve energy savings in a building. Consequently, measures to improve the energy efficiency of the building envelope, measures to improve the energy efficiency of the mechanical system (considering different heating system types), installation of a solar PV system, and combinations of these strategies constitute the focus of these upgrade approaches.

The research process is divided into the following tasks (shown in Figure 3-1):

- Select a series of advanced window types based on ABC 2014 requirements and analyze them to determine the type with the lowest LCC, and also investigate window-related design parameters (style, roof overhang depth, and size) with the aim of identifying a window design which minimizes overall annual heat loss in the house.
- Evaluate different thermal insulations within above-grade and below-grade wood-framed walls to find the code-compliant wall insulation (according to the code's prescriptive requirements) with the lowest LCC.
- Conduct an investigation of potential upgrades by comparing the LCC of different upgrade approaches that could be applied to the base house design and result in the same energy-efficiency improvement (EGH 82). The energy efficiency of different systems such as building envelope, mechanical system (considering different heating system types),

installation of a PV system, and their combinations are the focus for these upgrade approaches.

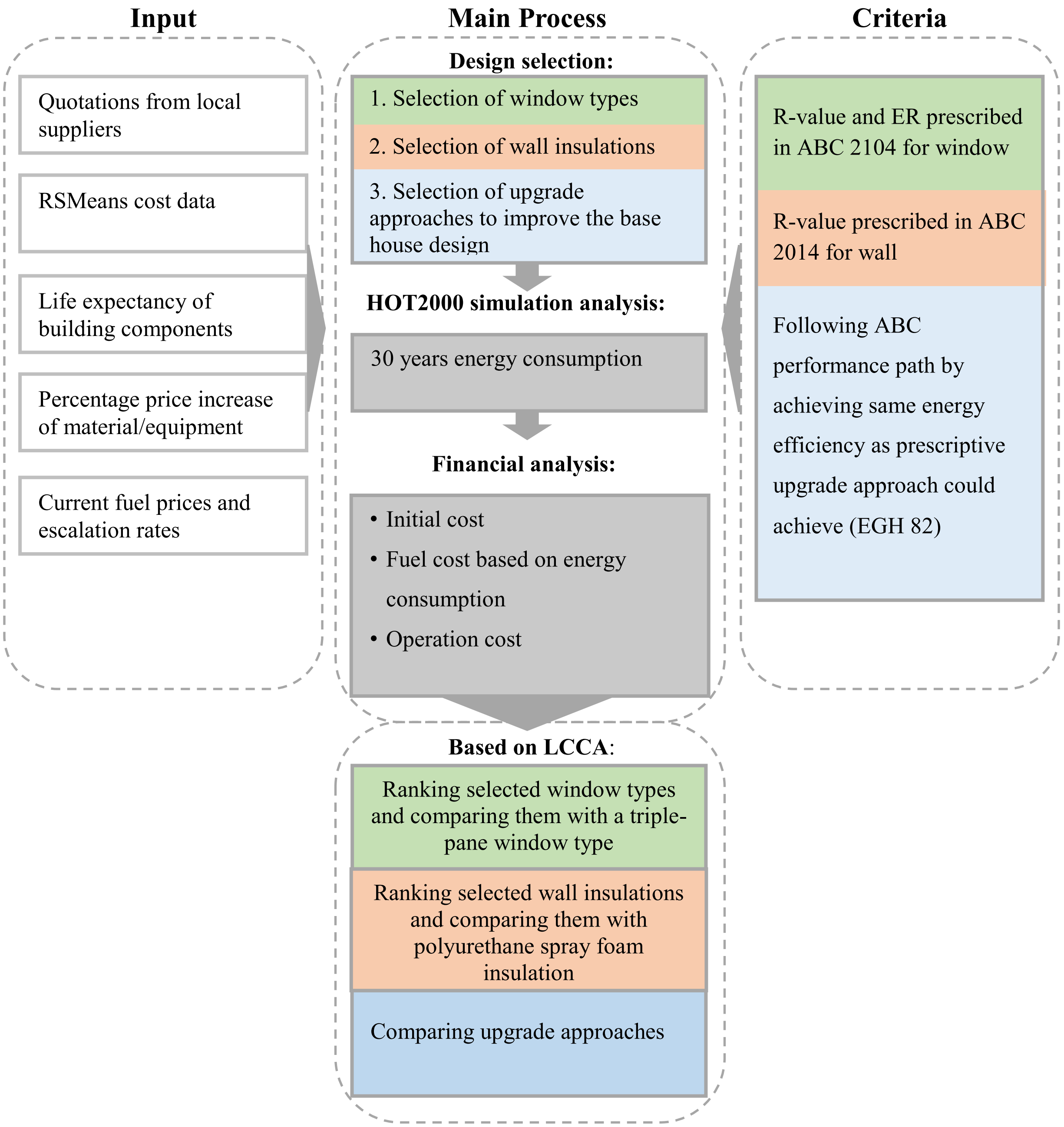

Figure 3-1: Summary of research methodology

3.2 Selection of house type

A base house design selected for this study is a south-facing, two-storey, single-family home. The house has a 1,610 ft^2 total floor area (excluding the basement) and a 128 ft^2 window area, which covers 6% of the exterior walls. Table 3-1 reviews general characteristics of the base house design and Table 3-2 reviews technical characteristics of the house. Detailed drawings of the base house design are provided in the Appendix.

Table 3-1: General house characteristics

Floor area (main and second floor)	1,610 ft^2
Width	40 ft
Depth	20 ft
Height (including attic)	26 ft
Exterior wall area	2,019 ft^2
Window area	61 ft^2 on south wall 51 ft^2 on north wall 16 ft^2 on west wall

Table 3-2: Technical house characteristics

Component	Characteristic
Attic	Attic truss, 38×89 mm (2×4 in), Spacing: 600 mm (24 in),

	Cavity insulation: RSI 2.28 (R 13) blown-in cellulose Interior: 12 mm (½ in) gypsum board
Above-grade wall	Wood framing 38×140 mm (2×6 in), Spacing: 600 mm (24 in) Cavity insulation: RSI 1.94 (R 11) batt, Interior: 12 mm (½ in) gypsum board Sheathing: Wafer board/OSB 9.5 mm (3/8 in) Exterior: Hollow metal/vinyl cladding
Below-grade wall	38×89 mm (2×4 in) wood, Spacing: 600 mm (24 in) Cavity insulation: RSI 1.94 (R 11) batt Interior: 12 mm (½ in) gypsum board
Floors	Composite wood joist, 38×302 mm (2×11.875 in), Spacing: 487 mm (19 in) no insulation Interior: Wood Sheathing: Wafer board/OSB 15.9 mm (5/8 in)
Exposed floor	Composite wood joist, 38×302 mm (2×11.875 in), Spacing: 487 mm (19 in), Cavity insulation: RSI 2.3 (R13) batt Interior: Carpet and underpad Sheathing: Plywood/Particle board 18.5 mm (3/4 in)
Basement	Concrete walls and floor, interior surface of wall insulated over full-height
Window	DG, low-e 0.20 (hard) coating, 13 mm argon-filled cavity, vinyl frame (Effective RSI = 2.84)

Air tightness level	0.72 ACH @ 50 Pa
Ventilation	Sensible heat recovery efficiency at 32 °F: 57 % Sensible heat recovery efficiency at −13 °F: 53%
Heating system	Natural gas furnace, AFUE: 80%
Domestic hot water	Gas fired, energy factor: 59%

Due to using HOT2000 software for energy simulation in this study, the following assumptions are made:

- Although the average occupancy of houses in Canada is estimated to be less than 3 persons in 2009 (NRCan 2011b), based on the HOT2000 program, the occupancy of 2 adults and 2 children for 50% of the time is assumed in the simulations. The number of occupants is an important factor in order to calculate their contribution to heat generation and water loads.

- The heating set point of 21 °C (69.8 °F) and cooling set point of 25 °C (77 °F) for the main and upper floors are set in HOT2000. In addition, a daily temperature rise of 2.8 °C (5 °F) above the heating set point in a house is allowed in order to reduce the furnace operation. This extra heat may result due to internal heat gain or solar heat gain.

- The average household lighting and appliances consumption is set to the following defaults in HOT2000:
    - Electric appliance (non-gas stove/dryer): 14.00 kWh/day
    - Gas stove: 2.00 kWh/day
    - Gas dryer: 2.00 kWh/day
    - Lighting: 3.00 kWh/day
    - Other electric appliances: 3.00 kWh/day
- It is assumed that the hot water demand throughout the entire year is constant in an occupied house and is calculated based on the number of occupants using the following equation:

$$\frac{\text{Litres}}{\text{Day}} = 85 + (35 \times \text{number of occupants in the house}) \tag{1}$$

3.3 Lifecycle cost analysis

As mentioned before, this study investigates and compares different window types, wall insulations, and house upgrade approaches based on the LCCA over the lifespan of 30 years. According to Lutz et al. (2006), LCCA is defined by initial and operation costs, as expressed in Equation 2.

$$\text{LCC} = \text{Initial cost} + \left(\sum_{\text{n}=1}^{\text{lifetime}} \text{Operation cost} \right) \tag{2}$$

where lifetime is 30 years.

The initial cost is the material or equipment costs used in the investigated designs derived from RSMeans cost data or quotations obtained from builders. The operation cost is the sum of the annual energy costs associated with the design based on HOT2000 simulated energy consumption and is converted to dollar values using present fuel prices.

In addition, for building equipment or materials used in designs that have to be replaced within the 30 year period (i.e., furnace, hot water heater), additional operation cost is considered for replacement based on current equipment prices plus the percentage price increase in the future (also known as the consumer price index).

Finally, the LCC of windows and insulations are estimated per unit area and LCC (30 years) of house upgrade approaches are estimated for the whole house. The following sections discuss fuel price escalation rates, consumer price index (CPI), life time of building components, and cost data sources in more detail.

3.3.1 Natural gas and electricity price escalation rates

Future fuel prices are predicted based on the average percentage change of natural gas and electricity prices, which are determined to be 5.08% and 1.35%, respectively, as shown in 3-2 and Figure 3-3.

In this study, the annual energy cost associated with designs is estimated based on HOT2000 simulated energy consumption and is converted to a dollar value using current fuel prices, and the percentage fuel price change is considered to predict future prices. It should be noted that since 81% of houses in Alberta consume natural gas as their primary energy source (NRCan 2007b), the energy cost associated with space heating, such as heat loss from windows and walls, is estimated based on natural gas prices. The energy cost of whole house designs is estimated based on both natural gas and electricity prices for space heating, DHW heating, electric appliances (constant in HOT2000 simulations—see Section 3-2), and HRV. Equation 3 expresses how to predict future energy cost based on current energy cost and percentage of fuel price change.

$$\begin{aligned}&\text{Energy cost associated with the design}\\&\quad = \text{Current energy cost}\\&\quad \times (1 + \text{ fuel price change})^{\text{year of prediction (from 1 to 30)}}\end{aligned} \tag{3}$$

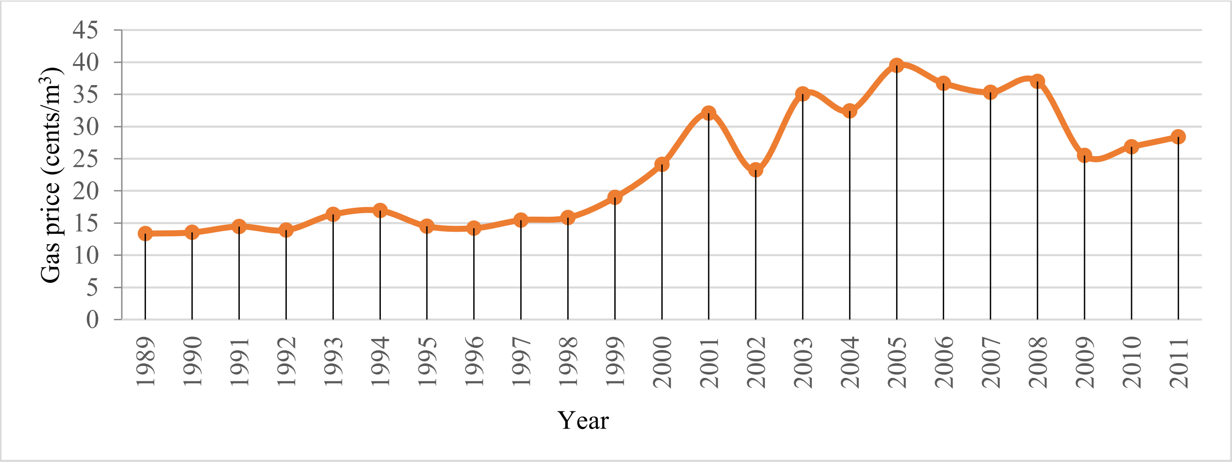

Figure 3-2: Natural gas prices for residential buildings in Alberta (Canada Statistics 2015)

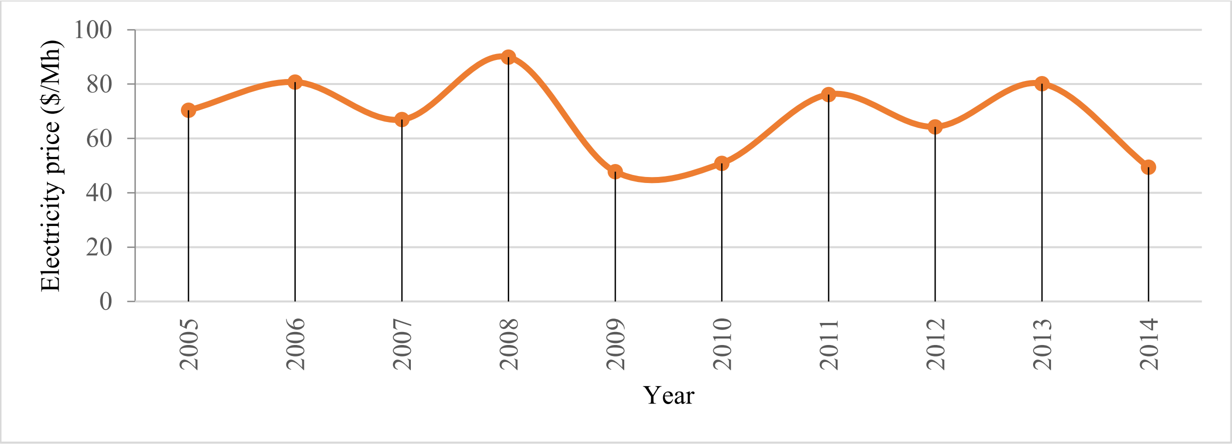

Figure 3-3: Electricity prices for residential buildings in Alberta (AESO 2014)

3.3.2 Consumer price index in Canada

Consumer price index (CPI) is a percentage price increase of any goods in future. According to Bank of Canada (2016), the CPI of goods from 1996 to 2015 is 1.87% (shown in Figure 3-4). The CPI change is used in this study to estimate additional operation cost of equipment used in house designs which will require replacement within the 30 year lifespan (i.e., furnace, hot water heater). Equation 4 expresses how to predict equipment price in future years based on current price and CPI change.

$$\begin{aligned}&\text{Cost associated with equipmet replacement in future years} \qquad (4)\\&\quad = \text{Current price of equipment}\\&\quad \times (1 + \text{CPI})^{\text{year of replacement (from 1 to 30)}}\end{aligned}$$

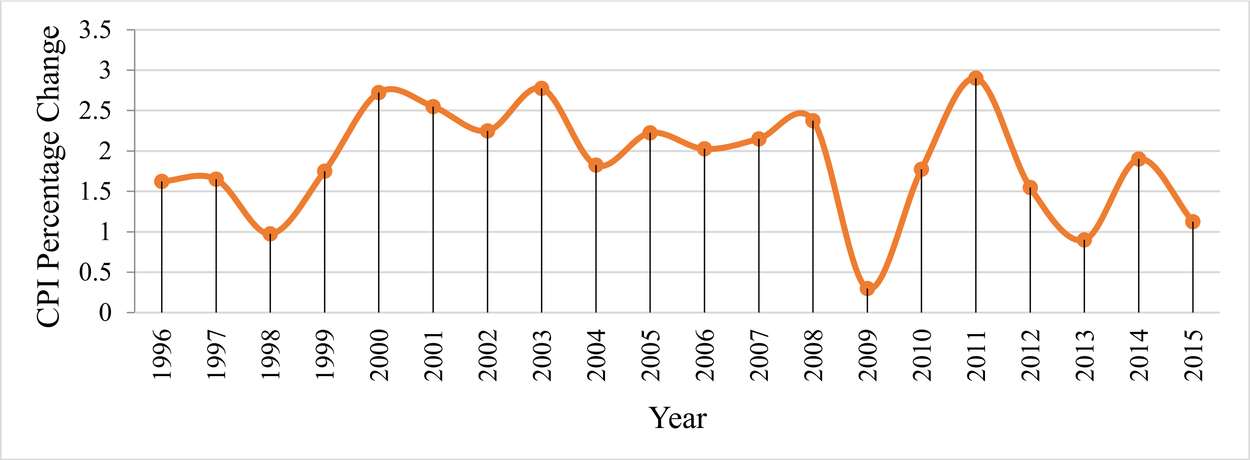

Figure 3-4: CPI percentage change in Canada (Bank of Canada 2016)

3.3.3 Life expectancy of home components

Life expectancy of building components varies and depends on different factors such as maintenance and climate condition. Based on the 30-year lifecycle analysis considered in this study, the average life time of building components used in designs is summarized in Table 3-3 (NAHB 2006).

Table 3-3: The average lifespan of home components

Equipment	Life expectancy (years)
HVAC	
Gas boiler	21
Gas furnace	18
Heat recovery ventilator	20+
Water heater, tankless	20+

Gas water heater, tanked	10
PVC pipe	100
Ducting	30
Electric baseboard	20
Air-source heat pump	15-20
Hydronic pump	16
Diffuser	25
Cast iron radiator	Assumed more than 30 years
Fan	15
INSULATION	
Insulation Material	
Cellulose; Fibreglass; Foam	100+
Insulation Type	
Batts/Rolls; House Wrap; Loose Fill	Lifetime
Window Framing	
Wood; Vinyl	30+
Fibreglass	50+
Aluminum-clad wood	15-20

Source: (Burn et al. 2005; Alphen Inc. 2015; NRCan 2016a; SquareOne Insurance Inc.)

3.3.4 Cost data sources

The majority of the cost information used in this study is obtained from RSMeans construction cost data (RSMeans 2016) to estimate the initial cost of material or equipment used in house designs. RSMeans is an up-to-date North American database that assists the construction industry to track project costs quickly and accurately, including material, labour, profit rates, and overhead costs for both new and renovation construction projects. The costs listed in this program are based on local currency in North America (RSMeans 2016).

Due to the limited models listed in RSMeans, some construction costs are derived from local suppliers. In addition, some window types studied in this thesis are not available on the local market. Therefore, their material costs are estimated based on other comparable window types that are available. The construction costs used in this study are summarized in the Appendix.

3.4 Wall configurations

In this section, a series of thermal insulations for exterior and basement walls are selected based on ABC 2014 requirements (effective R-value of walls); then, wall LCC (initial and operation) is estimated per unit area for each selected insulation type. Initial costs of insulations are derived from RSMeans cost data and local suppliers. Wall operation cost is estimated based on annual heat loss from walls simulated by HOT2000 and is converted to a dollar value using the current natural gas price.

3.4.1 Main criteria for selecting thermal insulations for walls

Effective thermal resistance (R-value) of exterior and basement walls prescribed in ABC (2014) is the main criteria to select thermal insulations in this study and is calculated by Equation 5 in HOT2000. A higher thermal resistance indicates less heat loss through a wall.

$$R = \frac{A_1 + A_2 + \cdots + A_n}{{}^{A_1}\!/_{R_1} + {}^{A_2}\!/_{R_2} + \cdots + {}^{A_n}\!/_{R_n}} \quad (5)$$

R = Effective thermal resistance of wall (m^2•K/W)

A_n= Area of wall components (m^2)

R_n= Thermal resistance of wall components (m^2•K/W)

Above-grade and below-grade wall components considered for R-value estimation are illustrated in Figure 3-5.

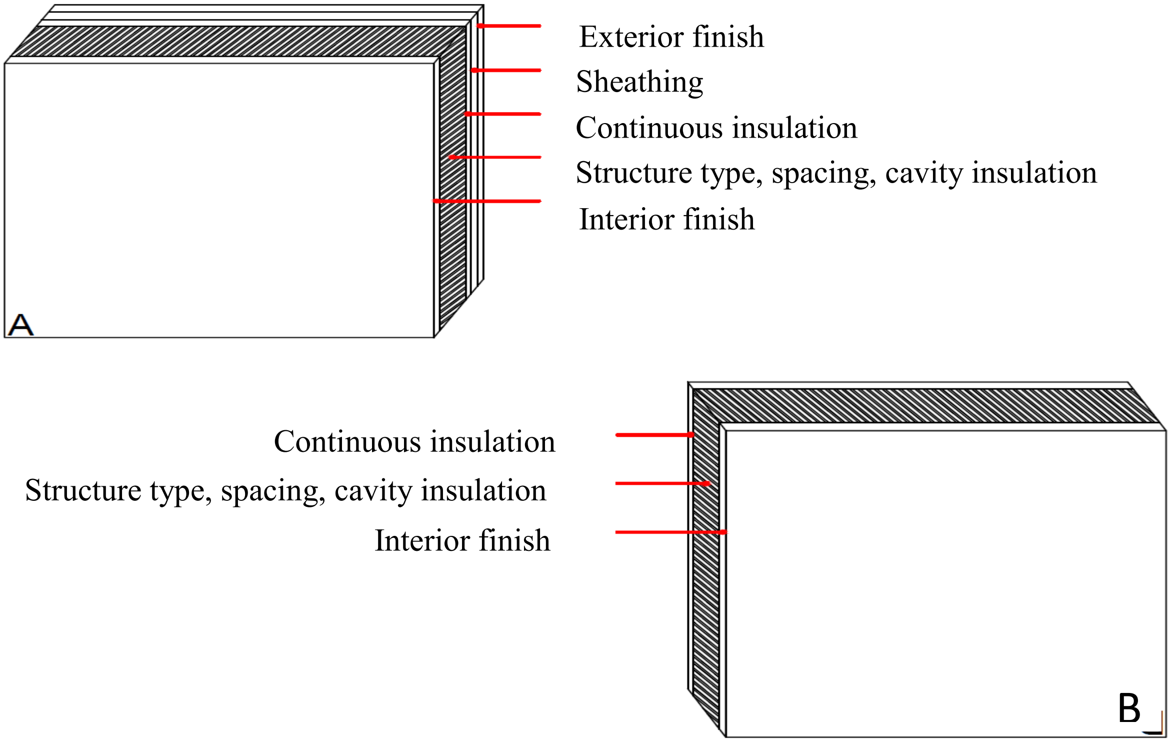

Figure 3-5: Cross section of (a) above-grade and (b) below-grade wall components (NRCan 2010b)

3.4.2 Selection of thermal insulations for exterior and basement walls

Since the impact of different insulation types on wall LCC is the focus of this study, the structure of exterior and basement walls is consistent with the base house design (Section 3-2). Thus, the only difference between the evaluated walls is the type of insulation. There are several insulation choices on the market for walls, but the common insulations, which are available in HOT2000 and could meet the previously mentioned criteria (from Section 3.4.1), are selected to study. Table 3-4 summarizes the insulation types selected for exterior and basement walls.

Table 3-4: Insulation types used for walls

Exterior Wall		
Type	**Cavity Insulation**	**Continuous Insulation**
1	Polyurethane spray foam (5½″)	_
2	Polyurethane spray foam (5″)	_
3	Polyurethane spray foam (4″)	_
4	Polyurethane spray foam (3½″)	_
5	Fibreglass batt R19	Rigid XTPS (1.0″)
6	Fibreglass batt R19	Rigid EPS (1.0″)
7	Fibreglass batt R19	Rigid Isocyanurate (1.0″)
8	Fibreglass batt R19	Semi-rigid fibreglass (1.0″)
9	Fibreglass batt R13	Rigid EPS (1.0″)
10	Blown-in cellulose R20	_

11	Blown-in cellulose R20	Rigid XPTS (1.0″)
12	Blown-in cellulose R20	Rigid EPS (1.0″)
13	Blown-in cellulose R20	Rigid Isocyanurate (1.0″)
14	Blown-in cellulose R20	Semi-rigid fibreglass (1.0″)
15	Blown-in fibreglass R23	Rigid XTPS (1.0″)
16	Blown-in fibreglass R23	Rigid EPS (1.0″)
17	Blown-in fibreglass R23	Rigid Isocyanurate (1.0″)
18	Blown-in fibreglass R23	Semi-rigid fibreglass (1″)
Basement Wall		
Type	**Cavity Insulation**	**Continuous Insulation**
1	Fibreglass batt R8	Fibreglass batt R12
2	Fibreglass batt R10	Fibreglass batt R12
3	Fibreglass batt R12	Fibreglass batt R12
4	Fibreglass batt R14	Fibreglass batt R12
5	Fibreglass batt R14	Fibreglass batt R14
6	Fibreglass batt R10	Rigid XTPS (2.0″)
7	Fibreglass batt R12	Rigid XTPS (2.0″)
8	Fibreglass batt R14	Rigid XTPS (1.0″)
9	Fibreglass batt R10	Rigid EPS (2.0″)
10	Fibreglass batt R12	Rigid EPS (2.0″)
11	Fibreglass batt R14	Rigid EPS (2.0″)

12	Fibreglass batt R10	Rigid Isocyanurate (2.0″)
13	Fibreglass batt R12	Rigid Isocyanurate (1.0″)
14	Fibreglass batt R14	Rigid Isocyanurate (1.0″)
15	Fibreglass batt R10	Semi-rigid fibreglass (2.0″)
16	Fibreglass batt R12	Semi-rigid fibreglass (2.0″)
17	Fibreglass batt R14	Semi-rigid fibreglass (2.0″)
18	Fibreglass batt R11	Fibreglass batt R11
19	Fibreglass batt R12	Polyurethane spray foam (3½″)

3.4.3 Lifecycle cost estimation of wall insulations

Wall LCC is defined by initial and operation cost over the lifespan of 30 years, as expressed in Equation 2. The initial cost of insulation is derived from RSMeans cost data or local suppliers, and annual heat loss from walls is the main variable considered for operation cost. The total monthly heat loss through wall area is estimated in HOT2000 as (ASHRAE 2009):

$$Q(I,N) = \frac{A(N)}{R(N)} \times \left(T_1 - T_r(I)\right) \tag{6}$$

A(N): Total wall area (m^2)

R(N): Effective thermal resistance of wall (m^2 k/W)

T_1: House set point temperature (k)

$\mathrm{T_r(I)}$: Monthly ambient temperature below the set point temperature (k)

To estimate the operation cost of a wall, the annual heat loss from the investigated wall (from Table 3-4) placed in the base house design (Section 3-2) is estimated for unit of wall area (ft^2) and is converted to a dollar value using the current natural gas price. Finally, wall LCC is estimated for unit area (ft^2).

$$\mathrm{LCC} = \text{Initial cost} + \left(\sum_{n=1}^{\text{lifetime}} \text{Operation cost} \right) \tag{2}$$

Initial cost: Insulations cost (\$) per ft^2

Operation cost: Annual net heat loss (GJ/ft^2) × current gas price (\$/GJ)

3.5 Window

In this section, a series of window types are selected based on ABC 2014 requirements (R-value and ER) and are ranked based on their LCC (initial and operation costs) per unit area. Initial costs of windows are derived from RSMeans cost data and local suppliers. Window operation cost is estimated based on net annual heat loss (annual heat gain minus heat loss) from windows simulated by HOT2000 and is converted to a dollar value using the current natural gas price.

In addition, with respect to the importance of window design on building energy performance, further analysis is conducted on window design parameters (i.e., size, style) aiming to minimize overall annual heat loss in the house.

3.5.1 Main criteria for window types selection

ABC 2014 (U-value and ER) is used in this section to select different code-compliant window types. U-value measures the rate of heat loss from windows, where, the lower the U-value, the better a window insulates (Efficient Window Co. 2016). Window energy rating refers to the overall window performance depending on the heat loss, solar heat gain, and air leakage rate, as expressed in Equation 7 (Natural Resources Canada 2015) and is used in this study to determine code compliance SHGC for window type selection.

$$\mathrm{ER} = (57.76 \times \mathrm{SHGC}) - (21.90 \times \mathrm{U_w}) - (1.97 \times \mathrm{L_{75}}) + 40 \tag{7}$$

ER: Energy rating

SHGC: Solar heat gain coefficient

$\mathrm{U_w}$: U-factor of window, W/m^2•K

$\mathrm{L_{75}}$: Air leakage rate at 75 pa pressure difference, ACH

The overall U-value of a window is estimated in HOT2000 based on the following equation (Karlsson 2001):

$$\mathrm{U_{tot}} = \frac{(\mathrm{U_{frame}} \times \mathrm{A_{frame}}) + (\mathrm{U_{edge}} \times \mathrm{A_{edge}}) + (\mathrm{U_{glass}} \times \mathrm{A_{glass}})}{\mathrm{A_{tot}}} \tag{8}$$

U: U-value, W/m^2•K

A: Area, m^2

SHGC depends on the incident angle and wavelength and is estimated in HOT2000 based on the following equation (ASHRAE 2009):

$$\mathrm{SHGC}\ (\theta, \lambda) = \mathrm{T}(\theta, \lambda) + \mathrm{N} \times \mathrm{A}(\theta, \lambda) \qquad (9)$$

SHGC: Solar heat gain coefficient

θ, λ: Angle of incident and wavelength

$\mathrm{T}(\theta, \lambda)$: Solar transmittance

N: Fraction of absorbed radiation

$\mathrm{A}(\theta, \lambda)$: Solar absorptance

3.5.2 Selection of potential window types

As mentioned previously, window configuration consists of different zones and each has an impact on its overall thermal performance. The following variables considered in window configurations in this study:

- Framing
- Glass sheets
- Distance spacing and gas-fill type
- Low emissivity (low-e) coating

There are several choices on the market for each of these variables, but since HOT2000 is used in this study, the options available in this software, which could meet the mentioned criteria (provided in Section 3.5.1), are selected.

Ultimately, 16 eligible window types are chosen, and for comparison purposes all types selected for study are the “slider with sash” style; (the reader may refer to the slider with sash window in Figure 3-7). Table 3-5 summarizes the window types selected for this study.

Table 3-5: Window types selected for study

Type	**Frame**
Description: DG + 1 HM 88, low-e coating (20%) hard, krypton 9 mm	
1	vinyl
2	wood
3	fibreglass
4	Aluminum-clad wood
Description: DG + 1 HM 88, low-e coating (20%) hard, argon 13 mm	
5	vinyl
6	wood
7	fibreglass
8	Aluminum-clad wood
Description: TG + 2 coating, low-e coating (20%) hard, krypton 9 mm	
9	vinyl
10	wood

11	fibreglass
12	aluminum-clad wood
Description: TG + 2 coating, low-e coating (20%) hard, argon 13 mm	
13	vinyl
14	wood
15	fibreglass
16	aluminum-clad wood

3.5.3 Lifecycle cost estimation of window types

As mentioned before, LCC is defined by initial and operation costs over the lifespan of 30 years, as expressed in Equation 2. The initial cost of a window is derived from RSMeans cost data or local suppliers, and annual heat loss and solar heat gain are the two main variables considered for window operation cost.

To estimate window operation cost, the net heat loss (annual solar heat gain minus heat loss) through windows placed on each side of the base house design (Section 3-2) is estimated by HOT2000 and is converted to a dollar value using the current natural gas price. Finally, window LCC is estimated using Equation 2 for unit area (ft^2) on each orientation.

$$\mathrm{LCC} = \mathrm{Initial\ cost} + \left(\sum_{\mathrm{n=1}}^{\mathrm{lifetime}} \mathrm{Operation\ cost} \right) \tag{2}$$

Initial cost: Material costs of window ($\$/ft^2$)

Operation cost: Annual net heat loss (GJ/ft^2) × current gas price[1] ($/GJ)

Heat loss from window is estimated in HOT2000 as (ASHRAE 2009):

$$\mathrm{Q(I, N)} = \mathrm{U(N)} \times \mathrm{A(N)} \times \left(\mathrm{T_1} - \mathrm{T_r(I)}\right) \tag{10}$$

$\mathrm{Q(I, N)}$: Total heat loss from window N for month I (MJ/day)

$\mathrm{U(N)}$: Overall U-factor of window (W/m^2°C)

$\mathrm{A(N)}$: Total glazing area (m^2)

$\mathrm{T_1}$: House set point temperature (°C)

[2]$\mathrm{T_r(I)}$: Monthly ambient temperature below the set point temperature (°C)

3.5.4 Window-related design parameters

Well-designed windows play a major role in reducing heating energy in cold climates. Therefore, this study also investigates window-related design parameters focusing on the impact of window style and roof overhang depth on the annual thermal performance and determining ideal window-to-wall ratio (WWR)[3], which could minimize the overall annual heat loss in the house.

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[1] Since the major fuel type used for house space heating in Alberta is natural gas (NRCan 2007b), the energy cost associated with heating spaces is estimated based on the price of natural gas.

[2] $T_r(I)$ is calculated by the mean and standard deviation of ambient temperature below set point temperature collected from weather data (Naidj 2000).

[3] In HOT2000, wall area cannot be defined for each orientation. Due to this limitation, window-to-wall ratio refers to window area to total exterior walls area.

Window-to-wall ratio: With respect to the importance of reducing heating energy, the WWR which could minimize the overall annual heat loss in the house is determined for each orientation. The investigation is conducted by assessing the annual total heat loss through wall and windows. The net heat loss from windows equals the heat loss through conduction minus the transmitted useful solar heat gain.

Window type 5 selected from Table 3-5 is placed on one side of the base house design (Section 3-2), and wall insulation type 6 from Table 3-4 is placed on the exterior walls. Then, net annual heat loss from windows (annual solar heat gain minus heat loss) and annual heat loss from exterior walls are estimated by HOT2000. This analysis is conducted for different WWR aiming to determine the window size that achieves the minimum overall annual heat loss on each orientation. The investigation is repeated for different house sizes including the base house design (between 1,451 ft^2 and 3,000 ft^2) to generalize the results, making them applicable to the majority of houses in Edmonton.

Large window versus a number of windows: Architects have varying design preferences such as one large window or a number of windows on a wall surface; this study thus aims to investigate if a large window has similar thermal performance as a number of smaller windows with the same total area (see Figure 3-6).

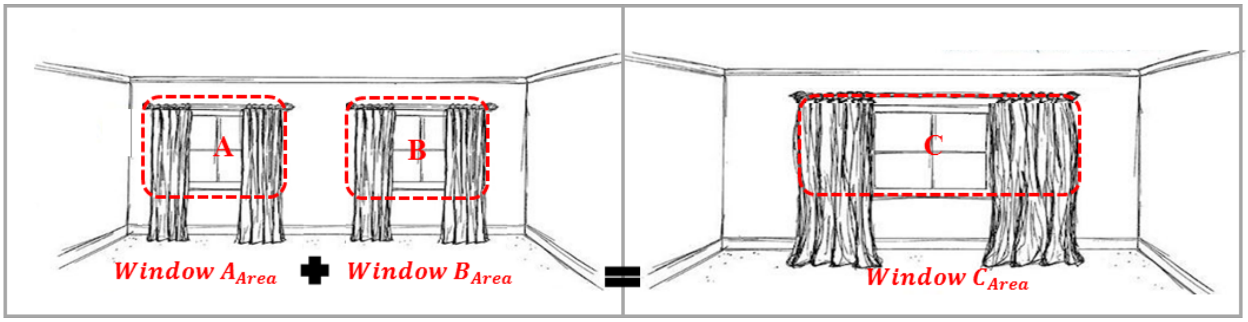


Figure 3-6: One window versus a number of windows with same total area

To carry out this study, the annual heat gain and loss through one 100 ft^2 window (Type 13 from Table 3-5) placed on the base house design (Section 3-2) are estimated by HOT2000. The results are compared with situations where the one 100 ft^2 window is replaced with two smaller windows (with 100 ft^2 total area) as well as three, four, and five smaller windows all with 100 ft^2 total areas.

Roof overhang depth: Since many houses in Edmonton are designed with roof overhangs, the impact of horizontal overhang depth on window thermal performance is studied. Basically, overhang has an impact on the solar heat gain through a window by blocking part of the window from sun radiation. As a result, the proper overhang depth should be considered in order to maximize solar heat gain through windows. This study first investigates the impact of overhang depth on annual solar heat gain through windows located on different orientations, followed by determining if long overhang depth reduces the solar hear gain through window during winter.

The analysis is conducted by placing a window (Type 13 from Table 3-5) on all orientations of the base house design (Section 3-2) and estimating the solar heat gain through the windows in HOT2000; then, the analysis is repeated for several roof overhang depths.

HOT2000 aids in the calculation of annual and monthly solar heat gain through windows. Therefore, when annual solar heat gain reduces due to the increase of overhang depth, the monthly solar heat gains are compared with previous simulation results to confirm when the reduction occurs (during the winter or other seasons). Finally, a formula is presented based on ASHRAE (2009) for designers to determine the proper overhang depth in order to maximize the solar heat gain during the winter.

Window style: In this section, the impact of window style on window thermal performance is investigated; picture (fixed), slider with sash, and hinged windows (shown in Figure 3-7) are selected as common window types in Edmonton. To carry out this study, the annual heat gain and loss through a slider window (Type 13 from Table 3-5) placed on one side of the base house design (Section 3-2) is estimated by HOT2000 and then the result is compared with a situation where the slider window is replaced with hinged and picture window styles.

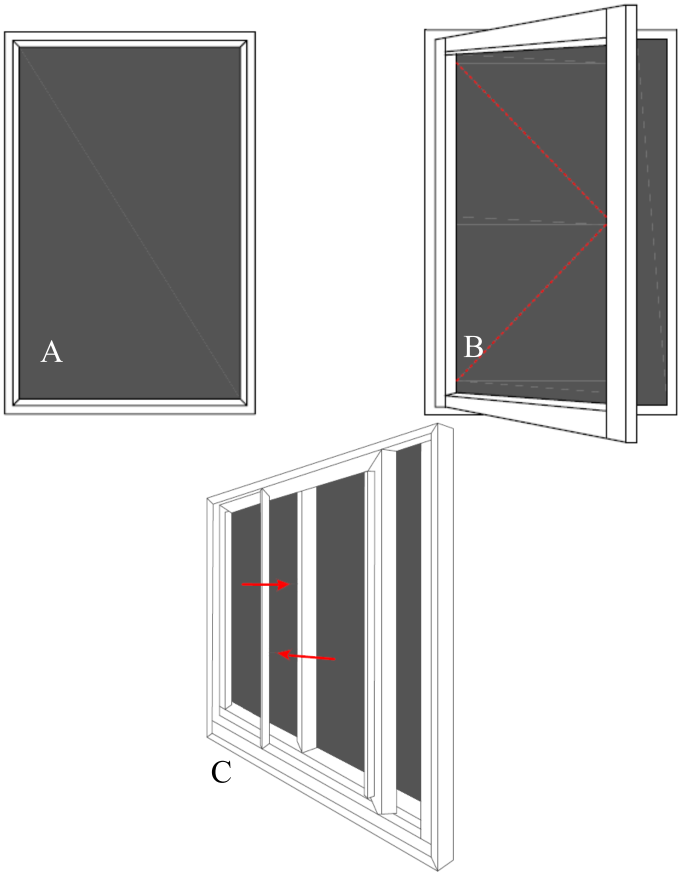


Figure 3-7: (a) Picture window, (b) Hinged window, (c) Slider with sash window (Clarke and Herrmann 2007; Stanek windows 2016)

3.6 House upgrade

According to the literature, improving building envelope, using more-efficient units for HVAC system and hot water heating system, and using a renewable energy system are common practices to achieve energy savings in a building which result in different cost impacts. Therefore, this section aims to conduct an analysis to answer the question of which of the following investments are more cost-effective in order to upgrade the energy efficiency of a house:

- Improving window type and insulations of building envelope;
- Using more-efficient units for mechanical system, and determining which type of heating system between furnace, boiler, electric baseboard, and air-source heat pump is the most cost-effective; and
- Installation of a PV panel system.

Prescriptive path and performance path are two methods of code compliance. Prescriptive path is basically a checklist which requires a certain level of efficiency for building components such as mechanical system (i.e., furnace, hot water heater, HRV) and building envelope (Thermal wise Co. 2016), while performance path offers more flexibility. To follow the performance path, it must be proven that the proposed design is as energy efficient as a building built to the prescriptive requirements (ABC 2014a).

The base house design (Section 3-2) is used for an investigation of potential upgrades (in terms of energy performance, initial cost, and operation cost). The energy performance of the base house is simulated by HOT2000 and has an EnerGuide rating (EGH) of 71. The first upgrade approach, which follows the ABC prescriptive requirements, results in an EGH of 82. As required by ABC performance path, the EGH of 82 generated from prescriptive design is used as the reference value for other alternative house designs. Seven other upgrade approaches are investigated aiming to achieve an EGH of 82 (following the performance path). In these approaches, improving window and insulations of building envelope, using more-efficient units for mechanical system (considering different heating system types), installation of a PV system, and their combinations are evaluated.

3.6.1 Main criteria for whole house upgrade selection

The base house design from section 3-2 (summarized in Table 3-2) with an EGH rating of 71, calculated from HOT2000, is used in this section for an investigation of potential upgrades. In the prescriptive upgrade approach, the base house design is improved to an EGH rating of 82. The key criterion in selecting specifications of prescriptive upgrade approach is to satisfy ABC, 2014 requirements.

As required by the performance path, the other upgrade approaches must achieve the same improvement on the base house design as that of the prescriptive approach (EGH 82). From that point, an EGH of 82 is the core criteria to select other upgrade approaches. The focus of upgrade approaches is listed in Table 3-6. Finally, the upgrade approaches are compared based on their LCCs.

Table 3-6: Focus on different systems for upgrade approaches

Building envelope
Improving window type Improving insulation used within: - exterior wall - basement wall - exposed floor - attic ceiling
Mechanical system

Improving the energy-efficiency of heating system, considering different heating systems: - Forced-air furnace - Hydronic boiler - Electric baseboard - Air-source heat pump Improving the energy-efficiency of heating recovery ventilation (HRV) Improving the energy-efficiency of domestic hot water heater (DHW)
Installation of a PV panel system

3.6.2 Selection of upgrade approaches

As mentioned before, seven different upgrade approaches are selected to apply to the base house design (Table 3-2) aiming to improve the energy performance rating from EGH 71 to EGH 82, and different systems (listed in Table 3-6) such as the mechanical system, building envelope and installation of a PV system are the focus of these upgrades. Table 3-7 lists the considered upgrade approaches in this study. In the following sections, upgrade approaches are described in more detail.

Table 3-7: Considered upgrade approaches in this study

Approach	Description
Upgrade approach 1	Improving building envelope including: - Window type - Insulation of basement and exterior walls

	- Insulation of exposed floor - Insulation of attic
Upgrade approach 2	1. Improving mechanical system (furnace heating system) 2. Minor building envelope upgrade
Upgrade approach 3	1. Improving mechanical system (boiler heating system) 2. Minor building envelope upgrade
Upgrade approach 4	1. Improving mechanical system (electric baseboard heating system) 2. Minor building envelope upgrade
Upgrade approach 5	Improving mechanical system (Air-source heat pump heating system)
Upgrade approach 6	1. Installation of a PV panel system 2. Improving building envelope
Upgrade approach 7	1. Installation of a PV panel system 2. Improving mechanical system (furnace heating system)

- **Upgrade Approach 1: Improving building envelopes**

  In approach one, the EGH rating of 82 is achieved by improving the insulations of the building envelope of the base house design, including exterior and basement walls, attic, and exposed floor, as well as improving windows.

The methodology of this study is based on LCC, but from the analysis and results of wall thermal insulation, it is found that the initial cost is closely related to minimum LCC; therefore, in selection of the best insulation combination for building envelope in approach one, initial cost is used rather than LCC, without causing any significant difference. Thus, the insulation combination of approach one is selected based on the minimum total initial cost between alternative solutions all with EGH of 82.

Accordingly, when deciding between alternative solutions to increase the overall R-value of building envelopes in the following approaches, the insulation combination is selected based on the minimum total initial cost.

- **Upgrade Approach 2: Improving the mechanical system and minor envelope upgrades**

In this approach the mechanical system units of the base house design (furnace heating system, HRV, and DHW) are upgraded to the highest efficiency level currently available; since such improvement is not effective enough to reach an EGH of 82, further minor upgrades to the building envelope are conducted.

According to the above mentioned upgrading procedures in approach one, among different solutions, the insulation combination is selected based on the minimum total initial cost.

- **Upgrade Approach 3: Improving mechanical system (hydronic boiler heating system) and minor envelope upgrades**

  In the third approach, the base house design is upgraded by replacing the furnace heating system with the most efficient boiler heating system currently available, and, in addition, the HRV and DHW systems are improved to the highest efficiencies currently available. As these upgrades are not effective enough to reach an EGH of 82, additional minor upgrades to the building envelope (similar to upgrade approach two) are conducted in this approach.

- **Upgrade Approach 4: Improving mechanical system (electric baseboard heating system) and minor envelope upgrades**

  In the fourth approach, the upgrade procedure is typically similar to the third approach, but a high-efficiency baseboard heating system is used in this approach.

  Upgrade Approach 5: Improving mechanical system (air-source heat pump heating system)

  In order to achieve an EGH of 82 in the fifth approach, the base house design is upgraded by replacing the furnace heating system with the most-efficient air-source heat pump heating system and HRV system currently available.

- **Upgrade Approach 6: Installing PV panel system and improving building envelope**

  In the sixth approach, the base house design is upgraded by installing a PV panel system and improving the building envelope. Table 3-8 summarizes the parameters considered for PV panel system.

Similar to the second approach, among different alternative solutions of improving the overall R-value of the building envelope, the insulation combination is selected based on the minimum total initial cost.

- **Upgrade Approach 7: Installing PV panel system and improving mechanical system**

  In the seventh approach, the base house design is upgraded by installing the PV panel system and improving the efficiency of the mechanical system (furnace heating system, HRV, and DHW).

Table 3-8: Parameters considered for PV panel system

Component	**Value**
Panel area	13.78 ft^2
Collector slope	58°
Azimuth of array	0°
Miscellaneous array losses	3 %
Inverter efficiency	90 %
Collector area	450 ft^2
Number of required panels	33

3.6.3 Lifecycle cost and payback period estimation of different house designs

The LCC for house design is estimated in the same way as that of window and wall by considering initial cost and operation cost over the lifespan of 30 years (Equation 2). The initial cost is estimated for materials and equipment used in the house designs, and is listed below. The operation cost is estimated based on HOT2000 simulation of the house energy consumption for space heating, DHW heating, electric appliances (constant in HOT2000 simulations (see Section 3-2), and HRV. Then, estimated energy is converted to a dollar value based on current prices of natural gas and electricity.

$$\mathrm{LCC} = \mathrm{Initial\ cost} + \left(\sum_{\mathrm{n}=1}^{\mathrm{lifetime}} \mathrm{Operation\ cost} \right) \tag{2}$$

LCC: lifecycle cost of house design

Initial design cost:

A. The following is a list of house component costs at construction phase:
  - Material costs of insulations used within exterior and basement walls, exposed floor and attic in the house design ($)
  - Material costs of windows used in the house design ($)
  - Total cost of heating system equipment including:
    - ✓ gas furnace, fan, air ducts, diffusers and HRV (forced-air space heating system using natural gas furnace);

    - ✓ boiler, pump, water piping, radiators, and HRV (for hydronic boiler heating system);
    - ✓ electric baseboard heater and HRV (for electric baseboard heating system);
    - ✓ air-source heat pump, fan, air ducts, diffusers, and HRV (for air source electric heat pump heating system);
- Cost of hot water heater unit used in the house design ($)
- Material and installation cost of PV panel system for those designs which are upgraded with PV panel system ($)

B. Cost of replacing some equipment which has less than a 30-year life expectancy + CPI percentage of price adjustment on the year of replacement (Equation 4)

Operation cost:

Natural gas cost: Annual gas consumption (GJ) × current gas price ($/GJ)

+

Electricity cost: Annual gas consumption (MWh) × current electricity price ($/MWh)

As mentioned previously, the main purpose in this section is to understand which upgrade approaches are more cost-effective to reach the desired building energy performance (EnerGuide rating of 82). Thus, for the purpose of comparison, a simplified payback period is estimated for all developed designs representing the duration required to recover additional upgrade costs in the house. The payback year for each design is calculated and explained as follows:

A= difference in initial house design cost between base house model and upgraded house.

i_1= energy cost savings due to the upgrade approach at first year – replacement cost (if required)

i_{1+2}= sum of energy cost savings at first and second years – replacement cost (if required)

i_{1+2+3}= sum of energy cost savings at first, second, and third years– replacement cost (if required)

When $i_{1+\cdots+n} \geq$ A, then n is considered as payback year

CHAPTER 4: RESULTS AND DISCUSSION

The previous chapter presented a methodology to select and evaluate the cost effectiveness of energy-efficient designs focusing on windows, wall thermal insulations, and house upgrades using lifecycle cost analysis (LCCA). The analysis results are provided in the present chapter.

4.1 Window design from energy efficiency perspective

As discussed above, analysis is conducted in this study to determine window to exterior wall ratio on each orientation, which could minimize the overall annual heat loss in the house. Results indicate that window to exterior wall ratios of 34% for south-facing window area and 18% for west- or east-facing window area result in the minimum respective annual heat loss in the house (shown in Figure 4-1 and Figure 4-2). However, the larger north-facing window area achieves the greater annual heat loss (shown in Figure 4-3). The results are generalized to different house sizes investigated in this study.

This result can be explained by the impact of directional orientation on transmitted useful solar heat gain through windows, which offsets a portion of the heat loss in the house. The maximum annual transmitted useful solar heat is received mostly through south-facing windows, followed by west- and east-facing windows, respectively, while north-facing windows see the least annual solar heat gain. Therefore, the ideal proportion of window area to exterior wall area to achieve the minimum total heat loss is highest on south, then east and west, and finally north orientations.

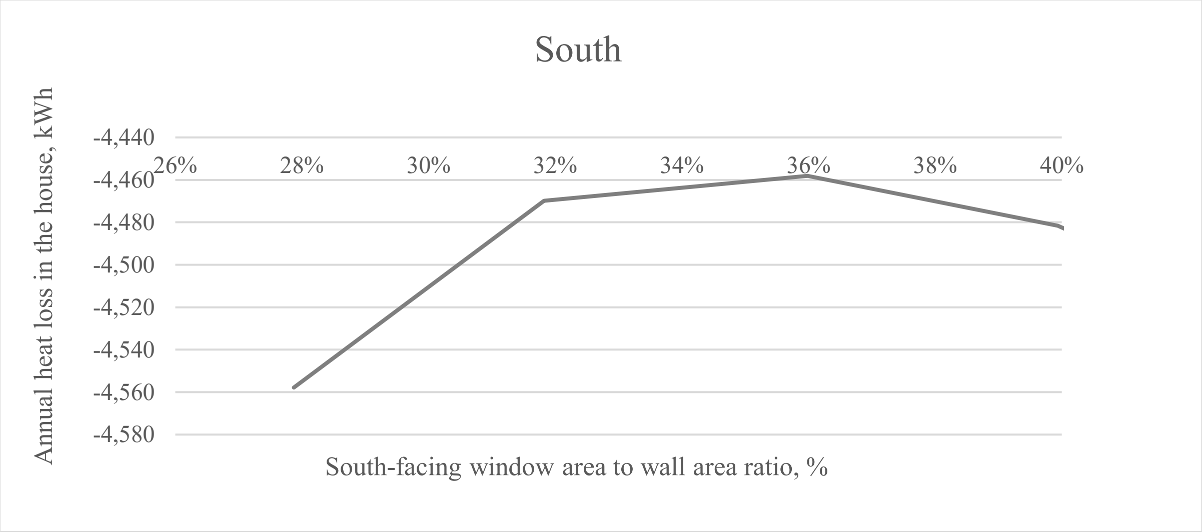


Figure 4-1: South-facing window area to total exterior walls area ratio versus total annual heat loss

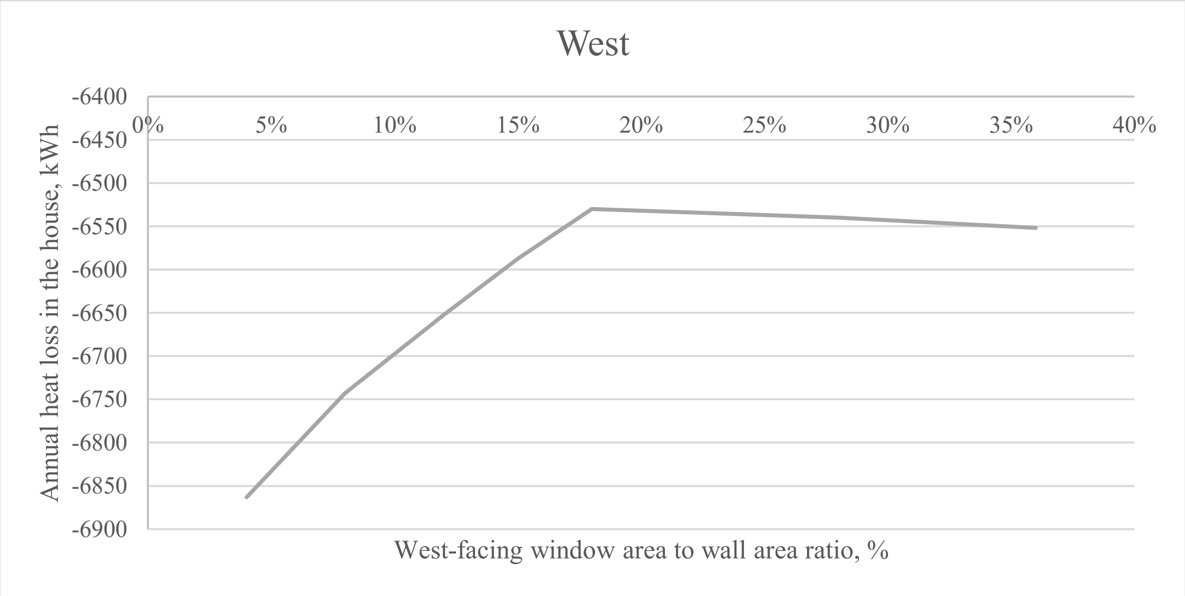


Figure 4-2: West-facing window area to total exterior walls area ratio versus total annual heat loss

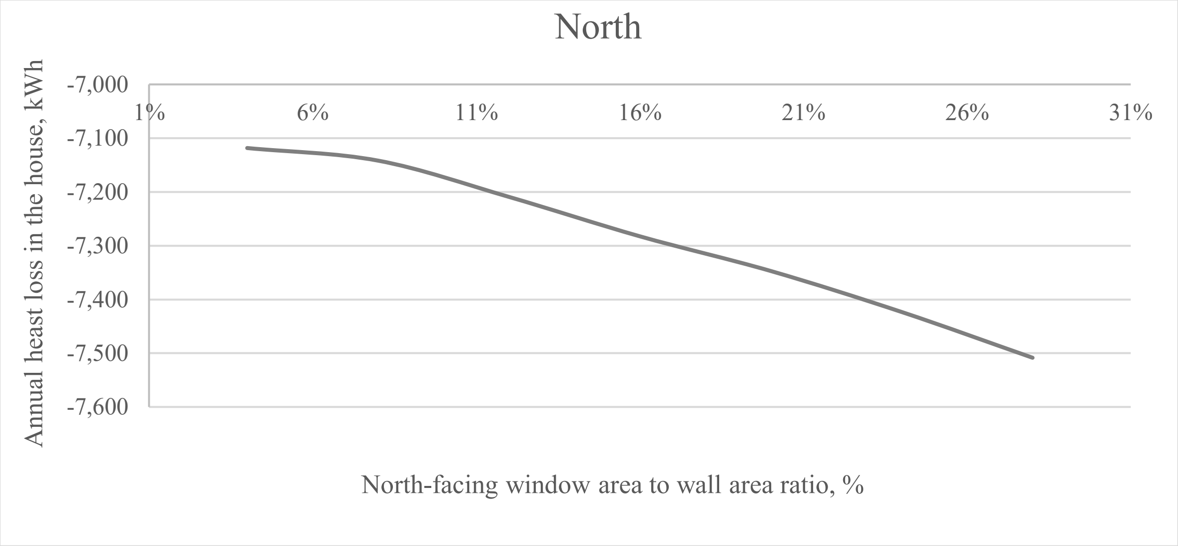


Figure 4-3: North-facing window area to total exterior walls area ratio versus total annual heat loss

An investigation on the thermal performance of a large window versus multiple smaller windows with the same total area indicates that more solar heat gain is achieved from a larger window due to the larger glass area, and thus a higher R-value and less heat loss (see Figure 4-4). The total R-value of a window is the opposite of U-factor, and is calculated based on the thermal resistance of frame, edge, and centre of glass as:

$$R_{tot} = \frac{A_{tot}}{(A_{frame}/R_{\ Frame}) + \ (A_{edge}/R_{\ edge}) + \ (A_{\ glass}/R_{\ glass})} \tag{11}$$

The centre of glass usually has a higher R-value than the frame and edge (Aclara Technologies LLC 2010). Therefore, when there is one large window, the total R-value of the window would be higher due to there being less frame and more glass area

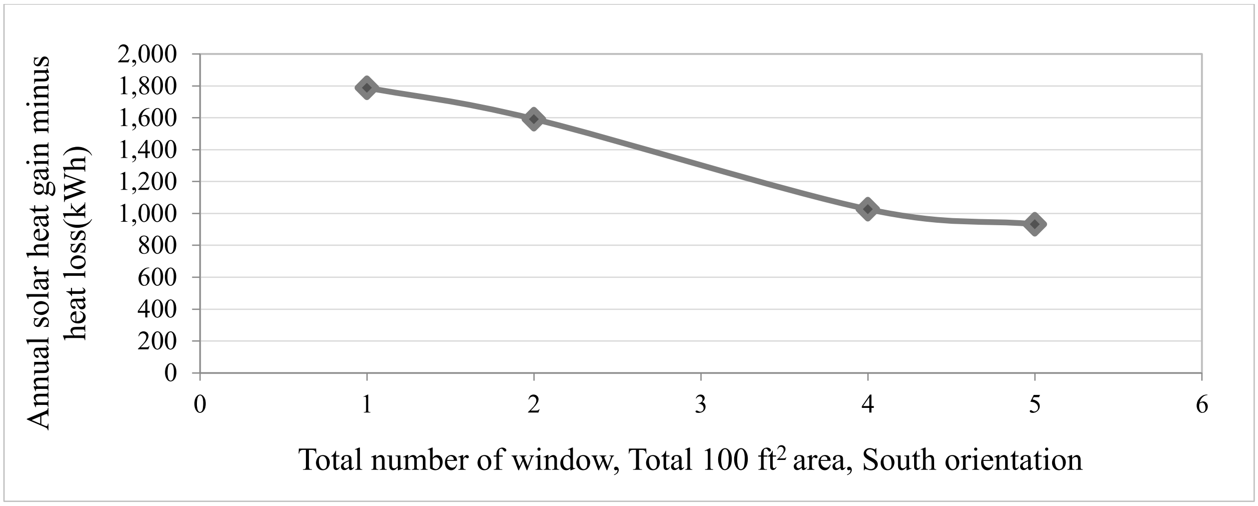


Figure 4-4: One large window vs. a number of smaller windows

Roof overhang depth is another parameter that has been investigated in this study. Figure 4-5 illustrates the impact of overhang depth on annual solar heat gain through south-, west- and north-facing windows.

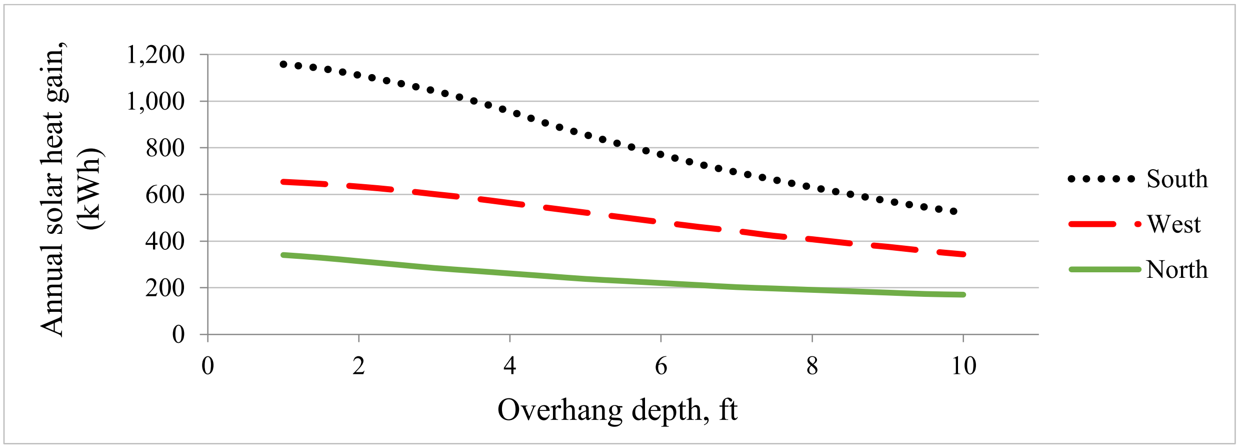


Figure 4-5: Impact of overhang depth on solar heat gain through windows on different orientations

As can be seen from Figure 4-5, increasing roof overhang depth on the south orientation reduces the annual solar heat gain dramatically. However, HOT2000 results show that this reduction occurs during late spring, summer, and early-fall, which can be explained due to the high solar altitude. Therefore, if the roof overhang depth is not excessively great, it does not block the solar radiation from entering any windows on the south façade. Equation 12 may assist designers to determine a proper overhang depth on the south façade that does not block south-facing windows from sun radiation during the winter (ASHRAE 2009).

$$Y = H - D \times \left(\frac{tan\beta}{\cos\gamma}\right) \qquad (12)$$

Y= Window height which is not under shade

H= Total window height

D= Overhang depth

β= Solar altitude

γ= Solar-wall azimuth angle

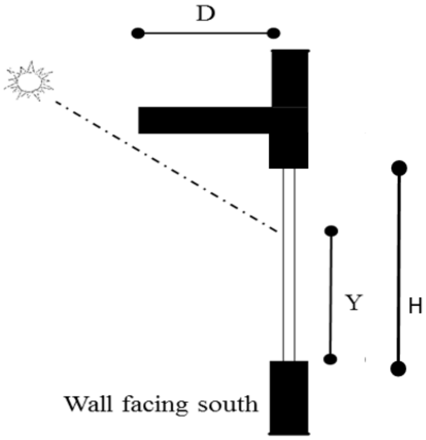


Figure 4-6: Shadow cast by an overhang

The comparison analysis between thermal performances of different window styles indicates the following results (shown in Figure 4-7):

- Hinged window has 15% to 30% better performance than slider window

- Picture window has 20% to 50% better performance than slider window

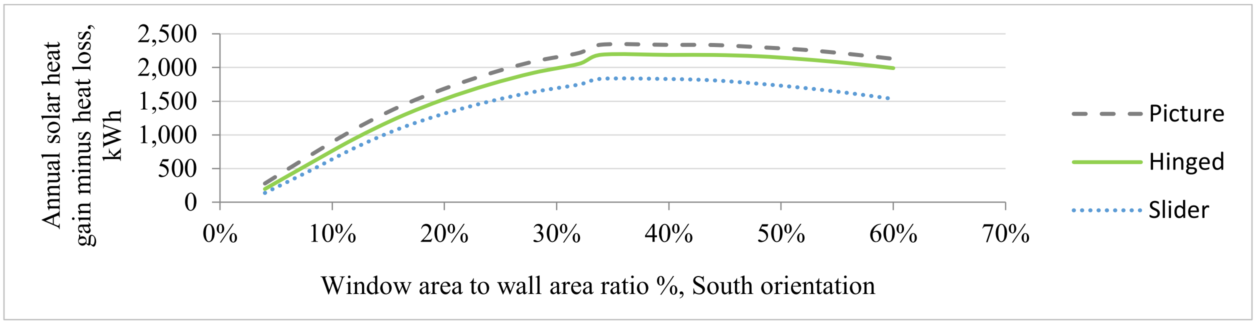


Figure 4-7: The thermal performance of picture, hinged, and slider window types

4.2 Detailed analysis with selected window types

Lifecycle cost analysis (LCCA) is conducted on a series of window types (from Table 3-5) based on their initial and 30-year operation costs per unit area (see Figure 4-8). It is important to note that although fibreglass as a frame material has good insulation value, the results obtained from the LCCA indicate that windows with fibreglass framing have higher LCC than do other frame materials (vinyl, wood, or aluminum-clad wood). In contrast, vinyl-framed windows have a lower LCC in comparison. Although annual heat loss through windows with fibreglass frame is less than that through vinyl-framed windows, the finding is due to the significantly lower initial price of a vinyl frame compared to fibreglass frame.

In addition, although krypton gas has better thermal performance than argon gas, the LCC of both double-pane windows with one heat mirror film in between and triple-glazed windows is less when their cavity is filled with argon gas. Furthermore, double-pane windows with one heat mirror film between the panes show a decrease in LCC compared to triple-pane windows.

As a result, window type 5—low-e double-pane with one heat mirror film in between, 13 mm argon-filled cavity, and vinyl frame—is determined to have the lowest LCC and ranks the highest on all orientations.

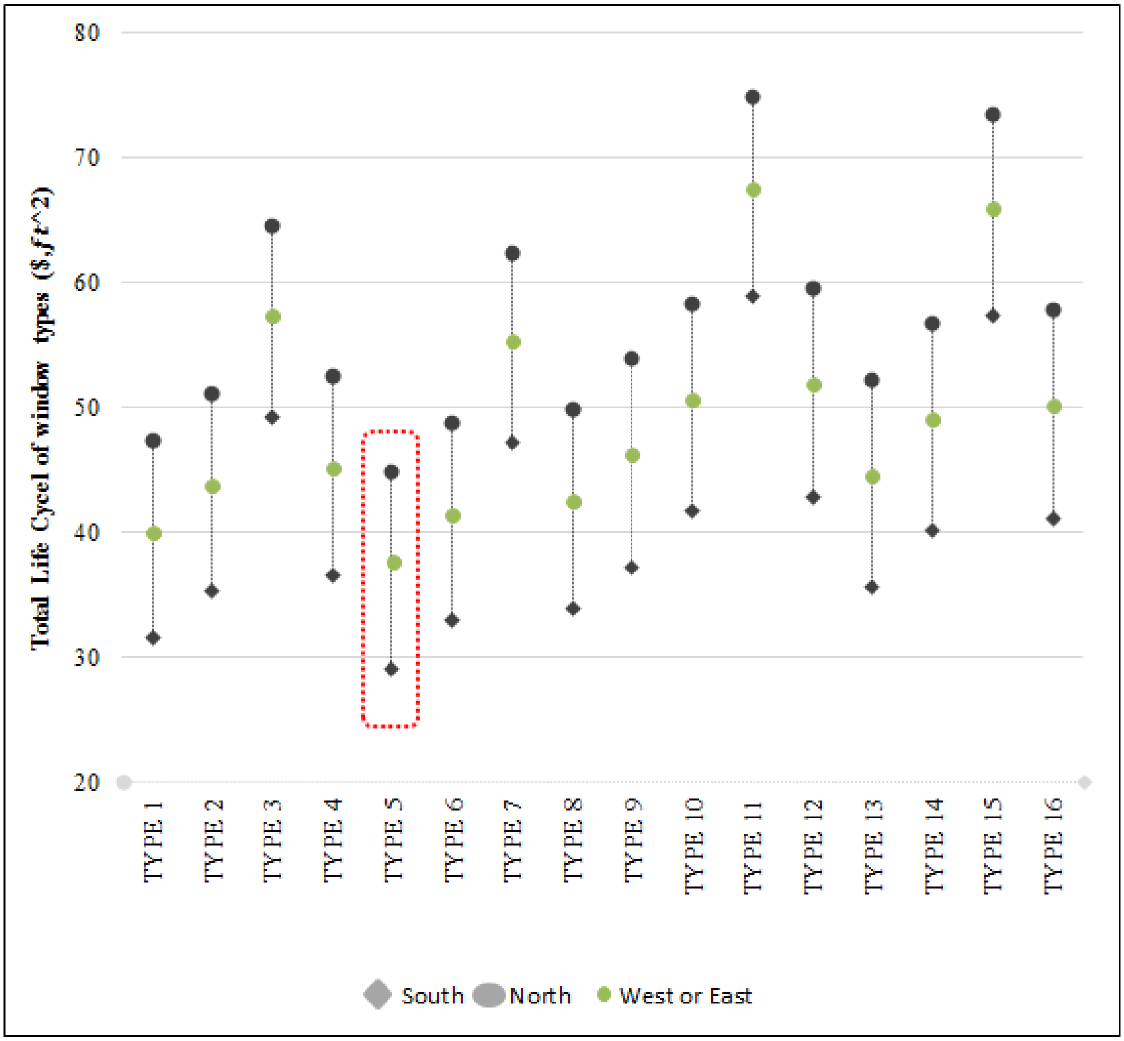


Figure 4-8: Total LCC of different window types on each orientation (see detailed information of different types in Table 3-5)

Since the low-e triple-pane window filled with argon gas and vinyl frame (type 13 from Table 3-5) is common practice in low-energy designs, the LCC percentage improvement of using the studied window types (from Table 3-5) versus triple-pane window in different house sizes, including the base house design, (house sizes between 1,451 ft^2 and 3,000 ft^2), is estimated. Table 4-1 summarizes the LCC of studied window types ($/ ft^2) and LCC improvement of using window type 13 instead of the studied window types.

The results indicate that by using double-pane windows with one heat mirror film in between (Type 5 from Table 3-5) in the house, a 18% increase in window LCC on south-facing, 14% on north-facing, and 16% on west- or east-facing is achieved compared with using triple-pane windows.

Table 4-1: The LCC ($/ ft2) and LCC percentage improvement of studied window types versus the window type 13 from Table 3-5

Window types	South-facing Window		North-facing Window		West or East-facing Window	
	LCC ($/ ft^2), LCC improvement (%)		LCC ($/ ft^2), LCC improvement (%)		LCC ($/ ft^2), LCC improvement (%)	
Type 5	$29.08	18%	$44.87	14%	$37.61	16%
Type 1	$31.48	11%	$47.26	9%	$39.92	10%
Type 6	$32.88	7%	$48.67	7%	$41.41	7%

Type 8	$33.91	5%	$49.77	5%	$42.43	5%
Type 2	$35.28	1%	$51.06	2%	$43.72	2%
Type 13	$35.54	0%	$52.19	0%	$44.54	0%
Type 4	36.46	−3%	$52.40	0%	$45.06	-1%
Type 9	$37.15	−5%	$53.80	−3%	$46.15	−4%
Type 14	$40.07	−13%	$56.72	−9%	$49.06	−10%
Type 16	$41.09	−16%	$57.82	−11%	$50.17	−13%
Type 10	$41.67	−17%	$58.33	−12%	$50.67	−14%
Type 12	$42.70	−20%	$59.43	−14%	$51.78	−16%
Type 7	$47.13	−33%	$62.37	−19%	$55.26	−24%
Type 3	$49.13	−38%	$64.45	−23%	$57.34	−29%
Type 15	$57.30	−61%	$73.40	−41%	$65.98	−48%
Type 11	$58.83	−66%	$74.93	−44%	$67.51	−52%

A sensitivity analysis is conducted to estimate LCC of windows in order to determine how increasing natural gas prices would affect the results of this study. In this analysis, three different scenarios are considered for future natural gas prices. Scenario 1 uses the present natural gas escalation rate, which is determined in section 3.3.1 to be 5.08%. Scenario 2 assumes a 7% escalation rate for future natural gas prices. Due to the impact of carbon taxation on natural gas prices beginning in January, 2017, scenario 3 assumes a 7% escalation rate and increases the current natural gas price from 2.6 GJ/$ to 3.7 GJ/$. The results of the sensitivity analysis are summarized in Table 4-2, where positive value denote heat gain and cost savings, whereas negative values denote heat loss for space heating.

Table 4-2: Summary of sensitivity analysis of increasing predicted natural gas prices

South-facing window								
		Net heat loss or gain per sf^2 (GJ)	Sc 1	Sc 2	Sc 3	Sc 1	Sc 2	Sc 3
Window	Initial cost per sf^2 ($)		30 years heat saving or heat loss cost ($)				LCC ($)	
5	$38.00	0.0477	$8.52	$12.17	$17.06	$29.48	$25.83	$20.94
1	$40.00	0.0456	$8.52	$12.17	$17.06	$31.48	$27.83	$22.94
6	$41.80	0.0477	$9.87	$14.09	$19.74	$31.93	$27.71	$22.06
8	$41.80	0.0422	$7.34	$10.48	$14.69	$34.46	$31.32	$27.11
2	$43.80	0.0456	$8.92	$12.73	$17.85	$34.88	$31.07	$25.95
13	$45.25	0.0519	$8.92	$12.73	$17.85	$36.33	$32.52	$27.40
4	$43.80	0.0393	$9.87	$14.09	$19.74	$33.93	$29.71	$24.06
9	$47.25	0.0541	$7.89	$11.27	$15.79	$39.36	$35.98	$31.46
14	$49.78	0.0519	$10.10	$14.43	$20.22	$39.67	$35.35	$29.56
16	$49.78	0.0465	$10.10	$14.43	$20.22	$39.67	$35.35	$29.56
10	$51.78	0.0541	$11.05	$15.78	$22.11	$40.73	$36.00	$29.66

12	$51.78	0.0486	$9.08	$12.96	$18.16	$42.70	$38.81	$33.61
7	$57.00	0.0528	$9.71	$13.86	$19.43	$47.29	$43.14	$37.57
3	$59.00	0.0528	$9.71	$13.86	$19.43	$49.29	$45.14	$39.57
15	$67.88	0.0566	$10.58	$15.10	$21.16	$57.30	$52.77	$46.71
11	$69.88	0.0591	$8.68	$12.40	$17.37	$61.19	$57.48	$52.50
North-facing window								
5	$38.00	−0.037	−$6.87	−$9.80	−$13.74	$44.87	$47.80	$51.74
1	$40.00	−0.039	−$7.26	−$10.37	−$14.53	$47.26	$50.37	$54.53
6	$41.80	−0.037	−$6.87	−$9.80	−$13.74	$48.67	$51.60	$55.54
8	$41.80	−0.043	−$7.97	−$11.38	−$15.95	$49.77	$53.18	$57.75
2	$43.80	−0.039	−$7.26	−$10.37	−$14.53	$51.06	$54.17	$58.33
13	$45.25	−0.037	−$6.94	−$9.92	−$13.90	$52.19	$55.17	$59.15
4	$43.80	−0.046	−$8.60	−$12.28	−$17.22	$52.40	$56.08	$61.02
9	$47.25	−0.035	−$6.55	−$9.35	−$13.11	$53.80	$56.60	$60.36

14	$49.78	−0.037	−$6.94	−$9.92	−$13.90	$56.72	$59.69	$63.67
16	$49.78	−0.043	−$8.05	−$11.50	−$16.11	$57.82	$61.27	$65.89
10	$51.78	−0.035	−$6.55	−$9.35	−$13.11	$58.33	$61.13	$64.88
12	$51.78	−0.041	−$7.66	−$10.93	−$15.32	$59.43	$62.71	$67.10
7	$57.00	−0.029	−$5.37	−$7.66	−$10.74	$62.37	$64.66	$67.74
3	$59.00	−0.029	−$5.45	−$7.78	−$10.90	$64.45	$66.78	$69.90
15	$67.88	−0.030	−$5.52	−$7.89	−$11.06	$73.40	$75.76	$78.93
11	$69.88	−0.027	$0.39	$0.56	$0.79	$37.61	$37.44	$37.21
West-facing window								
5	$38.00	0.0021	$0.39	$0.56	$0.79	$37.61	$37.44	$37.21
1	$40.00	0.0004	$0.08	$0.11	$0.16	$39.92	$39.89	$39.84
6	$41.80	0.0021	$0.39	$0.56	$0.79	$41.41	$41.24	$41.01
8	$41.80	−0.0034	−$0.63	−$0.90	−$1.26	$42.43	$42.70	$43.06
2	$43.80	0.0004	$0.08	$0.11	$0.16	$43.72	$43.69	$43.64

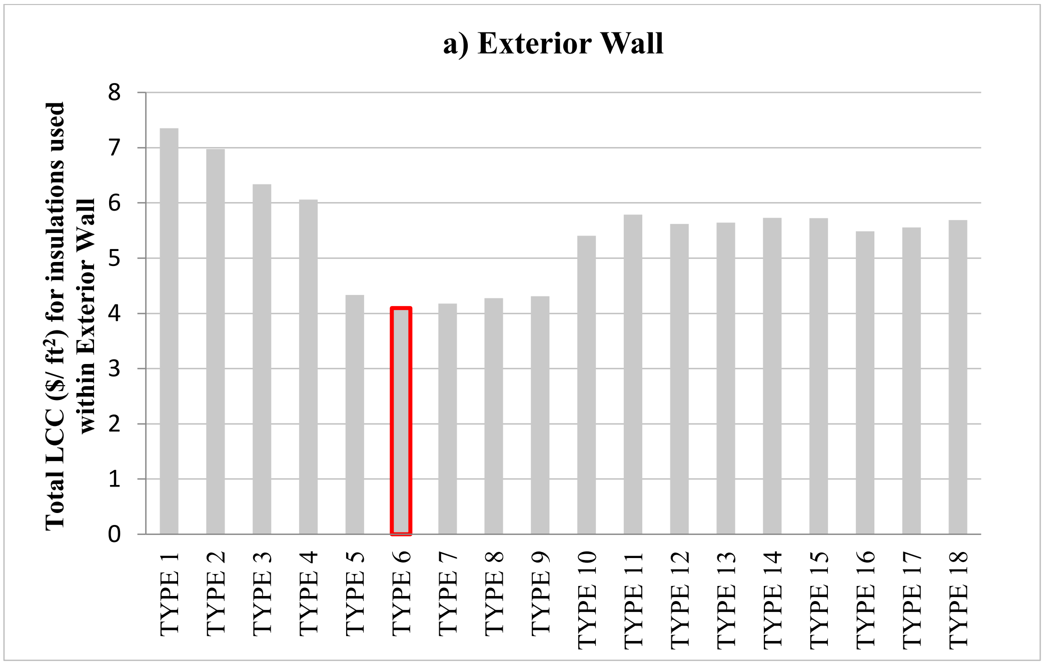
13	$45.25	0.0038	$0.71	$1.01	$1.42	$44.54	$44.24	$43.83
4	$43.80	−0.0068	−$1.26	−$1.80	−$2.53	$45.06	$45.60	$46.33
9	$47.25	0.0059	$1.10	$1.58	$2.21	$46.15	$45.67	$45.04
14	$49.78	0.0038	$0.71	$1.01	$1.42	$49.06	$48.76	$48.35
16	$49.78	−0.0021	−$0.39	−$0.56	−$0.79	$50.17	$50.34	$50.56
10	$51.78	0.0059	$1.10	$1.58	$2.21	$50.67	$50.20	$49.56
12	$51.78	0.0000	$0.00	$0.00	$0.00	$51.78	$51.78	$51.78
7	$57.00	0.0093	$1.74	$2.48	$3.47	$55.26	$54.52	$53.53
3	$59.00	0.0089	$1.66	$2.37	$3.32	$57.34	$56.63	$55.68
15	$67.88	0.0101	$1.89	$2.70	$3.79	$65.98	$65.17	$64.08
11	$69.88	0.0127	$2.37	$3.38	$4.74	$67.51	$66.49	$65.14

As can be seen from Table 4-2, the results of sensitivity analysis indicate that double-pane windows with one heat mirror film in between (Type 5 from Table 3-5) achieve the lowest LCC on all orientations in scenario 1, 2 and 3, and that by using double-pane windows with one heat mirror film in between in the house rather than triple-pane windows (type 13 from Table 3-5) the following LCC reduction is achieved:

- On south-facing window: 18% in scenario 1, 20% in scenario 2, and 22% in scenario 3,
- On north-facing window: 14% in scenario 1, and 13% in scenarios 2 and 3,
- On west-facing window: 16% in scenario 1 and 15% in scenarios 2 and 3.

4.3 Detailed analysis with identified wall insulations

The lifecycle cost analysis (LCCA) is conducted on a series of thermal insulations for basement and exterior walls based on their initial and 30-year operation costs; the results are illustrated in Figure 4-9.



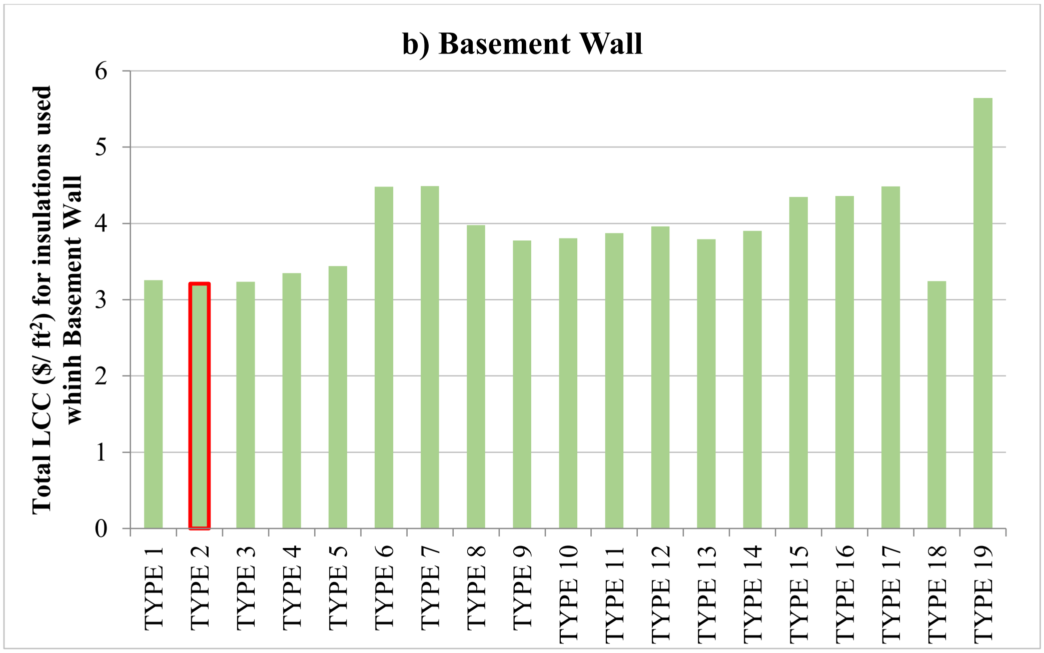


Figure 4-9: Total LCC ($/ ft^2) of insulations used within (a) exterior wall and (b) basement wall

As shown in Figure 4-9, the LCCA indicates that the following two insulation configurations achieve the lowest LCC per unit of wall area:

- Insulation type 6 from Table 3-4: fibreglass batt R19 (cavity) and 1″ expanded polystyrene (continuous insulation) for exterior wall.
- Insulation type 2 from Table 3-4: fibreglass batt R10 (cavity) and fibreglass batt R12 (continuous insulation) for basement wall.

Since polyurethane spray foam insulation is common practice in low-energy designs, Table 4-3 summarizes the LCC percentage improvement of using Type 6 insulation configurations from Table 3-4 versus Type 4 3½″ polyurethane spray foam insulation for the exterior wall of the reference house. The results indicate that, by using fibreglass batt and rigid foam insulations in exterior walls of the base house design, 30% savings can be achieved in wall LCC compared with polyurethane spray foam insulation.

Table 4-3: The LCC percentage improvement of studied insulations configurations for exterior wall versus 3.5″ polyurethane spray foam insulation

EXTERIOR WALL	IMPROVEMENTS
Type 6	30%
Type 7	29%
Type 8	27%
Type 9	26%
Type 5	26%
Type 10	8%
Type 16	6%
Type 17	5%
Type 12	4%
Type 13	4%
Type 18	3%
Type 14	2%
Type 15	2%
Type 11	1%

Type 4	−4%
Type 3	−8%
Type 2	−19%
Type 1	−26%

A sensitivity analysis is conducted to estimate the LCC of exterior wall insulations in order to determine how increasing natural gas prices would affect the results of this study. In this analysis, three different scenarios are considered for future natural gas prices. Scenario 1 uses the present natural gas escalation rate, which is determined in section 3.3.1 to be 5.08%. Scenario 2 assumes a 7% escalation rate for future natural gas prices. Due to the impact of carbon taxation on natural gas prices beginning in January, 2017, scenario 3 assumes a 7% escalation rate and increases the current natural gas price from 2.6 GJ/$ to 3.7 GJ/$. The result of sensitivity analysis is summarized in Table 4-4.

Table 4-4: summary of sensitivity analysis of increasing natural gas prices

Exterior wall					
Type	**Initial cost per sf^2**	**Annual heat loss per sf^2(GJ)**	**Scenario 1 30 years Operation cost ($)**	**Scenario 2 30 years Operation cost ($)**	**Scenario 3 30 years Operation cost ($)**
TYPE 1	$4.89	−0.013	$2.46	$3.51	$4.92
TYPE 2	$4.45	−0.014	$2.52	$3.61	$5.05

TYPE 3	$3.56	−0.015	$2.78	$3.96	$5.56
TYPE 4	$3.11	−0.016	$2.95	$4.21	$5.9
TYPE 5	$1.82	−0.013	$2.51	$3.59	$5.03
TYPE 6	$1.44	−0.014	$2.66	$3.79	$5.32
TYPE 7	$1.76	−0.013	$2.42	$3.45	$4.84
TYPE 8	$1.7	−0.014	$2.58	$3.68	$5.16
TYPE 9	$1.23	−0.017	$3.08	$4.4	$6.16
TYPE 10	$3.37	−0.013	$2.42	$3.45	$4.84
TYPE 11	$2.99	−0.014	$2.63	$3.75	$5.26
TYPE 12	$3.31	−0.013	$2.33	$3.33	$4.67
TYPE 13	$3.25	−0.013	$2.48	$3.54	$4.97
TYPE 14	$2.34	−0.016	$3.06	$4.38	$6.13
TYPE 15	$2.98	−0.015	$2.75	$3.92	$5.5
TYPE 16	$2.6	−0.015	$2.89	$4.12	$5.78
TYPE 17	$2.92	−0.014	$2.63	$3.76	$5.27

TYPE 18	$2.86	−0.015	$2.83	$4.04	$5.66

As can be seen from Table 4-4, the results of the sensitivity analysis indicate that insulation type 6 for scenario 1 and Type 7 for scenarios 2 and 3 achieve the lowest LCCs, which are fibreglass and rigid foam insulations, and that polyurethane spray foam insulation is between 25% and 30% less cost-effective than fibreglass and rigid foam insulations.

The results pertaining to the LCC of wall insulations with close thermal resistance (R-value) reveal that the LCC here depends mainly on initial cost rather than operation cost. For instance, Type 1 from Table 4-3 has less operation cost than Type 6, but the savings during operation is considerably less than the additional cost of initial investment. Therefore, in selection of the best insulation combinations for building envelope in the following upgrade approaches, initial cost is used rather than LCC without causing any significant difference.

4.4 Comparative analysis of upgrades solutions

LCCA is conducted to compare different house upgrade approaches over the base house design (Section 3-2) with the aim of improving the overall energy efficiency of the base house design from EGH 71 to 82. Table 4-5 provides the specifications of building envelopes and mechanical systems used for the prescriptive upgrade approach, and Table 4-6 through Table 4-10 summarize the specifications of upgraded components in the seven approaches. Finally, Table 4-11 summarizes the results of LCCA and payback period for all upgrade approaches studied.

Table 4-5: Specifications of building envelope and mechanical system in prescriptive upgrade approach

	Component		Characteristic
1. Building Envelopes:	Below-grade wall	Insulation used:	- Cavity Insulation: Fibreglass batt R10 - Continuous Insulation: Fibreglass batt R12
	Above-grade wall		- Cavity Insulation: Fibreglass batt R13 - Continuous Insulation: Rigid EPS(1″)
	Exposed floor		- Cavity Insulation: Fibreglass batt R28
	Attic		- Cavity Insulation: Blown-in cellulose R30 - Continuous Insulation: Blown-in cellulose R30
	Window type		Double glazing + one heat mirror film 88, low-e 20% hard coating, vinyl frame, argon 13 mm
2.Mechanical System:	Heating system		Natural gas furnace, AFUE: 92%
	Heating recovery ventilation		HRV: SRE @ 0 °C: 65% SRE −25 °C: 64%
	Domestic hot water heater		Gas fired, Energy Factor: 67%

Table 4-6: Specifications of upgraded components in approach 1

	Component		Characteristic
Building Envelopes.	Below-grade wall	Insulation used:	- Cavity Insulation: Fibreglass batt R10 - Continuous Insulation: Fibreglass batt R12

Above-grade wall	- Cavity Insulation: Fibreglass batt R19 - Continuous Insulation: 1″ EPS
Exposed Floor	- Cavity Insulation: Fibreglass batt R40 - Continuous Insulation: 3″ Rigid EPS
Attic	- Cavity Insulation: Fibreglass batt R40 - Continuous Insulation: Fibreglass batt R40
Window	Double glazing + one heat mirror film 88, low-e 20% hard coating, vinyl frame, argon 13 mm

Table 4-7: Specifications of upgraded components in approaches 2, 3, and 4

		Component		Characteristic
1.Building		Above-grade wall	Insulation used:	Cavity Insulation: Fibreglass batt R19
		Attic		Cavity Insulation: Fibreglass batt R19
2. Mechanical System	Upgrade 2	Heating system		- Natural gas furnace, AFUE: 98% - HRV: SRE @ 0 °C: 81% SRE @ −25 °C: 69%
	Upgrade 3			- Hydronic gas boiler, AFUE: 95% - HRV: SRE @ 0 °C: 81% SRE @ −25 °C: 69%
	Upgrade 4			- Electric baseboard system, AFUE: 100% - HRV: SRE @ 0 °C: 81% SRE @ −25 °C: 69%

	Domestic hot water heater	Gas fired, Energy factor: 82%

Table 4-8: Specifications of upgraded components in approach 5

	Component	Characteristic
Mechanical system	Heating system	- Air source electric heat pump system, HSPF: 9.7% - HRV: SRE @ 0 °C: 81% SRE @ −25 °C: 69%

Table 4-9: Specifications of upgraded components in approach 6

	Component		Characteristic
1.Building Envelope:	Above-grade wall	Insulation used:	- Cavity Insulation: Fibreglass batt R19 - Continuous Insulation: 1″ EPS
	Attic		- Cavity Insulation: Fibreglass batt R19
2. Solar PV panel system installed in the house			

Table 4-10: Specifications of upgraded components in approach 7

	Component	Characteristic
1.Mechanical system	Heating system	- Natural gas furnace, AFUE: 98% - HRV: SRE @ 0 °C: 81% - SRE @ −25 °C: 69%
	Domestic hot water heater	Gas fired, Energy factor: 82%
2.PV panel system installed in the house		

Table 4-11: Summary of LCCA for upgrade solutions

Upgrade	Estimated annual energy consumption (kWh)	LCC ($)			Payback period (years)
	Space heating + DHW heating + HRV	initial cost	30 years operation cost	Total	
Base house design	35,816	13,100	46,915	60,015	-
Prescriptive design	18,891	21,102	35,869	56,970	25
Upgrade 1	19,875	20,073	36,070	56,144	22
Upgrade 2	19,214	16,101	38,166	54,267	13
Upgrade 3	19,024	20,094	39,215	59,309	17
Upgrade 4	17,625	13,223	49,642	62,865	30
Upgrade 5	18,556	17,895	45,449	63,344	+30
Upgrade 6	28,852 8,265	35,277	27,039	$62,316	+30
Upgrade 7	28,111 8,265	35,874	29,095	$64,969	+30

The results in Table 4-11 reveal that, among all upgrades evaluated, upgrade approach 2—improving the mechanical system (furnace heating system) and minor building envelope upgrades—achieve the lowest LCC, and the forced-air space heating system using natural gas furnace is found to be the most economical heating system when compared with boiler, electric baseboard, and air-source heat pump. In addition, upgrading the house by installing a PV panel system (approaches 6 and 7) takes a long period of time for return on the incremental investment and is thus not considered a cost-effective solution.

In this analysis the 30 years of estimated fuel consumption is converted to a dollar value using current fuel prices and the percentage change for future fuel price, which is determined to be 5.08% for natural gas and 1.35% for electricity. Since the predicted price of natural gas is much lower than that of electricity, a sensitivity analysis is conducted to determine how increasing predicted natural gas prices will affect the results of this study. In this analysis, three different scenarios are considered for future natural gas prices. Scenario 1 uses the present natural gas escalation rate, which is determined in section 3.3.1 to be 5.08%. Scenario 2 assumes a 7% escalation rate for future natural gas prices. Due to the impact of carbon taxation on natural gas prices beginning in January, 2017, scenario 3 assumes a 7% escalation rate and increases the current natural gas price from 2.6 GJ/$ to 3.7 GJ/$. The results of the sensitivity analysis are summarized in Table 4-12.

Table 4-12: Summary of sensitivity analysis for upgrade approaches

Upgrade	initial cost ($)	Sc 1	Sc 2	Sc 3	Sc 1	Sc 2	Sc 3
		Operation cost ($)			LCC ($)		
Base house design	13,100	46,915	86,537	100,123	60,015	99,637	113,223
Prescriptive design	21,102	35,869	70,366	77,452	56,970	91,468	98,554

Upgrade 1	20,073	36,070	70,821	78,292	56,144	90,894	98,365
Upgrade 2	16,101	38,166	72,826	80,028	54,267	88,927	96,129
Upgrade 3	20,094	39,215	73,822	80,951	59,309	93,915	101,044
Upgrade 4	13,223	49,642	117,225	119,300	62,865	130,447	132,523
Upgrade 5	17,895	45,449	87,817	93,697	63,344	105,712	111,593
Upgrade 6	35,277	27,039	38,504	49,425	62,316	73,781	84,702
Upgrade 7	35,874	29,095	40,484	51,100	64,969	76,358	86,974

As can be seen from Table 4-12, by increasing the predicted natural gas prices in scenario 2 and 3, Approaches 6—Installation of a PV panel system and improving building envelope—is found to achieve the lowest LCC among all investigated upgrades.

CHAPTER 5: CONCLUSION

5.1 Conclusion

This research presents a methodology to determine energy-efficient solutions with the lowest LCC with respect to the National Building Code 2011, which was adopted in Alberta in 2014 as the Alberta Building Code (ABC). The primary focus of this research is window design and wall insulation (exterior and basement), due to their major influence on building energy performance. The research also focuses on common house upgrades to achieve energy savings, such as more-efficient units for mechanical system, improving building envelope, and installation of a PV system.

The majority of the cost information considered in this study is obtained from RSMeans (RSMeans 2016) residential cost data; other data is also collected from local suppliers. In addition, HOT2000 (NRCan 1987) software is selected as an appropriate simulation tool due to its applicability to the Canadian context, capability to simulate building energy performance and PV panel system, and also because HOT2000 is the only designated tool in the ABC. EnerGuide (EGH) rating calculated from HOT2000 is used in this study to evaluate the energy efficiency of designs.

The base house design selected for this study is a two-storey, single-family home with 1,610 ft^2 total floor area. A series of windows and wall thermal insulations are selected based on ABC requirements according to the prescriptive path. Then, these types are ranked based on their LCC (initial and operation costs) per unit of wall area. The operation costs are based on HOT2000 simulated energy consumption converted to dollar values using the current natural gas price. An investigation is also conducted on the impact of roof overhang depth and window style on window thermal performance and to determine the window-to-wall ratio (WWR) for each directional orientation that minimizes the overall annual heat loss in the house. This analysis considers different house sizes, including that of the reference house, those ranging from 1,451 ft^2 to 3,000 ft^2, in order to generalize the results to the majority of houses in Edmonton.

An investigation is conducted of potential upgrades to the base house design following performance path code compliance. The first upgrade approach, following the ABC prescriptive requirements, improves the base house design from an EGH of 71 to 82. As required by the ABC performance path, an EGH of 82 generated from prescriptive design is used as the reference target for seven other upgrade approaches in this study.

The methodology is based on LCC, but, from the analysis and results of wall thermal insulation, it is found that the initial cost is closely related to LCC. Therefore, when deciding between different alternative insulation combinations for building envelope with equal performance (EGH 82), the selection is made based on initial cost rather than LCC. At the end of the study, upgrade approaches are compared based on their LCCs. The operation costs are based on HOT2000 simulated energy consumption converted to dollar values using present natural gas and electricity prices. The results shows that a low-e double-glazed window with one heat mirror film in between, 13 mm argon-filled cavity, and vinyl frame has the lowest LCC among the 16 selected window types. By using this type rather than the triple-pane window, the following window LCC savings can be achieved:

- 18% on south orientation;

  - 14% on north orientation;
  - 16% on west orientation;

Additionally, the benefit of double-pane window with one heat mirror film in between is that it is of nearly equal weight to a double-pane window.

A sensitivity analysis is conducted on windows to determine how increasing predicted natural gas prices would affect the results of this study. The results indicate that, by increasing gas prices over the course of 30 years of operation, a double-pane window with one heat mirror film in between still achieves a lower LCC than does a triple-pane window.

Furthermore, it is found that:

  - Windows with a fibreglass frame have a higher LCC compared to windows with vinyl, wood, or aluminum-clad wood frame materials. In contrast, vinyl-framed windows have the lowest LCC in this comparison.
  - Although krypton gas has better thermal performance than argon gas, the LCC of argon-filled window types is lower than that of krypton-filled.

Some of the highlights from the window design investigation are as follows:

- The following window areas achieve the minimum overall annual heat loss for homes ranging in size from 1,451 ft^2 to 3,000 ft^2:
  - 34% south window on south-facing wall ratio,
  - 18% west window on west-facing wall ratio.

  Furthermore, the larger north-facing WWR achieves the more annual heat loss in the house.

- Increasing the roof overhang depth on the south orientation reduces annual solar heat gain dramatically compared with other orientations. However, this reduction occurs during late spring, summer, and early fall due to high solar latitude, so, if the overhang is not excessively long, the solar radiation will be able to enter the window during the winter.
- Based on the annual solar heat gain minus heat loss through the window:
    - Hinged window has 15% to 30% better thermal performance than slider window;
    - Picture window has 20% to 50% better thermal performance than slider window;
    - A single large window performs better compared with multiple smaller windows with the same total area as the large window. This can be explained due to the fact that the center of a pane of glass usually has a higher R-value than the frame and the edge. Therefore, the total R-value of larger windows with less frame area and more glass area is higher.

For wall insulations, it is found that fibreglass batt R19 (cavity) and 1″ expanded polystyrene (continuous insulation) for exterior walls achieves the lowest LCC among the investigated insulations. Although the high insulation value of polyurethane spray foam is well known, it is found that those designs which use this insulation type have higher LCCs compared with those using other insulations due to the high initial cost of polyurethane spray foam. By using fibreglass batt R19 (cavity) and 1″ expanded polystyrene (continuous insulation) within the exterior walls of the base house design, a 30% savings on wall LCC can be achieved compared with using 3½″ polyurethane spray foam insulation. Furthermore, fibreglass batt R10 (cavity) and fibreglass batt

R12 (continuous insulation) achieve the lowest LCC for basement walls among other investigated insulations.

A sensitivity analysis is conducted on exterior wall insulations to determine how increasing natural gas prices will affect the results of this study. The results indicate that with increasing gas prices over the 30 years of operation, fibreglass and rigid insulation still achieve less LCC compared to polyurethane spray foam insulation.

Results from the investigation of potential house upgrades indicate that the mechanical system (furnace heating system) plus minor building envelope upgrades (upgrade approach 2) on the base house design achieve the lowest LCC. Furthermore, it is found that the forced-air space heating system using natural gas furnace is found to be the most economical heating system compared with boiler, electric baseboard, and air-source heat pump. Upgrading the house by installing a PV panel system returns the incremental investment over a long period of time and is not considered a cost-effective solution.

As with the investigation conducted for windows and exterior wall insulations, a sensitivity analysis is conducted to estimate the LCC of house upgrades by increasing natural gas prices. The results indicate that, by assuming increasing gas prices over the 30 years of operation, approach 6—installation of a PV panel system and improving building envelope—achieves the lowest LCC among the investigated upgrades.

5.2 Recommendation and future work

The research presented in this thesis is limited to a cold region in Canada (Edmonton). Therefore, further investigation is recommended to verify the concluded results for milder weather conditions (e.g., Vancouver, British Columbia). Additionally, the presented methodology in this study is based on a 30-year lifetime for windows, wall insulation, and whole house upgrades, whereas wall assemblies and insulation typically have a lifecycle longer than 30 years. Thus, it is recommended to investigate the LCC of insulations over longer operation duration (i.e., 50 years) and compare it with the results obtained from this study.

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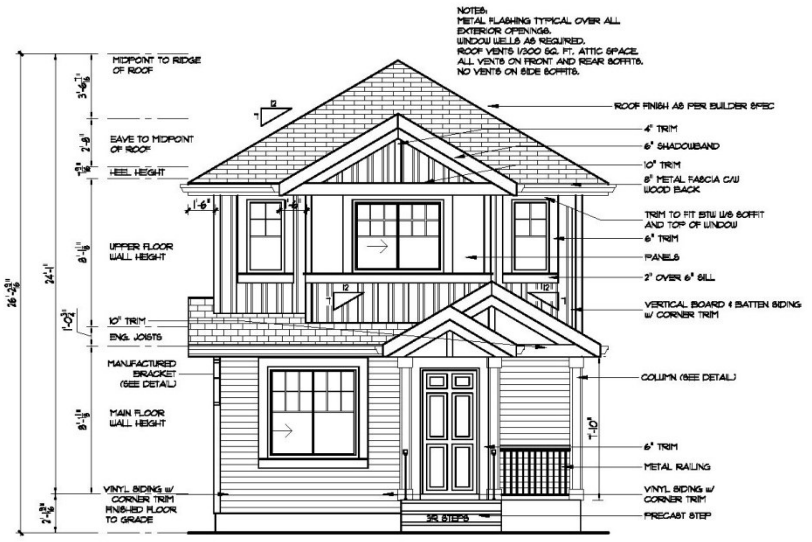
APPENDICES

Architectural __drawings of base house design

A-1	Front elevation
A-2	Right elevation
A-3	Left elevation
A-4	Rear elevation
A-5	Basement plan
A-6	Main floor plan
A-7	Second floor plan
A-8	Section A



FINAL FOR CONSTRUCTION: APRIL 9, 2015 - SPECS OVERRIDE PRINTS

5520 Crabapple Loop SW (Orchards) Edmonton LOT:25 BLOCK:2 PLAN:122-3499

NO.	DATE	BY
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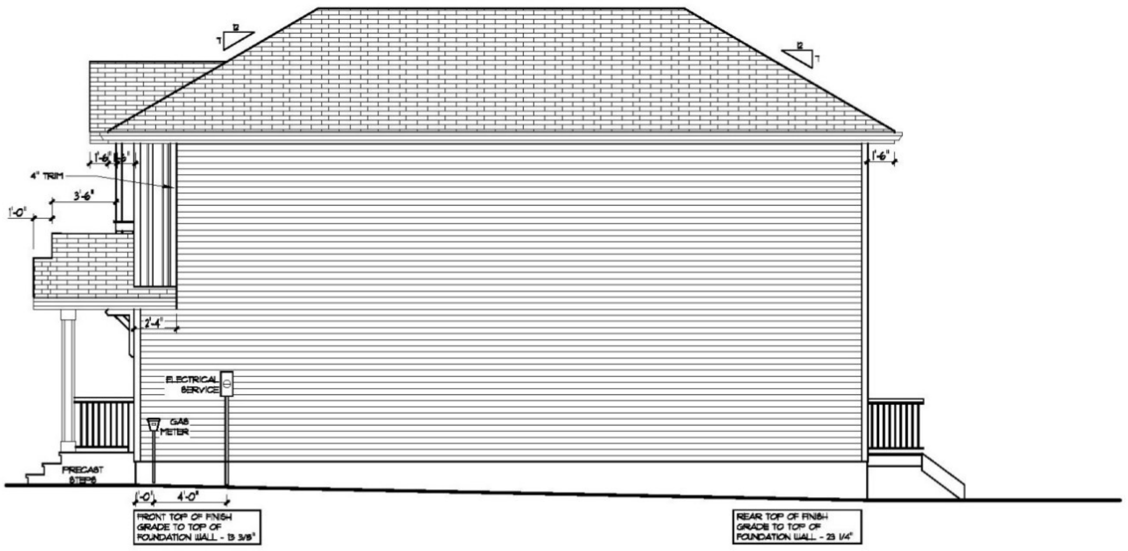
2	–	–
1	Sep 16 3rd Bsmt w/dow	JRF

REVISIONS

OWNER SPEC
AREA 1600 Sq Ft
SPECIFICATION: GOLD
WIDTH 20 Ft
© COPYRIGHT EXCLUSIVE TO LANDMARK GROUP OF BUILDERS INC.
BASE MODEL Franklin-20 Heritage C
DRAWING Front Elevation

LANDMARK
LEGACY HOMES
EDMONTON

JOB NO: 0400-14-0123
SCALE: 3/16"=1'-0"
DRAWN BY: RT
LAST MODEL UPDATE: MAR 28/2013
MODEL CREATION DATE: JAN 24/2013
SHEET NO. 1/12



FINAL FOR CONSTRUCTION: APRIL 9, 2015 - SPECS OVERRIDE PRINTS

5520 Crabapple Loop SW (Orchards) Edmonton LOT:25 BLOCK:2 PLAN:122-3499

NO.	DATE	BY
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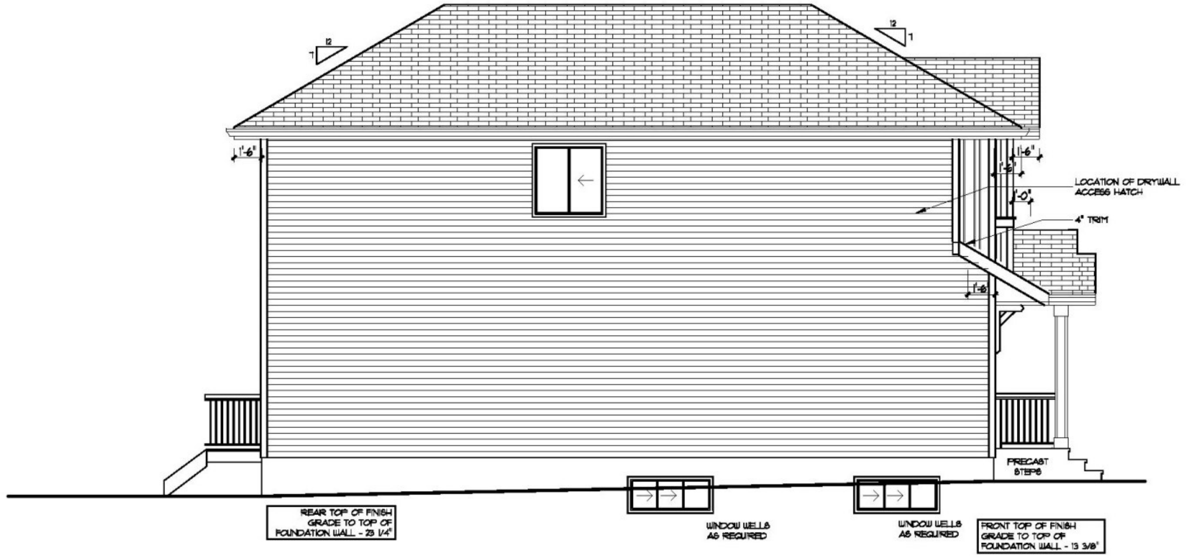
2	-	-
1	Sep 16 3rd Bsmt w/cov	JRF

REVISIONS

OWNER	SPEC
AREA	1600 Sq Ft — SPECIFICATION: GOLD
WIDTH	20 Ft — © COPYRIGHT EXCLUSIVE TO LANDMARK GROUP OF BUILDERS INC.
BASE MODEL	Franklin-20 Heritage C
DRAWING	Right Elevation

LANDMARK
LEGACY HOMES
EDMONTON

JOB NO: 0400-14-0123
SCALE: 3/16"=1'-0"
DRAWN BY: RT
LAST MODEL UPDATE: MAR 28/2013
MODEL CREATION DATE: JAN 24/2013
SHEET NO. 2/12



FINAL FOR CONSTRUCTION: APRIL 9, 2015 - SPECS OVERRIDE PRINTS

5520 Crabapple Loop SW (Orchards) Edmonton LOT:25 BLOCK:2 PLAN:122-3499

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4	-	-
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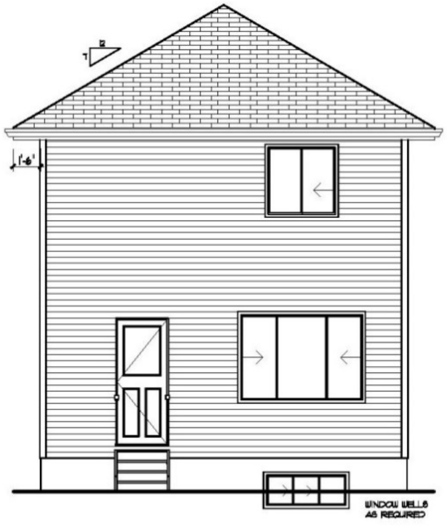
2	-	-
1	Sep 16 3rd Bsmt w'dow	JRF

REVISIONS

OWNER SPEC
AREA 1600 Sq Ft
SPECIFICATION: GOLD
WIDTH 20 Ft
© COPYRIGHT EXCLUSIVE TO LANDMARK GROUP OF BUILDERS INC.
BASE MODEL Franklin-20 Heritage C
DRAWING **Left Elevation**

LANDMARK
LEGACY HOMES
EDMONTON

JOB NO: 0400-14-0123
SCALE: 3/16"=1'-0"
DRAWN BY: RT
LAST MODEL UPDATE: MAR 28/2013
MODEL CREATION DATE: JAN 24/2013
SHEET NO. 3 / 12



5520 Crabapple Loop SW (Orchards) Edmonton LOT:25 BLOCK:2 PLAN:122-3499

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1	Sep 16 3rd Bsmt w/cow	JRF

REVISIONS

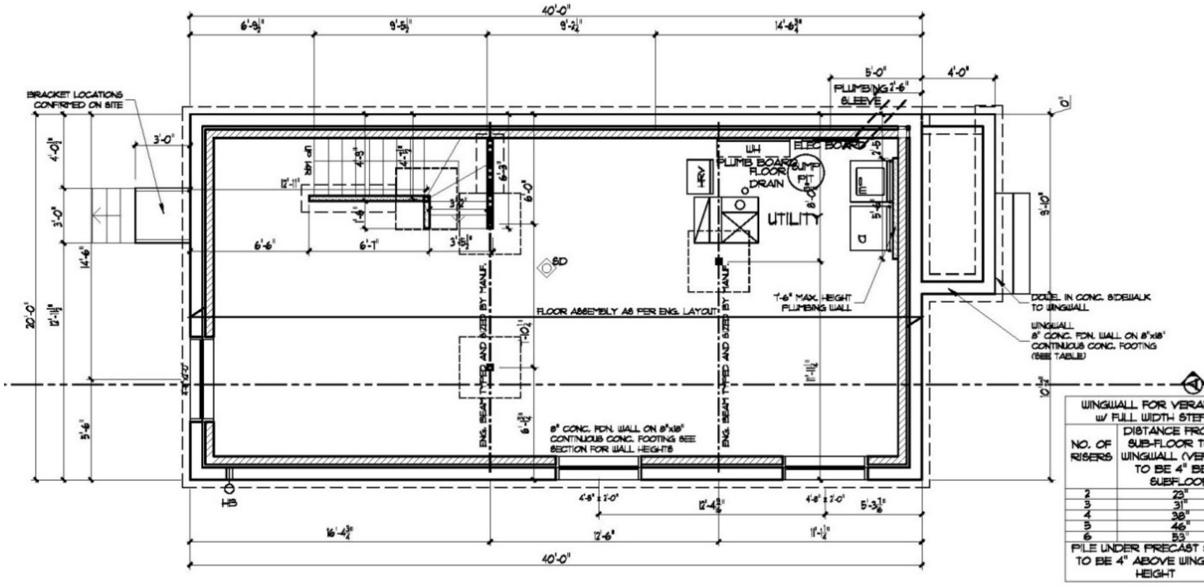
OWNER	SPEC
AREA	1600 Sq Ft / SPECIFICATION: GOLD
WIDTH	20 Ft / © COPYRIGHT EXCLUSIVE TO LANDMARK GROUP OF BUILDERS INC.
BASE MODEL	Franklin-20 Heritage C
DRAWING	Rear Elevation & Section

LANDMARK
LEGACY HOMES
EDMONTON

JOB NO: 0400-14-0123
SCALE: 3/16"=1'-0"
DRAWN BY: RT
LAST MODEL UPDATE: MAR 28/2013
MODEL CREATION DATE: JAN 24/2013
SHEET NO. 4 / 12

FINAL FOR CONSTRUCTION: APRIL 9, 2015 - SPECS OVERRIDE PRINTS

5520 Crabapple Loop SW (Orchards) Edmonton LOT:25 BLOCK:2 PLAN:122-3499



WINGWALL FOR VERANDA w/ FULL WIDTH STEPS	
NO. OF RISERS	DISTANCE FROM T/O SUB-FLOOR TO T/O WINGWALL (VERANDA TO BE 4" BELOW SUBFLOOR)
2	23"
3	31"
4	38"
5	46"
6	53"
PILE UNDER PRECAST STEPS TO BE 4" ABOVE WINGWALL HEIGHT	

FINAL FOR CONSTRUCTION: APRIL 9, 2015 - SPECS OVERRIDE PRINTS

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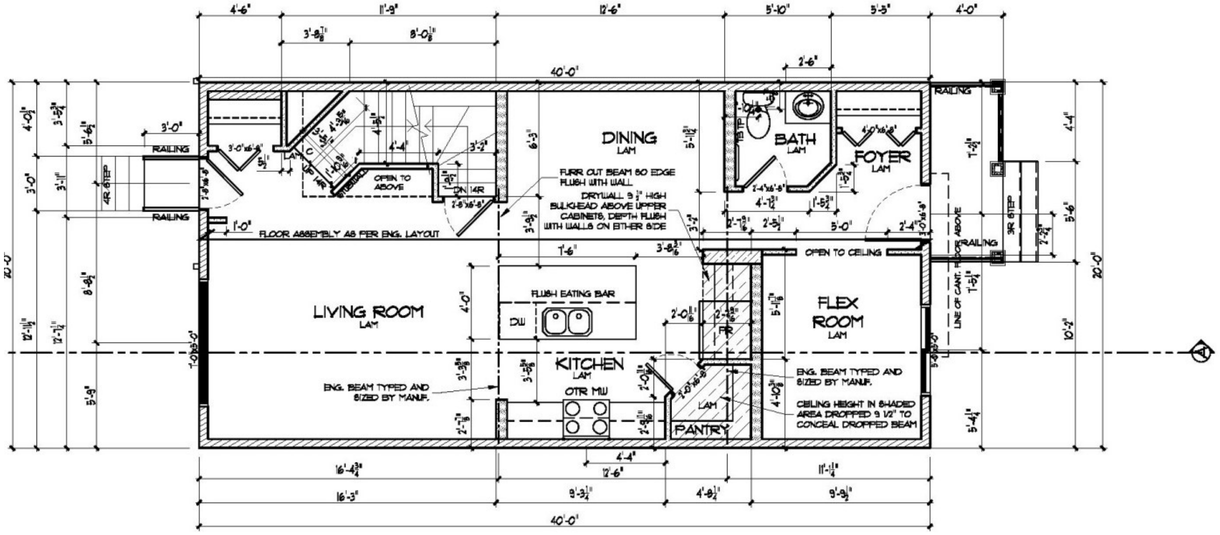
1	Sep 16 3rd Bsmt w/dow	JRF

REVISIONS

OWNER	SPEC	
AREA	1600 Sq Ft	SPECIFICATION: GOLD
WIDTH	20 Ft	© COPYRIGHT EXCLUSIVE TO LANDMARK GROUP OF BUILDERS INC.
BASE MODEL	Franklin-20 Heritage C	
DRAWING	Basement Plan	

LANDMARK
LEGACY HOMES
EDMONTON

JOB NO: 0400-14-0123
SCALE: 3/16"=1'-0"
DRAWN BY: RT
LAST MODEL UPDATE: MAR 28/2013
MODEL CREATION DATE: JAN 24/2013
SHEET NO. 5 / 12



MAIN FLOOR AREA

A: 800 SQ FT

H: 8'-1 1/8"

FINAL FOR CONSTRUCTION: APRIL 9, 2015 - SPECS OVERRIDE PRINTS

5520 Crabapple Loop SW (Orchards) Edmonton LOT:25 BLOCK:2 PLAN:122-3499

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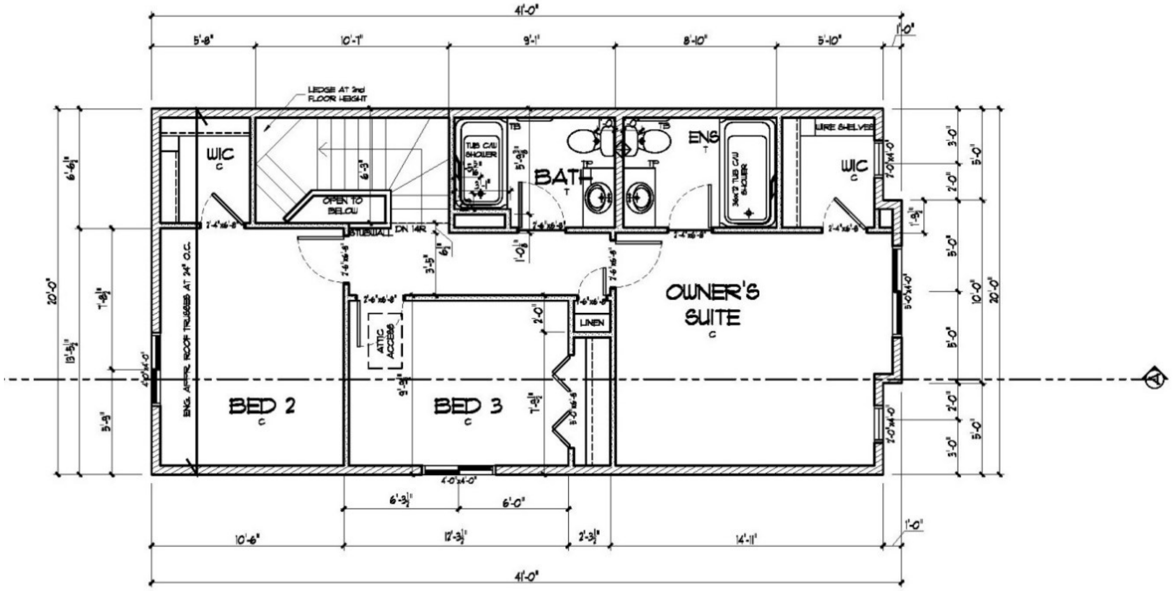
1	Sep 16 3rd Bsmt w/dow	JRF

REVISIONS

OWNER: SPEC
AREA: 1600 Sq Ft
SPECIFICATION: GOLD
WIDTH: 20 Ft
© COPYRIGHT EXCLUSIVE TO LANDMARK GROUP OF BUILDERS INC.
BASE MODEL: Franklin-20 Heritage C
DRAWING: Main Floor Plan

LANDMARK LEGACY HOMES
EDMONTON
JOB NO: 0400-14-0123
SCALE: 3/16"=1'-0"
DRAWN BY: RT
LAST MODEL UPDATE: MAR 28/2013
MODEL CREATION DATE: JAN 24/2013
SHEET NO. 6 / 12



SECOND FLOOR AREA

A: 800 SQ FT
H: 8'-1 1/8"

FINAL FOR CONSTRUCTION: APRIL 9, 2015 - SPECS OVERRIDE PRINTS

5520 Crabapple Loop SW (Orchards) Edmonton LOT:25 BLOCK:2 PLAN:122-3499

NO.	DATE	BY
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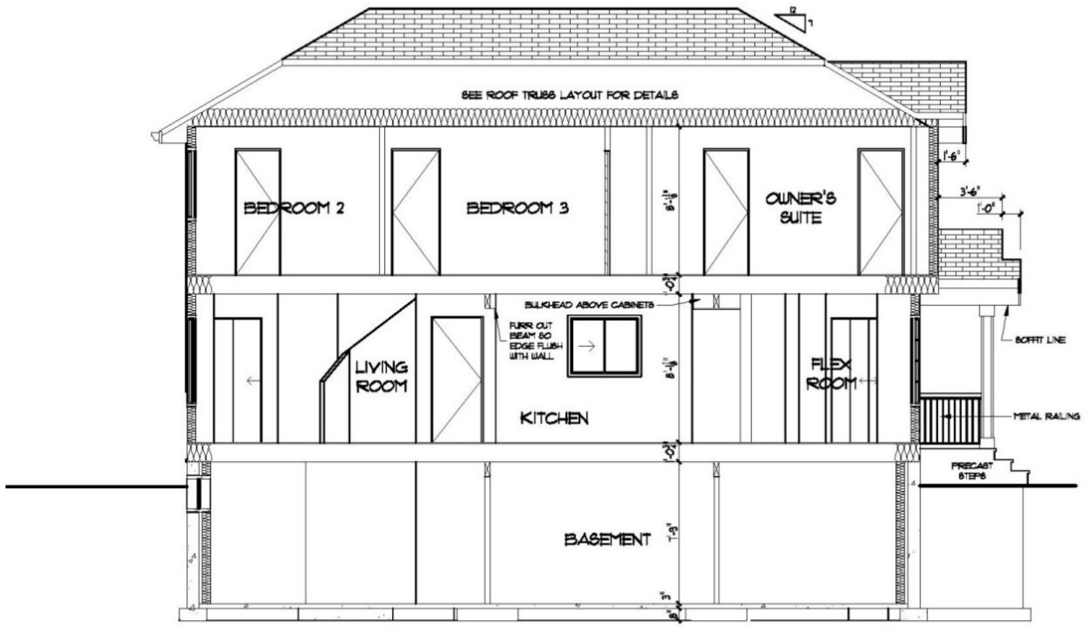
1	Sep 16 3rd Bsmt w/cow	JRF

REVISIONS

OWNER SPEC
AREA 1600 Sq Ft
SPECIFICATION: GOLD
WIDTH 20 Ft
© COPYRIGHT EXCLUSIVE TO LANDMARK GROUP OF BUILDERS INC.
BASE MODEL Franklin-20 Heritage C
DRAWING Second Floor Plan

LANDMARK
LEGACY HOMES
EDMONTON

JOB NO: 0400-14-0123
SCALE: 3/16"=1'-0"
DRAWN BY: RT
LAST MODEL UPDATE: MAR 28/2013
MODEL CREATION DATE: JAN 24/2013
SHEET NO. 7 / 12



5520 Crabapple Loop SW (Orchards) Edmonton LOT:25 BLOCK:2 PLAN:122-3499

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3	-	-
2	-	-
1	Sep 18 3rd Bsmt w/cow	JRF

REVISIONS

OWNER: SPEC
AREA: 1600 Sq Ft
SPECIFICATION: GOLD
WIDTH: 20 Ft
© COPYRIGHT EXCLUSIVE TO LANDMARK GROUP OF BUILDERS INC.
BASE MODEL: Franklin-20 Heritage C
DRAWING: Section A

LANDMARK
LEGACY HOMES
EDMONTON
JOB NO: 0400-14-0123
SCALE: 3/16"=1'-0"
DRAWN BY: RT
LAST MODEL UPDATE: MAR 28/2013
MODEL CREATION DATE: JAN 24/2013
SHEET NO. 8 / 12

FINAL FOR CONSTRUCTION: APRIL 9, 2015 - SPECS OVERRIDE PRINTS

Summary of the construction costs in Alberta, Edmonton

Fuel		
Fuel type	**Price**	**Source**
Natural gas (GJ)	$2.64	(AER 2016)
Electricity (MWh)	$49.2	(Utilities Consumer Advocate 2016)

Insulation				
Component	**Model**	**Description**	**Price**	**Source**
Wall Insulation				
Blanket insulation (ft^2)		Fibreglass, R8,23″ wide	$0.51	(shopbot 2016)
Blanket insulation (ft^2)		Fibreglass, R10,23″ wide	$0.53	(shopbot 2016)
Blanket insulation (ft^2)	721162 00030	Fibreglass, R11,23″ wide	$0.55	(RSMeans Online 2016)
Blanket insulation (ft^2)		Fibreglass, R12,15″ wide	$0.57	(shopbot 2016)
Blanket insulation (ft^2)	721162 00821	Fibreglass, R13,15″ wide	$0.58	(RSMeans Online 2016)
Blanket insulation (ft^2)		Fibreglass, R14,11″ wide	$0.70	(shopbot 2016)

Blanket insulation (ft^2)	721162 00120	Fibreglass, R15,15″ wide	$0.81	(RSMeans Online 2016)
Blanket insulation (ft^2)	721162 00180	Fibreglass, R19,23″ wide	$0.79	(RSMeans Online 2016)
Rigid insulation (ft^2)	721131 02100	Expanded polystyrene, 1″ thick, R3.85	$0.65	(RSMeans Online 2016)
Rigid insulation (ft^2)	721131 02120	Expanded polystyrene, 2″ thick, R7.69	$1.01	(RSMeans Online 2016)
Rigid insulation (ft^2)	721131 00370	Fibreglass, 1″ thick, R4.3	$0.91	(RSMeans Online 2016)
Rigid insulation (ft^2)	721131 00400	Fibreglass, 2″ thick, R8.7	$1.61	(RSMeans Online 2016)
Rigid insulation (ft^2)	721131 01640	Isocyanurate, 1″ thick	$0.97	(RSMeans Online 2016)
Rigid insulation (ft^2)	721131 01660	Isocyanurate, 2″ thick	$1.3	(RSMeans Online 2016)
Rigid insulation (ft^2)	721131 01900	Extruded polystyrene, 1″ thick, R5	$1.03	(RSMeans Online 2016)

Rigid insulation (ft^2)	721131 01940	Extruded polystyrene, 2″ thick, R10	$1.78	(RSMeans Online 2016)
Rigid insulation (ft^2)		Extruded polystyrene, 3″ thick, R11	$2.53	(shopbot 2016)
Sprayed foam insulation (ft^2)	721291 00310	polyurethane,1″ thick, R6.5	$0.94	(RSMeans Online 2016)
Sprayed foam insulation (ft^2)	721291 00330	polyurethane, 3″ thick, R20	$2.68	(RSMeans Online 2016)
Sprayed foam insulation (ft^2)	721291 00335	polyurethane, 3½″ thick, R23	$3.11	(RSMeans Online 2016)
Sprayed foam insulation (ft^2)	721291 00340	polyurethane, 4″ thick, R26	$3.56	(RSMeans Online 2016)
Sprayed foam insulation (ft^2)	721291 00350	polyurethane, 5″ thick, R32.5	$4.45	(RSMeans Online 2016)
Sprayed foam insulation (ft^2)	721291 00355	polyurethane, 5½″ thick, R36	$4.89	(RSMeans Online 2016)
Blown-in insulation (ft^2)	721261 03000	Fibreglass in wall, 5½″ thick, R23	$1.95	(RSMeans Online 2016)

Blown-in insulation (ft^2)		Fibreglass in wall, 5½″ thick, R20	$2.34	(shopbot 2016)
		Floor Insulation		
Component	**Model**	**Description**	**Price**	**Source**
Blanket insulation (ft2)	72116102100	Fibreglass, 3½″ thick, R13	$0.88	(RSMeans Online 2016)
Blanket insulation (ft2)		Fibreglass, 9½″ thick, R28	$1.38	(shopbot 2016)
Blanket insulation (ft2)	72116102210	Fibreglass, 9½″ thick, R30	$1.44	(RSMeans Online 2016)
Rigid insulation (ft2)		Extruded polystyrene insulation, 1.5	$1.77	(shopbot 2016)
Sprayed Foam insulation (ft2)	72129100360	polyurethane, 6″ thick, R39	$5.61	(RSMeans Online 2016)
Attic insulation				
Component	**Model**	**Description**	**Price**	**Source**
Blanket insulation (ft2)	72116103030	Fibreglass, 11″ thick, R 40	$1.55	(RSMeans Online 2016)

Blanket insulation (ft2)		Fibreglass, R 20			$0.77	(shopbot 2016)
Blown-in insulation (ft2)	7212610 0020	Cellulose, 3½″ thick, R13			$0.57	(RSMeans Online 2016)
Blown-in insulation (ft2)	7212610 0030	Cellulose, 5½″ thick, R20			$0.79	(RSMeans Online 2016)
Blown-in insulation (ft2)	7212610 0100	Cellulose, $8\ {}^{11}/_{16}''$ thick, R30			$1.16	(RSMeans Online 2016)
Window Type	**Glazing**	**Coating**	**Framing**	**Gas-filled**	**Price**	**Source**
Double-glazed window						
(ft2)	DG	low e 20 hard	vinyl	argon 13 mm	$20	(durabuiltwindows 2016)
TYPE 1 (ft2)	DG + 1 HM 88	low e 20 hard	vinyl	krypton 9 mm	$40	Estimated based on quotations from (durabuiltwindows 2016; ecoglass 2016)
TYPE 2 (ft2)	DG + 1 HM 88	low e 20 hard	wood	krypton 9 mm	$43.8	Estimated based on quotations from (durabuiltwindows

						2016; ecoglass 2016)
TYPE 3 (ft2)	DG + 1 HM 88	low e 20 hard	fibreglass	krypton 9 mm	$59	Estimated based on quotations from (durabuiltwindows 2016; ecoglass 2016)
TYPE 4 (ft2)	DG + 1 HM 88	low e 20 hard	Aluminum-clad wood	krypton 9 mm	$43.8	Estimated based on quotations from (durabuiltwindows 2016; ecoglass 2016)
TYPE 5 (ft2)	DG + 1 HM 88	low e 20 hard	vinyl	argon 13 mm	$38	Estimated based on quotations from (durabuiltwindows 2016; ecoglass 2016)
TYPE 6 (ft2)	DG + 1 HM 88	low e 20 hard	wood	argon 13 mm	$41.8	Estimated based on quotations from (durabuiltwindows 2016; ecoglass 2016)
TYPE 7 (ft2)	DG + 1 HM 88	low e 20 hard	fibreglass	argon 13 mm	$57	Estimated based on quotations from (durabuiltwindows 2016; ecoglass 2016)

TYPE 8 (ft2)	DG + 1 HM 88	low e 20 hard	Aluminum-clad wood	argon 13 mm	$41.8	Estimated based on quotations from (durabuiltwindows 2016; ecoglass 2016)
Type	**Glazing**	**Coating**	**Framing**	**Gas-filled**	**Price**	**Source**
Triple-glazed windows						
TYPE 9 (ft2)	TG + 2 coating	low e 20 hard	vinyl	krypton 9 mm	$47.25	Estimated based on quotations from (durabuiltwindows 2016; ecoglass 2016)
TYPE 10 (ft2)	TG + 2 coating	low e 20 hard	wood	krypton 9 mm	$51.77	Estimated based on quotations from (durabuiltwindows 2016; ecoglass 2016)
TYPE 11 (ft2)	TG + 2 coating	low e 20 hard	fibreglass	krypton 9 mm	$69.87	Estimated based on quotations from (durabuiltwindows 2016; ecoglass 2016)
TYPE 12 (ft2)	TG + 2 coating	low e 20 hard	Aluminum-clad wood	krypton 9 mm	$51.77	Estimated based on quotations from (durabuiltwindows

						2016; ecoglass 2016)
TYPE 13 (ft2)	TG + 2 coating	low e 20 hard	vinyl	argon 13 mm	$45.25	(durabuiltwindows 2016)
TYPE 14 (ft2)	TG + 2 coating	low e 20 hard	wood	argon 13 mm	$49.77	(durabuiltwindows 2016)
TYPE 15 (ft2)	TG + 2 coating	low e 20 hard	fibreglass	argon 13 mm	$67.87	(durabuiltwindows 2016)
TYPE 16 (ft2)	TG + 2 coating	low e 20 hard	Aluminum-clad wood	argon 13 mm	$49.77	Estimated based on quotations from (durabuiltwindows 2016; ecoglass 2016)

Domestic Hot Water Heater

Component	**Model**	**Description**	**Total Price**	**Source**
Natural Gas Hot Water	Rheem (630083)	EF: 0.59, Tank system	$457	(amazon 2016)
Natural Gas Hot Water	Rheem (630151)	EF: 0.67, Tank system	$895	(amazon 2016)
Natural Gas Hot Water	Rheem (RTG-84DVLN)	EF: 0.82,Tankless	$983	(amazon 2016)

Natural Gas Hot Water	Navien (NPE180 S-NG)	EF: 0.97, Tankless	$1,559	(amazon 2016)
Solar PV Panel System				
Component	**Model**	**Description**	**Price**	**Source**
Solar panels	2.63114 E+11	PV module, 150 W, 33 V	$271.11	(RSMeans Online 2016)
DC to AC inverter	2.63114 E+11		$3,153.50	(RSMeans Online 2016)
Combiner box	2.63114 E+11	PV components, combiner box, 10 lug, NEMA 3R enclosure	$361.68	(RSMeans Online 2016)
Fuse for Combiner box	2.63114 E+11	PV components, fuse, 15 A for combiner box	$30.68	(RSMeans Online 2016)
DC circuit breaker	2.63114 E+11	PV components, DC circuit breaker, 175 amp	$222.76	(RSMeans Online 2016)
Conduit box for inverter	2.63114 E+11	PV components, conduit box for inverter	$93.52	(RSMeans Online 2016)
Low voltage disconnect	2.63114 E+11	PV components, low voltage disconnect	$100.50	(RSMeans Online 2016)

PV rack system	2.63114 E+11	PV rack system, roof, penetrating surface mount, on steel framing, 1 panel	$219.33	(RSMeans Online 2016)
Rooftop mounting hardware			$99.00	(solardirectcanada 2016)
HVAC System				
Component	**Model**	**Description**	**Price**	**Source**
Gas Furnace	Goodman (GMVM970603BN)	AFUE: 98%	$1,570.09	(amazon 2016)
Gas Furnace	Goodman (GMSS960803BN)	AFUE: 96%	$1,152.19	(amazon 2016)
Gas Furnace	Goodman (GMSS920603BN)	AFUE: 92%	$961.84	(amazon 2016)
Gas Furnace	Goodman (GMS80604BN)	AFUE: 80%	$758.14	(amazon 2016)

Heat Pump	(Mitsubishi Zuba Central)	Cold Climate Air-Source heat Pump (Outdoor Unit)	$7,118.00	(weiss-johnson 2016)
Boiler	2.35219E+11	Condensing boilers, AFUE: 95.2%	$4,085.60	(RSMeans Online 2016)
Gas Furnace	Goodman(GMVM970603BN)	AFUE: 98%	$1,570.09	(amazon 2016)
Gas Furnace	Goodman(GMSS960803BN)	AFUE: 96%	$1,152.19	(amazon 2016)
Gas Furnace	Goodman(GMSS920603BN)	AFUE: 92%	$961.84	(amazon 2016)
Electric Baseboard Heaters	2.38333E+11		$800.00	(RSMeans Online 2016)
HRV	Lifebreath (195ECM)	SRE @ 0 °C: 81, SRE @ −25 °C: 69	$1,639.02	(amazon 2016)
HRV	Fantech (VHR150R)	SRE @ 0 °C: 66, SRE @ −25 °C: 60	$1,370.51	(amazon 2016)

HRV	Lifebreath (RNC5ES)	SRE @ 0 °C: 65, SRE @ −25 °C: 64	$777.62	(amazon 2016)
HRV	Fantech (VH 704)	SRE @ 0 °C: 57, SRE @ −25 °C: 53	$653.04	(amazon 2016)
Fan	2.33416 E+11		$2,159.86	(RSMeans Online 2016)
Duct work	230713103060, 233113130580	Duct work, Duct thermal insulation	$1,726.00	(RSMeans Online 2016)
Diffusers	2.33713 E+11		$218.31	(RSMeans Online 2016)
Pump	2.32123 E+11	Cast iron, heated or chilled water application	$1,096.57	(RSMeans Online 2016)
Piping	2.21114 E+11	L.F.: 32.66	$2,612.80	(RSMeans Online 2016)
Radiator (10 section)	2.38229 E+11	Cast Iron, hydronic heating, radiator	$631.60	(RSMeans Online 2016)

Alberta building code requirements

Table 5-1: Thermal characteristics of envelope in a building with heat-recovery ventilator

Component	Zone 7A: 5000 to 5999

		Minimum RSI, $(m^2 \cdot K)$ / W
Above-ground opaque building Assembly	Ceiling below attics	8.67
	Cathedral ceiling and flat roofs	5.02
	Walls	2.97
	Floors over unheated spaces	5.02
Assembly in contact with the ground opaque building Assembly	Foundation walls	2.98
	Unheated Floors (Below frost line)	uninsulated
	Unheated Floors (Above frost line)	1.96
	Heated floor	2.84
	Slabs-on-grade with an integral footing	2.84
		Maximum U-value, $W/(m^2 \cdot K)$
Fenestration and Doors	Max. U-value, W / $(m^2 \cdot K)$	1.60
	Min. Energy Rating	25
Skylights	Max. U-value, W / $(m^2 \cdot K)$	2.70

Source: (ABC 2014c)

Table 5-2: Heating equipment

Component or equipment	**Heating or cooling capacity (KW)**	**Efficiency**

Boilers and Furnaces	Electric boilers	≤ 88	Must be equipped with automatic water temperature control
	Gas-fired boilers		AFUE ≥ 90%
	Oil-fired boilers		AFUE ≥ 85%
	Gas-fired warm-air furnaces	≤ 65.9	AFUE ≥ 92%
	Oil-fired warm-air furnaces	≤ 66	AFUE ≥ 85%
Heat Pump Equipment	Split system heat pumps	≤ 19	SEER 14.5, EER = 11.5 HSPF = 7.1
	Single-package system		SEER 14, EER = 11
	Open loop ground-source and water-source heat pumps	< 40	Cooling COP ≥ 4.75 Heating COP ≥ 3.6
	Closed loop ground-source and water-source heat pumps		Cooling COP ≥ 3.93 Heating COP ≥ 3.1
	Direct-expansion ground-source heat pumps	≤ 21	EER = 13 Heating COP = 3.1

Source: (ABC 2014d)

Table 5-3: Heat-recovery ventilation system

2.5% January design temperature at building location	**Outside air test temperature**	**Sensible-heat-recovery ventilators** **Sensible-heat-recovery efficiency, (%)**

≥ −10	0 °C	At least 60%
< −10	−25 °C	At least 55%

Source: (ABC 2014c)

Table 5-4: Water heating equipment

Component		Input	Efficiency
Tanked	Electric	≤ 12 KW (50-270 L capacity)	SL ≤ 35 + 0.20 V(top inlet) SL ≤ 40 + 0.20 V (bottom inlet)
	Oil-fired	≤ 35.5	EF ≥ 0.59-0.0005 V
	Gas-fired	< 22 KW	EF ≥ 0.67-0.0005 V
Thank less	Oil-fired	≤ 61.5 KW	EF ≥ 0.59-0.0019 V_m
	Gas-fired	≤ 73.2 KW	EF ≥ 0.80

Source: (ABC 2014b)