Least-Construction-Cost Approaches for New Housing to Achieve Higher Energy-Efficiency Requirements of Building Codes

by

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ABSTRACT

Effective November 1, 2016, new homes constructed in Alberta, Canada, are required to comply with "Section 9.36: Energy-Efficiency Requirements" of the Alberta Building Code (ABC) 2014. This section introduces ~57% stricter energy requirements for building envelope than the previous code; therefore, it is important to investigate its implications on current housing construction practices and energy performance, and to develop a methodology for selecting cost-effective approaches for code compliance. In this context, this thesis investigates the mentioned code and codes from other countries in cold-climate regions, identifies the current common practices, develops least-construction-cost approaches to meet the code's energy requirements, and assess the lifecycle economic performance of a code-compliant house. Three approaches for code compliance are developed in this thesis: (1) least-construction-cost upgrades for building envelope (attic ceiling, above- and below-grade walls, and windows) meeting code-specified thermal insulation values specified in the prescriptive path of the code; (2) carry out approach (1) with energy-efficient tankless domestic hot water system and optimal window sizing for less lifecycle operation cost; and (3) least-construction-cost upgrade for the performance path of the code. To perform this assessment, a 30-year lifecycle analysis is conducted using HOT2000 simulations to estimate the energy performance and operation cost of a home Edmonton. By deploying approach (1), a reduction of ~12% on energy consumption is achieved with a return on investment (ROI) of ~ −3.44%. By applying approach (2), a reduction of energy consumption of ~27% is obtained with an ROI of ~68.08%. Alternatively, in approach (3), a reduction of energy consumption of ~10% with an ROI of ~527.21% is achieved. By applying the methodology developed in this research, least-construction-cost code-compliant upgrades are easily identified for other climatic conditions and Canadian locations.

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GLOSSARY OF TERMS

AB: Alberta

ABC: Alberta Building Code

AC: Cavity Percentage Area

A_{CELEC}: Annual Cost of Electricity

ACH: Air Change per Hour

A_{CNG}: Annual Cost of Natural Gas

AcSGS: Actual Savings

AESO: Alberta Electric System Operator

AF: Framing Percentage Area

AFUE: Annual Fuel Utilization Efficiency

$AOPCS_n$: Annual Operation Cost Savings at Time *n*

$AOPCS_{NG}$ or $AOPCS_{ELEC}$: Annual Operation Cost Savings for Natural Gas, Electricity

ASHP: Air Source Heat Pump

ASHRAE: American Society of Heating, Refrigerating and Air-Conditioning Engineers

BBR 19: Boverket's Building Regulations

BC: British Columbia

BCT: Baseline Cost of Current Construction Practice

BPIE: Buildings Performance Institute Europe

BR10: Danish Building Regulation

CAD: Canadian Dollars

CMHC: Canadian Mortgage and Housing Corporation

Cp: Specific Heat of Air, 1.005 kJ/(kg·°C)

C_{Up}: Cost of Upgrade

DHW: Domestic Hot Water

DOE: U.S. Department of Energy

EEA: European Environmental Agency

EF: Energy Factor

EGR: EnerGuide Rating

EIA: Energy Information Administration

EPBD: Energy Performance of Buildings Directive

EPS: Expanded Polystyrene

ERV: Energy Recovery Ventilator

EU-28: European Union 28 Countries

EUI: Energy Usage Intensity

$FVn_{AOPCS_{NG}}$ or $FVn_{AOPCS_{ELEC}}$: Future Value of Annual Operation Cost Savings for Natural Gas, Electricity

FWR: Fenestration-to-Wall Ratio

GBPN: Global Buildings Performance Network

GJ: Giga Joules

GSHP: Ground Source Heat Pump

HDD: Heating Degree Days

HP: Heat Pump

HRV: Heat Recovery Ventilator

HVAC: Heating, Ventilation and Air Conditioning

$i_{inflation}$: Canadian Inflation Rate

i_{NG} or i_{ELEC}: Escalation Rates, Natural Gas or Electricity

ISO: Polyisocyanurate

kJ: Kilojoule

kWh: Kilowatt-hour

LCCA: Life Cycle Cost Analysis

LEH: Low Energy Home

Low-E: Low-Emissivity

m: Mass of Fluid Within a Time Interval per Area, $l/(s \cdot m^2)$

MNECB: Model National Energy Code for Buildings

n: Time

NAHB: National Association of Home Builders

NECB: National Energy Code of Canada for Buildings

NRCan: Natural Resources Canada

nZEH: Net-Zero Energy Home

OBC: Ontario Building Code

OEE: Office of Energy Efficiency

OSB: Oriented Strand Board

Pa: Pascal

PAC: Potential Attic Ceiling

PAW: Potential Above-Grade Exterior Wall

PBW: Potential Below-Grade Exterior Wall

PVC: Polymerizing Vinyl Chloride

PV_{AOPCSn}: Present Value of Annual Operation Cost Savings at Time n for Electricity and Natural gas

PV_{rep}: Present Cost from Equipment Repositions in Current Construction Practice

$PVSOPC_{30}$: 30-year Operation Cost Savings

$PVSOPC_{acc}$: Accumulated Operation Cost Savings

RmH: Room Height

ROI: Return on Investment

RSI, RSI_{total}, $RSI_{parallel}$, RSI_F, RSI_C or R: Thermal Resistance $(m^2 \cdot K)/W$ or $(ft^2 \cdot F)/W$

TACC: Total Additional Construction Cost

TSER: Total Savings from Equipment Repositions

US: United States

U-value or U_{total}: Overall Coefficient of Heat Transfer $W/(m^2 \cdot K)$

WWR: Window-to-Wall Ratio

XPS: Extruded Polystyrene

ρ_{air}: Density of Air, 1.2 kg/m^3

CHAPTER 1: INTRODUCTION

Research indicates that the residential building sector contributes substantially to global energy consumption (Figure 1.1). In 2013, approximately 27% and 22% of the total energy consumed by countries in the European Union (EU-28) and the United States, respectively, was attributed to the residential sector (EEA 2015; EIA 2016). Furthermore, in Europe housing consumes ~184 kWh/m^2 per year, and space heating accounts for 67% of this consumption (EEA 2016a). In Canada, the residential sector is the third major end-user of energy, accounting for ~17% of all energy consumed in the country. In Canada housing consumes ~214 kWh/m^2 per year, and ~63% of this consumption results from space heating (NRCan 2016j). In Alberta, Canada, housing energy consumption, ~291.69 kWh/m^2 per year, is significantly higher than the country's average, and space heating is responsible for 64.1% of this consumption (Statistics Canada 2016; NRCan 2016b). In addition, natural gas and electricity are the main secondary energy sources used in Canadian housing, particularly in Alberta, where natural gas accounts for 77% of the energy consumed by housing in the province (Figure 1.2) (NRCan 2016i).

Thus, it is noted that the energy for space heating represents a large portion of the energy consumed by residential buildings. Nevertheless, in this regard, researchers in Europe indicate that, as a consequence of improvements in housing energy performance, the energy required for space heating is being reduced at a rate of ~1.2% per year in EU countries (EEA 2016a). Better thermal performance of building envelope, driven by mandatory regulations governing energy efficiency of new housing, and the introduction of heat pumps and boilers are indicated as the primary causes of this reduction (EEA 2016a). Inspired by these results, efforts toward finding solutions to improve housing energy performance and, simultaneously, minimize consumption of non-renewable energy sources are highly encouraged by regulations in EU countries.

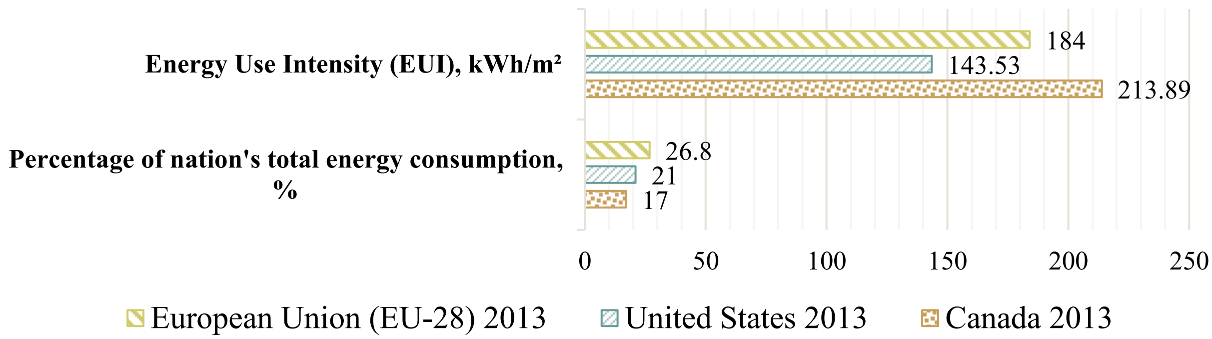

Figure 1.1: Residential Energy Consumption in Canada, the United States, and the European Union.

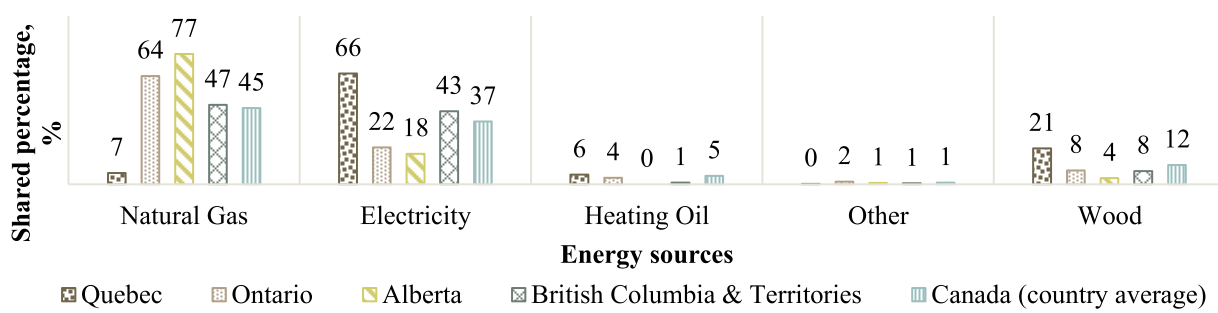

Figure 1.2: Residential Sector Secondary Energy Source by Province in 2013.

In regards to mandatory regulations governing energy performance of housing, in 2011, the Government of Canada released a new version of its energy code for buildings, the National Energy Code of Canada for Buildings (NECB) 2011, in an effort to improve the energy efficiency of Canadian buildings. In Alberta, the NECB 2011 is referenced in the Alberta Building Code (ABC) 2014 under "Section 9.36: Energy Performance Requirements", which covers energy requirements for homes and small buildings regarding building envelope and domestic systems for ventilation, cooling, and space and water heating (NRC 2014). Alberta government states the ABC 2014 energy requirements, equivalent to an EnerGuide rating of 80, will result in increased initial construction cost which will be minimized by savings resulting from the improved energy standard (Alberta Municipal Affairs 2016). In this context, an investigation of the actual impacts of the energy requirements set by the ABC 2014 and the NECB 2011 on current housing construction practices and operation costs in Alberta is crucial.

In light of the circumstances described above, this thesis provides an extensive literature review on regulations governing energy-efficiency requirements for new housing in cold-climate regions, identifies least-construction-cost code-compliant upgrades for new housing in Edmonton, and assesses the impacts of these upgrades on current construction practice in light of construction cost, energy consumption, and operation costs.

1.1. Research Objectives and Scope

The primary objective of this research is to assess the impacts of the energy-efficiency requirements of building codes on energy performance and current construction practice for new housing in cold-climate regions. To achieve this purpose, this research encompasses four sub-objectives:

1) Investigate and compare current regulations governing construction and energy performance of new housing in cold-climate regions, and, in this context, evaluate the energy requirements introduced by the ABC 2014 in comparison with other building energy codes set by jurisdictions with similar climatic conditions: Based on this evaluation, recommendations for the upcoming version of the ABC are proposed.

2) Define the current construction practices commonly applied by builders to new housing in Edmonton, Alberta: A design baseline, which will be used for construction cost and energy performance analyses, is established based on this definition.

3) Identify least-construction-cost upgrades to be deployed in current construction practice to meet energy code requirements: These least-construction-cost upgrades are identified taking into consideration materials for building envelope and equipment for domestic hot water.

4) Assess the additional construction cost, energy performance, return on investment (ROI), and actual savings of a newly built home: This assessment draws on three different approaches for code-compliance, as follows:

    i. Least-construction-cost upgrades for building envelope meeting code-specified thermal insulation values;

    ii. Least-construction-cost upgrades for building envelope, energy-efficient tankless domestic hot water system, and optimal window sizing for less lifecycle operation cost; and

    iii. Least-construction-cost upgrade for code-compliant energy performance.

It is important to clarify that this thesis investigates the impacts of the building code's energy-efficiency requirements on the construction of new housing in the climate zone within which Edmonton is located. The mentioned energy-efficiency requirements establish design and construction specifications for building envelope (e.g., effective thermal resistance) and domestic hot water system (e.g., efficiency factors) per housing climate zone. In this context, least-construction-cost upgrades are investigated in this thesis for building envelope (attic ceiling, above- and below-grade exterior walls, and windows) and domestic hot water system meeting code-specified thermal insulation values and energy-efficiency factors defined in the ABC 2014.

1.2. Thesis organization

Chapter 1 (Introduction) describes the research motivation, objectives, scope, and thesis structure. Chapter 2 (Literature Review) focuses on energy-efficient construction practices, technologies, and initiatives for residential buildings in cold-climate regions. It begins with a review of relevant regulations and guidelines governing energy performance of new housing. Then, state-of-the-art energy-efficient solutions applied to new housing in cold-climate regions are presented, and Canadian government initiatives for highly energy-efficient homes are reviewed. Finally, an overview of studies recently conducted on Canadian energy-efficiency standards is outlined. Chapter 3 (Research Methodology) describes the methodology followed in this research to identify least-construction-cost code-compliant upgrades for building envelope and domestic hot water systems. Chapter 4 (Identification and Analysis of Least-Construction-Cost Code-Compliant Upgrades) encompasses determination of least-construction-cost upgrades for building envelope, sensitivity analyses, assessment of the ABC 2014 in relation to other building energy regulations, and a general approach developed in this research to identify least-construction-cost code-compliant upgrades for other climatic conditions. Chapter 5 (Case Studies of Least-Construction-Cost Code-Compliant Upgrades) looks at the impacts of the identified upgrades on construction cost, energy consumption, and operation cost of a home in Edmonton, Canada. Finally, Chapter 6 (Discussion and Conclusion) summarizes the results obtained, including key contributions, limitations, and recommendations for future work.

CHAPTER 2: LITERATURE REVIEW

This chapter begins with a review of energy performance requirements currently applied to new housing in Edmonton, Canada, and in other jurisdictions with similar climatic conditions. It proceeds with an overview of energy-efficient practices and technologies for new housing in cold-climate regions, and with Canadian government initiatives for highly energy-efficient homes. The chapter ends with a review of previous research conducted on Canadian energy-efficiency standards.

2.1. Energy-Efficiency Requirements for New Housing in Cold-Climate Regions

Researchers in this field assert that a key driver for improving the energy efficiency of buildings is to introduce specifications in this regard through building codes (BPIE 2011; EEA 2016b). In light of this finding, an extensive literature review is performed focusing on building codes governing energy performance of new housing set by jurisdictions with cold-climatic conditions. The literature review on building energy regulations is conducted pursuing two key objectives:

1) Investigate and compare energy codes currently applied for new housing.
2) Propose new parameters to be implemented in forthcoming versions of the Alberta Building Code based on energy regulations in other cold-climate jurisdictions.

To assess energy requirements defined by jurisdictions with climatic conditions similar to those of Edmonton, a climate indicator, the annual Heating Degree-Day (HDD), is chosen as the selection criterion in this research. The daily HDD is a metric which measures the daily difference, in degrees Celsius, between the average temperature of the day and a reference temperature of 18 °C (ASHRAE 2010; Government of Canada 2016). The annual HDD is the sum of daily degree-days in a calendar year, calculated as expressed in Equation (1) (ASHRAE 2013). Thus, according to this metric, there are five climate zones and two climate subzones in Canada, as illustrated in Figure 2.1 (NRC 2011). The two largest cities in Alberta, Edmonton and Calgary, are in Climate Zone 7A, which features an HDD that varies from 5,000 to 5,999 (NRC 2014).

$$\textit{Annual Heating Degree Days (HDD)} = \sum_{i\text{-}1}^{N} \dot{T} - T_i \tag{1}$$

where

$\dot{T} \geq T_i$;

$\dot{T}$: Reference temperature, 18 °C;

T_i : Average daily temperature; and

N: Number of days in a year.

Since most of the Nordic countries have an HDD similar to Edmonton's (Table 2.1), Nordic regulations governing energy performance of new residential buildings are analyzed in this research (ASHRAE 2010; BPIE 2011; Benestad 2008). Thus, findings pertaining to requirements for the energy performance of new housing in Canada (Edmonton/Alberta), Denmark, Finland, Iceland, Norway, and Sweden are presented in this section.

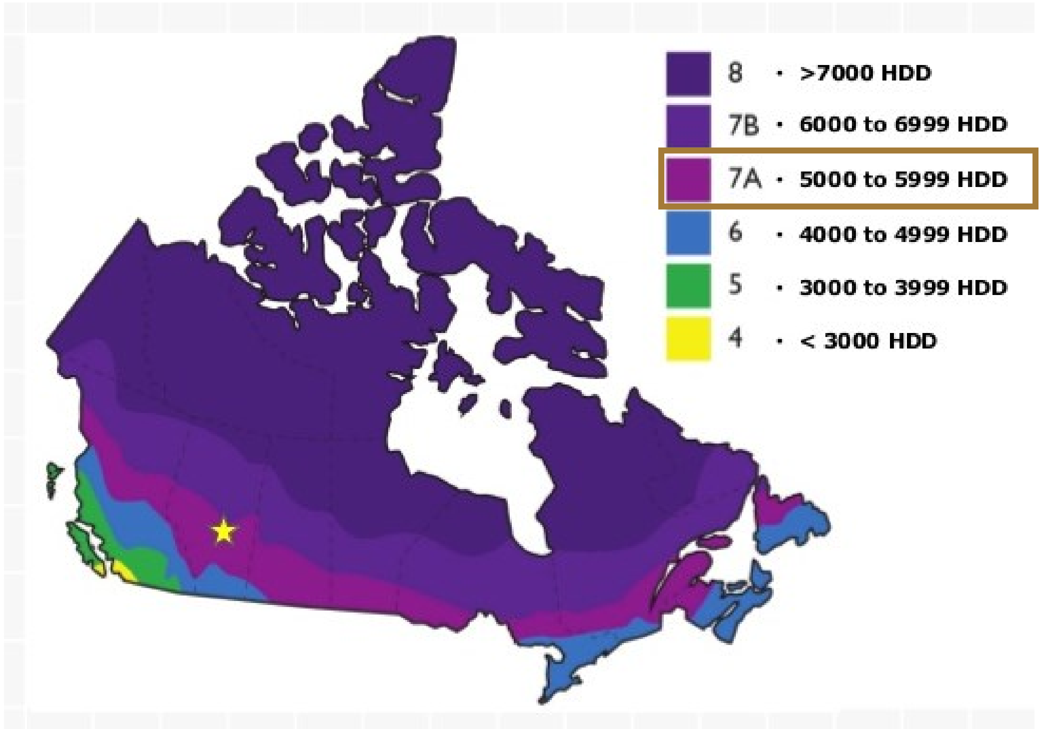

Figure 2.1: Climate Zones in Canada as per the NECB 2011 (Finch 2014).

Table 2.1: Climate Zone of Jurisdictions Whose Regulations are Analyzed in this Research.

Zone Number and Name	Thermal Criteria (SI Units)	Jurisdiction
5 - Cool	3,000 < HDD 18 °C ≤ 4,000	Denmark
7 - Very Cold	5,000 < HDD 18 °C ≤ 7,000	Canada (Edmonton and Calgary) Iceland (Reykjavik) Finland Norway Sweden

2.1.1. Energy-Efficiency Requirements for New Housing in Alberta (Edmonton)

Effective November 1, 2016, two codes regulate energy efficiency of residential buildings in Alberta: (a) the National Energy Code of Canada for Buildings (NECB) 2011, and (b) the Alberta Building Code (ABC) 2014 through the new “Section 9.36: Energy-Efficiency Requirements”. The NECB 2011 regulates residential buildings greater than three storeys in height and whose building area exceeds 600 m^2, as well as non-residential buildings whose combined total floor area surpasses 300 m². In contrast, the ABC 2014 regulates construction and design of small buildings and homes in Alberta. The application of each code according to building type and building area is detailed in Table 2.2 (NRC 2011; NRC 2014).

Table 2.2: Building Codes Compliance Options per Building Type in Alberta.

Building Type	**Compliance Options**	
	2014 ABC	**2011 NECB**
- Home[1] with or without secondary suite. - Building containing only dwelling units with common spaces ≤ 20% of building total's floor area. - Group C (residential) occupancies. - Building with a mix of Group C (residential) and D (business and personal services), E (mercantile) or F3 (low-hazard industrial) occupancies where the non-residential portion's combined total floor area ≤ 300 m² (excluding parking garage that serves residential occupancies).	✓	
- Other occupancies not specified above. - Non-residential building more than 3 storeys in height and with a combined floor area > 300 m². - Residential building more than 3 storeys in height and/or with a combined floor area > 600 m².		✓

Therefore, in accordance with the delimitation described above, most of the new housing in Edmonton is now required to comply with the ABC 2014, as 80% of housing in Edmonton has an area between 134.80 m² and 278.71 m² (City of Edmonton 2013). The single-family detached home is the most common structural type of residence in the province, representing ~64% of housing in Alberta, as detailed in Figure 2.2 (Statistics Canada 2013b). For this reason, with

[1] The term "house" includes detached, semi-detached, duplexes, triplexes, townhouses, row houses, and boarding houses.

reference to Canadian regulations for designing and constructing new housing in Edmonton, this research focuses on reviewing the requirements set by the mentioned section of the ABC 2014.

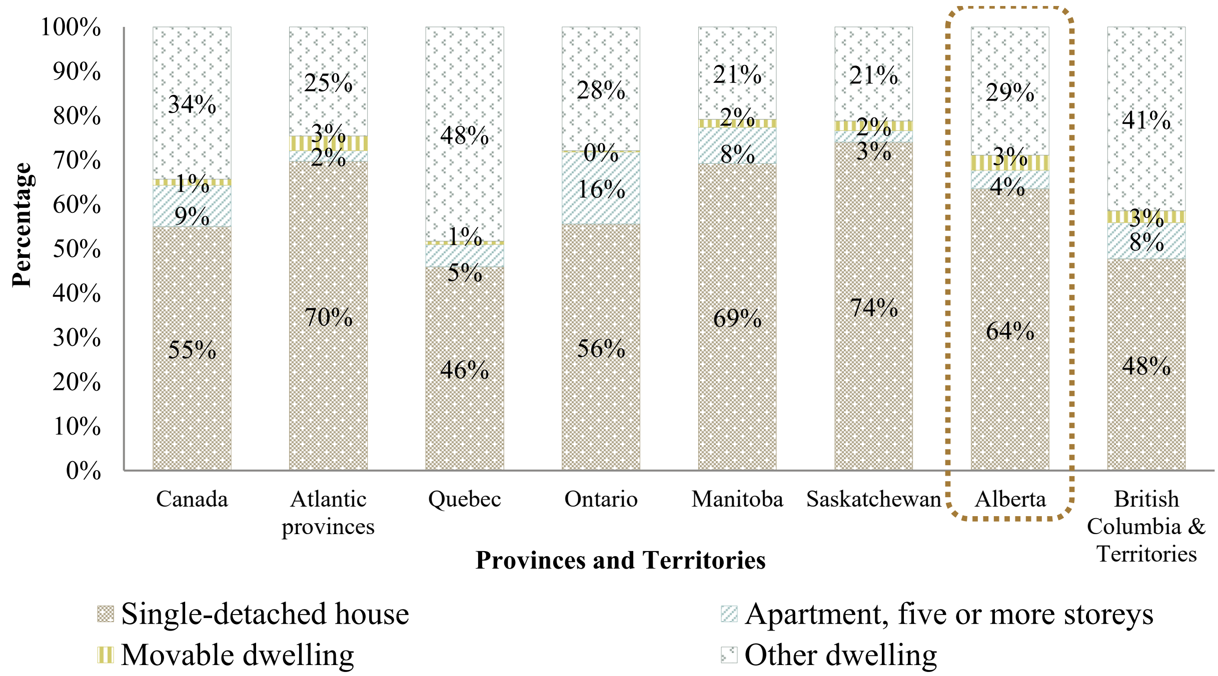

Figure 2.2: Structural Type of Dwelling by Canadian Provinces and Territories in 2013.

This recent enhancement of energy-efficiency requirements through building codes in Alberta was driven by the release of the NECB 2011, which introduced requirements 25% more restrictive compared to the previous national code, the Model National Energy Code for Buildings (MNECB) 1997 (CCBFC 1997; NRC 2015). As the other national model construction code in Canada, the NECB 2011 acts as a guideline with minimum requirements which must be adopted and enforced by Canadian provinces and territories (NRC 2015). In this context, among the provinces which have adopted and/or adapted the NECB 2011 as part of their regulations, British Columbia was the first to enforce it, in December, 2013, and Alberta was the last, enforcing it in November, 2015 (NRC 2016).

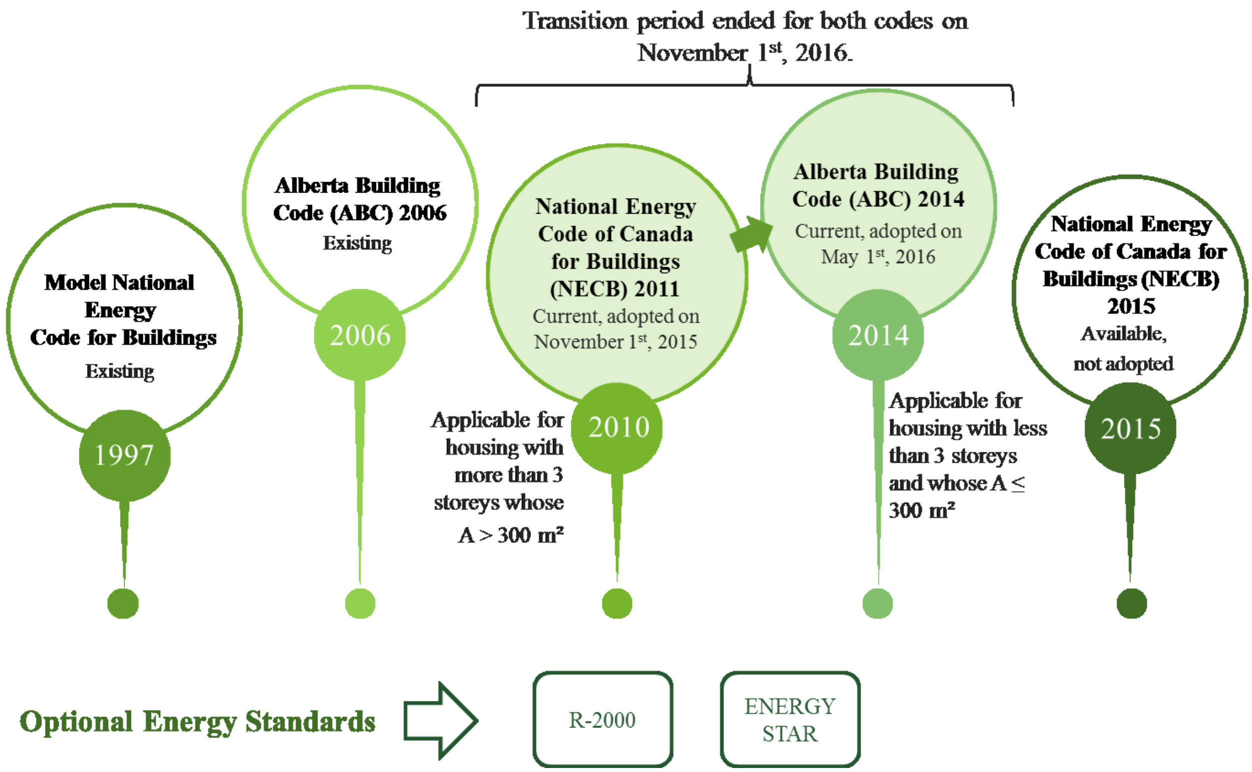

Figure 2.3: Timeline of Energy-Efficiency Regulations Applied to Residential Buildings in Alberta.

Section 9.36 of the ABC 2014 was adopted on May 1, 2016, followed by a transition period of six months. It introduced the NECB 2011 into the province as well as replaced the previous energy requirements defined under the Subsection 9.25.2.1 of the ABC 2006 (Figure 2.3) (Alberta Government 2016a). Both codes, NECB 2011 and ABC 2014, offer three paths of compliance: prescriptive, trade-off, and performance. Conformity by prescriptive path is achieved once requirements for building envelope and domestic systems are fully met. Additionally, this path acts as a baseline for other compliance options, as it defines the minimum standard of energy performance required for new housing in Alberta. The second option is the trade-off path, which affords some flexibility in design, allowing builders to trade effective RSI values of above-grade building envelope assemblies. Finally, the performance path offers total flexibility in design, provided that the energy demand of the proposed housing is estimated to be equal to or lower than the energy demand of the same housing designed based on the requirements of the prescriptive path (NRC 2011; NRC 2014). For assessment purposes, Table 2.3 presents the principal prescriptive requirements for building envelope, such as minimum thermal resistance (RSI), airtightness in air change per hour (ACH), maximum window and door areas, determined by the ABC 2006, NECB 2011, and ABC 2014—with and without a heating recovery ventilator (HRV) (NRC 2011; NRC 2006; NRC 2014).

As observed in Table 2.3, there are close similarities among the updated national and provincial regulations reviewed in this research. This consistency is to be expected, as the requirements adopted by Alberta's government are an adaptation of the NECB 2011 to the province's context. Moreover, both codes aim for the standard EnerGuide rating of 80, which classifies a home as energy efficient according to the Natural Resources Canada (NRCan) EnerGuide rating system (NRCan 2015a).

Table 2.3: Comparison of Principal Building Envelope Requirements Set by the ABC 2006, NECB 2011, and ABC 2014.

Building envelope		ABC 2006	NECB 2011	ABC 2014 w/o HRV	ABC 2014 with HRV
RSI values ($m^2 \cdot K/W$) of above-ground assemblies	Walls	2.10	4.76	3.08	2.97
	Roofs[2]	6.00	6.17	5.02 / 10.43	5.02 / 8.67
	Floors[3]	3.50	6.17	5.02	5.02
	Fenestration	-	0.45	0.63	0.63
RSI values ($m^2 \cdot K/W$) of in contact with the ground assemblies	Walls	1.40	3.52	3.46	2.98
	Floors[4]	2.10	NA / 1.32	NA / 2.84	NA / 2.84
Airtightness at 50 Pascal (Pa) pressure difference[5] (ACH)		-	-	2.50	2.50

On the other hand, comparing the ABC 2006 and the ABC 2014, a substantial disparity is observed between these codes' energy requirements. The overall RSI value of building envelope defined by the 2014 version has a global enhancement of ~57% in homes with HRV and ~73%, in homes without HRV, as demonstrated in Table 2.4. The most notable upgrade is observed on the RSI values of exterior walls in contact with the ground, which increase more than 113% in homes with HRV and 146% in homes without HRV. Other significant modifications are: (a) introduction of maximum thermal transmittance (U-value) of fenestrations and doors, which had not been addressed in the 2006 version, (b) addition of more stringent details for a building's airtightness, and (c) introduction of effective thermal resistance of building envelope assemblies,

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[2] When applied, the first value refers to cathedral ceiling and flat roofs, and the second value is applicable for ceiling below attics. NA: not applicable.
[3] Exposed cantilever floors.
[4] When applied, the first value refers to unheated floors below frost line, and the second value is applicable for heated floors.
[5] The airtightness of building envelope is not defined for the prescriptive path; prescriptive details are given instead. The value in the table is required for the reference house in the performance path.

which accounts for the thermal bridging effect of repetitive structural and ancillary members, rather than nominal RSI value of insulation materials (NRC 2006; NRC 2014).

Table 2.4: Comparison of the ABC 2006 and ABC 2014 Energy-Efficiency Requirements for Building Envelope.

Building Envelope		**ABC 2006 (A)**	**ABC 2014 w/ HRV (B)**	**% of improvement [(B/A) − 1]**	**ABC 2014 w/o HRV (C)**	**% of improvement [(C/A) − 1]**
RSI values (m^2·K/W) of above-ground assemblies	Walls	2.10	2.97	41%	3.08	47%
	Roofs	6.00	8.67	44.5%	10.43	74%
	Floors	3.50	5.02	43%	5.02	43%
	Fenestrations	-	0.63	n/a	0.63	n/a
RSI values (m^2·K/W) of in contact with the ground assemblies	Walls	1.40	2.98	113%	3.45	146%
	Floors	2.10	2.84	35%	2.84	35%

Despite the fact that both codes, NECB 2011 and ABC 2014, have introduced tighter energy requirements for new housing compared to their previous versions, the national and provincial governments missed an opportunity to introduce targets for maximum annual energy consumption per heated area. Other countries with similar climatic conditions have already included this metric in their building codes, e.g., Finland, Norway, and Sweden (Concerted Action 2010; Laustsen 2008). Currently, as stated in NECB 2011 and ABC 2014, the energy performance of a home is assessed by determining whether it meets minimal specifications for building envelope and domestic systems. Although this method results in decreased overall housing energy consumption, improvements in other energy-related areas and in the development of new technologies and/or construction practices are not encouraged by this method.

2.1.2. Energy-Efficiency Requirements for New Housing in Nordic Countries

Several investigations have been developed covering energy efficiency of residential buildings in Nordic countries (Danielski 2014; Smeds and Wall 2007; Thullner 2010). In addition, a strong commitment to enhance the energy performance of buildings through regulations is observed in these countries. In this regard, the first country to determine energy requirements for buildings was Denmark, in 1985, followed by Norway and Sweden. Iceland was the last Nordic country to set energy requirements for residential buildings, likely due to the country's abundance of renewable energy sources and consequently the low cost of energy. Nevertheless, all Nordic countries currently have strict and ambitious regulations governing residential building energy performance. The majority of them not only regulate building envelope thermal transmittance and domestic system energy efficiency, but also establish limits for maximum housing annual energy consumption per heated area, which is measured in kWh/m^2 per year (Sand et al. 2012).

In addition, most of the Nordic countries (Denmark, Finland, Norway, and Sweden) are confronting a transition period toward full implementation of the Energy Performance of Buildings Directive (EPBD) 2010/31/EU. The EPBD's primary objective is to gradually define energy performance standards in the direction of nearly net-zero buildings aligned with the European goal of constructing solely net-zero buildings from 2020 onward (European Commission 2016; EPBD Recast 2010). The aim of this subsection of the thesis is thus to explore energy-efficiency requirements addressed by the national buildings codes of Denmark, Finland, Iceland, Norway, and Sweden (Figure 2.4).

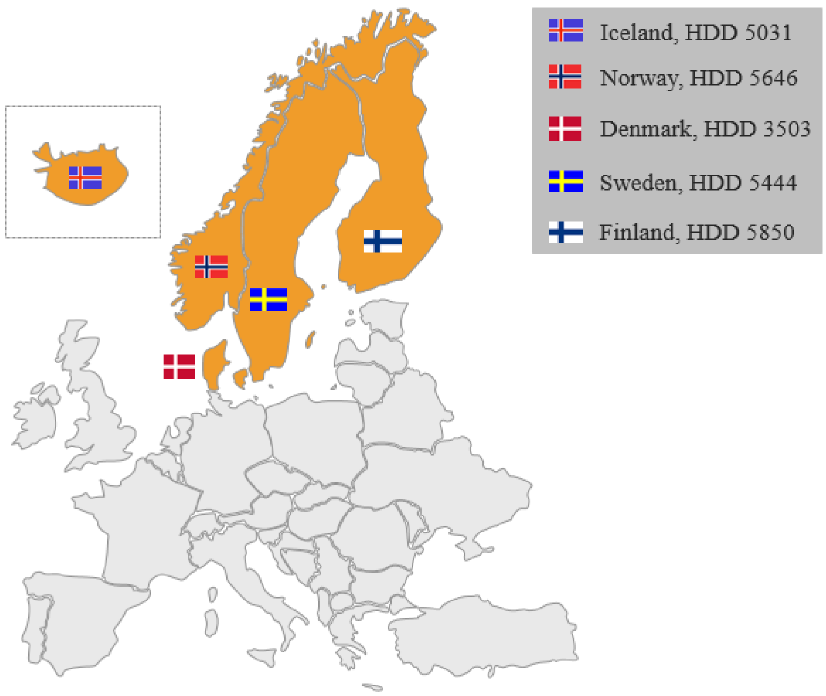

Figure 2.4: Nordic Countries Investigated in this Research with Respective HDD.

2.1.2.1.1. Energy-Efficiency Requirements in Denmark (HDD = 3,503)

In the past 25 years, energy requirements defined by Danish building codes have been tightened progressively and substantially (Danish Energy Agency 2016). A major amendment to the Danish building code occurred in 2006 when the energy performance standards for residential buildings proposed by the EPBD 2002/91/EC were implemented and a limitation for the maximum primary energy demand of buildings was introduced (Allard et al. 2013; Tommerup et al. 2007). In 2010, a revision of the Danish Building Regulation (BR10) announced energy requirements 25% more restricted than the 2006 version. The BR10 updated the minimum energy requirements for all building types, and also introduced two voluntary classes of energy improvements, low-energy class 2015 and low-energy class 2020, which are expected to become mandatory in the coming years. These two voluntary classes propose even stricter requirements for building envelope thermal resistance, airtightness, and maximum allowed energy consumption. Table 2.5 presents the minimum RSI values specified by the BR10. Other complementary energy requirements are summarized in Table 2.6 (Aggerholm et al. 2011; Thomsen and Wittchen 2013; Aggerholm 2013; Thomsen et al. 2015).

Table 2.5: Minimum RSI Values for Building Envelope in Denmark.

		2010	Low energy 2015
RSI values ($m^2 \cdot K/W$)	Walls	3.33	3.33
	Roofs	3.33	5.0
	Floors	5.0	5.0
	Windows	0.56	0.71

Table 2.6: Other Energy Requirements Defined by Danish Regulations.

	2010	Low energy 2015	Low energy 2020
Airtightness at 50 Pa pressure difference ($L/s \cdot m^2$)	≤ 1.5	≤ 1.0	≤ 0.5
Energy consumption ($kWh/m^2/year$)	$52.5 + 1{,}650/m^2$	$30.0 + 1{,}000/m^2$	20.0
Annual Efficiency for HRV	80%	-	-

In addition to the requirements defined in the BR10, the Danish Energy Agreement set in 2012 prohibits the installation of oil- and natural gas-fired boilers in new buildings in Denmark. Additionally, the Danish Energy Agency has proposed a plan for promoting information on an end-user level, as requested by the EU Energy Efficiency Directive policy, with the objective of improving the energy efficiency of buildings by changing user behaviour (Danish Energy Agency 2016). All these mentioned policies are part of a long-term goal set by the Danish Government of becoming carbon neutral by 2050 (Danish Government 2013).

2.1.2.1.2. Energy-Efficiency Requirements in Finland (HDD = 5,850)

Over the last 40 years, Finnish building codes have been through several updates with the objective of improving building energy performance. In 2012, the Finland National Building

Code introduced a new approach to calculating the total energy load of buildings which considers weighted factors that vary according to a building's primary energy source (GBPN 2016; Haakana and Laitila 2013). In the case of residential buildings, the maximum allowed energy consumption is determined per heated area of a building, as presented in Table 2.7 (Haakana 2011). Table 2.8 presents a comparison among the RSI values for building envelope as defined by the Finnish government in past years (Haakana 2011). As a consequence of these efforts toward improved energy performance, housing energy consumption in Finland decreased by ~5.7% in 2013 (Government of Finland 2015).

Table 2.7: Maximum Annual Energy Demand per Area for Residential Buildings According to the Finish Building Code 2012.

	A_{net}[6] < 120 m^2	120 m^2 ≤ A_{net} ≤ 150 m^2	150 m^2 ≤ A_{net} ≤ 600 m^2	A_{net} > 600 m^2
Energy consumption (kWh/m^2/year)	204	372 – 1.4 · A_{net}	173 – 0.07 · A_{net}	130

Table 2.8: Comparison of Finnish Building Envelope Requirements.

		1976	1978	1985	2003	2007	2010	2012
RSI-value (m^2·K/W)	Walls	2.50	3.45	3.57	4.00	4.17	5.88	5.88
	Roofs	2.86	4.35	4.55	6.25	6.67	11.11	11.11
	Floors	2.50	2.50	2.78	4.00	4.17	6.25	11.11
	Windows	0.48	0.48	0.48	0.71	0.71	1.00	1.00
	Doors	1.43	1.43	1.43	0.71	0.71	1.00	1.00
Annual Efficiency of HRV (%)					30	30	45	45
Total area of glass/doors (%)								50
Airtightness at 50 Pa pressure difference (L/s·m^2)								1.11

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6 A_{net} = Heated net area.

Although all types of energy sources are permitted to be used for heating space and water in Finland, the use of renewable energy is encouraged, as the maximum allowed energy consumption varies, as mentioned above, according to building energy source, building type, and area. Based on the weighting factors in Table 2.9 (Haakana and Laitila 2013), it is observed that fossil fuels and electricity have a great impact on the maximum building weighted energy load, whereas renewable energy sources have the lowest impact. In this context, ground source heat pumps are the heating system most used in newly built single-family homes in Finland (Motiva 2015).

Table 2.9: Weighting Factor for Energy Source.

Energy source	Weighting factor
Fossil fuel	1.0
Electricity	1.7
District heating	0.7
District cooling	0.4
Renewable fuels	0.5

2.1.2.1.3. Energy-Efficiency Requirements in Iceland (HDD = 5,031)

Disregarding the fact that previous efforts to increase the Icelandic building code's energy requirements faced great resistance from the construction industry, in 2011 the government released and adopted a new regulation which redefined minimum RSI values for building envelope (Table 2.10) (Sand et al. 2012). Due to the ready availability of renewable energy resources, Icelandic regulations have been less ambitious regarding housing energy performance than those in Finland. Moreover, it can be observed from Table 2.10 that the approach adopted by the government of Iceland to evaluate energy performance in residential buildings differs significantly from the approach followed by other Nordic countries, e.g., Denmark and Finland. Icelandic building code emphasizes thermal resistance and other aspects of building envelope rather than total building energy consumption, which is similar to the approach currently applied to housing in Alberta by the NECB 2011 and the ABC 2014.

Table 2.10: Building Envelope Requirements for Residential Buildings in Iceland.

		$\Theta_i \geq 15$ °C	15 °C > $\Theta_i \geq 5$ °C
RSI-values ($m^2 \cdot K/W$)	Walls	4.00	3.33
	Roofs	6.67	4.00
	Floors	5.00	4.00
	Windows	0.59	0.50
	Doors	0.59	0.50
Airtightness at 50 Pa pressure difference		1.5 L/s · m^2	1.5 L/s · m^2

2.1.2.1.4. Energy-Efficiency Requirements in Norway (HDD = 5,646)

In contrast with Iceland, although most of the energy used in Norway comes from renewable sources, the country has strict regulations governing the energy performance of residential buildings. Targeting 2030 as the deadline to become a carbon neutral country, Norwegian building regulations have been revised twice in the past 10 years (Sand et al. 2012). The 2007 code presented an extensive review of the energy requirements, which were even further tightened in the 2010 version, as presented in Table 2.11 and Table 2.12 (Dahl 2013). Reflecting this gradual upgrade of energy requirements, Norwegian residential energy consumption decreased at a rate of about 1.7% per year between the years 2000 to 2012 (Institute for Energy Technology 2015).

Table 2.11: Comparison of Energy Requirements Defined by Norwegian Regulations.

	1997	2007	2010
Energy consumption ($kWh/m^2/year$)	-	125 + 1,600/m^2	120 + 1,600/m^2 (Option 1)
Total area of glass/doors (%)	20% of heated floor area	20% of heated floor area	20% of heated floor area
Thermal bridging ($W/m^2 \cdot K$)	-	0.03/$m^2 \cdot$K	0.03/$m^2 \cdot$K
Annual Efficiency for HRV	60%	70%	70%

Table 2.12: Comparison of Norwegian Building Envelope Requirements.

		1997	2007	2010 Option 1	2010 Option 2
RSI-value ($m^2 \cdot K/W$)	Walls	4.55	5.56	4.55	5.56
	Roofs	6.67	7.69	5.56	7.69
	Floors	5.00	5.00	5.56	6.67
	Windows/doors	0.63	0.83	0.63	1.20
Airtightness at 50 Pa pressure difference (ACH)		≤ 4.0	≤ 2.5	≤ 2.5	≤ 3.0

The Norwegian 2010 regulation sets values for 13 building categories which have an impact on the energy performance of housing, ranging from building envelope thermal characteristics to annual energy demand, airtightness, thermal bridging, and minimum efficiency factors for domestic systems (Isachsen et al. 2011). Two alternatives of compliance are outlined in the code: (1) energy usage intensity, and (2) energy framework. Alternative (1) centres on satisfying the maximum energy consumption per heated area per year and on complying with minimum RSI specifications for building envelope. Since this option is based on a net energy limit, the RSI value of a building envelope component treated alone is allowed to deviate from the code requirement, provided that the thermal resistance of the whole building envelope is still code-compliant (Allard et al. 2013; Strand and Isachsen 2013). The second option is an energy framework which is fulfilled when any eleven of the thirteen requirements established by the code are successfully achieved (Allard et al. 2013; Strand and Isachsen 2013). Thus, it is noted that the second approach is similar to the approach adopted by the ABC 2014.

Requirements for energy supply are also addressed in Norwegian regulations. For a residential building the area of which is less than 500 m^2 it is required that at least 40% of the net energy demand for space heating be met using renewable energy sources. However, this requirement is not applicable to residential buildings the heating demand of which is lower than 15,000 kWh per year (Strand and Isachsen 2013). In addition, boilers which use fossil fuels as their energy source have not been allowed in Norway since 2010; also, since 2013, air leakage tests performed by a third party are mandatory for all building types (Concerted Action 2015). Furthermore, in the coming years, an updated version of the Norwegian building code is expected which will propose requirements for housing ~26% stricter than those currently applied (Institute for Energy Technology 2015).

2.1.2.1.5. Energy-Efficiency Requirements in Sweden (HDD = 5,444)

In 2006, the Swedish building regulation underwent a major change when it established a limit for building energy consumption (Laustsen 2008). In contrast with other Nordic countries, which use the estimated energy demand of a building as an evaluation criterion, the Swedish regulation requests a proof of the actual energy consumed by the building. This proof must be provided within two years after a building's construction completion date (Sand et al. 2012).

For regulation purposes, the country is divided into three zones corresponding to different climates; each zone has its own energy performance requirements, including the maximum building total energy demand (Danielski 2014). Climate zone I covers the northern area of the country, and it is the zone with the most restrictive requirements; central Sweden is part of climate zone II, and zone III covers the southern region, which has the least restrictive requirements (Hjorth et al. 2011; Dodoo and Gustavsson 2014). The primary metric used in the Swedish Building Code (BBR 19) to evaluate energy efficiency is energy use intensity, measured in kWh/m^2 per year (Table 2.13). The BBR 19 also specifies an alternative option of compliance, which is applicable to buildings with (a) a floor area lower or equal to 100 m^2 whose windows and doors areas do not exceed 20% of the heated floor area, and (b) no cooling system. If these restrictions are met, RSI values for building envelope must not be inferior to the values presented in Table 2.14 (Boverket 2012).

Table 2.13: Primary Approach to Measure Residential Buildings Energy Performance in Sweden.

	Zone I	Zone II	Zone III
Energy consumption ($kWh/m^2/year$)[7]	95 / 130	75 / 110	55 / 90
Average thermal transmittance ($W/m^2 \cdot K$)	0.4	0.4	0.4

Table 2.14: Alternative Option of Compliance Set by the Sweden Building Code – BBR 19.

		Residential building with electric heating and floor area within 51 to 100 m^2	Residential building without electric heating
RSI-value ($m^2 \cdot K/W$)	Walls	10.00	5.56
	Roofs	12.50	7.69
	Floors	10.00	6.67
	Windows/doors	0.91	0.77
Airtightness at 50 Pa pressure difference		$0.6\ L/s \cdot m^2$	$0.6\ L/s \cdot m^2$

2.2. Highly Energy-Efficient New Housing

2.2.1. Energy-Efficient Solutions for Building Envelope and Domestic Systems

Researchers indicate that the design community is more inclined to invest in materials for building envelope than in domestic systems (Kerr and Kosar 2011). However, Kerr and Kosar (2011) and Anderson et al. (2006) emphasize that accomplishing high levels of energy efficiency in housing in cold-climate regions is costly and requires the most advanced solutions and technologies available. Thus, in this context, the role of building envelope and domestic systems in reducing energy demand and energy consumption during housing operation is crucial.

[7] First values account for residential buildings with electric space heating and second values for residential buildings with non-electric space heating.

In regards to building envelope, two properties require further attention: (1) thermal transmittance, and (2) thermal inertia (Goia et al. 2015). Small values of thermal transmittance, which opposes thermal resistance, prevent heat loss from interior space to exterior (colder) space in cold ambient conditions. In parallel, thermal inertia refers to the capability of a material to store heat (Hutcheon and Handegord 1989). In this regard, in cold-climate jurisdictions, studies indicate that the thermal transmittance property must prevail during the process of material selection since it has an impact on both heating and cooling demand (Goia et al. 2015). Moreover, as presented in Section 2.1, thermal transmittance and/or thermal resistance is also used in building codes to determine energy requirements for building envelope (ceiling, exterior walls, basements, floors, and fenestration). Therefore, based on this information, this thesis focuses on thermal transmittance/resistance properties of materials for selecting potential upgrade configurations that are compliant with the prescriptive path of ABC 2014 rather than on thermal inertia and solar absorptance properties.

Regarding domestic hot water (DHW) systems, the U.S. Department of Energy (DOE) indicates that tankless domestic water heaters are an affordable option for upgrading and enhancing DHW's energy performance (DOE 2012). Standby losses that are likely to occur in storage type systems are eliminated in tankless systems, since in the latter case water is heated only when requested (DOE 2012). In this regard, a recent survey performed by Enbridge Gas Distribution Inc. and Canada Mortgage and Housing Corporation (CMHC) investigates the implications, on natural gas and on water consumption, of upgrading from a storage tank to a tankless system. The analyses of twenty-three homes located in the Toronto area indicate an average reduction of ~44% in gas consumption in homes with tankless condensing systems compared to the previous gas consumption of storage tank systems (CMHC 2011). Condensing tankless domestic water heaters are more energy efficient than the non-condensing type, as the system's waste and energy demand is reduced. While in non-condensing systems gases produced by fuel combustion are vented out by pipes, in condensing systems these gases are captured and condensed, and the latent heat released during condensation is also used for heating water (DOE 2012).

Another alternative for domestic systems is the utilization of heat pumps (HP) for DHW and space heating and cooling purposes. HPs are divided into two major categories: air source heat pump (ASHP), which uses air as the heat source, and ground source heat pump (GSHP), which uses the ground as the heat source (Hakkaki-Fard et al. 2015). Safa et al. (2015) analyze energy performance of ASHP and GSHP systems in various cities in Canada, concluding that ASHP and GSHP systems have their energy performance restricted in Edmonton due to climatic conditions. However, although both systems operate contrary to expectation, the GSHP performs better than ASHP, as the latter never actually reaches the temperature set point defined in the study (Safa et al. 2015). That being said, GSHP installation is costly and more difficult than that of other energy-efficient domestic systems such as tankless DHW.

In addition to tankless DHW and HP, heat recovery ventilators (HRVs) and energy recovery ventilators (ERVs) are also recommended to boost energy performance of housing in cold-climate regions. HRVs reduce the energy required to warm fresh air entering the interior space by exchanging sensible heat between air flows (incoming and outgoing). Alternatively, ERVs, besides exchanging sensible heat, also exchange latent heat, taking advantage of the humidity present in incoming air (Zhang and Fung 2015). Researchers state that the introduction of HRVs into homes is cost effective and that energy savings increase in proportion to system usage

(Akbari and Oman 2013). Therefore, the payback time is shorter in regions with longer and harsher cold seasons. Regarding energy performance, in a single-family detached home, it is estimated that HRVs with high energy-efficiency factors are able to recover ~74% of the heat lost by conventional exhaust fan ventilators (Akbari and Oman 2013). In apartment buildings, the heat recovered is slightly lower, ~67% (Jokisalo et al. 2003), but still significant. Furthermore, the impact of HRVs and ERVs on space heating demand reduces the energy consumed by heating systems and also increases the interior air quality (Justo Alonso et al. 2015; Ng and Payne 2016).

Therefore, based on the literature review on energy-efficient options for domestic systems, tankless DHW and HRVs are chosen for further analysis in this thesis. Tankless DHW is easier to install, more affordable, and demands fewer changes in design parameters when compared to other energy-efficient domestic systems, e.g., GSHP. HRVs are widely used in new housing in Edmonton, and their application also has an impact on the RSI values specified for building envelope in the ABC 2014. Thus, HRV application is also considered in this thesis.

2.2.2. Canadian Initiatives for Highly Energy-Efficient Homes

In Canada, three initiatives are applied for energy-efficient homes: (a) EnerGuide rating, (b) ENERGY STAR, and (c) R-2000. NRCan developed the EnerGuide rating in order to provide a rating system which can be easily comprehended by builders and users. The rating uses a scale from 0 to 100, where 0 represents a home with no insulation and a great level of infiltration that consumes a massive amount of energy. In contrast, 100 represents an airtight, appropriately ventilated, and well-insulated home which produces, annually, as much energy as it consumes (NRCan 2016e). Figure 2.5 depicts the EnerGuide rating for Alberta (NRCan 2016c). In this context, as a result of elevated energy-efficiency standards in Canada, it is expected that all new Canadian housing will be required to have an EnerGuide rating of 80 in the coming years. Thus, although the ABC 2014 has not included EnerGuide rating as an energy requirement, an EnerGuide rating of 80 will be pursued in this research.

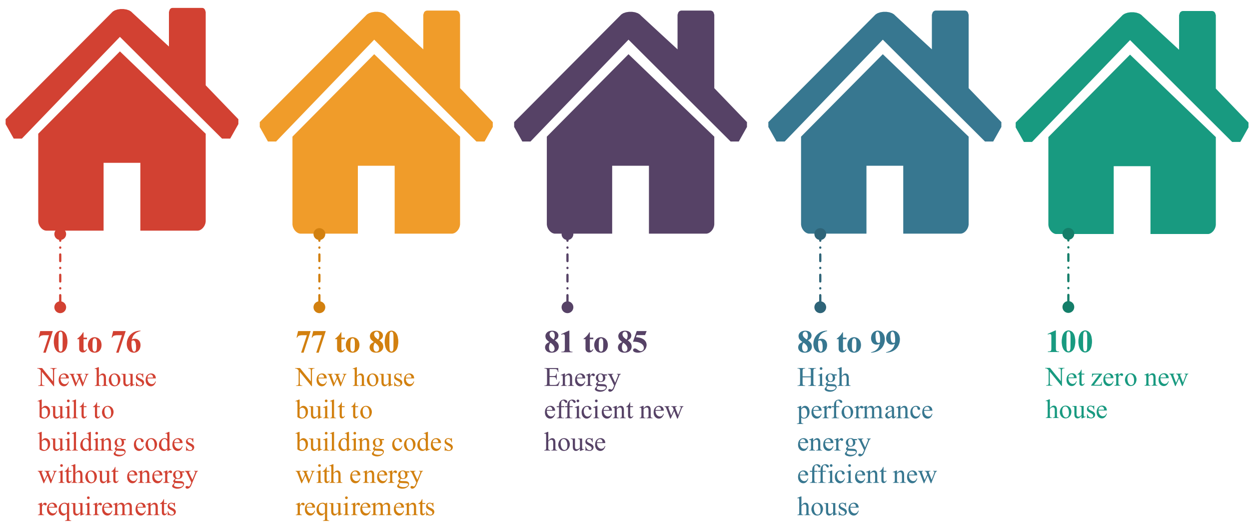

Figure 2.5: House Type and EnerGuide Rating for Alberta Region.

In contrast to the EnerGuide rating initiative, ENERGY STAR and R-2000 initiatives are not ranking systems, but they do measure housing energy performance. ENERGY STAR is a voluntary program regulated by NRCan's Office of Energy Efficiency (OEE) that is applied not only to housing but also to products and nonresidential buildings. The program's primary objective is to reduce greenhouse gas emissions (NRCan 2016f). Thus, a new home that is ENERGY STAR-qualified is ~20% more energy efficient than a typical code-compliant new Canadian home (NRCan 2016g). Alternatively, R-2000 homes are "*best-in-class energy-efficient homes*" (NRCan 2015d), corresponding to the concept of low-energy homes (LEHs) in Canada. R-2000 homes are on average ~30% more energy efficient than a typical new home which complies with the minimum requirements specified by provincial buildings codes (NRCan

2015b). Thus, to achieve this superior level of energy performance, homes are typically built to be airtight and highly insulated (ceiling, floors, and walls) with energy-efficient windows, doors, and domestic systems (especially for space heating purposes) (NRCan 2015d).

In addition to R-2000 standard, NRCan has developed the R-2000 Net Zero Energy pilot, which aims to identify and award net-zero energy homes and builders (NRCan 2015e). A net-zero energy home (nZEH) is one designed with highly energy-efficient technologies which reduce its energy demands to an extent that the remaining energy needed can be supplied by renewable energy sources (Torcellini et al. 2006). According to this definition and to Figure 2.5, nZEHs correspond to level 100 in the EnerGuide rating. In Canada today, LEHs, near-nZEHs, and nZEHs occupy a small niche market the viability of which is still greatly dependent on policies and incentive programs (Maruejols et al. 2013). User acceptance or apprehension regarding whether positive experiences with LEHs and nZEHs in other locations would be replicated in a climate with more severe weather conditions, limited knowledge of potential energy savings during occupation phase, and increased purchase cost are indicated as potential causes of the limited growth of LEHs and nZEHs in Canada (Maruejols et al. 2013; Mlecnik et al. 2012). It is likely that the R-2000 Net Zero Energy pilot will address some of these concerns in the coming years.

2.2.3. Investigations on Canadian Improved Energy-Efficiency Regulations

As mentioned in Section 2.1, the Canadian national energy model building code, and in turn the provincial building code, recently underwent a comprehensive review. As an outcome of the changes made to these codes, research is being conducted to investigate the implications of these restrictive energy-efficiency regulations on Canadian housing.

In this regard, Dembo (2011) conducts a study aiming to identify cost-effective specifications to meet the energy-efficiency standards set by the Ontario Building Code (OBC) 2012 based on life cycle cost analysis (LCCA). The OBC 2012 increased the housing energy requirements in Ontario by ~40% in comparison to the requirements of the OBC 2006 (Di Placido et al. 2014). In order to overcome the changes imposed by the OBC 2012, Dembo (2011), Dembo and Fung (2012), and Dembo et al. (2013) develop a methodology using the brute force sequential search (BFSS) approach. The analyses performed by Dembo (2011) and Dembo et al. (2013) account for government incentives—e.g., Ontario's micro Feed-in Tariff—that are applied to certain upgrade alternatives, focusing on long-term operational savings rather than on initial construction cost. Other alternative approaches to meet Canada's updated energy regulations are investigated by Lohonyai and Korany (2013) and Di Placido et al. (2014). Lohonyai and Korany (2013) conduct a study comparing nine exterior wall assemblies with approximately the same U-value, ~0.21 W/m^2K, designed to meet the requirement established by the NECB 2011 for climate zone 7A. In parallel, Di Placido et al. (2014), continuing the research developed by Dembo et al. (2013), conduct a study that explores three upgrade configurations designed to surpass the energy standards defined by the OBC 2012. Focusing on the economic and environmental implications, Di Placido et al. (2014) conclude that the upgrades they propose are not profitable if analyzed solely from the owner's perspective. Nonetheless, the introduction of mandatory energy performance certificates, preferential mortgage rates, and carbon tax are indicated by Di Placido et al. (2014) as approaches to boost energy performance of housing beyond building code regulations.

Hence, based on the literature review performed in this subsection, it is observed that relatively few studies investigate the implications and adaptations imposed by building code energy requirements in Canada. Those that are available mostly cover the weather conditions in Toronto (climate zone 5), which is substantially milder than that of Edmonton (climate zone 7A) (NRC 2011). Therefore, the impacts of energy standards on current construction practice for new housing in a more severe climatic condition have not yet been analyzed. Additionally, the studies previously conducted have been limited in this following respects: (a) limited to a single aspect, such as exterior wall, e.g., Lohonyai and Korany (2013); (b) improvements of housing energy performance have been from an owner's perspective focusing on total life cycle analysis rather than on additional investment, e.g., Dembo (2011); Dembo and Fung (2012); Dembo et al. (2013); or (c) they have targeted upgrades to surpass current energy standards rather than to merely meet them, e.g., Di Placido et al. (2014). In this context, the objective of this thesis is to bridge a gap in the research by analyzing the impacts of energy-efficiency standards from the builder's perspective in cold-climatic conditions. Potential upgrades are identified aimed at minimizing the additional construction cost required to meet new Canadian energy regulations.

CHAPTER 3: RESEARCH METHODOLOGY

In this chapter, the methodology of this research is presented in detail. Figure 3.1 provides a visual summary of the methodology.

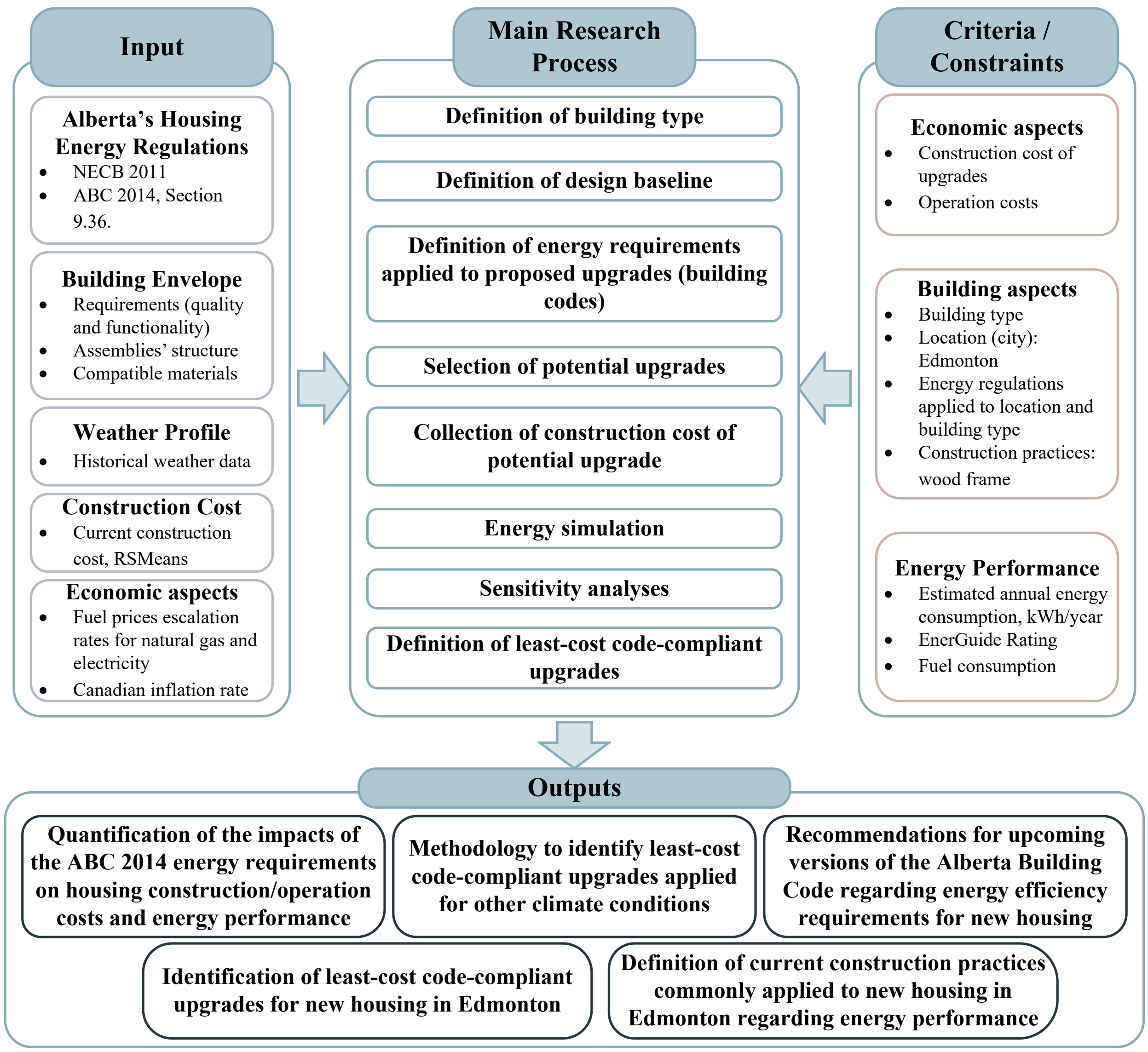

Figure 3.1: Overview of Research Methodology.

This research investigates the construction cost, energy consumption, and operation costs of different code-compliant upgrade options, with a focus on building envelope and domestic hot water (DHW) system. The configurations for building envelope are initially identified based on least additional construction cost in accordance with thermal insulation values specified in the prescriptive path of the ABC 2014. Additionally, ease of construction, utilization of materials that the industry is already familiar with, different insulation materials with various levels of thermal resistance, and application of local materials and resources are some of the aspects also considered during the identification of upgrades.

Once the least-construction-cost code-compliant envelope is selected, sensitivity analyses are performed using HOT2000 to assess the impacts of several parameters on the energy consumption of the reference house built using current construction practice. These analyses are conducted with three fundamental objectives: (1) improve housing energy performance by optimizing the sizing of south-facing windows, (2) assess the energy performance of tankless DHW systems, and (3) minimize alterations to current construction practice by identifying the least-construction-cost prescriptive upgrade which meets code-compliant energy performance by the performance path of the code. Then, simulation models are developed in HOT2000 representing the reference house built with the identified least-construction-cost code-compliant envelope and the results of the sensitivity analyses. The objective of these HOT2000 models is to estimate the energy consumption, EnerGuide rating, and operation cost of the reference house built using current construction practice and with the code-compliant upgrades identified in this research. To conclude, impacts of energy code requirements are assessed, regarding additional construction cost, energy performance, return on investment (ROI), total lifecycle cost, and actual savings, for the three code-compliant approaches investigated in this thesis (Figure 3.2) as follows:

1) Identify least-construction-cost prescriptive upgrades for building envelope;

2) Identify least-construction-cost prescriptive upgrades for building envelope, optimal window sizing for less lifecycle operation cost, and energy-efficient DHW system; and

3) Identify the simplest least-construction-cost upgrade for code-compliant energy performance.

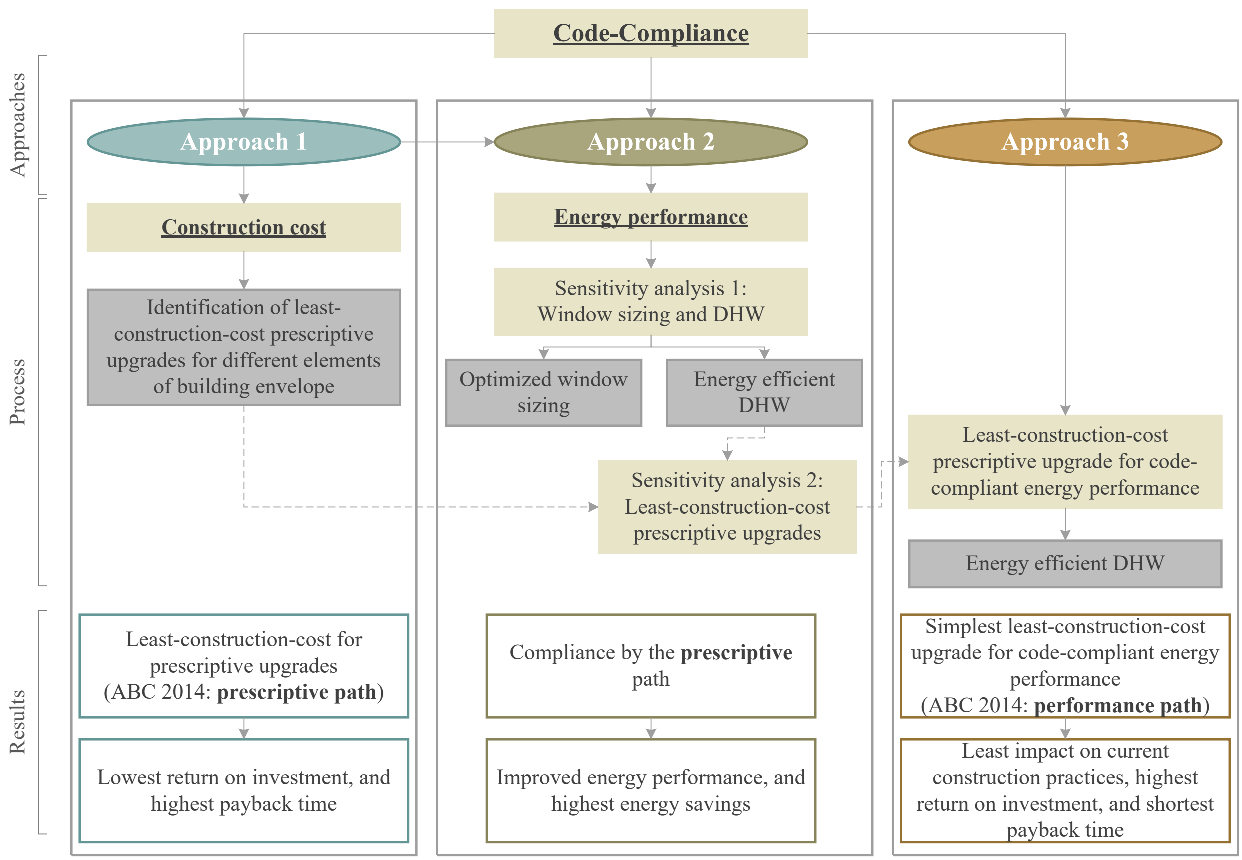

Figure 3.2: Approaches for Code-Compliance Investigated in this Research.

To accomplish the key objectives of this research, a reference house design is used with the following two objectives: (1) assess the impacts of the ABC 2014 on current construction practice, and (2) develop a methodology for identifying suitable least-construction-cost code-compliant upgrades. This developed methodology is applicable to other design conditions (e.g., other locations and house sizes) for the purpose of determining least-construction-cost code-compliant upgrade solutions, and consequently, assessing the impacts of other building codes. With this in mind, a typical new home in Edmonton is chosen as the reference house in this thesis. Then, key architectural characteristics, occupancy, and energy specifications are defined based on the chosen house type and location (city). The building code relevant to the reference house size and location climate zone is identified, and subsequently the code requirements applied to potential upgrades are defined. Then, the criteria for selecting potential upgrades and for estimating additional construction cost are described. Finally, least-construction-cost upgrades compliant with the prescriptive path of the code are determined.

Furthermore, the energy requirements defined by the ABC 2014 are also evaluated and compared to other building energy codes (reviewed in Subsection 2.1.2). The objective of this assessment is to suggest requirements to be included in upcoming versions of the ABC in order to further enhance new housing energy performance in Alberta. A thorough description of each process mentioned above is presented in the subsequent section of this chapter and in Chapter 4.

3.1. Detailed Description of Research Methodology

A detailed description of each phase observed to accomplish the objectives of this research is presented in this section.

3.1.1. Selection of Housing Type

For the purpose of representing Edmonton's current housing market, two primary factors are analyzed for defining the reference house: (a) housing structural type, and (b) housing area. In regards to structural type, the single-family detached home represents a large percentage of Canadian housing, accounting for 55% of all residential buildings in the country. A similar proportion is also found in the metropolitan area of Edmonton, where 59% of the housing is also single-family detached, as shown in Figure 3.3 (Statistics Canada 2013b). In terms of floor area, excluding basement most of the homes being built in Edmonton fall into two major size categories: (a) from 134.80 m^2 to 190.45 m^2, or (b) 190.54 m^2 to 278.71 m^2. Each category accounts for 40% of housing in Edmonton (City of Edmonton 2013). In light of this information, an existing single-family detached home with a total area of 149.57 m^2, excluding basement, is selected in this thesis to represent a typical Edmonton home. This home is referred to herein as the "reference house".

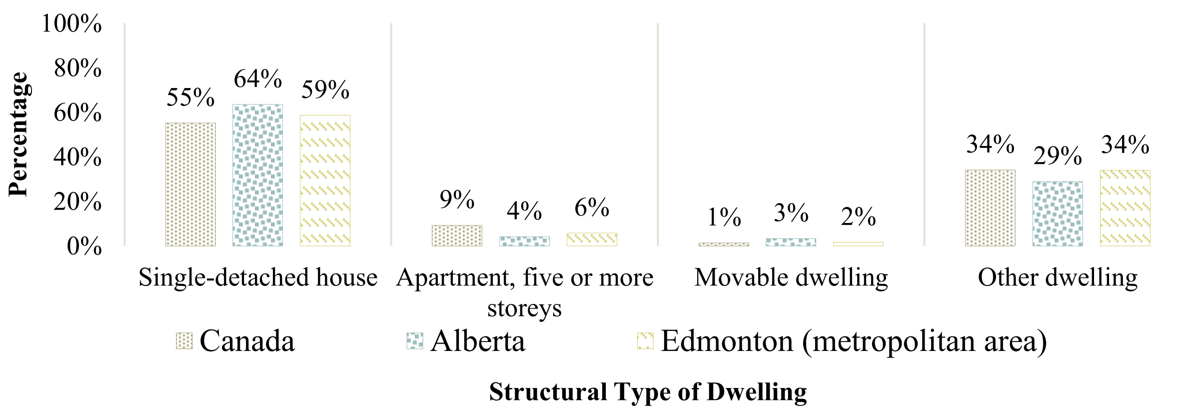

Figure 3.3: Structural Types of Dwellings in Canada, Alberta, and Edmonton metropolitan area[8].

[8] "Other dwelling" includes: semi-detached house, row house, flat in a duplex, apartment building with less than five storeys and other single-family attached house.

3.1.1.1.1. Reference House Characteristics

The reference house is a wood-frame panelized home built by a major Alberta-based home builder. The house is a two-storey single-family dwelling with detached garage and a semi-developed basement. Its internal configuration is described below:

- Main floor: living areas, including kitchen, living room, and dining room plus one bathroom and a bonus room.
- Second floor: two bedrooms, one bathroom, and one master suite.
- Basement: utilities such as space and domestic hot water heaters.

The reference house features a total of three bedrooms and three bathrooms (two being fully equipped). The house is rectangular, 12.19 m × 6.10 m, and its main entrance faces south. The total window area accounts for ~7% of the above ground gross building envelope area[9], and windows are mostly located on the south and north façades, with the exception of three windows that face west. Moreover, the total fenestration-to-wall ratio (FWR), which accounts for window and door areas combined, is approximately 0.08 (8%). Figure 3.4 summarizes the primary characteristics of the reference house that would impact its energy performance. *Appendix A.1. Reference House Blueprints* presents the blueprint of the reference house for further detail on its structure and layout.

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[9] Gross building envelope area is equal to above-ground building envelope area including fenestration.

General

- **Floor area:** 149.57 m²
- **Ceiling type:** Attic ceiling
- **Internal ceiling area:** 71.44 m²
- **Building envelope above ground gross area:** 216.93 m²
- **House volume:** 554.38 m²
- **Total fenestration-to-wall ratio:** 0.08 (8%)

Windows

- **Total window area:** 14.50 m²
- **Window-to-wall percentage:** 7%

Window-to-wall percentage per façade:

- **South**: 16% | **West**: 4%
- **North:** 16% | **East:** 0%

Doors

- **Total door area:** 3.51 m²
- **Door-to-wall percentage:** 2%

Door-to-wall percentage per façade:

- **South**: 5% | **West**: 0%
- **North:** 5% | **East:** 0%

Figure 3.4: Reference House Information.

3.1.1.1.2. Occupancy, Domestic Hot Water Consumption, Electricity Demand and Temperature Set Points

This subsection provides information pertaining to the simulation and analysis of building operation, such as temperature set point, domestic hot water usage, and electricity demand by appliances and lighting. Although the 2011 Canadian Census indicates that the average number of persons per household in Canada is ~2.5 and in Alberta is ~2.6, the simulated occupancy applied in this research accounts for two adults and two children present in the house for 50% of the time. This assumption is made based on the occupancy recommended and applied by NRCan in the EnerGuide rating, R-2000, and HOT2000 calculations (NRCan 2016d; Statistics Canada

2013a). Moreover, based on the occupancy scenario described above, the domestic hot water consumption is estimated to be 225 L per day (NRCan 2016d).

With respect to estimated electricity demand by lighting and appliances, the default values set by HOT2000 simulation software are applied, as they are compliant with the NRCan recommendations for housing energy simulation procedures. NRCan suggests that interior lights should account for 3.40 kWh per day, exterior lighting for 4.00 kWh per day, appliances for 9.00 kWh per day, and other loads for 7.60 kWh per day, resulting in an estimated electricity consumption of 24.00 kWh per day (NRCan 2016e). Additionally, the simulation models that are performed in this research also account for a minimum ventilation rate, including mechanical and natural ventilation, of 0.30 ACH per month during the heating season and indoor thermostat temperature set-points of 21 °C for main and upper floors and 19 °C for basement (NRCan 2016d).

3.1.1.1.3. Definition of Design Baseline for New Housing in Edmonton

With the aim of capturing the current construction practice for housing in Edmonton, a comprehensive web search survey is conducted to collect common design configurations used by major builders in the city. The objective of this survey is to verify whether builders are building as per the ABC 2006 energy standard or have already surpassed the code requirements due to market demands. Thus, design configurations of seventeen builders are collected and then divided into two groups based on energy performance (Table 3.1). From the seventeen builders investigated in this thesis, three are found to be using a higher energy standard and fourteen, accounting for 82.35% of the builders analyzed, are using a nearly identical design configuration. This design configuration used by most of the builders is subsequently referred to as “current construction practice". The differences between these two groups of design parameters are emphasized in bold in Table 3.1.

Table 3.1: Current Construction Practice for Single-Family Detached Home.

	Current Construction Practice	High Energy Standard
Attic ceiling	RSI 7.04 (R 40) Blown-in cellulose	**RSI 8.81 (R 50)** Blown-in cellulose
Above-grade exterior walls	Wood framing 50.8 × 152.4 mm (2 × 6 in.) @ 610 mm (24 in.) o.c. RSI 3.52 (R 20) fibreglass batt	Wood framing 50.8 × 152.4 mm (2 × 6 in.) @ 610 mm (24 in.) o.c. RSI 3.52 (R 20) fibreglass batt
Exposed floors	RSI 4.93 (R 28) fibreglass batt	RSI 4.93 (R 28) fibreglass batt
Below-grade exterior walls	RSI 2.11 (R 12) fibreglass batt	**RSI 3.52 (R 20)** fibreglass batt
Doors	Insulated fibreglass	Insulated fibreglass
Windows	Double-pane, Low-E argon-filled, PVC frame	**Triple-pane**, Low-E argon-filled, PVC frame
Ventilation system	Heat Recovery Ventilator (HRV)	Heat Recovery Ventilator (HRV)
Heating/Cooling system	92% high-efficiency gas-fired furnace	**95%** high-efficiency gas-fired furnace
Domestic hot water	Power direct vented 189.27 L (50 US gal) | EF = 0.67 (assumed)[10]	Power direct vented 189.27 L (50 US gal) | EF = 0.67

Based on the web survey performed, it is verified that the energy specifications defined by the ABC 2006 are no long being used by builders (Table 3.2). For this reason, current construction practice is considered as the design baseline for the upgrades identified in this research.

[10] Information regarding energy efficiency of domestic hot water systems is not available on builder's website.

Table 3.2: Comparison of the ABC 2006 Energy Requirements and Current Construction Practice.

Building Envelope / Domestic Systems	ABC 2006	Current Construction Practice
Attic ceiling	RSI 6.00	RSI 7.04 (R 40) Blown-in cellulose
Above-grade exterior walls	RSI 2.10	RSI 3.52 (R 20) fibreglass batt
Exposed floors	RSI 3.50	RSI 4.93 (R 28) fibreglass batt
Below-grade exterior walls	RSI 1.40	RSI 2.11 (R 12) fibreglass batt
Doors	Minimal value for thermal resistance is not specified	Insulated fibreglass
Windows	Minimal value for thermal resistance is not specified	Double-pane, Low-E argon-filled, PVC frame
Ventilation system	Energy efficiency is not specified	Heat Recovery Ventilator (HRV)
Heating/Cooling system	Energy efficiency is not specified	92% high efficiency gas-fired Furnace
Domestic hot water	Energy efficiency is not specified	Power direct vented 189.27 L (50 US gal)

3.1.2. Identification of Building Code Relevant to the Selected Housing Type and City

Beginning November 1, 2016, new housing built in Alberta will be required to comply either with the NECB 2011 or with Section 9.36 of the ABC 2014 (Alberta Government 2016b; Alberta Government 2016a). In this context and based on the information about codes presented in Subsection 2.1.1, the reference house must comply with the requirements specified in the ABC 2014 for Edmonton's climate zone.

3.1.3. Selection of Potential Upgrades

The criteria for selecting potential upgrades to be deployed in current construction practice for new homes in Edmonton are presented in this subsection. As mentioned in the introduction to this chapter, besides the need to meet building code requirements, other aspects such as different RSI-values and types of insulation materials, ease of construction, and compatibility with current construction practice are also considered in the identification of potential upgrades. In this regard, it is important to emphasize that this thesis proposes improvements for domestic hot water system and building envelope by selecting equipment, materials, and assembly configurations rather than proposing new design solutions. In addition, the least-construction-cost upgrades identified in this research are compliant with the prescriptive path of the ABC 2014.

Thus, based on the scope described above and on current construction practice, potential upgrade configurations for building envelope and for energy-efficient domestic hot water system are identified in this research. First, the effective RSI values of building envelope assemblies built using current construction practice, summarized in Table 3.1 in Subsection 3.1.1.1.3, are calculated according to the method detailed in the ABC 2014 (NRC 2014). In the case of wood-frame assemblies, the ABC 2014 determines that the parallel-path flow method must be used for calculation purposes as it accounts for the thermal bridging effect. By applying percentage factors which vary according to the assembly's structural type and spacing, the effective thermal resistance of each building envelope element is determined, as expressed in Equation (2) and exemplified in Figure 3.5.

$$RSI_{effective} = \frac{100}{\frac{\%AF}{RSI_F} + \frac{\%AC}{RSI_C}} \tag{2}$$

where

$RSI_{effective}$: Effective thermal resistance of wood frame assembly;

%AF: Framing percentage area per assembly type, as detailed in *Appendix B.1. Determination of Effective RSI Values* for the assemblies calculated in this thesis;

%AC: Cavity percentage area per assembly type, as detailed in *Appendix B.1. Determination of Effective RSI Values* for the assemblies calculated in this thesis;

RSI_F: Thermal resistance of framing area; and

RSI_C: Thermal resistance of cavity area.

Exterior Walls			
Assembly Components			**Thermal Resistance (m²·K/W)**
Exterior air film			0.03
Vinyl Siding			0.11
Housewrap			0.00
3/8" (9.5 mm) OSB			0.093
	RSI f through studs	RSI c through cavity	
Framing percentage (wood stud @ 610 mm o.c.)	20	80	
Wood studs 2x6" (140 mm x 0.0085 RSI/mm)	1.19	-	2.53
Fiberglass Batt Insulation R20	-	3.52	
6 mil Poly Vapour Barrier			0.00
1/2" (12.7 mm) Gypsum board			0.08
Interior air film			0.12
RSI-value total			**2.96**
R-value total			**16.82**

Figure 3.5: Sample of Exterior Wall Calculation as per the ABC 2014 Approach.

Then, with the effective RSI values of current construction practice calculated, a comparison to the energy requirements of the prescriptive path of the ABC 2014 is performed. During this assessment, it is verified that a small number of building envelope assemblies comply with the code requirements. However, the majority of them require enhanced effective RSI values. Table 3.3 presents the results of this assessment; green marks indicate code compliance and red marks indicate areas where improvements are needed. As one of the key objectives of this research is to determine upgrades whose impacts on current construction practice and construction cost are reduced, potential upgrades are identified for design configurations that do not comply with the code. Thus, increased RSI values are identified for attic ceiling, above-grade exterior walls, below-grade exterior walls, and windows.

Table 3.3: Comparison of Current Construction Practice and ABC 2014 Energy Requirements.

Building Envelope / Domestic Systems	ABC 2014 Requirements	Current Construction Practice	Code-compliance
Attic ceiling	RSI 8.67 (R 49.23)	RSI 6.22 (R 35.33)	✘
Above-grade exterior walls	RSI 2.97 (R 16.87)	RSI 2.96 (R 16.81)	✘
Exposed floors	RSI 5.02 (R 28.50)	RSI 5.32 (R 30.18)	✓
Below-grade exterior walls	RSI 2.98 (R 16.92)	RSI 1.99 (R 11.31)	✘
Doors	RSI 0.63 (R 3.55)	RSI 0.98 (R 5.57)	✓
Windows	RSI 0.63 (R 3.55)	RSI 0.50 (R 2.82)	✘
Heating Systems (Gas-fired furnace, condensing type)	AFUE[11] ≥ 92%	AFUE = 92%	✓
Domestic Hot Water System (Power direct vented 189.27 L (50 US gal)	EF[12] ≥ 0.65	Information is not enough to determine EF of current industry standard.	-

According to the web survey performed, builders are using wood-frame exterior walls with lumber the dimensions of which vary according to floor level. Main and upper floors are built with lumber measuring 38 mm × 140 mm (nominal 2×6) and basement walls with lumber measuring 38 mm × 89 mm (nominal 2×4), both with 610 mm (24 in) spacing on center (o.c.). Therefore, with the objective of avoiding the need for major structural changes to current construction practice, the selection of insulation materials applied inside a wall cavity is limited

[11] AFUE: Annual Fuel Utilization Efficiency.

[12] EF: Energy Efficiency.

by the wall thickness of 139.7 mm (5.5 in) for main and upper floors and 89 mm (3.5 in) for basement. In cases where insulation in wall cavities and ceiling assemblies is not sufficient to accomplish code requirements, rigid insulation such as expanded polystyrene (EPS), extruded polystyrene (XPS), and polyisocyanurate (ISO) are proposed on the exterior side of above- and below-grade walls and on the outer surface of the attic ceiling. Furthermore, the addition of rigid insulation, which is able to provide a greater thermal resistance with minimal thickness, placed on the exterior side of building envelope assemblies also reduces the thermal bridging effect.

Concerning thermal performance of windows, although nearly all builders are using double-pane windows with 13 mm argon and vinyl frame, it is noted that a few builders have already adopted triple-pane windows filled 13 mm argon. In the case of site-built windows and glazed doors, the ABC 2014 specifies combinations of framing, glazing, Low-E coating, and spacers that are compliant with the code requirements. In this regard, for Edmonton's climate zone none of the provided combinations include double-glazed windows (NRC 2014). In this context, additional construction cost and impacts on housing energy performance of upgrading windows from double-pane to triple-pane with 13 mm argon are also investigated in this research.

Given that the furnace type currently used by most builders in Edmonton complies with the ABC 2014, upgrades regarding space heating are not explored in this thesis. On the other hand, assessing water heater energy performance against code requirements is not possible due to the shortage of information in this regard on the specifications collected in the web survey performed. Hence, two scenarios are evaluated in this research: (1) tank systems used by builders comply with the code having an EF equal to 0.67, as assumed in Table 3.1 in Subsection 3.1.1.1.3, and, consequently, improvement is not needed; and (2) highly efficient tankless water heaters are deployed in current construction practice and, therefore, the additional construction cost of this upgrade must be analyzed.

3.1.4. Estimated Construction Cost of Potential Upgrades

With the objective of identifying least-construction-cost upgrades compliant with the prescriptive path of the ABC 2014, construction cost is ascertained mainly using the RSMeans platform. RSMeans is a construction cost database which provides updated information regarding materials, crew compositions, equipment, and productivity rates for several cities in North America, including Edmonton (RSMeans 2016). Initially, the construction cost of current construction practice for building envelope assemblies that are not compliant with the ABC 2014 and for DHW systems are collected and defined as the baseline cost. Some clarifications are necessary at this point due to the incompatibility between current materials used by builders and the RSMeans cost database. To solve this issue, costs of materials the thermal characteristics of which are similar to those in current construction practice are selected. Table 3.4 presents all the assumptions made in this respect.

Table 3.4: Construction Cost of Materials Currently Used by Builders in Housing in Edmonton.

Building Envelope / DHW System	Design configuration	Material selected for baseline construction cost (RSMeans)	Estimated cost[13] CAD/ft² or CAD/unit (RSMeans)
Attic ceiling	2 layers of RSI 3.52 (R 20) blown-in cellulose	Blown-in insulation, ceilings, with open access, cellulose, 6 1/2″ thick, R22	1.80
Above-grade exterior walls	RSI 3.52 (R 20) fibreglass batt	Blanket insulation, for walls or ceilings, unfaced fibreglass, 6″ thick, R19	0.63
Below-grade exterior walls	RSI 2.11 (R 12) fibreglass batt	Blanket insulation, for walls or ceilings, unfaced fibreglass, 3 ½″ thick, R13	0.55
Windows	Double-pane, 13 mm argon-filled	Average RSMeans price per ft² of windows plus 10% due to argon-filled upgrade (RSMeans cost accounts for double-pane windows with 13 mm of air between panes)	28.70
Domestic Hot Water System	Water tank with 50 US gal capacity, power direct vented. EF: 0.67	Water heater, residential, natural gas-fired, 50 US gal, direct vented (sealed)	895.00

Then, construction costs of potential upgrades are identified according to their configuration. As previously stated in this chapter, the potential upgrades for building envelope avoid the modification of current assembly structure and other materials that have a low impact on effective RSI values (e.g., gypsum board, oriented strand board, house wrap, and vapour barrier). Hence, the estimated additional cost in CAD per ft^2 of building envelope is determined by calculating the difference between the cost of potential insulation materials to the baseline cost of insulation materials, as expressed in Equation (3).

[13] Estimated cost accounts for material, labour, and equipment expenses.

$$Additional\ cost\ (CAD) = C_{Upgrade} -\ BCT \tag{3}$$

where

$C_{Upgrade}$: Cost of upgrade, insulation material; and

BCT: Baseline cost of current construction practice, insulation material.

Determination of additional cost of windows requires some clarification, as the information provided in RSMeans varies based on window characteristics (e.g., operation type, glazing, and coating) and dimensions. To obtain an average cost per ft^2, the cost of several windows with identical configuration (double-pane, Low-E, air filled, and casement vinyl frame), but different dimensions are collected and the average price is determined. However, neither argon-filled nor triple-pane windows are covered by the RSMeans cost database. Hence, two assumptions are made in order to estimate the additional construction cost of triple-pane argon-filled windows. It is commonly accepted in the industry that argon-filled windows are ~10% more expensive than air-filled windows and triple-pane windows are ~30% more expensive than double-pane windows. Therefore, first, the calculated cost per ft^2 of windows is increased by 10% accounting for upgrading from air- to argon-filled. Then, the new cost is increased by 30% accounting for the extra layer of glazing pane.

RSMeans is not used to estimate the additional cost of tankless DHW heaters, due to the shortage of information regarding the equipment's energy factor. Thus, a web search is performed with the objective of acquiring updated information on tankless water heaters currently available in the market with their respective efficiency factor (EF). The web survey is used to collect information on system energy performance and equipment price for two types of tankless DHW systems, condensing and non-condensing. The lowest value for each system type is selected for future analysis.

3.1.5. Determination of Life Expectancy of Potential Upgrades, Fuel Price Escalation Rates, and Inflation Rate

In this thesis, energy consumption, the cost of upgrades, the cost of replacing selected items, and estimated savings from fuel costs are investigated, based on 30 years of occupancy. Thus, in this subsection, factors that impact lifecycle cost analysis such as life expectancy of potential upgrades, fuel price escalation rates, and Canadian inflation rate are determined.

3.1.5.1.1. Estimated Life Expectancy of Potential Upgrades

Estimated life expectancy of potential upgrades is analyzed with the objective of predicting repositioning dates of selected materials and items during the period evaluated in this research. Information in this regard is summarized in Table 3.5 (NAHB 2007).

Table 3.5: Life Expectancy of Different Housing Products, Items, and Materials.

Item/product/material	Lifetime (year)
Insulation materials	
Cellulose	100 or more
Fibreglass	Lifetime
Foam	Lifetime
House wrap	Lifetime
Windows	
Vinyl/Fibreglass	20 to 40
Domestic Hot Water Systems	
Water heaters, with tank, natural gas-fired	10
Water heaters, tankless, natural gas-fired	20 or more

As observed in Table 3.5, insulation materials have a life expectancy greater than the investigated 30-year period, so replacement of these materials is not further explored. Since the life expectancy of a fibreglass window with vinyl frame varies from 20 to 40 years, an average of 30 years is assumed as the life expectancy of this item. Thus, replacement of windows is also not further investigated. On the other hand, regarding domestic water heaters, a significant difference is noted in the estimated life expectancy of tankless and storage tank systems. Over the period studied, a gas-fired storage tank system will require replacement three times while a gas-fired tankless system will require replacement just once. Therefore, the cost of these replacements is accounted for in the lifecycle analysis performed in this research.

3.1.5.1.2. Estimated Fuel Price Escalation Rates for Natural Gas and Electricity

Based on historical data, price escalation rates for the two primary energy sources used in Alberta housing—natural gas and electricity (Figure 1.2)—are estimated in this subsection. When predicting the future price of electricity and natural gas, uncertainties arise due to price susceptibility to a variety of factors such as fuel source and climatic conditions, as well as the cost of energy production and distribution (Canadian Electricity Association 2016). A detailed description of the process of estimating fuel price escalation rates based on historical data analysis is presented in the following subsections.

3.1.5.1.3. Estimated Fuel Price Escalation Rates for Natural Gas

Historical prices of natural gas, excluding taxes, for residential use in Alberta are collected for the years 1989 to 2011, as shown in Figure 3.6 (Statistics Canada 2012). Based on this 23-year interval, the price escalation rate for natural gas is estimated to be ~5.08% per year. Thus, this value is applied for the purpose of estimating future operation cost of natural gas during the period analyzed in this research.

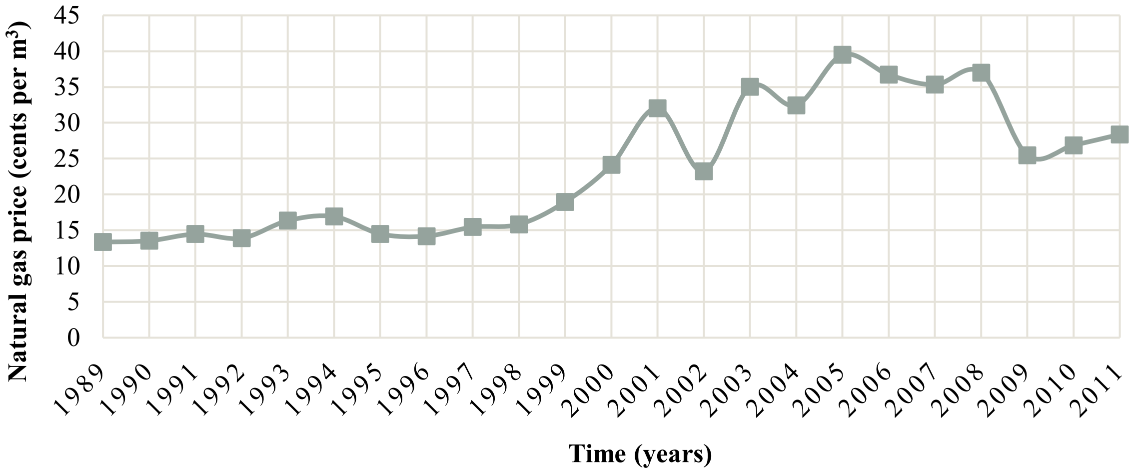


Figure 3.6: Historical Residential Price of Natural Gas in Alberta, 1989-2011.

3.1.5.1.4. Estimated Fuel Price Escalation Rates for Electricity

Canada has some of the lowest electricity rates in the world (Canadian Electricity Association 2016). In Canada, the electricity price varies based on supply and demand in a system called "power pool". In fact, the price varies by hour according to the system's peak and non-peak times. Therefore, to determine the escalation rate of electricity cost, the oscillation of the average pool price of electricity in Alberta is analyzed from 2005 to 2014 (Figure 3.7) (AESO 2015). Based on the evaluation of this historical data, the estimated price escalation rate is determined to be ~1.35% per year. Hence, this rate is applied for predicting future operation cost with electricity.

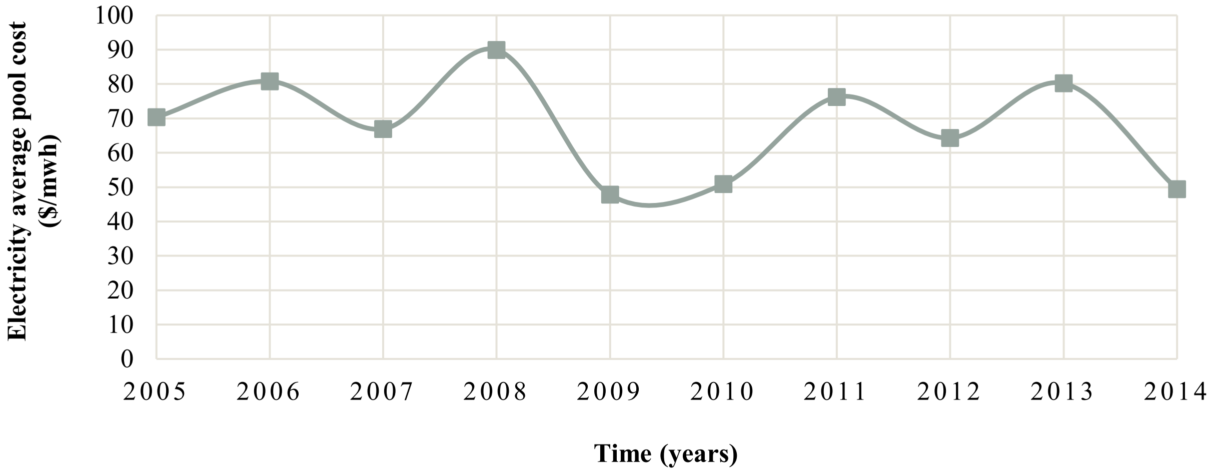


Figure 3.7: Historical Price of Electricity in Alberta, 2005-2014 (AESO 2015).

3.1.5.1.5. Estimated Canadian Inflation Rate

Estimating Canada's annual inflation rate is essential in predicting future replacement costs of selected items, e.g., water heaters. Historical inflation rates are analyzed, as presented in Figure 3.8 (Bank of Canada 2016). Based on this information, an inflation rate of ~1.87% per year is estimated. This rate in turn is used to calculate future replacement cost of storage tank and tankless water heaters.

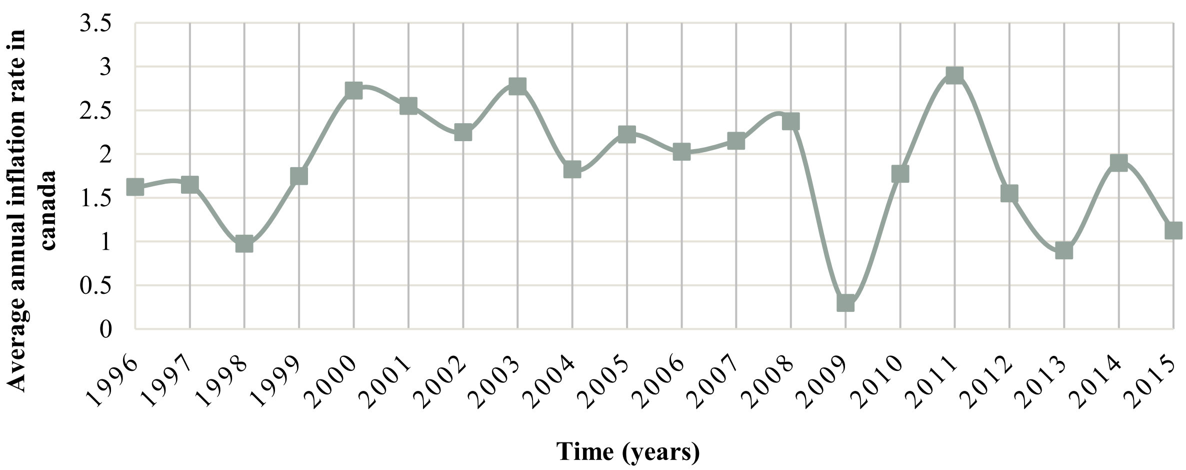


Figure 3.8: Historical Canadian Inflation Rate, 1996-2015.

3.1.6. Energy Simulation

Simulating housing energy performance is essential in evaluating the impacts of upgrades on energy consumption and on operation cost. In this context, this subsection provides information on the energy simulation software used to assess the energy performance of the reference house built using current construction practice and with the upgrades investigated in this research.

3.1.6.1.1. HOT2000

HOT2000 is a free evaluation tool developed by NRCan's Office of Energy Efficiency (OEE) to simulate energy consumption of homes and low-rise residential buildings in Canada. Although HOT2000 runs simplified calculations based on monthly weather profiles, through estimating heat gain, heat loss, and domestic system energy efficiency it accurately simulates housing energy consumption (Haltrecht and Fraser 1997).

HOT2000 features a user-friendly interface which allows for the following evaluations: (a) calculate effective thermal resistance of building envelope accounting for thermal bridging effect; (b) estimate annual space heating and DHW energy consumption; (c) estimate total and shared energy costs according to energy source (natural gas, electricity, oil, propane, and wood); (d) estimate greenhouse gas emissions; (e) verify code compliance; and (f) compare energy performance of different design solutions in early design phases. In addition, HOT2000 models and reports are being introduced as part of building code requirements, e.g., Vancouver, BC (City of Vancouver 2016), and most Canadian government initiatives for energy-efficient housing, such as R-2000, ENERGY STAR, and EnerGuide rating, base their calculations on HOT2000 simulation results (Mah 2011; NRCan 2016h; City of Vancouver 2016). Thus, HOT2000 (version 10.51) is chosen as the energy simulation tool in this research.

3.1.6.1.2. Definition of Baseline for Energy Consumption, Operation Cost, and EnerGuide Rating for New Housing in Edmonton

With the objective of estimating the energy performance of homes currently being built in Edmonton, a simulation model representing the reference house built using current construction practice is developed in HOT2000 (Model BL). The key objective of this model is to set a baseline to which the upgrades identified in this research will be compared regarding energy consumption and operation costs. As per the parameters input in Model BL (Table 3.6), a single-family detached home built using current construction practice achieves an EnerGuide rating of 78, and its total lifecycle cost accounts for ~CAD 87,878.54 (*Appendix D.1. Total Lifecycle Cost of the Reference House - Current Construction Practice*). Other simulation results relevant to this research are summarized in Figure 3.9, Figure 3.10, and Figure 3.11.

Table 3.6: Simulation Model Inputs of Model BL – Current Construction Practice.

Building Envelope / Systems configuration	Current Construction Practice (Model BL)
Attic ceiling, RSI	6.22
Above-grade exterior walls, RSI	2.96
Below-grade exterior walls, RSI	1.99
Exposed floors, RSI	5.28
Windows, RSI	From 0.47 to 0.51
Doors, RSI	0.98
Ventilation system, efficiency	66% at 0 °C | 60% at −25 °C
Heating system, AFUE	92%
Domestic hot water, EF	0.67
Airtightness, ACH	3.57

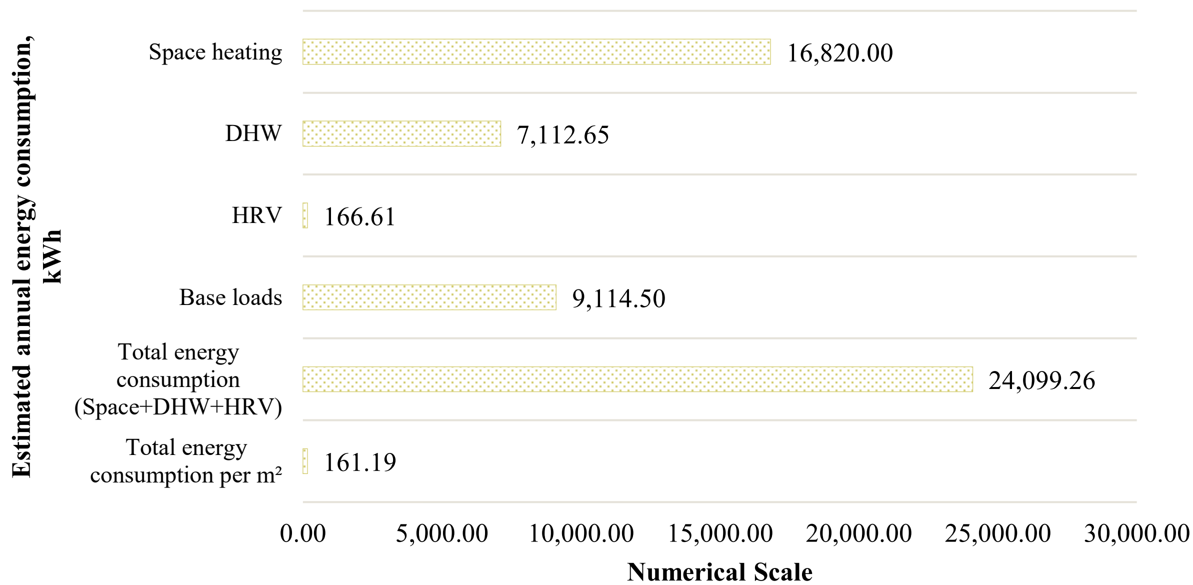


Figure 3.9: Model BL – Estimated Annual Energy Consumption (HOT2000 Result).

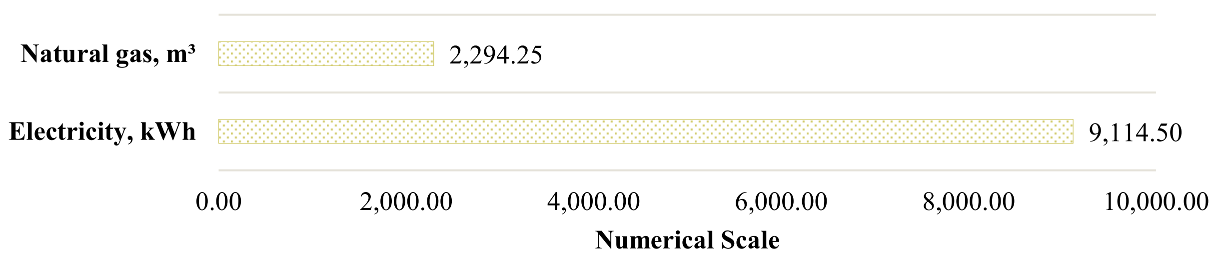


Figure 3.10: Model BL – Estimated Fuel Consumption (HOT2000 Result).

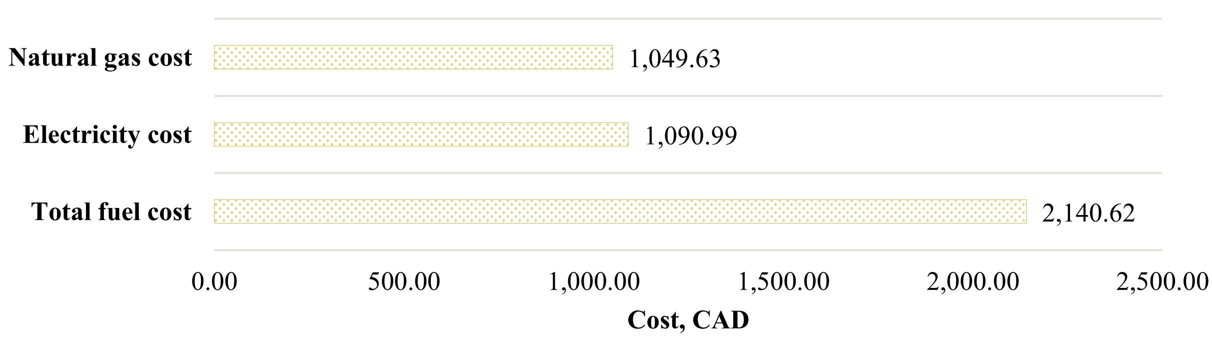


Figure 3.11: Model BL – Estimated Annual Operation Cost of Fuel (HOT2000 Result).

3.1.7. Determination of Operational Savings from Energy Consumption, Return on Investment (ROI), and Payback Time

In this subsection, mathematical equations used to estimate future savings from energy consumption, equipment repositioning, return on investment (ROI) of identified upgrades, and payback time are presented. HOT2000 energy simulation models provide cost of natural gas and electricity as an outcome of input parameters. However, this information is based on the present values of these energy sources. Therefore, estimation of future expenses from fuel and from equipment repositions is needed to determine the actual 30-year savings resulting from the upgrades identified in this research. First, simulation model outputs regarding fuel costs of models with identified upgrades must be compared to the results of the model with current construction practice (Model BL), as expressed in Equation (4) for natural gas and Equation (5) for electricity.

$$AOPCS_{NG},\ Cost\ (CAD) = A_{CNG}\ of\ Model\ BL\ -\ A_{CNG}\ of\ Model\ with\ Upgrade \qquad (4)$$

where

$AOPCS_{NG}$: Annual operation cost savings for natural gas; and

A_{CNG}: Annual cost of natural gas, HOT2000 output.

$$AOPCS_{ELEC},\ Cost\ (CAD) = A_{CELEC}\ of\ Model\ BL - A_{CELEC}\ of\ Model\ with\ Upgrade \qquad (5)$$

where

$AOPCS_{ELEC}$: Annual operation cost savings for electricity; and

A_{CELEC}: Annual cost of electricity, HOT2000 output.

Then, the values obtained from Equation (4) and Equation (5) are used as inputs in Equation (6) and Equation (7) to estimate their corresponding future values at year "n". The previously defined price escalation rates for natural gas and electricity (Subsection 3.1.5.1.2) are inserted in Equation (6) and Equation (7) as the interest rate. From that, total annual savings from fuel costs is determined as per Equation (8), and the present value of these savings are estimated as per Equation (9), which considers the inflation rate as interest rate (ASHRAE 2015).

$$FVn_{AOPCS_{NG}} = ASOP_{NG} \times (1 + i_{NG})^{n} \tag{6}$$

where

$FVn_{AOPCS_{NG}}$: Future value at time n of annual operation cost savings for natural gas;

i_{NG}: Escalation rate of natural gas, i_{NG} = 0.0508 (Subsection 3.1.5.1.3); and

n: varies from 1 to 30 representing an operation year.

$$FVn_{AOPCS_{ELEC}} = ASOP_{ELEC} \times (1 + i_{ELEC})^{n} \tag{7}$$

where

$FVn_{AOPCS_{ELEC}}$: Future value at time n of annual operation cost savings for electricity;

i_{ELEC}: Escalation rate of natural gas, i_{ELEC}= 0.0135 (Subsection 3.1.5.1.4); and

n: varies from 1 to 30 representing an operation year.

$$AOPCS_{n}\text{, } Cost\ (CAD) = FVn_{AOPCS_{NG}} + FVn_{AOPCS_{ELEC}} \tag{8}$$

where

$AOPCS_{n}$: Annual operation cost savings at time n for electricity and natural gas.

$$PV_{AOPCSn} = \frac{AOPCS_n}{(1 + i_{inf})^n} \tag{9}$$

where

PV_{AOPCSn}: Present value of annual operation cost savings at time *n* for electricity and natural gas;

$AOPCS_n$: Annual operation cost savings at time *n* for electricity and natural gas;

i_{inf}: Canadian inflation rate, i_{inf} = 0.0187 (Subsection 3.1.5.1.5); and

n: Varies from 1 to 30 representing an operation year.

The present value of 30-year operation costs savings, which accounts for the sum of each annual operation cost savings value during the 30-year period analyzed in this research, is determined as per Equation (10). Regarding acquisitions of DHW equipment for reposition purposes, as the interest rate applied to calculate the future cost of equipment is the same as the one used to calculate the present value of an estimated future cost, savings from equipment reposition are estimated as per Equation (11).

$$PVSOPC_{30} = \text{30-year savings from operation cost, (CAD)} = \sum_{i-1}^{30} PV_{AOPCSn} \tag{10}$$

$$TSER = \left(\sum PV_{rep\ common\ practice}\right) - \left(\sum PV_{rep\ upgrade\ solution}\right) \tag{11}$$

where

TSER: Accounts for total savings from equipment repositioning during the period analyzed;

$\sum PV_{rep\ common\ practice}$: Total present cost from equipment repositions in current construction practice; and

$\sum PV_{rep_{upgrade\ solution}}$: Total present cost from equipment repositions, identified upgrades.

With information on savings from energy costs and equipment repositions calculated, estimation of the ROI on upgrades is determined as per Equation (12) (Giel and Issa 2013). Positive values of ROI imply that an investment is profitable; as such, the higher the ROI obtained for an upgrade is, the more lucrative the upgrade will be. On the other hand, negative ROI values indicate unfruitful investment. Besides the determination of ROI, the present value of actual savings as an outcome of the upgrades identified in this research is also estimated by applying Equation (13). As can be observed in applying Equation (13), the present value of actual savings accounts for additional construction costs and total operation cost savings and equipment repositions.

$$ROI,\ \% = \frac{(PVSOPC_{30} + TSER) - \ Total\ additional\ construction\ cost\ (TACC)}{Total\ additional\ construction\ cost\ (TACC)} \times 100 \qquad (12)$$

where

ROI: Return on investment, %; and

Total additional construction cost (TACC): Accounts for the sum of the additional construction cost of upgrades.

$$Actual\ savings\ (AcSGS) = PVSOPC_{30} + \ TSER - \ TACC \qquad (13)$$

Finally, to determine the payback time, the fuel cost savings accumulating year by year can be calculated using the present value, as per Equation (14). When the monetary amount invested during the construction phase is surpassed by the savings during the operation phase, the payback begins, as in Equation (15).

$$\textit{Present value of cumulative fuel cost savings } (PVSOPC_{acc}) = PV_{AOPCS\, n=1} + PV_{AOPCS\, n=2} + \ldots + PV_{AOPCS\, n=29} + PV_{AOPCS\, n=30} \quad (14)$$

$$\textit{Payback time, in years} = PVSOPC_{acc} \geq TACC - TSER \quad (15)$$

CHAPTER 4: IDENTIFICATION AND ANALYSIS OF LEAST-CONSTRUCTION-COST CODE-COMPLIANT UPGRADES

This chapter begins with the identification of least-construction-cost upgrades for building envelope (attic ceiling, above- and below-grade exterior walls, and windows) compliant with the prescriptive path of the ABC 2014. It proceeds with sensitivity analyses of (a) window sizing, (b) tankless domestic water heaters, and (c) identified least-construction-cost prescriptive upgrades. Then, energy requirements for the codes reviewed in Chapter 2 are assessed. Finally, the chapter describes a general approach developed to identify least-construction-cost code-compliant upgrades for other climatic conditions.

4.1. Determination of Least-Construction-Cost Upgrades Complying with the Prescriptive Path

In this section, a least-construction-cost upgrade compliant with the prescriptive path of the ABC 2014 is designated for each building envelope element analyzed in this research.

4.1.1. Attic Ceiling

Potential code-compliant upgrade configurations for attic ceiling suggest the application of blown-in cellulose and blown-in fibreglass as the primary insulation materials as well as some combinations of these materials with EPS, XPS, and ISO rigid insulation. The effective RSI values of these configurations are found to range from 8.69 $(K \cdot m^2)/W$ to 11.51 $(K \cdot m^2)/W$, while additional construction cost varies from CAD 0.50 to CAD 2.40. Estimated additional construction cost and effective RSI value of each potential upgrade are presented in Figure 4.1.

For detailed information about design configuration and costs for attic ceiling, the reader may refer to *Appendix B.2.1. Attic Ceiling*.

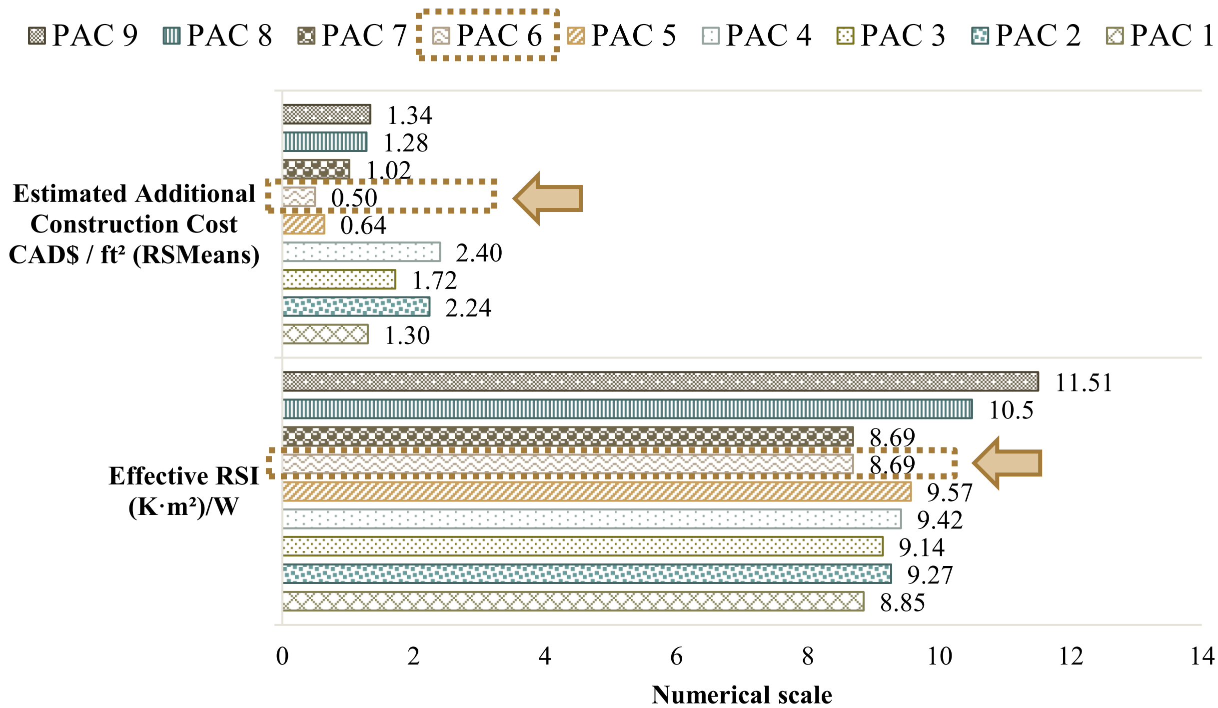


Figure 4.1: Estimated Additional Construction Cost and Effective RSI Value of Potential Upgrade Configuration for Attic Ceiling.

As can be observed from Figure 4.1, a direct relationship between additional construction cost and effective RSI value is not identified. Potential attic ceiling (PAC) 9 has the highest RSI value, though PAC 4 has the greatest additional construction cost. In regards to additional construction cost, among the nine potential upgrades investigated, PAC 6 is the configuration with the lowest value. It is thus selected as the attic ceiling least-construction-cost prescriptive upgrade to be deployed in current construction practice and whose impact on housing energy consumption will be investigated in this research. PAC 6 also shows the lowest RSI value and consists of two layers of blown-in cellulose with RSI 5.28 (K·m^2)/W, resulting in an effective RSI value of 8.69 (K·m^2)/W.

4.1.2. Above-Grade Exterior Walls

Fourteen potential upgrade configurations are investigated for above-grade exterior walls. These upgrades suggest usage of several levels of insulation, from RSI 3.02 (K·m^2)/W to RSI 5.53 (K·m^2)/W, and different types of insulation materials (mineral wool batt, faced and unfaced fibreglass batt, and polyurethane spray foam) to be applied to the interior of the wall cavity. Combinations of these insulation materials with varying thicknesses of EPS, XPS, and ISO rigid insulation applied on the exterior surface of walls are also suggested, as depicted in *Appendix B.2.2. Above-grade Exterior Walls*. The additional construction cost of potential upgrades varies from CAD 0.56 to CAD 3.02, and therefore a variation of ~19% is observed between the least and most costly potential upgrades.

As is the case for the upgrades for attic ceiling, a direct relationship here between additional construction cost and effective RSI value is not identified. The upgrade with the highest effective RSI value is the potential above-grade exterior wall (PAW) 14, and the upgrade with highest additional construction cost is PAW 11, which uses 101.6 mm (4 in) of polyurethane spray foam as the primary insulation material. As observed in Figure 4.2, the configuration with the least additional construction cost is PAW 7, whose effective RSI value is 3.08 (K·m^2)/W. The PAW 7 configuration consists of one layer of unfaced fibreglass batt RSI 2.29 (K·m^2)/W with 25.4 mm (1 in) of Type II EPS rigid insulation on the exterior surface of walls. This upgrade is recommended to be deployed in current construction practice as the least-construction-cost prescriptive upgrade for above-grade exterior walls.

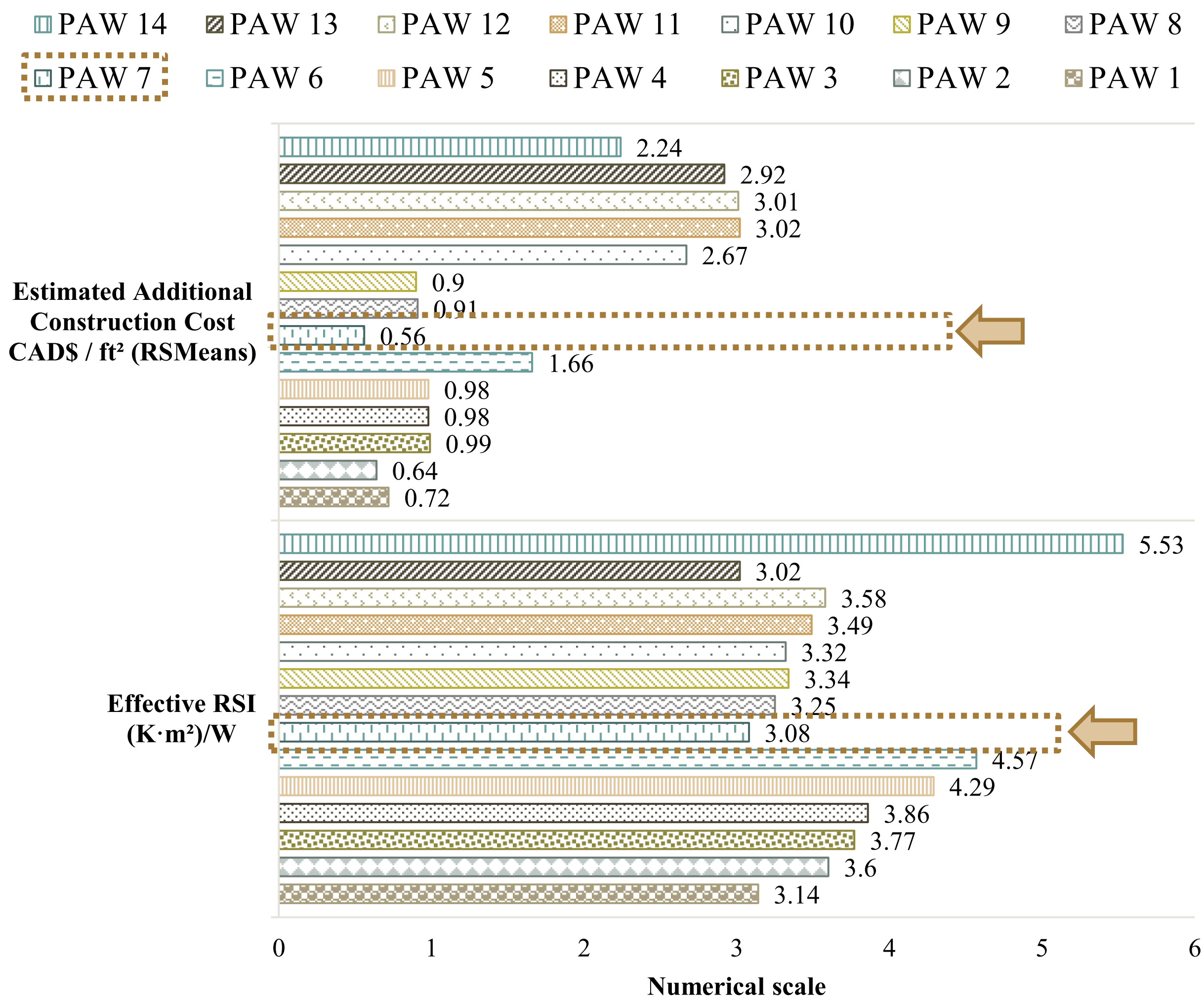


Figure 4.2: Estimated Additional Construction Cost and Effective RSI Value of Potential Upgrade Configuration for Above-Grade Exterior Walls.

4.1.3. Below-Grade Exterior Walls

For the identified upgrade configurations for below-grade exterior walls, batt insulation, fibreglass, and mineral wool are considered the primary insulation materials, as well as several combinations of these insulation materials and different thicknesses of EPS, XPS, and ISO rigid insulation on the exterior surface of walls. The effective RSI value of potential upgrades is found to range from 2.98 (K·m^2)/W to 4.91 (K·m^2)/W, and while additional construction cost ranges from CAD 0.45 to CAD 1.66, as detailed in *Appendix B.2.3. Below-grade Exterior Walls*. In the case of below-grade exterior walls, the least-construction-cost upgrade is the potential below-grade exterior wall (PBW) 1. PBW 1 consists of a Kraft-faced fibreglass batt RSI 1.94 $(K{\cdot}m^2)/W$ in the wall cavity in addition to one layer of the same material sandwiched between the concrete and wood-frame structure, resulting in an effective RSI value of 3.83 $(K{\cdot}m^2)/W$. Concordant with above-grade exterior walls and attic ceiling, the costliest upgrade for below-grade exterior walls, PBW 16, is not the upgrade with the best thermal performance, PBW 6 (Figure 4.3).

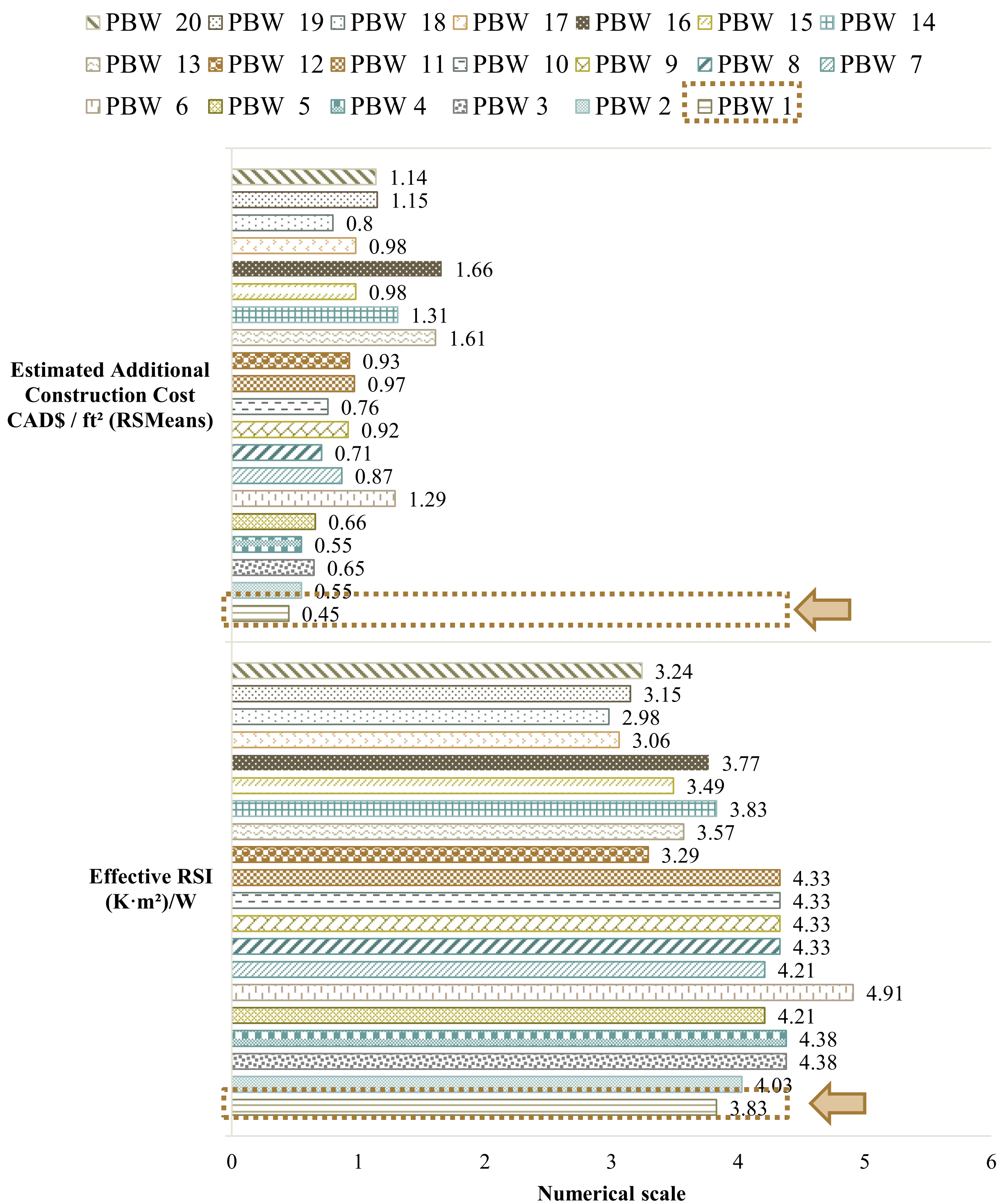


Figure 4.3: Estimated Additional Construction Cost and Effective RSI Value of Potential Upgrade Configurations for Below-Grade Exterior Walls.

4.1.4. Windows

Concerning improvements on thermal performance of windows, this research focuses on investigating two window configurations: (a) double-pane with 13 mm argon and vinyl frame, and (b) triple-pane with 13 mm argon and vinyl frame. Type (a) is currently the industry standard for windows in single-family detached homes in Edmonton, and type (b) is being applied by builders that focus on developing highly energy-efficient homes and/or net-zero homes. In light of these findings, the least-construction-cost prescriptive upgrade for windows investigated in this research is type (b) windows, as this configuration meets the energy code requirements and some local builders are already familiar with it. The additional construction cost of this upgrade is ~CAD 12.34/ft^2.

4.2. Sensitivity Analyses of Window Sizing

With the aim of decreasing expenses from fuel during the operation phase, sensitivity analyses are performed in this section to assess the impacts of window sizing for different façade orientations on housing energy consumption. To achieve this objective, first the HOT2000 model designed to simulate the reference house built using current construction practice (i.e., Model BL) is defined as the baseline for the upgrades investigated in this section. Then, window dimensions are changed progressively and continuously, in accordance with varying room functionality, and several HOT2000 simulation models are developed reflecting these alterations (Figure 4.4).

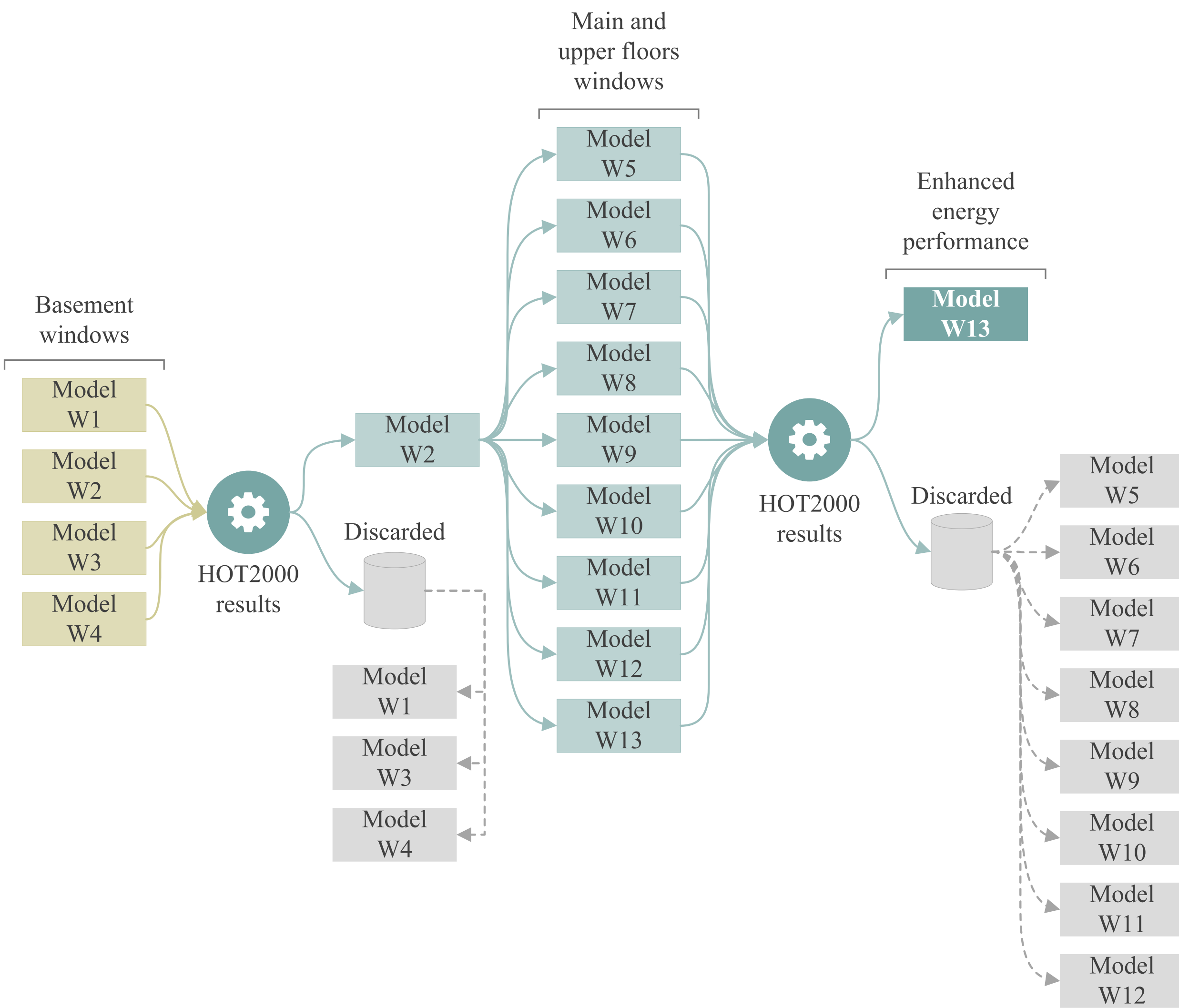


Figure 4.4: Overview of Methodology Followed in the Sensitivity Analyses of Window Sizing.

As observed in Figure 4.4, the analysis is performed in two phases. First, the sensitivity of basement windows is investigated. In this phase, four models are developed; window dimensions reflect those in the original design, but the orientations are different. The objective of this phase is to identify how directional orientation affects the annual energy consumption. In the second phase, the model with the best energy performance results from the first phase is defined as the baseline and another nine simulation models are developed to investigate windows located on the main and upper floors. Since the reference house faces south and its side walls are parallel to other houses, windows on the east and west sides, where exposure to the sun is limited, are not closely investigated in this research. Table 4.1 summarizes the energy consumption obtained by each simulation model developed in this sensitivity analysis. For further information, the reader may refer to *Appendix C.1. Sensitivity Analyses of Window Sizing*.

Table 4.1: Results of Sensitivity Analyses of Window Sizing.

HOT2000 Simulation Models	Annual Energy Consumption - Space Heating, kWh	Annual Energy Consumption, kWh	EnerGuide Rating, 0-100
Model BL	**16,820.00**	**24,099.26**	**78**
Model W1	16,692.04	23,968.92	79
Model W2	16,639.32	23,913.73	79
Model W3	16,745.68	24,024.84	78
Model W4	16,639.32	23,913.73	79
Model W5	15,990.21	23,266.71	79
Model W6	15,921.45	23,198.24	79
Model W7	15,856.04	23,133.11	79
Model W8	15,738.58	23,016.16	79
Model W9	15,640.08	22,918.11	79
Model W10	15,631.15	22,908.76	79
Model W11	15,462.54	22,736.69	79
Model W12	15,400.13	22,674.60	79
Model W13	**15,326.86**	**22,601.40**	**79**

As per the results obtained, the south orientation decreases the energy consumed for space heating as a result of the heat gained passively through window exposure to the sun. On the other hand, windows facing north increase the energy consumption, as the amount of heat lost by the glazed areas of the windows is higher than the heat gained. Thus, in this respect, Model W13 is the model with the best energy performance. In this model, performance of the windows on the west wall reflects the performance of those in the original design due to room constraints.

Moreover, windows facing north undergo a reduction in their dimensions, dropping from 16% (original design) to 11% of the façade area. On the other hand, the total area of windows on the south-facing façade increases from 16% (original design) to 44%. Regarding energy consumption, the annual energy consumed for space heating in Model W13 is estimated to be 10% less than in Model BL, which results in a reduction of ~7% of the total annual energy consumption. Therefore, it is concluded from this sensitivity analysis that windows have a significant impact on housing energy performance. Furthermore, efforts must be directed toward increasing window dimensions on the south façade and decreasing window dimensions on the north façade, optimally in accordance with interior space usage and configuration.

4.3. Sensitivity Analyses of Tankless Domestic Water Heaters

In this section, two types of tankless domestic water heaters, condensing and non-condensing, are assessed regarding their impacts on energy consumption. In this regard, HOT2000 simulation models are developed using Model BL as a baseline and the information presented in Figure 4.5 is used as the input for the DHW system. Figure 4.6 provides an overview of the methods followed in this section.

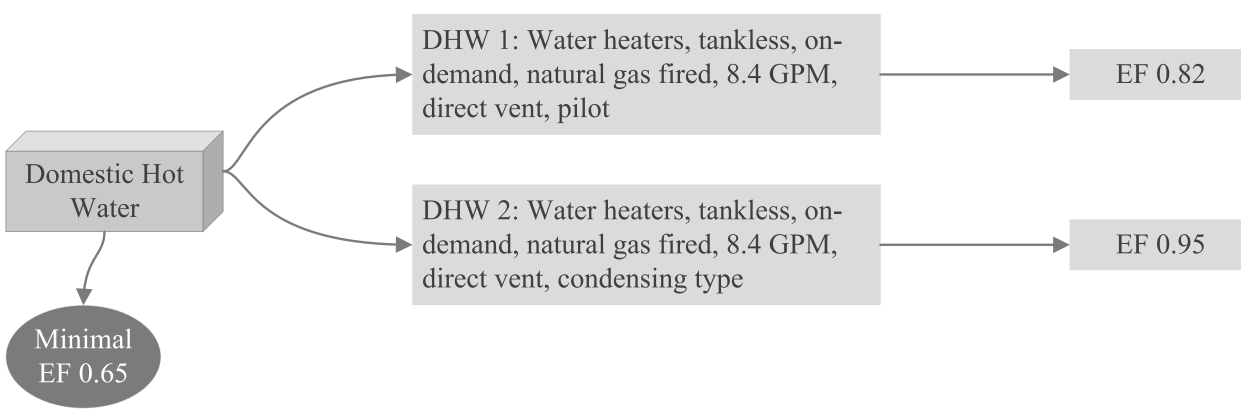


Figure 4.5: Potential Upgrades for Tankless Domestic Water Heaters.

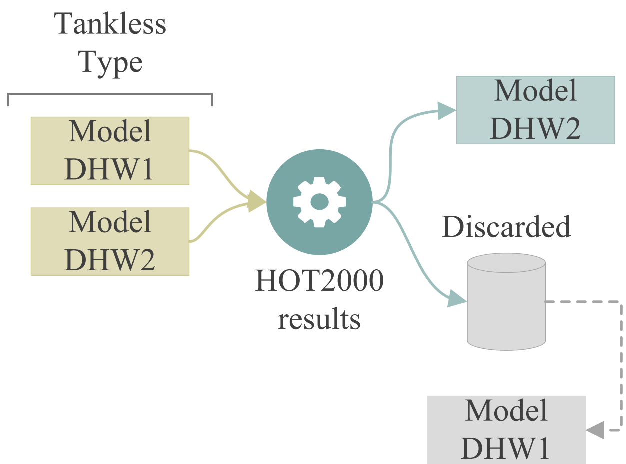


Figure 4.6: Overview of Methodology Followed in the Sensitivity Analyses of Tankless DHW.

As observed in Table 4.2, Model DHW2, which simulates the reference house built using current construction practice and a tankless condensing domestic water heater, consumes less energy than Model DHW1, which simulates a non-condensing water heater. An important conclusion of this analysis is that, by upgrading the conventional storage tank system currently used by most builders in Edmonton to a tankless system, the annual energy consumed for water heating drops markedly. Comparing the results of Model DHW1 and Model DHW2 to those of Model BL, reductions of ~18% and ~30%, respectively, are achieved with respect to water heating energy consumption. In this context, the DHW investigated in Model DHW2 is selected as the appropriated upgrade to boost DHW system energy performance.

Table 4.2: Results of Sensitivity Analyses of Tankless Water Heaters.

HOT2000 Simulation Models	Annual Energy Consumption – Water Heating, kWh	Annual Energy Consumption, kWh	EnerGuide Rating, 0-100
Model BL	7,112.65	24,099.26	78
Model DHW1	5,808.65	23,512.63	79
Model DHW2	**4,976.39**	**22,475.20**	**79**

4.4. Determination of Simplest Least-Construction-Cost Upgrade to Accomplish Code-Compliant Energy Performance

In Section 4.1, least-construction-cost upgrades compliant with the prescriptive requirements of the ABC 2014 are selected. In this section, these upgrades are analyzed, aiming to determine the simplest least-construction-cost approach to accomplish the ABC 2014 energy standards following the performance path. The key objective of this investigation is to minimize the impact of the ABC 2014 on housing construction cost by reducing alterations to current construction practice. In this context, Model BL is also used as a baseline in this subsection.

As stated in Subsection 2.1.1, the ABC 2014 specifies that compliance based on the performance path is achieved when the estimated energy consumption of a projected home is equal to or lesser than the energy consumption of the same home projected to the prescriptive requirements (NRC 2014). Thus, first a simulation model is developed in HOT2000 representing the reference house built to the prescriptive requirements of the ABC 2014. In other words, the minimum effective RSI values specified for building envelope (regardless of the assembly construction details), and the minimum energy performance of the domestic systems, are input to the HOT2000 model (Table 4.3). This HOT2000 model is referred to as Model CD and its relevant results are depicted in Figure 4.7.

Table 4.3: Model CD – HOT2000 Simulation Model Inputs.

Building envelope / Domestic Systems	ABC 2014 Requirements
Attic ceiling	RSI 8.67
Above-grade exterior walls	RSI 2.97
Exposed floors	RSI 5.02
Below-grade exterior walls	RSI 2.98
Doors	RSI 0.63
Windows	Triple-pane, 13 mm argon-filled, with PVC frame
Heating system (Gas-fired furnace, condensing type)	AFUE = 92%
Domestic hot water system (Power direct vented 189.27 L)	EF = 0.65

EnerGuide Rating, 0-100

- 80

Estimated annual energy consumption, kWh

- 22,177.56

Figure 4.7: Model CD –HOT2000 Results for Reference House.

Subsequently, HOT2000 models are developed with combinations of the least-construction-cost prescriptive upgrades, defined in Section 4.1, and the tankless condensing domestic water heater, defined in Section 4.3. In this phase, qualified upgrades are identified and their respective additional construction costs are verified. An overview of this process is illustrated in Figure 4.8 and results of the simulation models are summarized in Table 4.4. For further information on the simulation models developed in this phase, the reader may refer to *Appendix C.2. Sensitivity Analyses of Least-Construction-Cost Prescriptive Upgrades*.

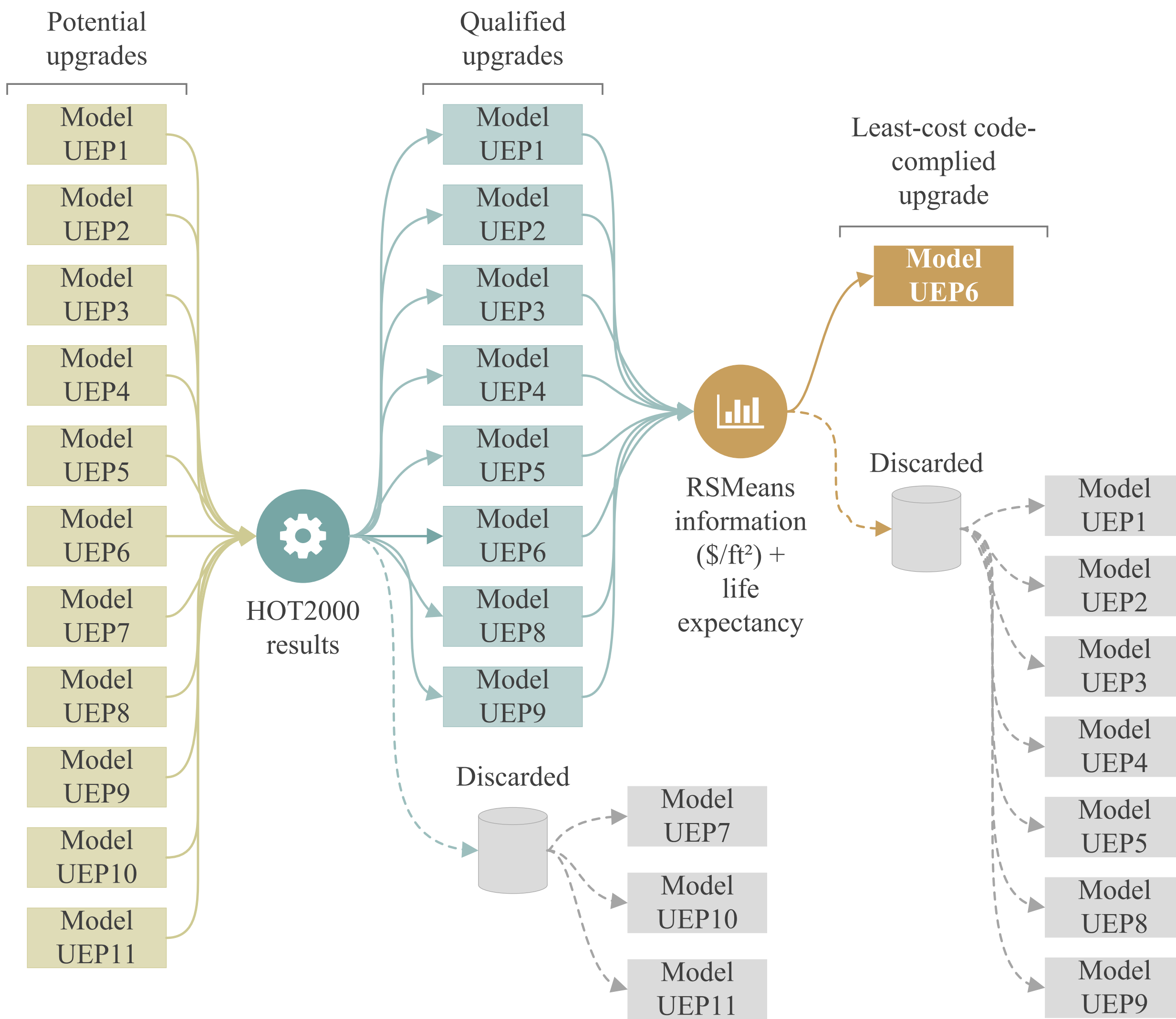


Figure 4.8: Overview of Methodology Followed in the Sensitivity Analyses of the Identified Least-Construction-Cost Prescriptive Upgrades.

Table 4.4: Results of Sensitivity Analyses of the Identified Least-Construction-Cost Prescriptive Upgrades.

HOT2000 Simulation Models	Annual Energy Consumption, kWh	EnerGuide Rating, 0-100	Difference for Model CD (Baseline ABC 2014) energy consumption, kWh	Total Additional Construction Cost, CAD
Model BL	24,099.26	78	1,922.00	-
Model CD	**22,177.26**	**80**	**0.00**	**-**
Model UEP1	20,867.86	80	−1,309.40	2,616.51
Model UEP2	20,684.90	80	−1,492.36	3,484.53
Model UEP3	20,519.20	80	−1,658.06	2,266.47
Model UEP4	21,186.41	80	−990.85	1,074.97
Model UEP5	21,005.62	80	−1,171.64	2,269.75
Model UEP6	**21,611.23**	**80**	**−566.03**	**690.48**
Model UEP7	22,817.86	79	640.60	384.49
Model UEP8	22,142.32	80	−34.94	1,575.99
Model UEP9	21,390.58	80	−786.68	3,502.02
Model UEP10	22,634.32	79	457.06	1,579.27
Model UEP11	22,494.20	80	316.94	1,926.03

As observed in Figure 4.8 and Table 4.4, the sensitivity analysis begins with ten potential upgrades. After the first round of analyses, three upgrades are discarded as they do not meet the code-compliant energy performance. Then, among the remaining options, the final least-construction-cost upgrade is selected in light of two parameters (in order of importance): (a) additional construction cost, and (b) life expectancy. It is determined that Model UEP6, which recommends implementation of a tankless condensing DHW system combined with enhanced house airtightness (ABC 2014's level), successfully achieves the criteria mentioned above. Besides savings in terms of energy consumption, it is estimated that Model UEP6 will also generate savings from equipment repositions, as the life expectancy of tankless DHW systems is higher than that of storage tank systems (Subsection 3.1.5.1.1–Table 3.5). Moreover, the upgrade investigated in this model is not dependent on building envelope area, and therefore the additional construction cost required to accomplish code-compliant energy performance is not project-based.

4.5. Analyses of Building Codes Governing Energy Performance of Housing in Cold-Climate Regions

Despite the fact that the Nordic countries have similar climatic conditions (5,000 ≤ HDD ≤ 5,999) to Edmonton, (except Denmark which has a milder climate), the literature review indicates that there is a substantial variation among approaches and requirements used to measure the energy performance of housing in these jurisdictions. Hence, the information reviewed in Section 2.1 on building envelope requirements and on methods to evaluate energy performance is further explored in this section. So, to synthesize the information collected (as presented in Figure 4.9), some elucidation is necessary as provided below:

a. ABC 2014: RSI values for building envelope of homes with HRV are used in the analysis presented in this chapter. The RSI value of ceiling below attic is selected as "roof".

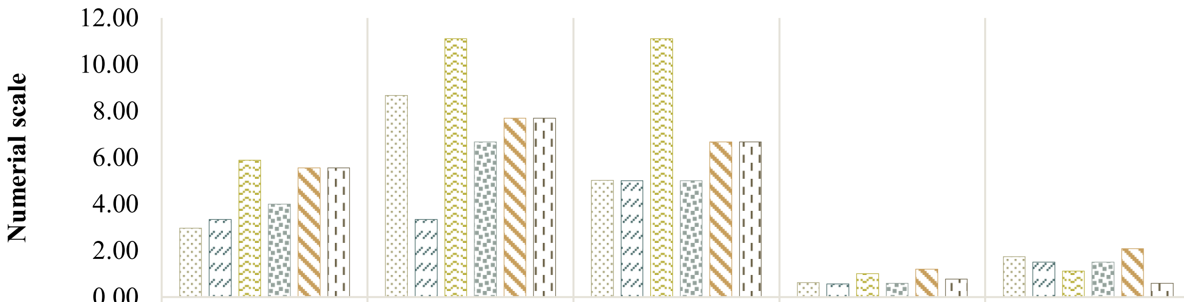
b. Denmark: values defined by BR10 are selected, as the requirements of "low energy class 2015" are not yet mandatory.

c. Finland: no considerations needed; the specifications of Finnish Building Code 2012 are used in the analysis.

d. Iceland: building envelope requirements for homes with indoor temperature greater or equal to 15 °C are selected.

e. Norway: values of "Option 2" are used, as they represent a prescriptive path similar to the approach followed by the ABC 2014.

f. Sweden: values defined for the alternative option for residences without electric heating are selected since natural gas is the primary energy source used for space heating in Alberta's housing (NRCan 2016a).



	Walls, RSI (m²·K/W)	Roofs, RSI (m²·K/W)	Floors, RSI (m²·K/W)	Windows/ Doors, RSI (m²·K/W)	Air tightness, (l/s·m²)
ABC 2014	2.97	8.67	5.02	0.63	1.74
Denmark	3.33	3.33	5.00	0.56	1.50
Finland	5.88	11.11	11.11	1.00	1.11
Iceland	4.00	6.67	5.00	0.59	1.50
Norway	5.56	7.69	6.67	1.20	2.08
Sweden	5.56	7.69	6.67	0.77	0.60

Building envelope assemblies

Figure 4.9: Above-Grade Building Envelope Requirements Set by Analyzed Regulations.

As observed in Figure 4.9, Finland and Denmark, respectively, have the most and least stringent requirements, in overall values, for building envelope, a finding aligned with the fact that these countries have the highest and lowest HDD, respectively. However, although the Danish regulation has the most lenient RSI value requirements for building envelope, the ABC 2014 is the code with the lowest specification for exterior walls. Furthermore, the value required by the ABC 2014 represents ~53% of the minimum RSI required by Norway and Sweden for the same building envelope component. For evaluation purposes, $l/(s{\cdot}m^2)$ is the metric used to evaluate housing airtightness. Thus, when information on this subject is specified by a jurisdiction's regulations in air change per hour (ACH), the relationship expressed in Equation (16) is applied. In this regard, the jurisdiction with the strictest requirement is Sweden with 0.60 l/(s·m^2), in contrast with Norway, which specifies 2.08 l/(s·m^2), as summarized in Figure 4.9. The ABC 2014 has the second lowest requirement, 1.74 l/(s·m^2), which is almost three times greater than the Swedish specification.

$$Ventilation\ rate\ \left(\frac{l}{s{\cdot}m^2}\right) = \frac{ACH \times R_mH\ (m) \times 1000\ \left(\frac{l}{m^3}\right)}{3600\ \left(\frac{s}{hr}\right)} \tag{16}$$

where

ACH: Air change per hour as specified by the jurisdiction's building code; and

R_mH: A room height of 2.50 m is assumed in calculations as it is the room height of the reference house in this thesis.

In regard to thermal resistance, housing total RSI (RSI_{total}) is calculated with the objective of accounting for the sum of the RSI values of building envelope component, the thermal resistance of buildings due to airtightness, and HRV efficiency in recovering heat from exhaust air. To determine the RSI_{total} specified by each jurisdiction's regulations, calculations are performed as per Equation (17) and Equation (18).

$$U_{total} = U_{infiltration} + U_{ventilation} + \sum U_{building\ envelope}$$

$$U_{total} = \left(m \times C_p \times \rho_{air}\right) + \left(1 - HRV_{efficiency}\right) + \sum U_{building\ envelope} \tag{17}$$

where

U_{total}: Thermal transmittance of building envelope system, W/(m^2·K);

m: Mass of fluid within a time interval per area, l/(s·m^2);

Cp: Specific heat of air, 1.005 kJ/(kg · °C);

ρ_{air}: Density of air, 1.2 kg/m^3; and

$1 - HRV_{efficiency}$: Accounts for heat loss due to mechanical ventilation.

$$RSI_{total} = \frac{1}{U_{total}} \tag{18}$$

where

RSI_{total}: Accounts for housing total thermal resistance, (m^2·K)/W.

Therefore, as observed in Figure 4.10, the evaluation of the RSI_{total} per code and HDD per location shows that Alberta, represented by Edmonton, features a climate comparable to Norway, Sweden, and Finland. However, the RSI_{total} specified by the ABC 2014 is similar to those of Iceland and Denmark. Moreover, to meet Norwegian and Swedish energy standards, increases of ~25% and ~15%, respectively, would be necessary in the RSI_{total} currently specified by the ABC 2014.

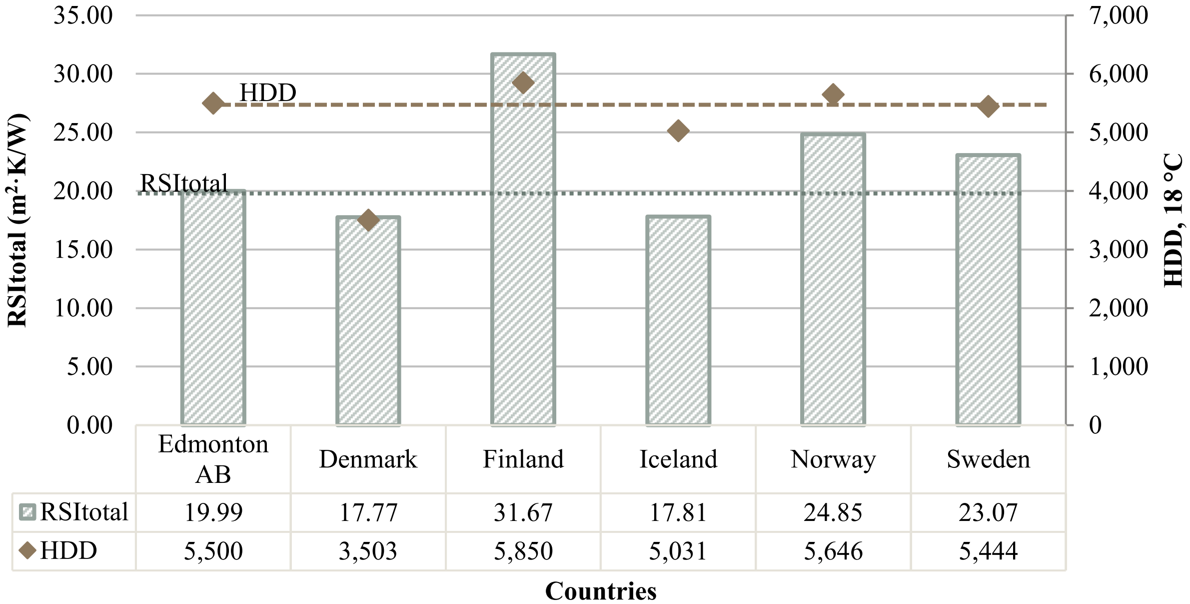
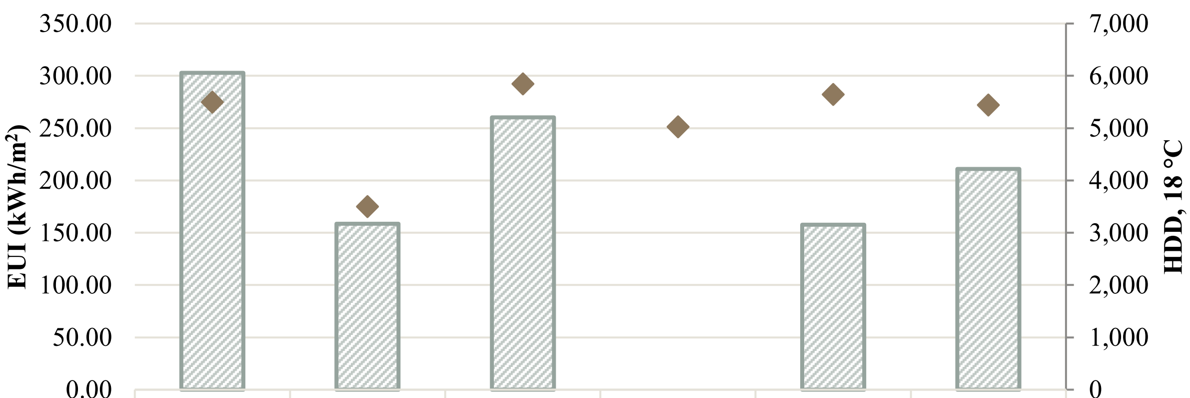


Figure 4.10: RSI_{total} and HDD per Location.

Additionally, energy use intensity (EUI), which is a metric that limits energy demand by housing based on floor area, has not been introduced as a requirement in the ABC 2014. The EUI is a metric commonly used to assess the energy performance of buildings, and it is calculated as per Equation (19) (NRCan 2015c). The introduction of EUI as a requirement permits freedom of design as long as the energy target, in kWh/m^2 per year, is not exceeded. Additionally, it encourages investments in efficient domestic systems, as it accounts for actual energy used rather than the energy demand. Thus, with the objective of controlling both energy usage and energy demand, most of the Nordic countries, i.e., Denmark, Finland, Norway, and Sweden, have established tight specifications for EUI and building envelope.

$$EUI = \frac{Total\ Energy\ Consumed\ over\ a\ Calendar\ Year\ (kWh)}{Total\ Area\ of\ Heated\ Floor\ (m^2)} \tag{19}$$

Regarding actual housing energy consumption, it is observed that Alberta has the highest consumption among the locations investigated in this thesis, consuming ~192% and ~144% more energy than Norwegian and Swedish housing, respectively, as per Figure 4.11 (Enerdata 2016; NRCan 2016a). Furthermore, researchers have identified an annual decrease in the energy consumption of the residential sector by a margin of 2% in Denmark (from 2007 to 2013) and 1.7% in Norway (from 2000 to 2012). This reduction rate is attributed to the introduction of rigid energy regulations (Danish Energy Agency 2016; Motiva 2015). Therefore, a similar reduction rate is expected in Alberta once the energy requirements set by the ABC 2014 have been fully implemented.



	Alberta	Denmark	Finland	Iceland	Norway	Sweden
EUI in 2012	302.80	158.75	260.16	0.00	157.82	210.97
HDD	5,500	3,503	5,850	5,031	5,646	5,444

Figure 4.11: Estimated EUI in 2012 and HDD by Jurisdiction.

4.6. Conclusion: General Approach Proposed to Identify Least-Construction-Cost Code-Compliant Upgrades

A general approach to identifying least-construction-cost upgrades to meet building code energy requirements is proposed as the conclusion of this chapter. By following the approach depicted in Figure 4.12, least-construction-cost upgrades compliant with prescriptive requirements of building codes are identified effortlessly for other climatic conditions. In addition, in cases where the key objective is to achieve code-compliant energy performance, aiming to minimize alterations to current construction practice and thereby to ensure compliance with code requirements by performance path, the approach presented in Figure 4.13 is followed.

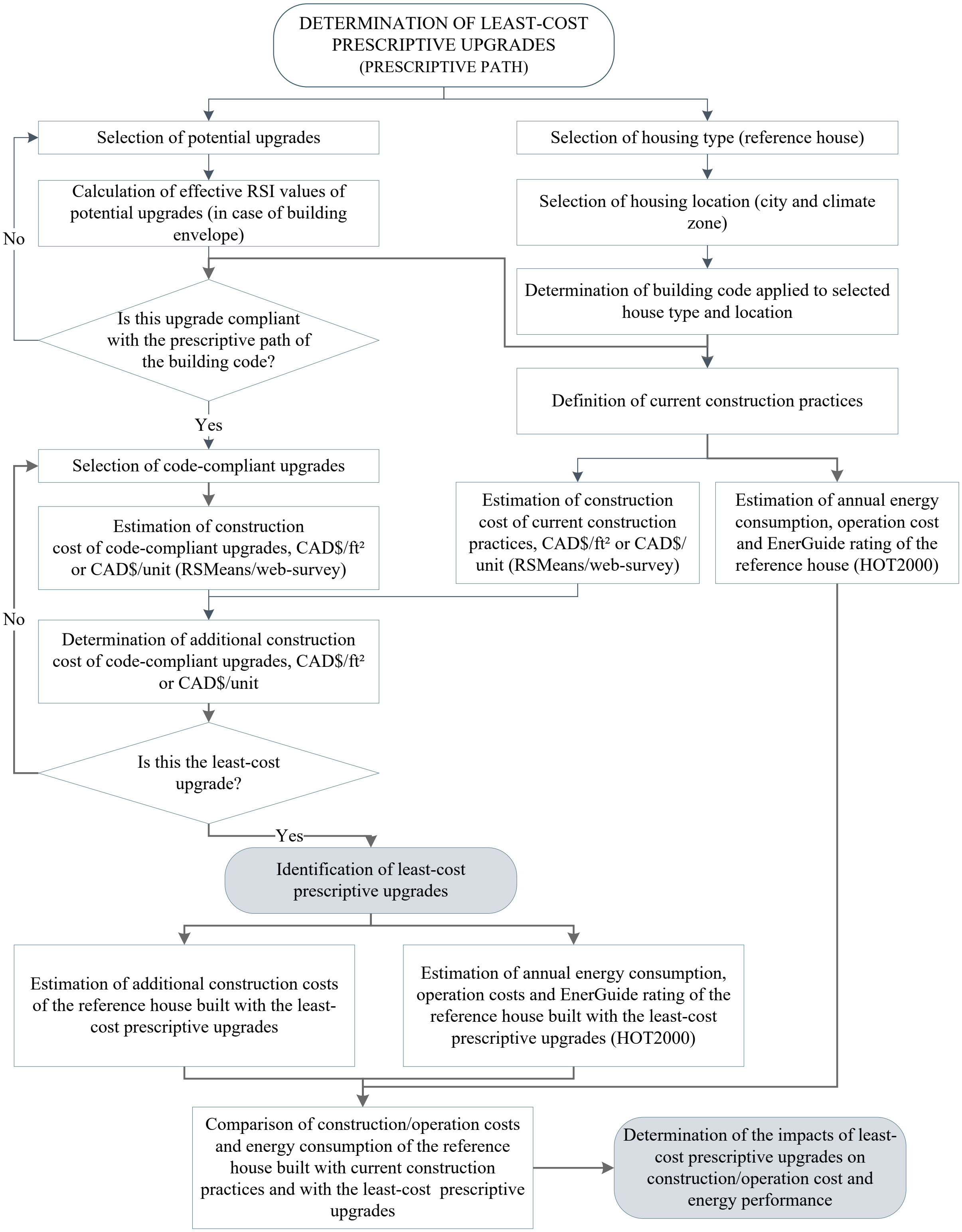


Figure 4.12: Proposed Approach for Identifying Least-Construction-Cost Code-Compliant Upgrades (Prescriptive Path).

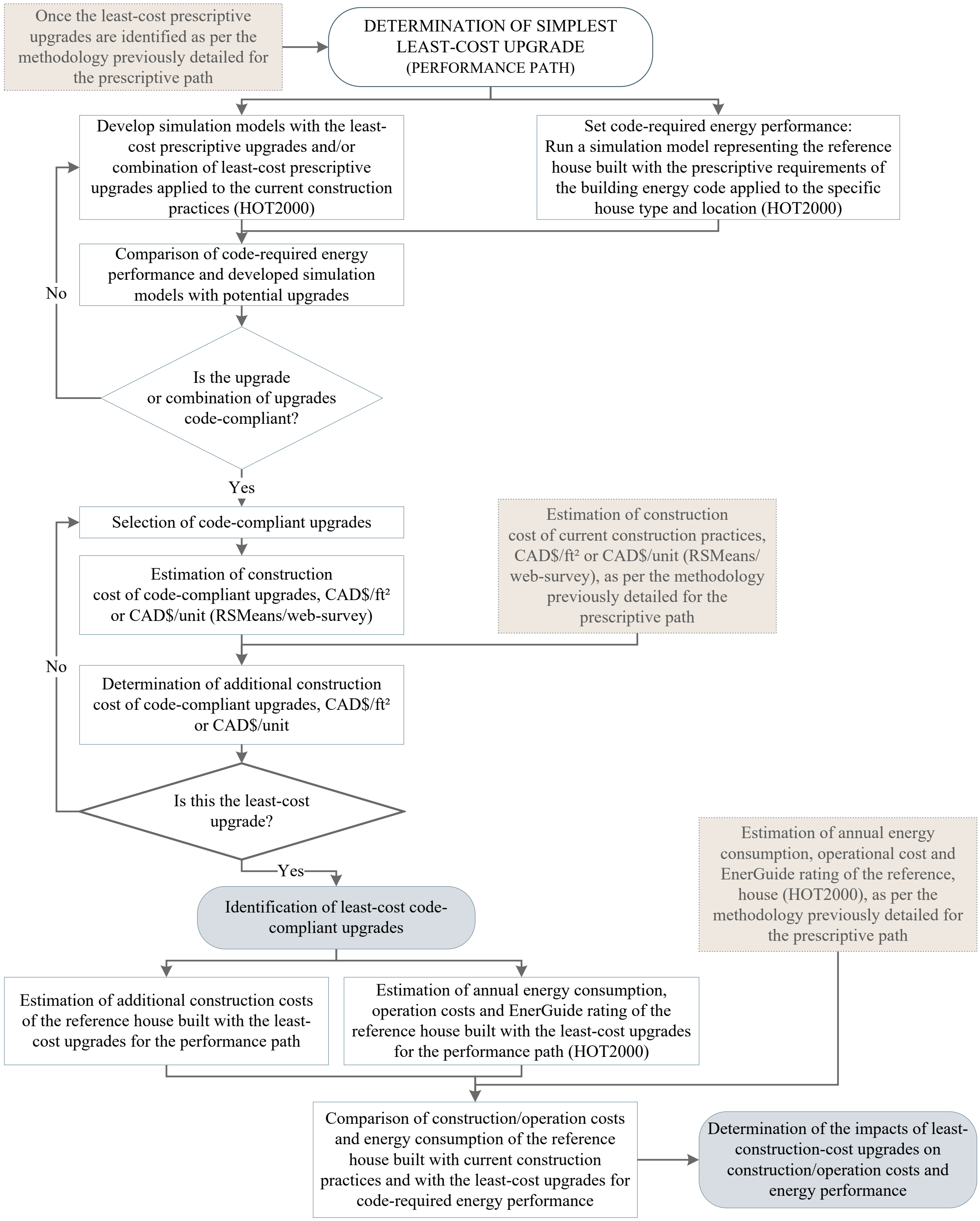


Figure 4.13: Proposed Approach for Identifying Simplest Least-Construction-Cost Upgrade to Achieve Code-Compliant Energy Performance (Performance Path).

CHAPTER 5: CASE STUDIES OF LEAST-CONSTRUCTION-COST CODE-COMPLIANT UPGRADES

In this chapter, impacts of the identified least-construction-cost code-compliant upgrades on the reference house's construction cost, energy consumption, and operation cost are assessed. In the first two case studies, code compliance is pursued in reference to the prescriptive path of the ABC 2014, while in the last case study, the performance path is chosen for compliance. First, in Case Study 1, the least-construction-cost upgrades for the prescriptive path are explored. Then, in Case Study 2, the upgrades applied in Case Study 1 as well as the results obtained from sensitivity analyses, conducted for energy-efficient tankless water heaters and window sizing, are investigated. Finally, in Case Study 3, modifications to current construction practice are minimized by applying the simplest least-construction-cost upgrade to accomplish code-compliant energy performance.

5.1. Case Study 1: Least-Construction-Cost Prescriptive Upgrade Configuration for Building Envelope

In this section, the upgrades defined in Section 4.1 are assessed regarding construction cost, energy consumption, operation cost, total lifecycle cost, and ROI. First, a simulation model is developed in HOT2000 (Model CS1). This model represents the reference house built with the upgrades identified in Section 4.1 (Figure 5.1) and the design configurations from current construction practice with energy performance compliant with the code (Figure 5.2).

Attic ceiling
- PAC 6: RSI 10.57 Blown-in cellulose. Effective RSI: 8.69

Above grade exterior walls
- PAW 7: RSI 2.29 unfaced fibreglass batt + 25.4 mm (1 in.) Type II EPS. Effective RSI: 3.08

Below grade exterior walls
- PBW 1: RSI 3.87 Kraft faced fibreglass batt. Effective RSI: 3.83

Windows
- Upgrade: Triple-pane, low-E argon-filled, and with vinyl frame

Airtightness
- 2.5 ACH at 50 Pa pressure difference

Figure 5.1: Case Study 1 – Simulation Model Input: Upgrades Identified in this Research.

Exposed floors
- Common practice: RSI 4.93 fibreglass batt. Effective RSI: 5.28.

Doors
- Common practice: Insulated fibreglass

Vetilation system
- Common practice: Heat Recovery Ventilator. Efficiency: 66% at 0 °C and 60% at −25 °C

Heating system
- Common practice: 92% high efficiency natural gas-fired furnace

Domestic hot water
- Common practice: Power direct vented with 189.27 (50 US gal) capacity and EF = 0.67.

Figure 5.2: Case Study 1 – Simulation Model Input: Current Construction Practice.

To conduct the mentioned assessment, outcomes of the simulation model such as estimated annual energy consumption for space heating, domestic water heating and ventilation system, EnerGuide rating, annual fuel consumption, and annual operation cost are collected. Then, this collected information is compared to the simulation results of Model BL (reference house built based on current construction practice). Figure 5.3 depicts the simulation results regarding the energy consumption of both models of the reference house.

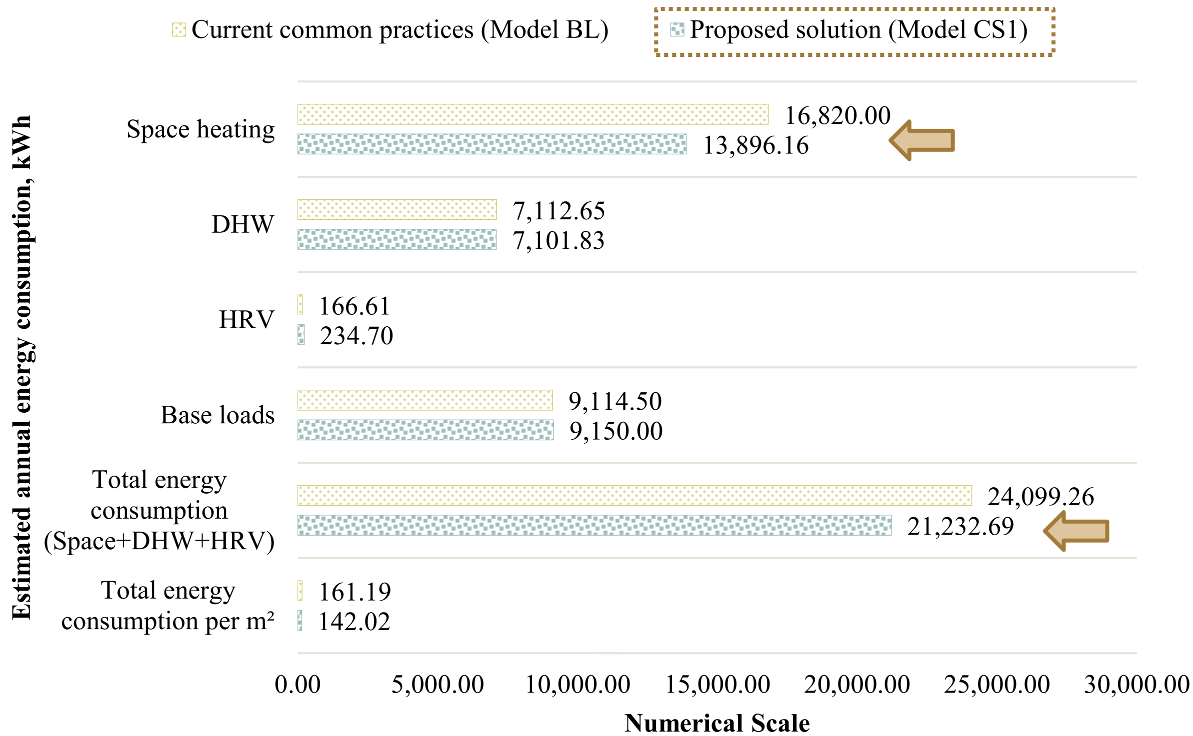


Figure 5.3: Case Study 1 – Estimated Annual Energy Consumption (HOT2000 results)[14].

As expected, no significant alteration is observed regarding the energy consumed for domestic water heating, this due to the fact that the same system is applied to both simulation models. On the other hand, in comparing and analyzing the energy consumed for space heating, a discrepancy is observed between the results of these simulation models. Model CS1 shows better energy performance compared to model BL, a finding which is mainly attributable to Model

[14] Base loads account for the average electrical load of interior lighting, appliances, other and exterior use (described in 3.1.1.1.2) and heating, ventilation and air conditioning (HVAC) fans for HRV/exhaust, space heating, and space cooling.

CS1's higher level of insulation and airtightness. The overall RSI[15] value of Model CS1's building envelope is ~21% higher than the overall RSI value of Model BL. Furthermore, accounting for RSI_{total}, calculated as per Equation (17) and Equation (18) in Section 4.5, an improvement of ~18% compared to Model BL's RSI_{total} is observed. As a result of these enhancements, the energy used for space heating in Model CS1 is found to be ~17% lower than the energy used for the same purpose in Model BL. Table 5.1 presents an overview of the simulation model inputs for Model BL and Model CS1.

Table 5.1: Case Study 1 – Overview of HOT2000 Simulation Model Inputs.

Building envelope / Systems	Current construction practice (Model BL)	Least-construction-cost prescriptive upgrade (Model CS1)
Attic ceiling, RSI	6.22	8.69
Above-grade exterior walls, RSI	2.96	3.08
Below-grade exterior walls, RSI	1.99	3.83
Exposed floors, RSI	5.28	5.28
Windows, RSI	From 0.47 to 0.51	From 0.67 to 0.80
Doors, RSI	0.98	0.98
Ventilation system, efficiency	66% at 0 °C 60% at −25 °C	66% at 0 °C 60% at –25 °C
Heating system, AFUE	92%	92%
Domestic hot water, EF	0.67	0.67
Airtightness, ACH	3.57	2.50

[15] The overall RSI value accounts for the sum of RSI values of attic ceiling, above-grade exterior walls, below-grade exterior walls, floor over unheated space, windows (lowest value), and doors.

On the other hand, an increase of ~41% is observed with respect to the energy consumed by Model CS1's ventilation system. The reason behind this is the improvement of airtightness, which diminishes natural air infiltration and air movement inside the house. Accordingly, to maintain a satisfactory level of air change, ventilator usage must increase. Still, through balancing reductions and increases in the energy consumption, an overall reduction of ~12% is obtained by deploying the identified least-construction-cost prescriptive upgrades in current construction practice.

Reflecting the results detailed above, a reduction in consumption of natural gas, which is the energy source used for space heating, is achieved in Case Study 1 (Figure 5.4). This reduction has an impact on estimated operation cost, decreasing it by ~9% compared to Model BL. In addition, the upgrades investigated in Model CS1 increase the EnerGuide rating from 78 to 80 (Figure 5.6).

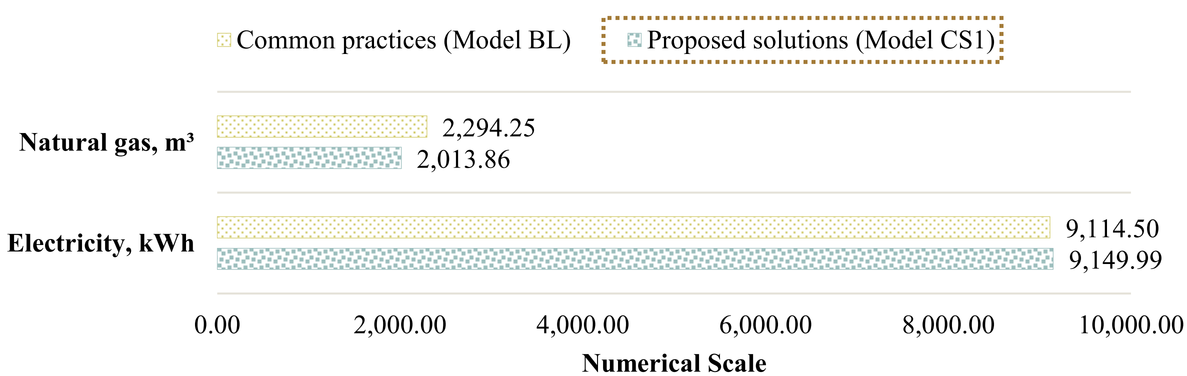


Figure 5.4: Case Study 1 – Estimated Annual Fuel Consumption (HOT2000 Results).

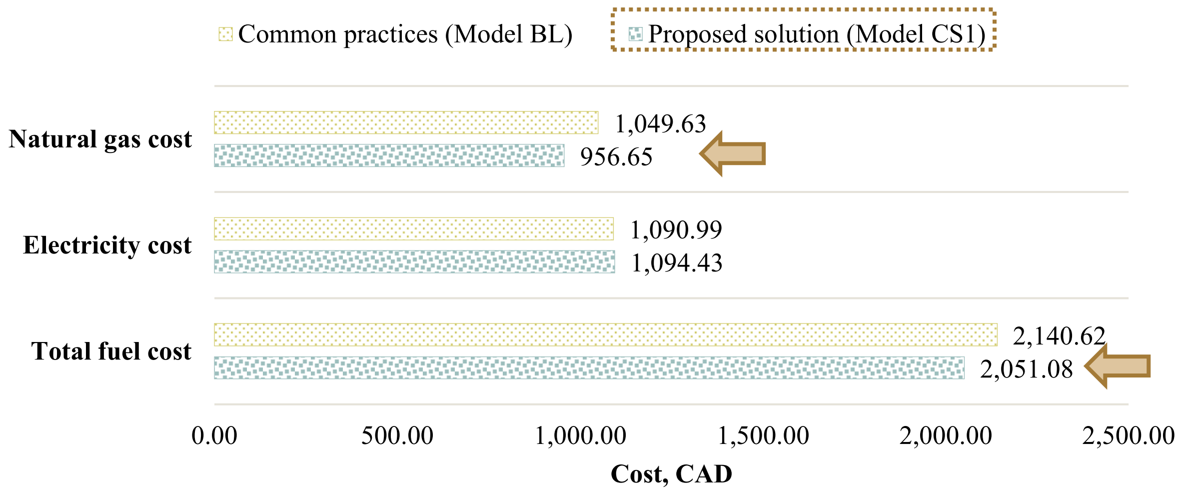


Figure 5.5: Case Study 1 – Estimated Annual Operation Cost (HOT2000 Results).

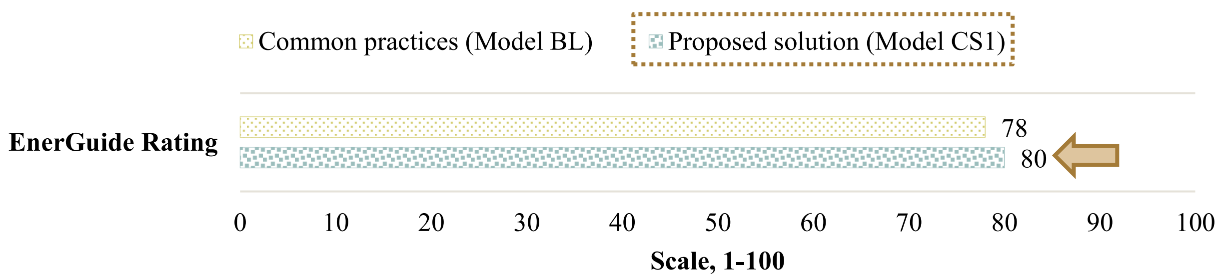


Figure 5.6: Case Study 1 – EnerGuide Rating (HOT2000 Results).

After the information regarding the energy performance and operation costs of the reference house is collected and analyzed, the next step is to verify the impacts on construction cost. Table 5.2 depicts the additional construction cost of each upgrade investigated in this case study, calculated as per Equation (3), according to the area of the reference house's building envelope.

Table 5.2: Case Study 1 – Estimated Additional Construction Cost of Upgrades Investigated.

	Additional CAD/ft²	Assembly area, ft²	Total cost, CAD
Attic ceiling	0.50	768.97	384.49
Above-grade walls	0.56	2,169.24	1,214.77
Below-grade walls	0.45	802.70	361.22
Windows	12.34	156.08	1,926.03
Total additional cost of reference house			3,886.50

As observed in Table 5.2, an investment of ~CAD 3,886.50 is needed to meet the energy requirements of the ABC 2014 by deploying the identified least-construction-cost prescriptive upgrades. Since this case study does not demand equipment repositions during the operation phase, the additional construction cost is the sole capital investment considered in the lifecycle analyses. Thus, by applying the mathematical equations given in Subsection 3.1.7 to the simulation results, fuel consumption savings, total lifecycle costs, ROI for upgrades, and estimated payback time are determined. By applying Equation (6) to estimated annual savings from reduced natural gas consumption and Equation (7) to estimated annual savings from reduced electricity consumption, which are expressed in Table 5.3, the annual fuel consumption savings are determined using Equation (8). Then, the present value of annual and of accumulated fuel consumption savings are determined as per Equation (9) and Equation (10).

Table 5.3: Case Study 1 – Estimated Annual Savings from Fuel Cost (HOT2000).

	Estimated Annual Savings from Natural Gas (CAD)	**Estimated Annual Savings from Electricity (CAD)**
Comparison of Model CS1 and Model BL	92.98	−3.44

The ROI for the upgrades investigated in this case study, calculated as per Equation (12), is found to be around −3.44%; hence, the period after which payback begins is longer than the 30-year period analyzed in this research. The present value of actual savings in fuel costs (operation costs), calculated as per Equation (13), is ~CAD −133.52. Moreover, the lifecycle cost of the reference house built with the upgrades analyzed in this case study is estimated to be ~CAD 84,409.64, as depicted in *Appendix D.2. Total Lifecycle Cost of the Reference House - Case Study 1*. A summary of the impacts of the least-construction-cost prescriptive upgrades applied to the reference house is presented in Table 5.4.

Table 5.4: Case Study 1 – Summary of Impacts on Current Construction Practice.

	Annual savings from natural gas (CAD)	Annual savings from elect. (CAD)	Present value of 30-year savings from fuel (CAD)	Total add. const. cost (CAD)	Present value of actual operation savings (CAD)	ROI (%)	Payback period (years)
Comparison of Model CS1 and Model BL	92.98	−3.44	3,752.98	3,886.50	−133.52	−3.44	31

Thus, the results obtained indicate that the savings resulting from the upgrades deployed in this case study fail to offset the additional investment required in the construction phase to meet the prescriptive energy requirements introduced by the ABC 2014.

5.2. Case Study 2: Least-Construction-Cost Prescriptive Upgrade for Building Envelope, Energy-Efficient Domestic Water Heater, and Improved Window Sizing

In Case Study 2, the identified least-construction-cost prescriptive upgrade for building envelope, which has been assessed already in Case Study 1, and the results obtained through the sensitivity analyses of energy-efficient domestic water heaters and window sizing are evaluated. To represent these upgrades, a simulation model is developed in HOT2000 (Model CS2), the inputs to which indicated in Figure 5.7 and Table 5.5. As observed in Table 5.5, the window area of the south façade increases from 16%, as in the original design of the reference house, to 44% in Model CS2. On the other hand, the total area of windows facing north decreases by ~5%, while the areas of east and west windows reflect those in the original design.

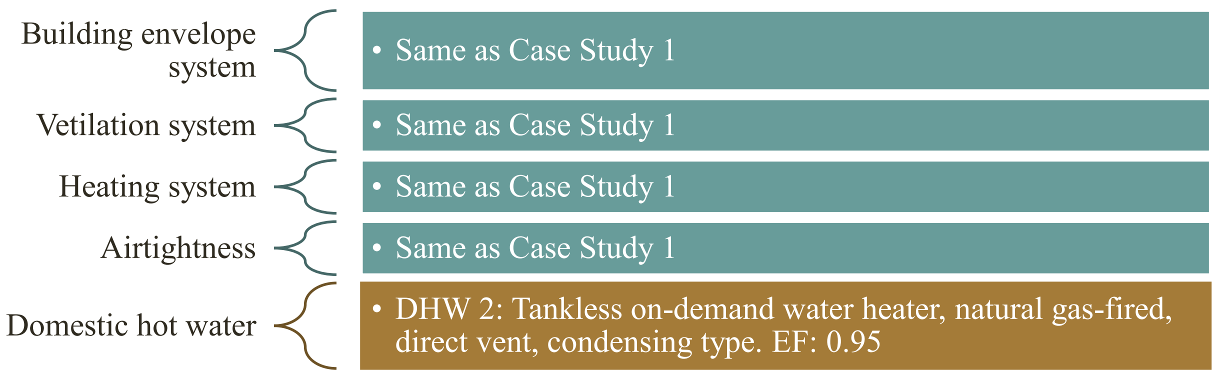


Figure 5.7: Case Study 2 – Simulation Model Input.

Table 5.5: Case Study 2 – Window-to-Wall Ratio (WWR) Per Façade Orientation – Comparison of Reference House and Model CS2.

	WWR, % (Façade area)				WWR, % (Exterior wall area)			
	South	West	North	East	South	West	North	East
Reference House	16.0%	4.0%	16.0%	0.0%	2.6%	1.5%	2.6%	0.0%
Model CS2	44.0%	4.0%	11.0%	0.0%	7.4%	1.5%	1.8%	0.0%

For comparison purposes, the same simulation model's outputs analyzed in Case Study 1 are also explored in Case Study 2. Figure 5.8 illustrates the annual base electrical loads; the energy consumed by domestic water heating, space heating, and ventilators; and the total energy consumed by the reference house modelled as per the configuration presented above. As a result of the alteration of the DHW system, the energy consumed to water heating is markedly lower in Model CS2 compared to the energy consumed by Model BL and Model CS1. Thus, this case study verifies that, by upgrading the conventional storage tank system used in current construction practice to a tankless condensing energy-efficient system, a reduction of ~30% is obtained on the energy consumed by DHW system. This reduction rate is aligned with the results of the sensitivity analyses performed in Section 4.3.

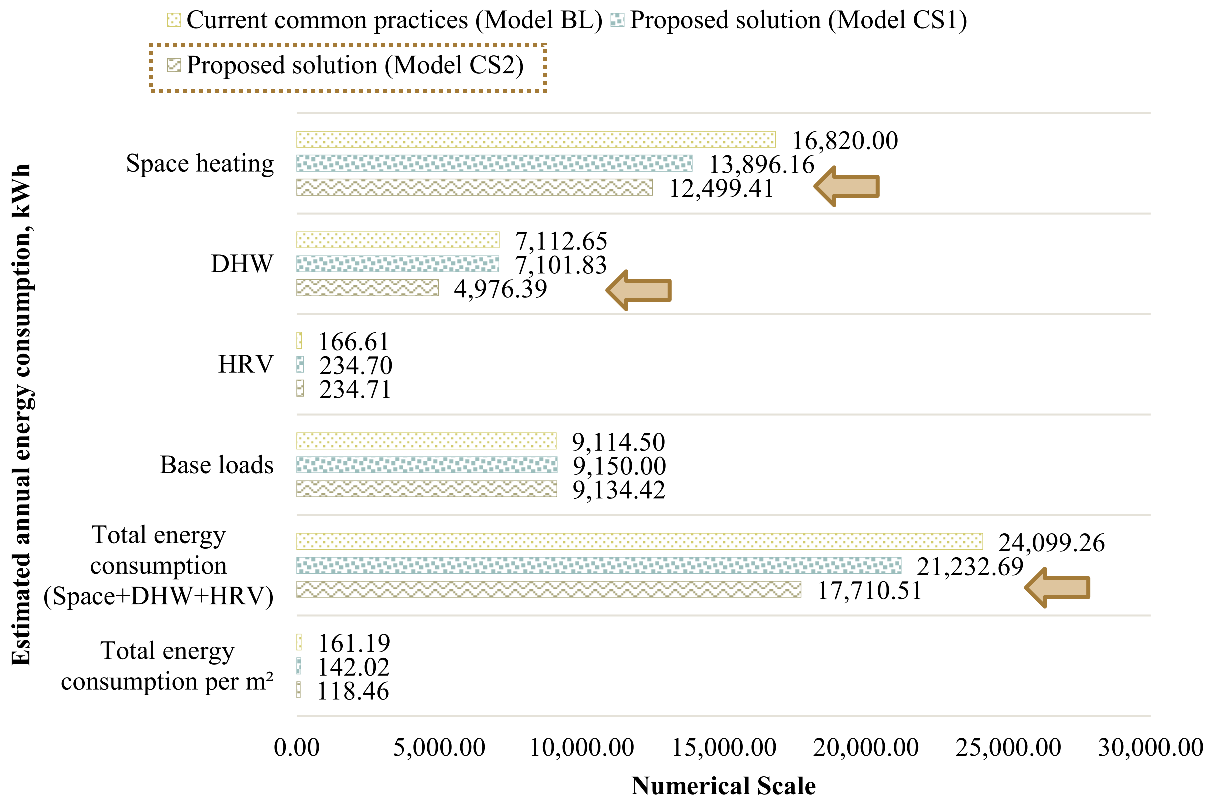


Figure 5.8: Case Study 2 – Estimated Annual Energy Consumption (HOT2000).

Moreover, regarding space heating, the energy consumed drops ~26% and ~10% comparing Model CS2's simulation result to the results of Model BL and Model CS1, respectively. Since the RSI_{total} of Model CS2 is the same as that of Model CS1, this variance of ~10% is attributed mainly to the passive heat gained through improved window sizing. In other words, the reference house, as modelled in Model CS2, is gaining heat through solar radiation, which raises its interior temperature, resulting in reduced demand for space heating and, consequently, lower energy consumption. Thus, accounting for the reduction of energy consumed by the DHW and space heating systems, a total decrease of ~27% compared to current construction practice (Model BL) is observed, more significant than the 12% previously achieved in Case Study 1.

Therefore, this case study indicates that by relocating windows and by investing in energy-efficient equipment for water heating, a reduction of ~17% in total energy consumption is accomplished.

Additionally, as a result of the findings discussed above, the EnerGuide rating of Model CS2 reaches 82. Accordingly, natural gas cost is reduced by roughly 20%, resulting in an operation cost ~10% lower than that of Model BL's (Figure 5.9).

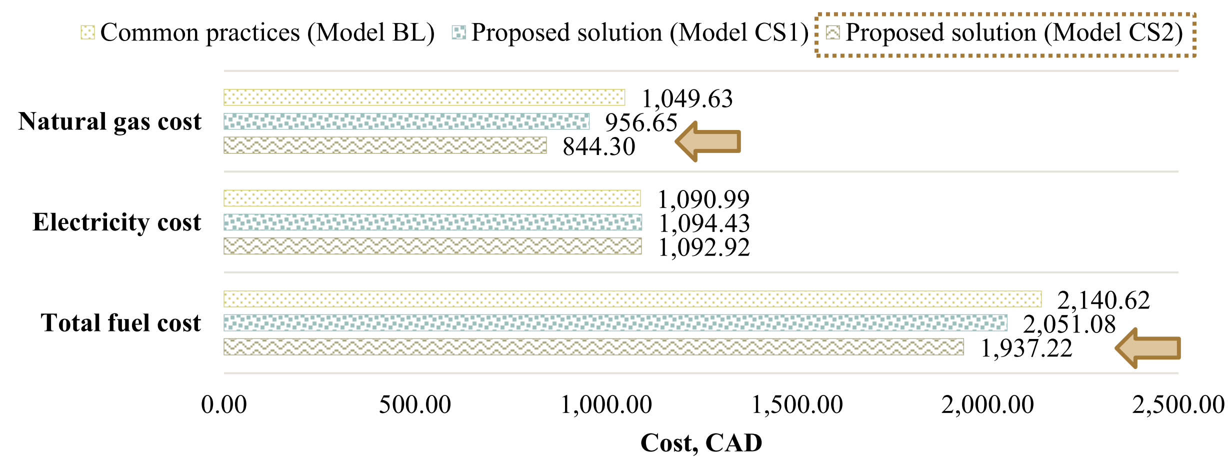


Figure 5.9: Case Study 2 – Estimated Annual Operation Cost (HOT2000 Results).

To verify the impacts of the upgrades investigated in Case Study 2 on construction cost, the total additional construction cost is calculated (Table 5.6). It is identified that an initial investment of ~CAD 5,658.82 is needed to build the reference house with the upgrades analyzed in this case study. Also, since the life expectancy of domestic water heaters is lower than the 30-year period evaluated in this research, as opposed to Case Study 1 here the reposition cost of this equipment is included in the lifecycle analysis. Since the interest rate applied to estimate the future value of water heaters is the inflation rate, which is the same as the interest rate used to calculate the present value of a future value, savings from equipment repositioning are determined by calculating the cost difference, in present value, of water heater acquisition, as per Equation (11) (Table 5.7 and Table 5.8).

Table 5.6: Case Study 2 – Estimated Additional Construction Cost of Upgrades Investigated.

	Additional CAD/ft² or CAD/unit	Assembly Area, ft² or product quantity, unit	Total Cost, CAD
Attic ceiling	0.50	768.97	384.49
Above-grade walls	0.56	2,092.17	1,171.62
Below-grade walls	0.45	788.07	354.63
Windows	12.34	247.78	3,057.61
Tankless DHW, condensing type	690.48	1.00	690.48
Total additional cost of reference house			**5,658.82**

Table 5.7: Estimated Replacement Cost of 50 US Gal Direct Vented Tank Water Heater.

REPLACEMENT TIME	Cost, CAD
Present cost	895.00
Replacement costs (in present value)	895.00 × 3 = 2,685.00

Table 5.8: Estimated Replacement Cost of Tankless Condensing Water Heater.

REPLACEMENT TIME	Cost, CAD
Present cost	1,585.48
Replacement costs (in present value)	1,585.48

Thus, as observed in Table 5.7 and Table 5.8, by selecting the tankless water heater investigated in this research, a savings of ~CAD 1,099.52 is obtained from equipment reposition, in addition to the savings in operation costs (Table 5.9). Following the same mathematical equations detailed in Case Study 1, the actual savings in present value resulting from the upgrades investigated in this case study are summarized in Table 5.10.

Table 5.9: Case Study 2 – Estimated Annual Savings from Fuel Cost (HOT2000).

	Estimated Annual Savings from Natural Gas (CAD)	Estimated Annual Savings from Electricity (CAD)
Comparison of Model CS2 and Model BL	205.33	−1.93

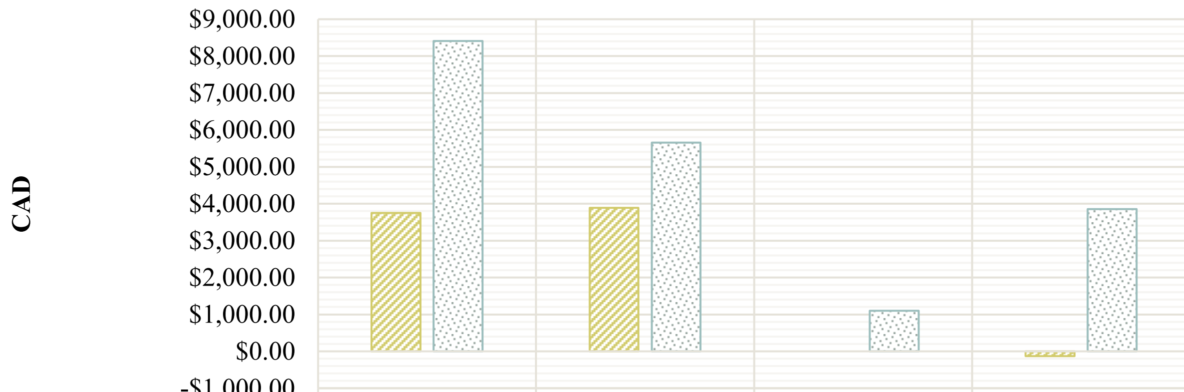
Table 5.10: Case Study 2 – Summary of Impacts on Current Construction Practice.

	Present value of 30-year savings from fuel (CAD)	Total add. initial const. cost (CAD)	Present value of savings from product reposition (CAD)	Present value of actual savings (CAD)
Comparison of Model CS2 and Model BL	8,411.90	5,658.82	1,099.52	3,852.60

Based on the information presented in Table 5.10, estimated ROI and payback time are determined accounting for additional construction cost versus savings from reduced fuel costs and equipment repositions, as per Table 5.11. In conclusion, the investment required to enhance the reference house energy performance by ~27%, considering the total energy consumed by Model CS2 and Model BL is returned in ~22 years, and the total lifecycle cost of this case study is ~CAD 81,961.23 (*Appendix D.3. Total Lifecycle Cost of the Reference House - Case Study 2*). Therefore, at the end of the analyzed 30-year period, an actual savings of CAD 3,852.60 is obtained. In light of these findings, the other recommends investment in least-construction-cost prescriptive upgrades for building envelope, energy-efficient DHW system, and improved window sizing, aiming not only to reach code requirements but also to maximize monetary savings in operation costs. Figure 5.10 compares the economic aspects of Case Study 1 and Case Study 2. As noted when comparing the results of Model CS2 and Model CS1, the savings in fuel costs are increased by ~124% for Model CS2. Also, through investing ~46% more during the construction phase than in Case Study 1, the actual savings of Case Study 2 increase by ~2,885% compared to Case Study 1.

Table 5.11: Savings, ROI, and Payback Time of Upgrades Investigated in Case Study 2.

	Present value of 30-year savings from fuel (CAD)	Total add. initial const. cost (CAD)	Present value of savings from product reposition (CAD)	Present value of actual savings (CAD)	ROI (%)	Payback (years)
Comparison of Model CS2 and Model BL	8,411.90	5,658.82	1,099.52	3,852.60	68.08	22



	Present value of 30-year savings from fuel cost	Total additional construction cost	Total savings from product reposition	Present value of actual savings
Model CS1 to Model BL	3,752.98	3,886.50	0.00	-133.52
Model CS2 to Model BL	8,411.90	5,658.82	1,099.52	3,852.60

Figure 5.10: Comparison of Case Study 1 and Case Study 2.

5.3. Case Study 3: Simplest Least-Construction-Cost Upgrade to Accomplish Code-Compliant Energy Performance

The objective of Case Study 3 is to evaluate the energy performance and construction costs of the reference house built based on the results obtained in the sensitivity analyses conducted in Section 4.4. In contrast with the previous case studies, which aim to comply with the ABC 2014 by the prescriptive path, in this case study code compliance is pursued by the performance path. The primary objective of this approach is to minimize the additional construction cost required to achieve code-compliant energy standards. Thus, the upgrade identified in Section 4.4 is utilized to build a new simulation model, Model CS3. Other parameters are modelled in Model CS3 as in the reference house original design; building envelope and domestic systems (heating and ventilation) are modelled as per current construction practice (Figure 5.11).

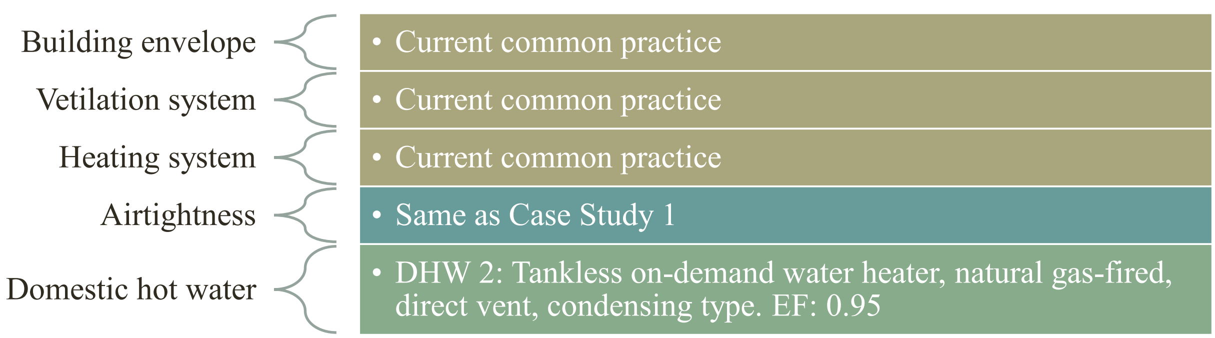


Figure 5.11: Case Study 3 – Simulation Model Input.

With the aim of assessing the three case studies in a similar manner, the same simulation outputs as those analyzed in Case Study 1 and Case Study 2 are investigated with respect to Case Study 3 (Figure 5.12). Therefore, as observed in Figure 5.12, Model CS2 and Model CS3 are found to consume the same amount of energy for the purpose of water heating, this due to the fact that both models have the same DHW system. On the other hand, the energy used for space heating in Model CS3 is comparable with the energy used for space heating in Model BL. The correlation between these results is reasonable, as the design configurations applied for building envelope in Model CS3 and Model BL are identical. Given that space heating is the major end-user of energy, the total energy consumption of Model CS3 is higher than the energy consumption of the previous case studies.

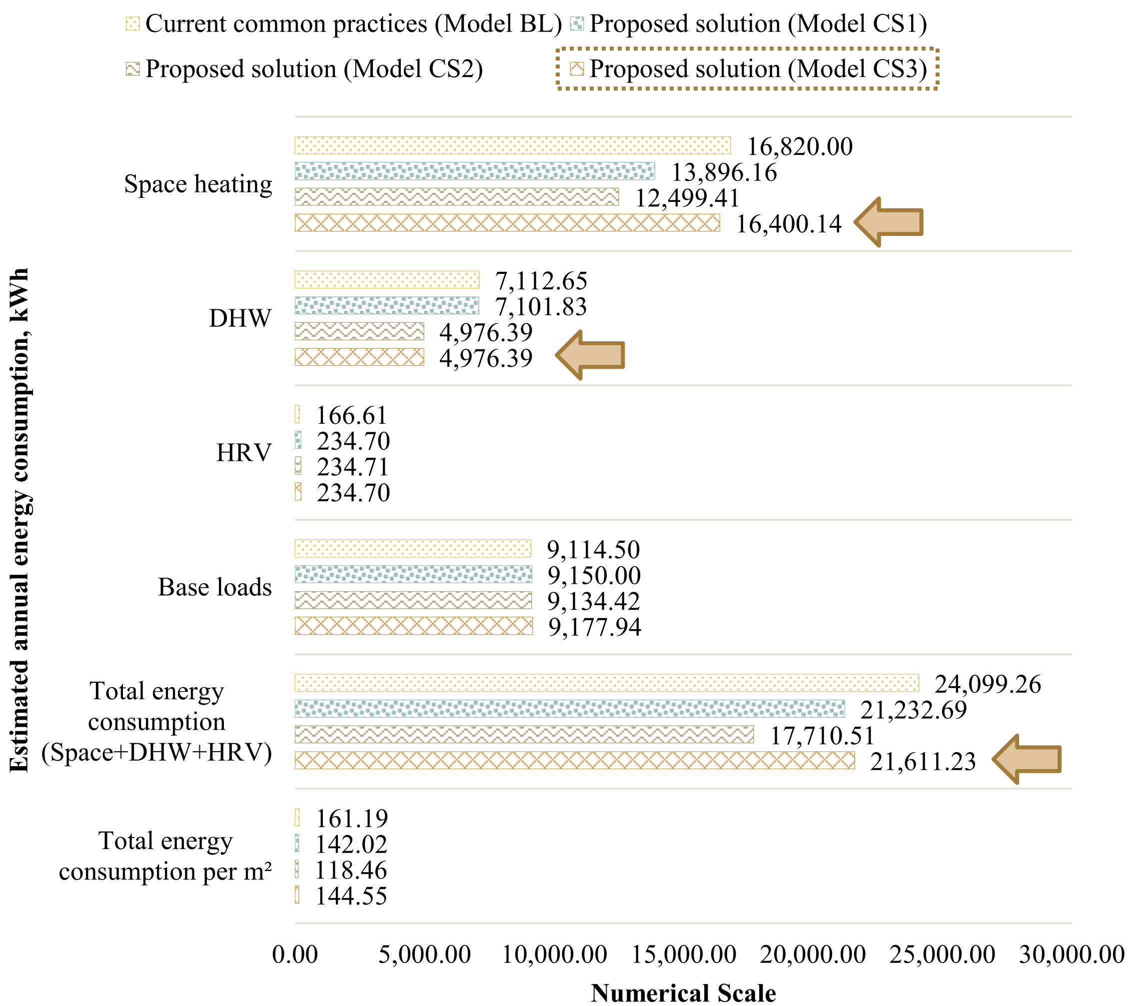


Figure 5.12: Case Study 3 – Estimated Annual Energy Consumption (HOT2000).

Although the energy consumed for space heating in Case Study 3 is greater than the energy consumed for the same purpose in the previous two case studies, a reduction of ~10% in comparison to Model BL's total energy consumption is still accomplished by means of the upgrade investigated in Model CS3. This reduction is reflected in the operation costs, as demonstrated in Figure 5.13. The costs of fuel in Model CS3 are slightly higher than in Model CS1. However, a decrease of ~4% compared to fuel costs for Model BL is still achieved, which is similar to the reduction rate for Model CS1.

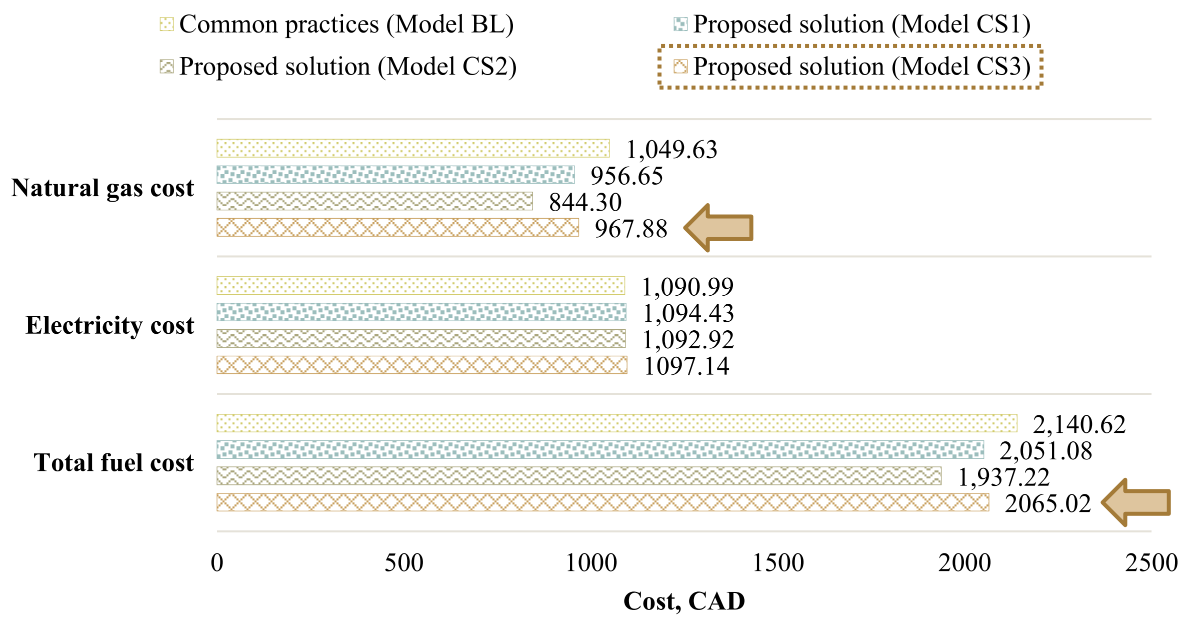


Figure 5.13: Case Study 3 – Estimated Annual Operation Cost (HOT2000 Results).

Regarding additional construction cost (Table 5.12), the investment required for applying the upgrades investigated in this case study is markedly lower than in the previous case studies—~CAD 690.48 to achieve the required energy performance of the ABC 2014. In addition, as demonstrated in Case Study 2, upgrading from storage tank DHW system to tankless condensing DHW system results in savings due to reduced fuel consumption and to equipment repositions (Section 5.2–Table 5.4). In this regard, Table 5.13 summarizes the operation savings from fuel and Table 5.14 presents the present value of 30-year savings in operation costs.

Table 5.12: Case Study 3 – Estimated Additional Construction Cost of Upgrade Investigated.

	Additional CAD/ft² or CAD/unit	Assembly Area, ft² or product quantity, unit	Total Cost, CAD
Tankless DHW, condensing type	690.48	1	690.48
Total additional cost of reference house			**690.48**

Table 5.13: Case Study 3 – Estimated Annual Savings from Fuel Cost (HOT2000 Results).

	Estimated Annual Savings from Natural Gas (CAD)	Estimated Annual Savings from Electricity (CAD)
Comparison of Model CS3 and Model BL	81.75	−6.15

Table 5.14: Case Study 3 – Summary of Impacts on Current Construction Practice.

	Present value of 30-year savings from fuel (CAD)	Total add. initial const. cost (CAD)	Present value of savings from product reposition (CAD)	Present value of actual savings (CAD)
Comparison of Model CS3 and Model BL	3,231.25	690.48	1,099.52	3,640.29

Accounting for additional construction cost, the 30-year savings from fuel, and equipment repositions, the ROI on the upgrade investigated in this case study is estimated to be ~527.21%, and the total lifecycle costs is estimated to be ~83,453.01 (*Appendix D.4. Total Lifecycle Cost of the Reference House - Case Study 3*). In addition, the payback time is reduced to ~8 years from 31 years in Case Study 1, and 22 years in Case Study 2. As observed in Table 5.15, the upgrade investigated in Case Study 3 requires the lowest monetary investment and, consequently, it presents the highest ROI and lowest payback time. In contrast, Case Study 3 exhibits the lowest present value of 30-year operation cost savings.

Table 5.15: Savings, ROI, and Payback Time of Upgrades Investigated in Case Study 3.

	Present value of 30-year savings from fuel (CAD)	Total add. initial const. cost (CAD)	Present value of savings from product reposition (CAD)	Present value of actual savings (CAD)	ROI (%)	Payback (years)
Comparison of Model CS3 and Model BL	3,231.25	690.48	1,099.52	3,640.29	527.21	8

CHAPTER 6: DISCUSSION AND CONCLUSION

In this chapter, conclusions, key contributions, and recommendations for future research are presented. First, the building energy codes governing energy performance of housing in cold-climate regions and the least-construction-cost code-compliant upgrades investigated in this thesis are discussed. Then, contributions of this research are summarized; finally, recommendations for future study are proposed.

6.1. Research Conclusions

6.1.1. Recommendations for Building Energy Codes Governing Energy Performance of Housing in Cold-Climate Regions

In light of the findings presented in the literature review on building codes conducted in Chapter 2 and the analyses performed in Section 4.5, this research proposes several recommendations with respect to the building regulations governing new housing in cold-climate regions. The recommendations are as follows: (a) introduction of strict RSI values for building envelope, (b) introduction of limited EUI, (c) promotion of renewable energy sources, (d) definition of a building code progression plan, and (e) promotion of information at the end-user level about the benefits of buying and living in an energy-efficient home.

The introduction of strict RSI requirements for building envelope is essential in cold-climate regions, given that it results in lower heat loss during cold seasons and thereby directly influences the energy demand for space heating (i.e., the principal end-user of energy). In this regard, Norway and Sweden, countries whose HDD are similar to that of Edmonton, have requirements for RSI_{total} of ~25% and ~15% higher, respectively, than the requirements set by the ABC 2014. This disparity is even more significant when values for exterior walls are analyzed, given that the ABC 2014 sets the lowest requirement for this specific building envelope element among the jurisdictions compared. Hence, the introduction of strict RSI values for building envelope is particularly important for upcoming versions of the ABC.

On the other hand, limited EUI (kWh/m^2/year) influences housing energy consumption, rather than specifying construction details as in the case of RSI requirements. The introduction of EUI as a code requirement allows flexibility in design, since users and builders are free to choose which area they are willing to invest in (building envelope, efficient domestic hot water systems, and/or utilization of renewable energy), provided that the limited EUI is not exceeded. This design freedom is possible since the EUI specifies a limit to annual energy consumption based on heated floor area. Therefore, energy consumption is first determined and set as a target in the initial design phase, and then materials and systems are specified to accomplish an energy goal. The introduction of this metric in building codes thus also results in a shift in designing flow, as energy consumption begins to act as a design input rather than a design output. In this context, energy-related studies to investigate improvements in terms of current construction practice, materials, technologies, and domestic hot water systems are encouraged. Therefore, the introduction of limited EUI aligned with strict RSI requirements for building envelope is highly recommended, since, if these two approaches are applied together, energy consumption and energy demand are effectively addressed.

This thesis also suggests inclusion of renewable energy sources in future building energy codes, e.g., solar panels, and limitation of fossil fuel usage for space heating purposes. In this regard, different approaches are applied in Nordic countries, such as (a) reduction of RSI requirements for homes whose primary energy source is renewable, (b) prohibition of oil- and gas-fired boilers in new housing, and (c) calculation of maximum allowable EUI based on weighting factors that vary according to the energy source used (Boverket 2012; Danish Energy Agency 2016; Strand and Isachsen 2013; GBPN 2016; Institute for Energy Technology 2015; Haakana and Laitila 2013). In contrast, Section 9.36 of the ABC 2014 does not include the use of renewable energy sources as a requirement, nor as an alternative to measure energy performance or as a compliance option. Thus, this research recommends the introduction of renewable energy sources in upcoming versions of the ABC in order to diminish usage of fossil fuels in the province, minimizing the environmental impact of the residential sector.

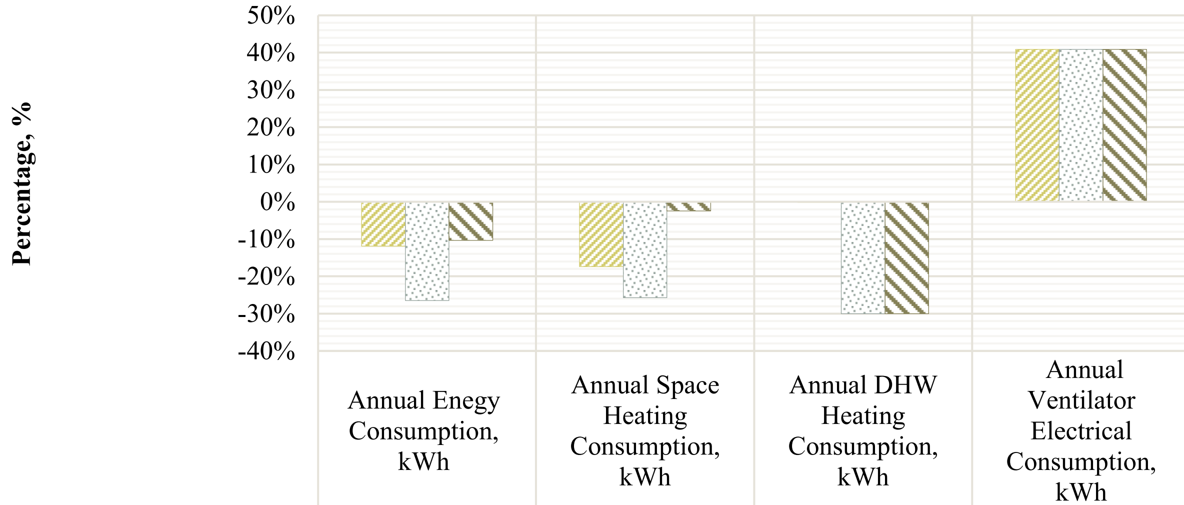
Another recommended approach to improve housing energy performance is the definition by governments and other regulatory institutions of an energy code progression plan. This is an essential step in efforts to balance information among all stakeholders, given that a progression plan anticipates requirements that will be mandatory in forthcoming versions of building codes. The construction industry will then be able to plan in advance for future alterations, reducing potential negative impacts on construction practice and shortening the duration of code transition periods. Furthermore, investigations of new materials and design solutions, technologies, and systems will also be stimulated by this practice as academia and industry are able to work together to develop suitable solutions in a cost-effective manner.

Finally, this research also encourages efforts to disseminate information pertaining to energy-efficient buildings to homebuyers as a method to boost housing energy performance. When acquiring a new home, conscientious homebuyers are then able to make their decision based on actual information rather than on pre-conceptions. Moreover, user behaviour during the operation phase has a significant impact on housing energy performance.

6.1.2. Discussion on Identified Least-Construction-Cost Code-Compliant Upgrades

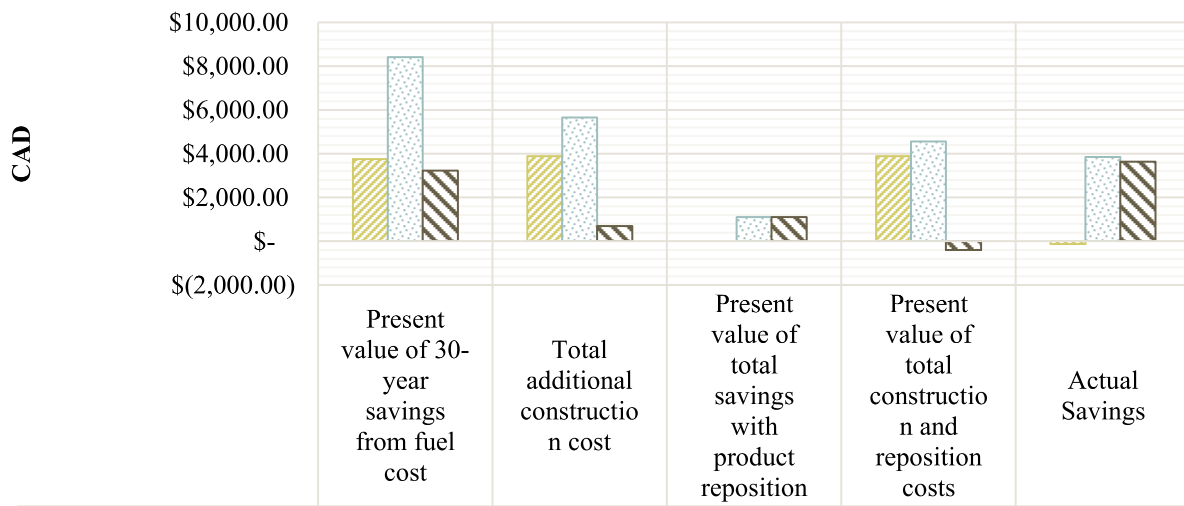
The case studies performed in this research investigate three approaches for code-compliance: (1) least-construction-cost prescriptive upgrades for building envelope (attic ceiling, above- and below-grade walls, and windows); (2) carry-out approach 1 with energy-efficient tankless domestic hot water system and optimal window sizing for less lifecycle operation cost; and (3) simplest least-construction-cost upgrade for code-compliant energy performance. Thus, for assessment purposes, the case study simulation results are compared to those of Model BL, which represents the reference house built based on current construction practice (Figure 6.1). In this context, Model CS1 simulates the energy performance of the reference house built with the upgraded building envelope configuration (approach 1, Case Study 1); Model CS2 simulates the implementation of approach 2 in the reference house (Case Study 2); and Model CS3 simulates the implementation of approach 3 in the reference house (Case Study 3).

Based on the findings presented in Chapter 5 and in Figure 6.1 and Figure 6.2, it is concluded that the investment needed to meet the energy requirements of the ABC 2014, as well as the energy performance of future homes in Edmonton, varies considerably based on the path selected for code-compliance. If the primary objective is to comply with the code by the prescriptive path (approach 1, Case Study 1), this research recommends the application of the identified least-construction-cost upgrades for the building envelope identified in Section 4.1. As demonstrated in Figure 6.1, a reduction of ~12% in total energy consumption and an EnerGuide rating of 80 are accomplished (Figure 6.3). Regarding economic aspects, the upgrades investigated in Case Study 1 (Model CS1) have the lowest ROI, consequently the highest payback time, and the lowest actual savings in present value (see Figure 6.4, Figure 6.5, and Figure 6.6).



	Annual Enegy Consumption, kWh	Annual Space Heating Consumption, kWh	Annual DHW Heating Consumption, kWh	Annual Ventilator Electrical Consumption, kWh
Model CS1 to Model BL	-12%	-17%	0%	41%
Model CS2 to Model BL	-27%	-26%	-30%	41%
Model CS3 to Model BL	-10%	-2%	-30%	41%

Figure 6.1: Case Study Simulation Results Compared to Model BL results.



	Present value of 30-year savings from fuel cost	Total additional construction cost	Present value of total savings with product reposition	Present value of total construction and reposition costs	Actual Savings
Model CS1 to Model BL	$3,752.98	$3,886.50	$-	$3,886.50	$(133.52)
Model CS2 to Model BL	$8,411.90	$5,658.82	$1,099.52	$4,559.30	$3,852.60
Model CS3 to Model BL	$3,231.25	$690.48	$1,099.52	$(409.04)	$3,640.29

Figure 6.2: Case Studies – Comparison of Monetary Results.

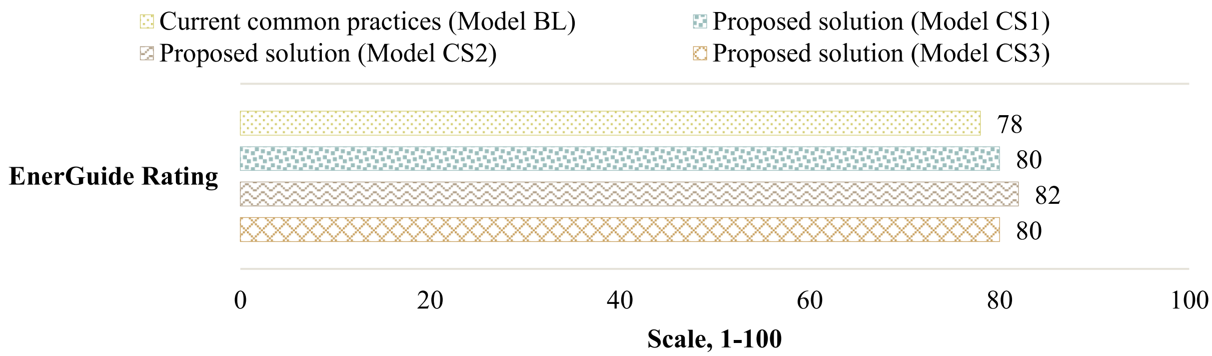


Figure 6.3: Case Studies – EnerGuide Rating Comparison (HOT2000 Results).

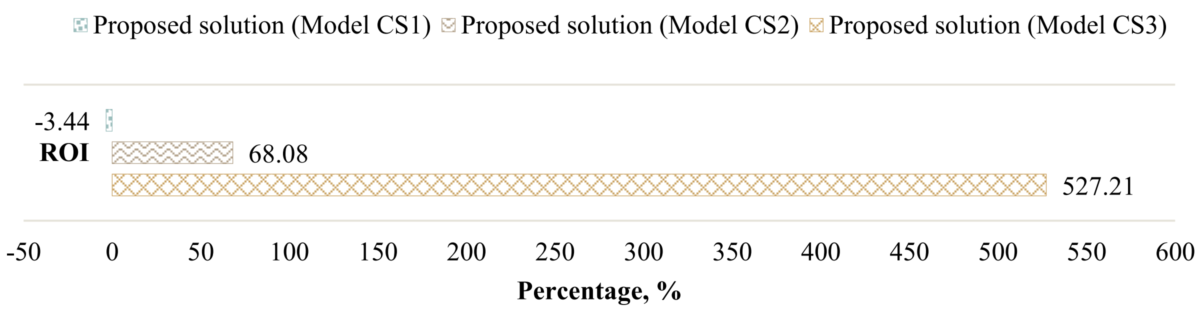


Figure 6.4: Case Studies – ROI Comparison.

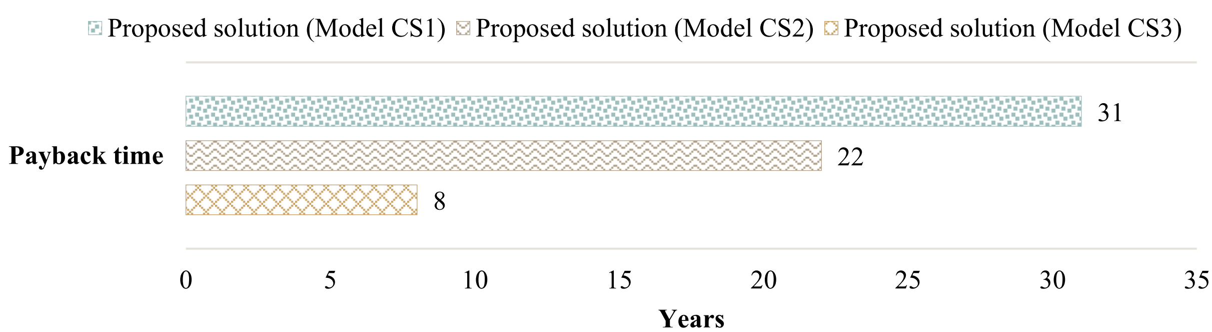


Figure 6.5: Case Studies – Payback Time Comparison.

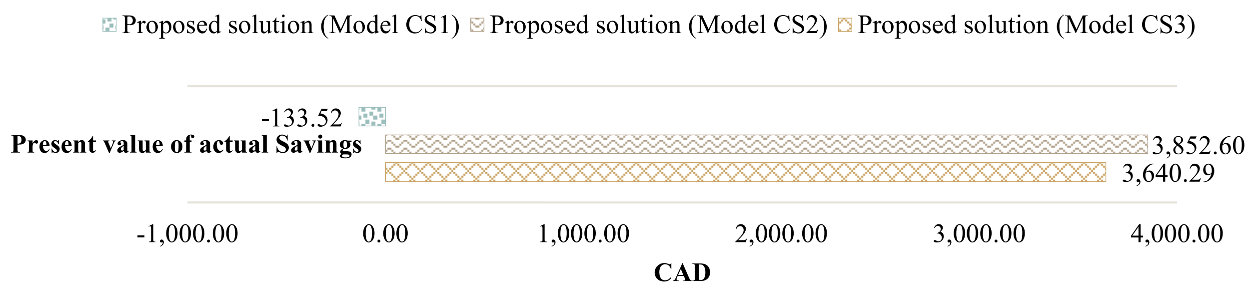


Figure 6.6: Case Studies – Actual Savings Comparison.

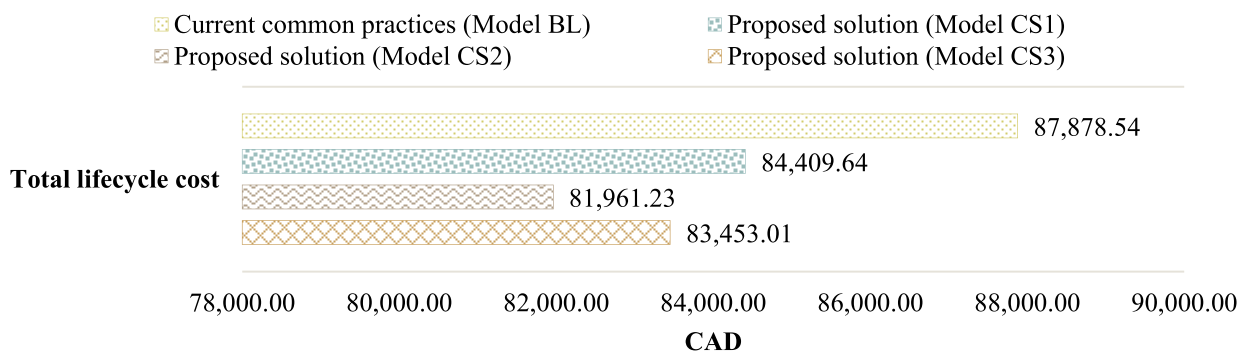


Figure 6.7: Case Studies – Total lifecycle cost.

Alternatively, if the aim is to comply with the ABC 2014 by the prescriptive path, and at the same time to enhance energy performance and maximize future savings from fuel costs (approach 2, Case Study 2), this research recommends the deployment of three upgrades to common construction practice: (1) least-construction-cost prescriptive upgrades for building envelope, (2) highly efficient tankless condensing DHW systems, and (3) optimal window sizing. Case Study 2 (Model CS2) investigates the implementation of these three upgrades in the reference house. As a result of these upgrades, a reduction of ~27% in total energy consumption is obtained comparing the results of Model CS2 to those of Model BL (Figure 6.1). This enhancement of energy performance also reflects on the EnerGuide rating of the reference house (Figure 6.3) and on the total lifecycle cost (Figure 6.7). Moreover, although the additional construction cost of the upgrades investigated in Model CS2 is higher than other upgrades identified in this thesis, the present value of 30-year savings and the actual savings are increased, reaching the highest levels of all the simulation models developed in this research (Figure 6.2 and Figure 6.6).

In cases where additional construction cost is a constraint, this research recommends investment to increase the airtightness to code level (2.5 ACH at 50 Pa) as well as in energy-efficient tankless condensing DHW systems as investigated in Case Study 3. This least-construction-cost upgrade meets the ABC 2014 energy requirements by the performance path with minimal capital investment (Model CS3 in Figure 6.2). The introduction of efficient tankless DHW also results in savings from equipment repositions, reflecting a negative total investment value (Figure 6.2). Nonetheless, regarding fuel cost savings in the operation phase, among the models analyzed in this research Model CS3 has the lowest accumulated 30-year savings. Yet the present value of actual savings of this model, which also accounts for expenses from construction and savings from equipment repositions, is estimated to be ~2,726% higher than the actual savings of Model CS1 (Figure 6.6). Furthermore, the upgrade investigated in Model CS3 presents the highest ROI, and consequently the lowest payback time (Figure 6.4 and Figure 6.5). The applicability of identified least-construction-cost code-compliant upgrades per objective and compliance path (i.e., prescriptive or energy performance) is visually summarized in Figure 6.8.

It is important to clarify the limitations of the findings summarized in this subsection. The investigation conducted to identify least-construction-cost code-compliant upgrades to be deployed in current construction practice accounts for the climatic conditions in Edmonton ($5,000 \leq HDD \leq 5,999$). Therefore, other climate zones would have different requirements for building envelope and domestic hot water system, which, most likely, would alter the selection of potential upgrades. Consequently, the additional construction costs and the energy consumption would also be different. Thus, analyses of additional construction cost, operation savings from fuel costs, and the ROI and payback time of upgrades are climate- and location-dependent. Nevertheless, by following the methodology proposed in Section 4.6, least-construction-cost code-compliant upgrades suitable for other climatic conditions and locations can be easily identified.

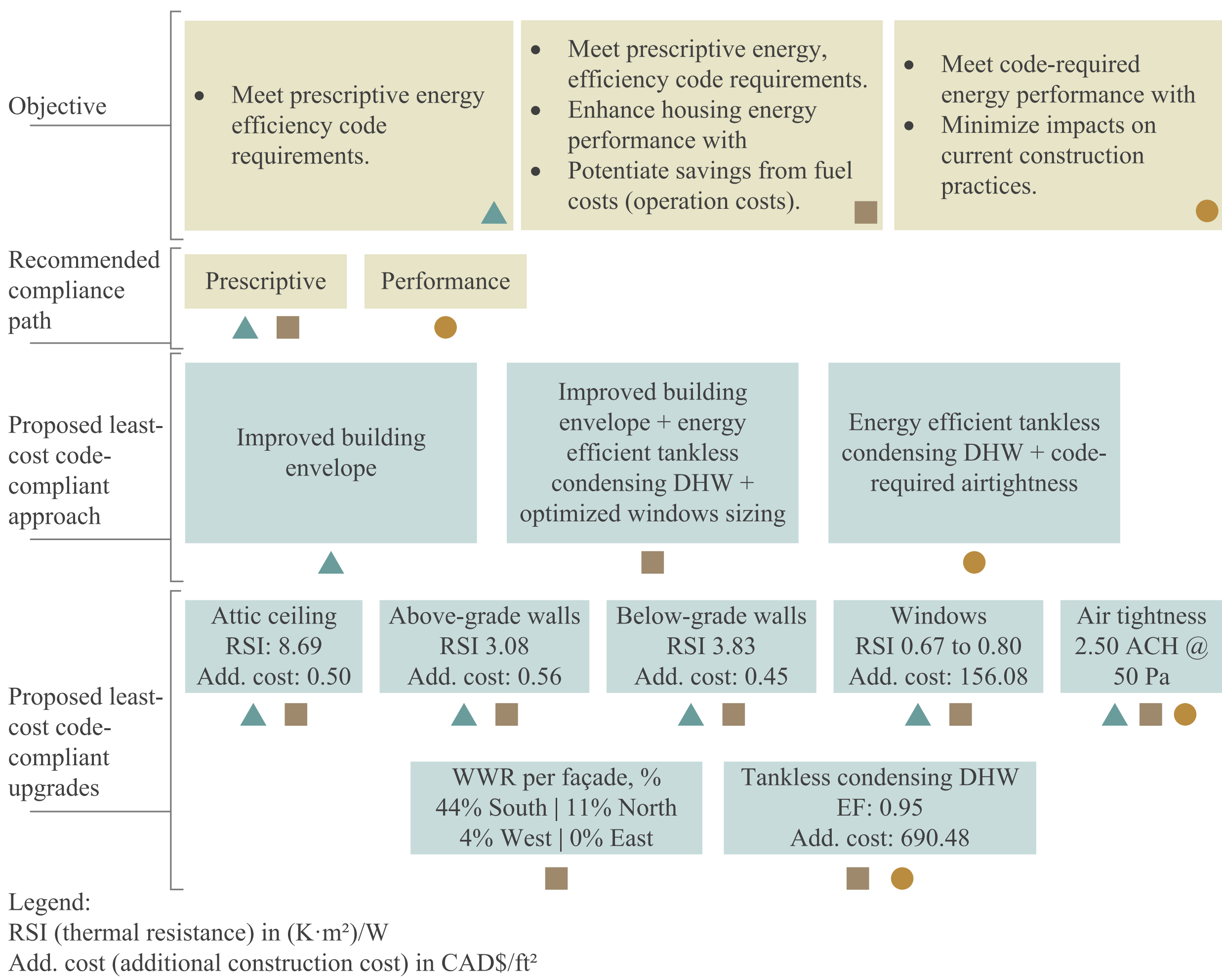


Figure 6.8: Applicability of Identified Upgrades per Objective and Compliance Path.

6.2. Research Contributions

This research presents a comprehensive review of energy requirements set by building codes regulating housing energy performance in cold-climate regions. In this context, the ABC 2014 is assessed in relation to other building code energy requirements, and recommendations for upcoming versions of the ABC are proposed. This study also assesses the impacts of the ABC 2014 on energy performance and on current construction practice for new housing in Edmonton, and identifies least-construction-cost code-compliant upgrades. In this context, the key contributions of this research are:

- Definition of the current construction practices commonly applied to new housing in Edmonton: By defining these practices, a baseline for the upgrades identified in this research is established. This baseline can be used in future research on energy performance of housing in Edmonton.

- Identification of least-construction-cost upgrades to be deployed in current construction practice for the purpose of meet energy code requirements by the prescriptive and performance paths.

- Evaluation of the impacts of the ABC 2014 energy requirements on current construction practice in Edmonton: In this regard, additional construction costs, energy performance, total savings, ROI, and payback time are analyzed for a new home built using three different approaches that identify the following scenarios:

    1) least-construction-cost prescriptive upgrades for building envelope;

2) least-construction-cost upgrades for building envelope, optimized window sizing, and energy-efficient tankless domestic hot water system; and
3) simplest least-construction-cost upgrade for code-compliant energy performance.

This research also develops a methodology to identify code-compliant least-construction-cost and best energy performance upgrade solutions through the investigation of a local home design. This methodology is also applicable to other locations and climatic conditions.

6.3. Recommendations for Future Research

This research focuses on assessing the impacts of the ABC 2014 energy requirements on current construction practice for new housing in Edmonton. Moreover, the identified least-construction-cost code-compliant upgrades aim to minimize the additional capital investment required to meet energy code requirements rather than to maximize energy savings. Thus, this thesis recommends future studies to investigate the following:

- *Performance path*. Although the performance path is analyzed in this research, it is pursued by identifying the least-construction-cost prescriptive upgrade that, if deployed in current construction practice, would achieve the code-compliant energy performance. Thus, further investigation on energy solutions to achieve the code-compliant energy performance regardless of compliance with the parameters specified in the prescriptive path is encouraged.

- *Design solutions*. This would include, for example, rearrangement of spaces and windows in a manner that minimizes heat loss and maximizes solar heat gain, thereby reducing annual energy consumption and satisfying the energy performance requirements in the ABC 2014.

- *Assessment of window configurations* other than triple-pane with 13 mm argon and vinyl frame. This window type is investigated as an upgrade in this research; however, other window configurations may also meet the code requirement in a cost-effective manner.

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APPENDIX A: Additional Information on the Ref_erence House

A.1. Reference House Blueprints

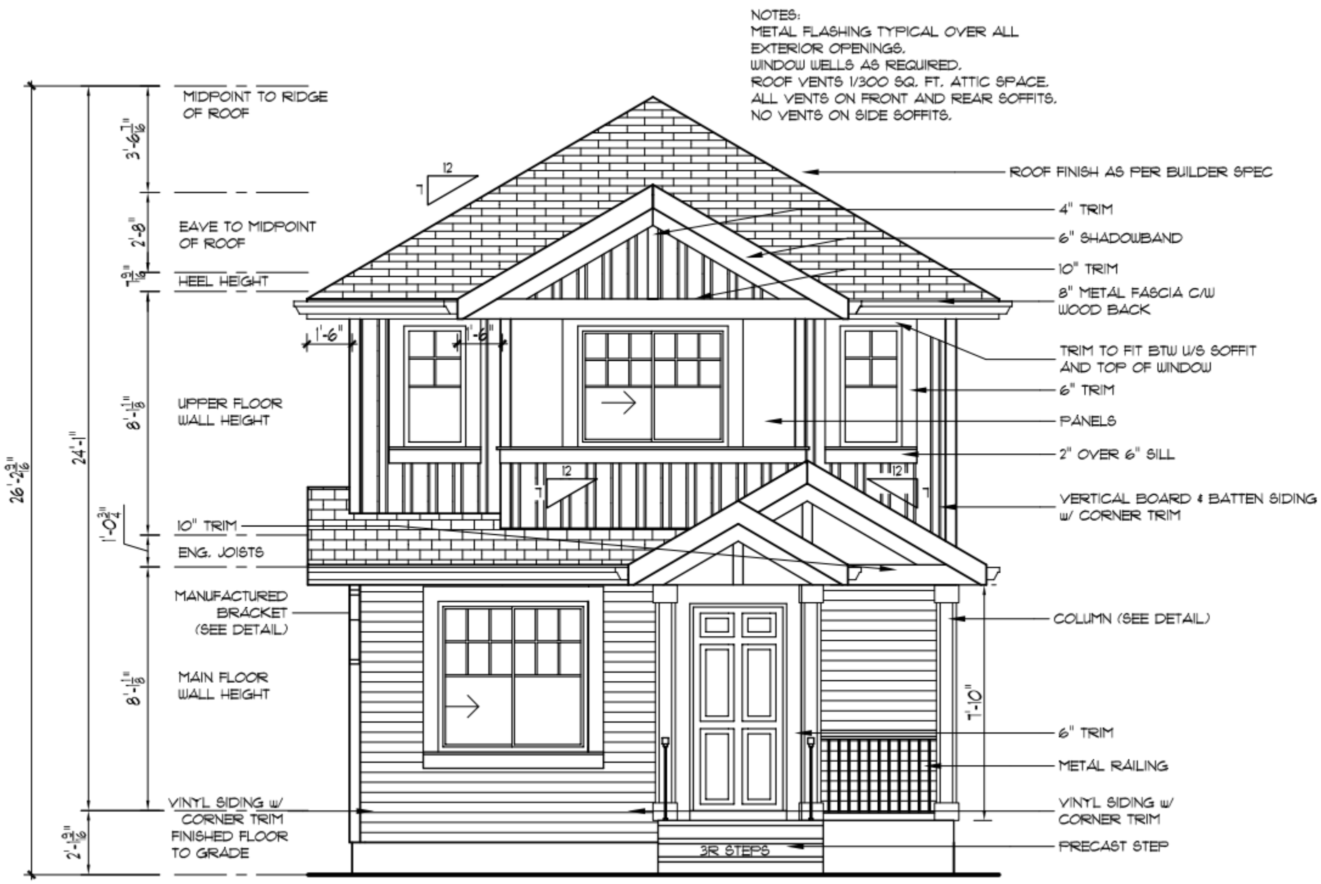


Figure A.1: South Elevation (Courtesy of Landmark Group of Companies).

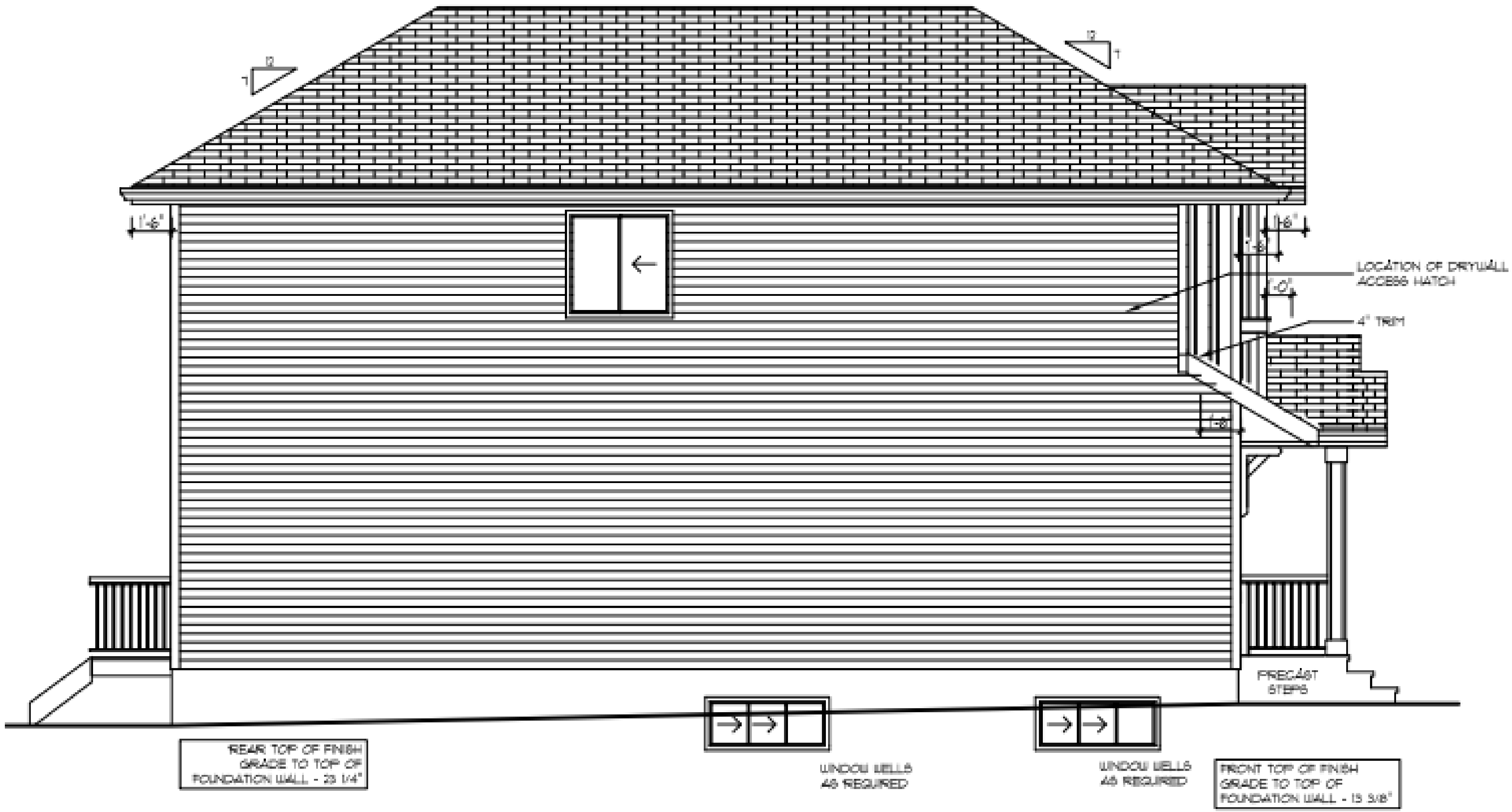
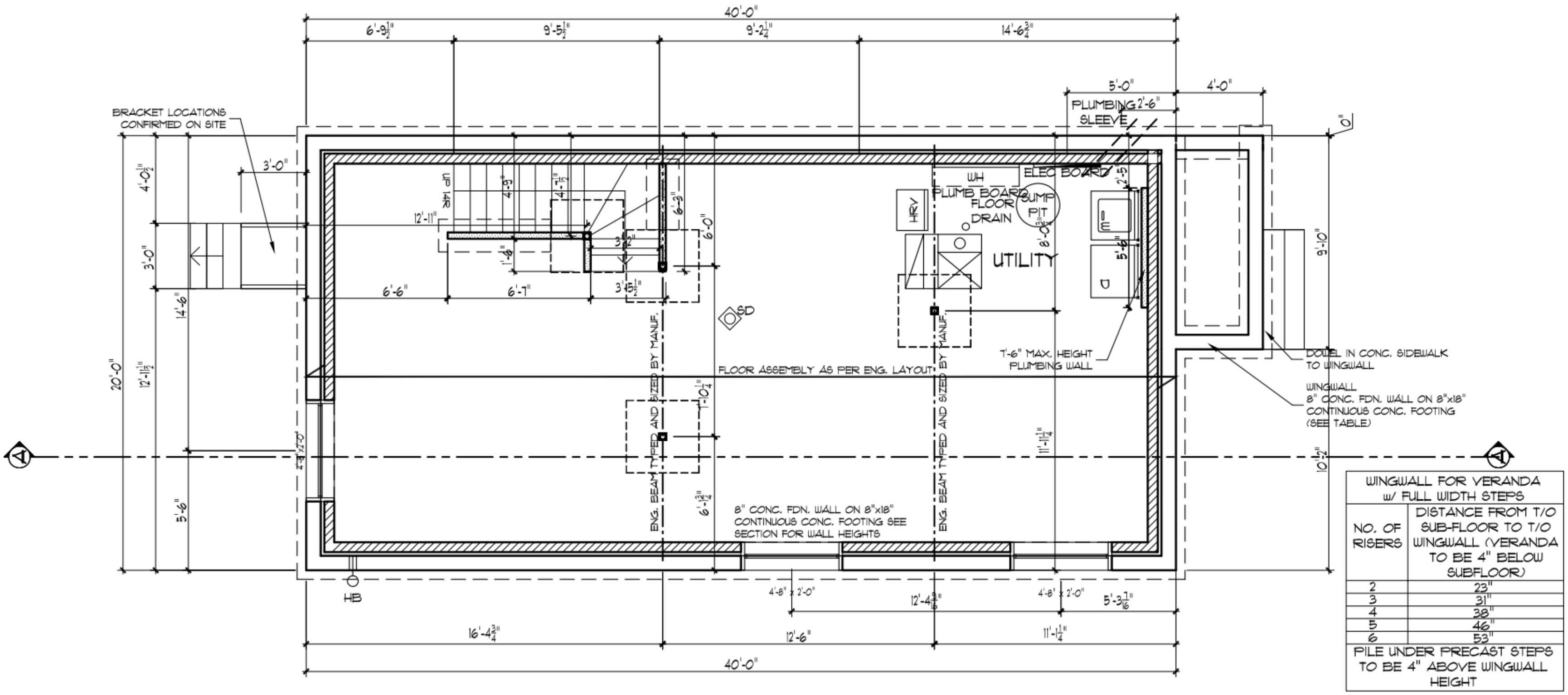


Figure A.2: West Elevation (Courtesy of Landmark Group of Companies).



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	

Figure A.3: Basement Floor Plan (Courtesy of Landmark Group of Companies).

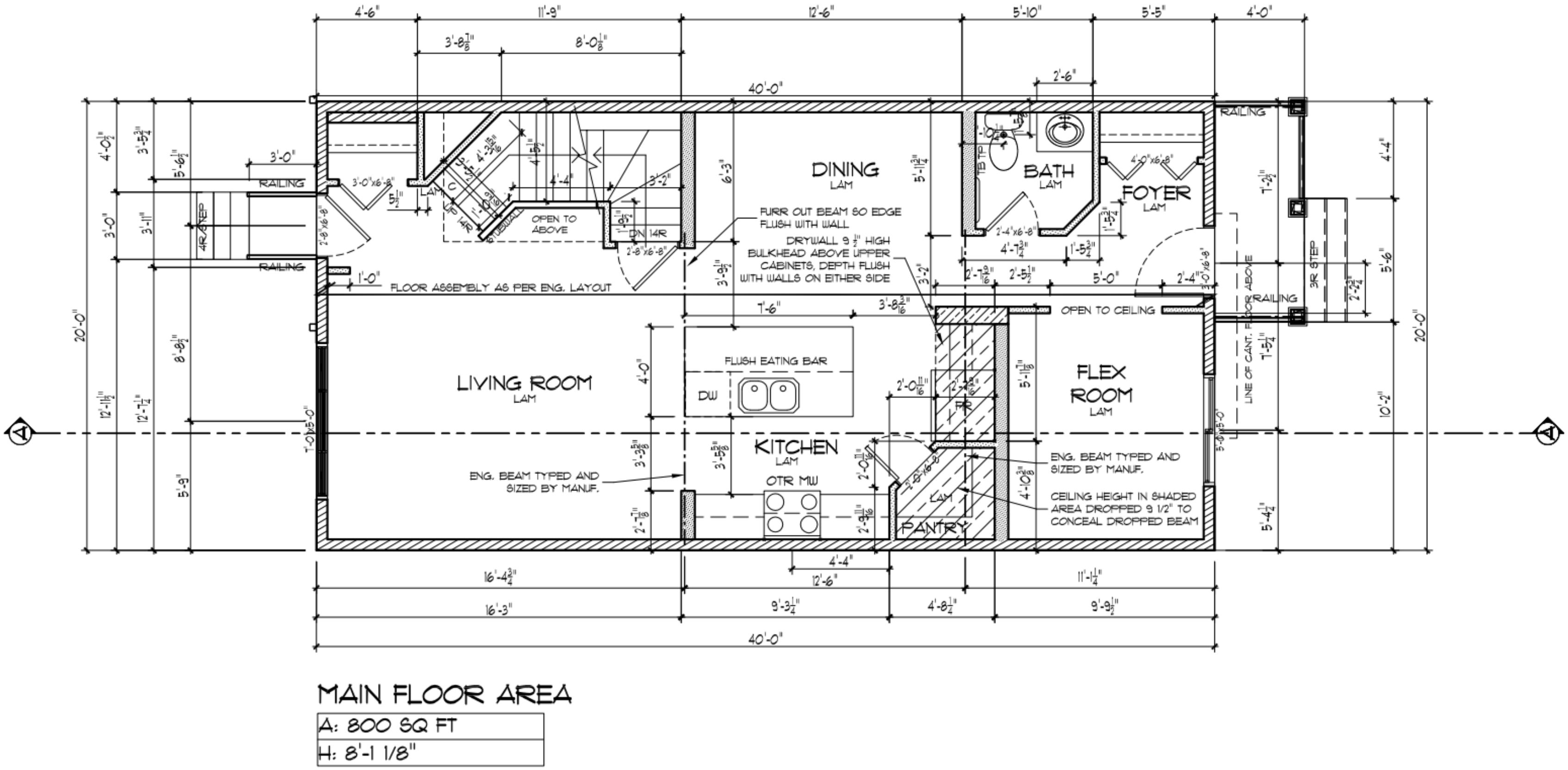


Figure A.4: Main Floor Plan (Courtesy of Landmark Group of Companies).

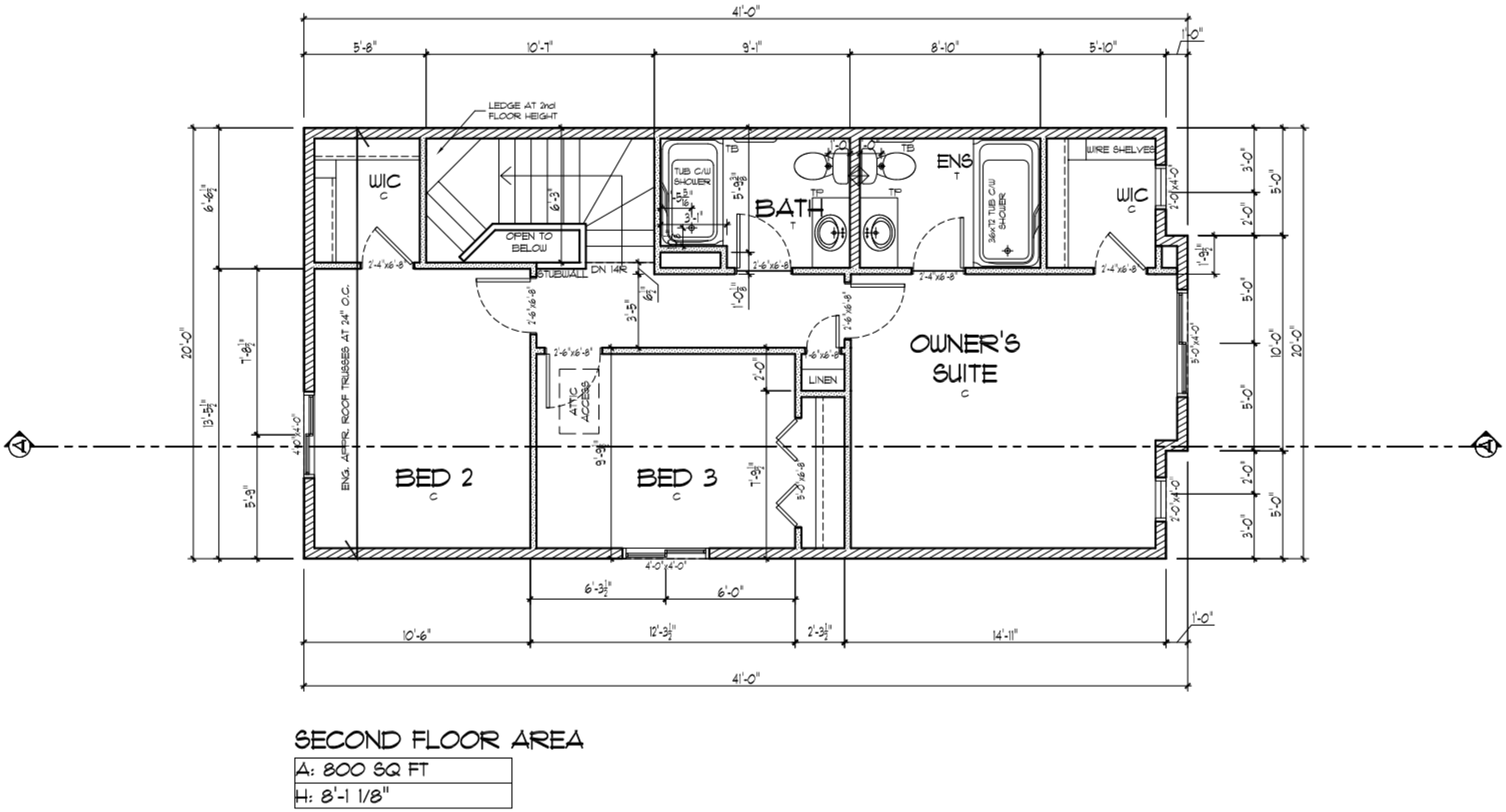


Figure A.5: Second Floor Plan (Courtesy of Landmark Group of Companies).

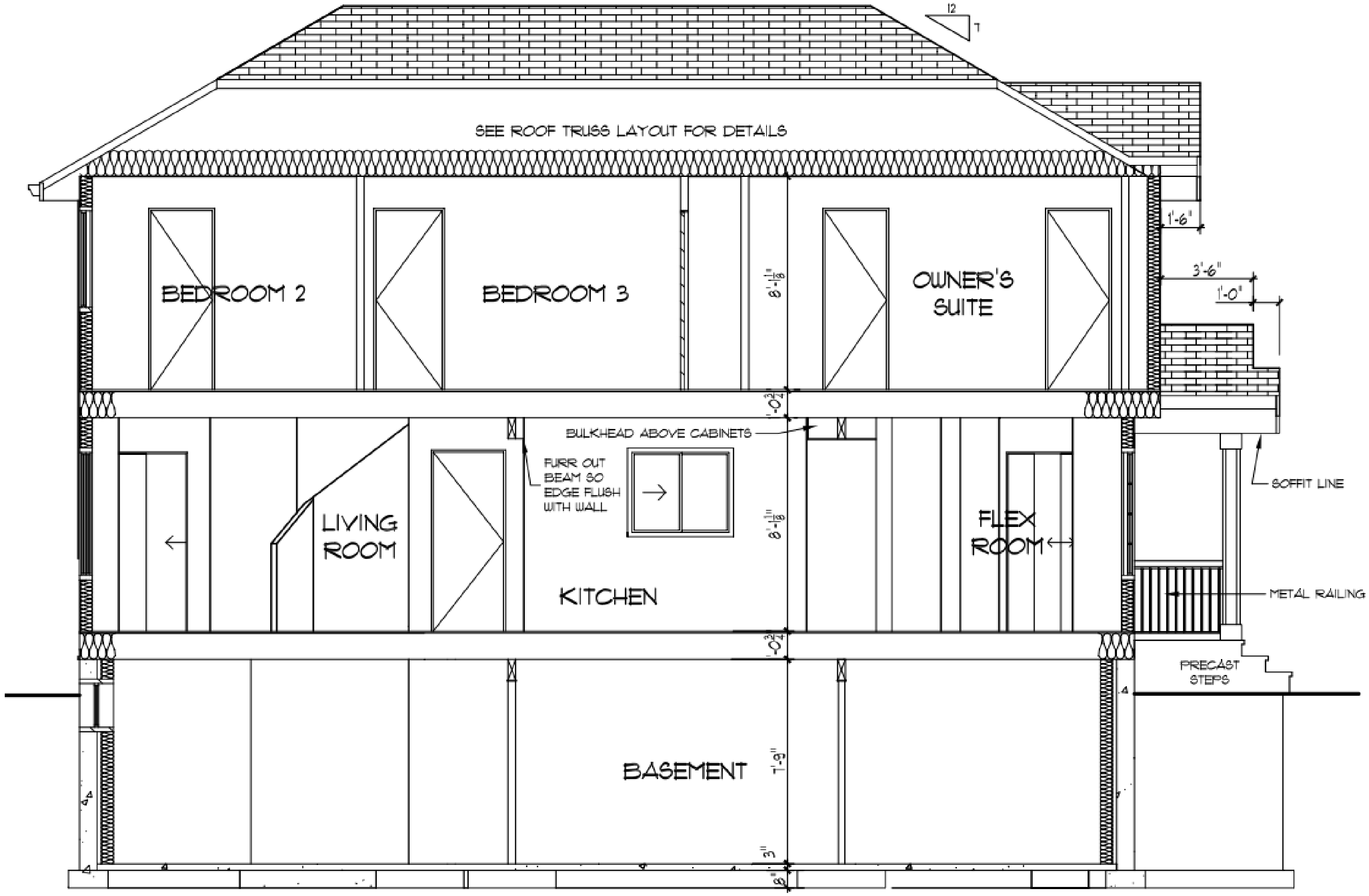


Figure A.6: Cross Section A (Courtesy of Landmark Group of Companies).

APPENDIX B: Additional Information on Potential Least-Construction-Cost Upgrades

B.1. Determination of Effective RSI Values

As stated in Subsection 3.1.3, the effective RSI values of building envelope elements are calculated in this thesis as per the parallel-path flow, as recommended by the ABC 2014-Appendix A-9.36.2.4.(1). The parallel-path flow accounts for thermal resistance of stud and cavity areas separately, as detailed in Figure B.1. Thus, to determine the effective RSI value of building envelope, percentage factors are applied to Equation (2)–Subsection 3.1.3. The factors used in this research are depicted in Table B.1.

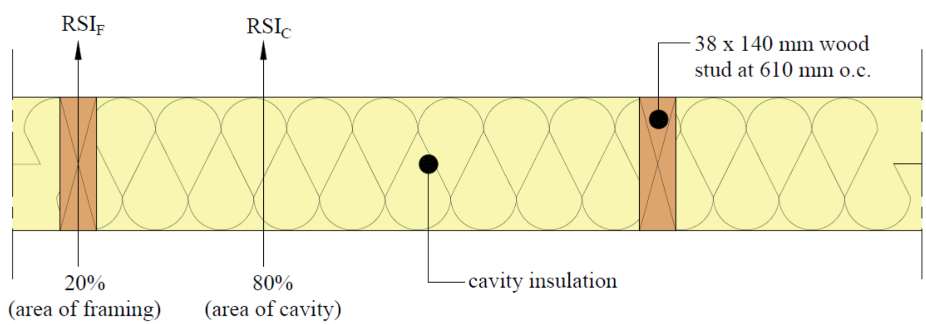


Figure B.1: Example of 38 × 140 mm (2 × 6 in.) with 610 mm (24 in.) on Center Spacing Wood Frame Wall Assembly.

Table B.1: Framing and Cavity Percentage Factors Used in this Research.

Wood-frame assemblies		**Frame spacing = 610 mm o.c. (24 in o.c.)**	
		% Area of Framing	% Area of Cavity
Floors	Lumber joists	10	90
Ceiling	Ceiling with typical trusses	11	89
Walls	Typical wood-frame	20	80
	Basement wood-frame inside concrete foundation wall	13	87

B.2. Detailed Information on Potential Upgrades for Building Envelope

In this section, detailed information on potential upgrades for attic ceiling (Figure B.2), above-grade exterior walls (Figure B.3), and below-grade exterior walls (Figure B.4) are presented regarding upgrade configurations, effective RSI values, and additional construction cost.

B.2.1. Attic Ceiling

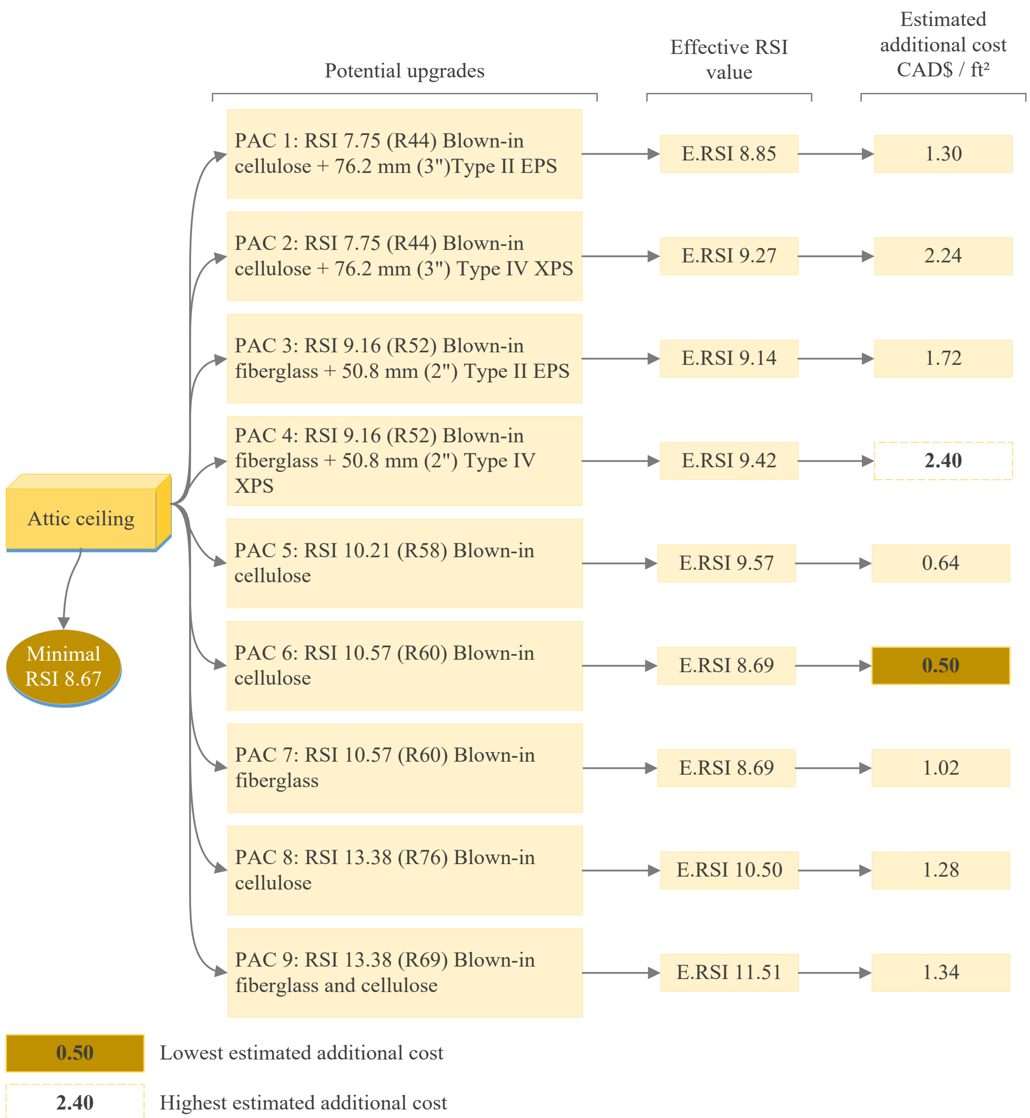


Figure B.2: Additional Information on Potential Upgrades for Attic Ceiling.

B.2.2. Above-grade Exterior Walls

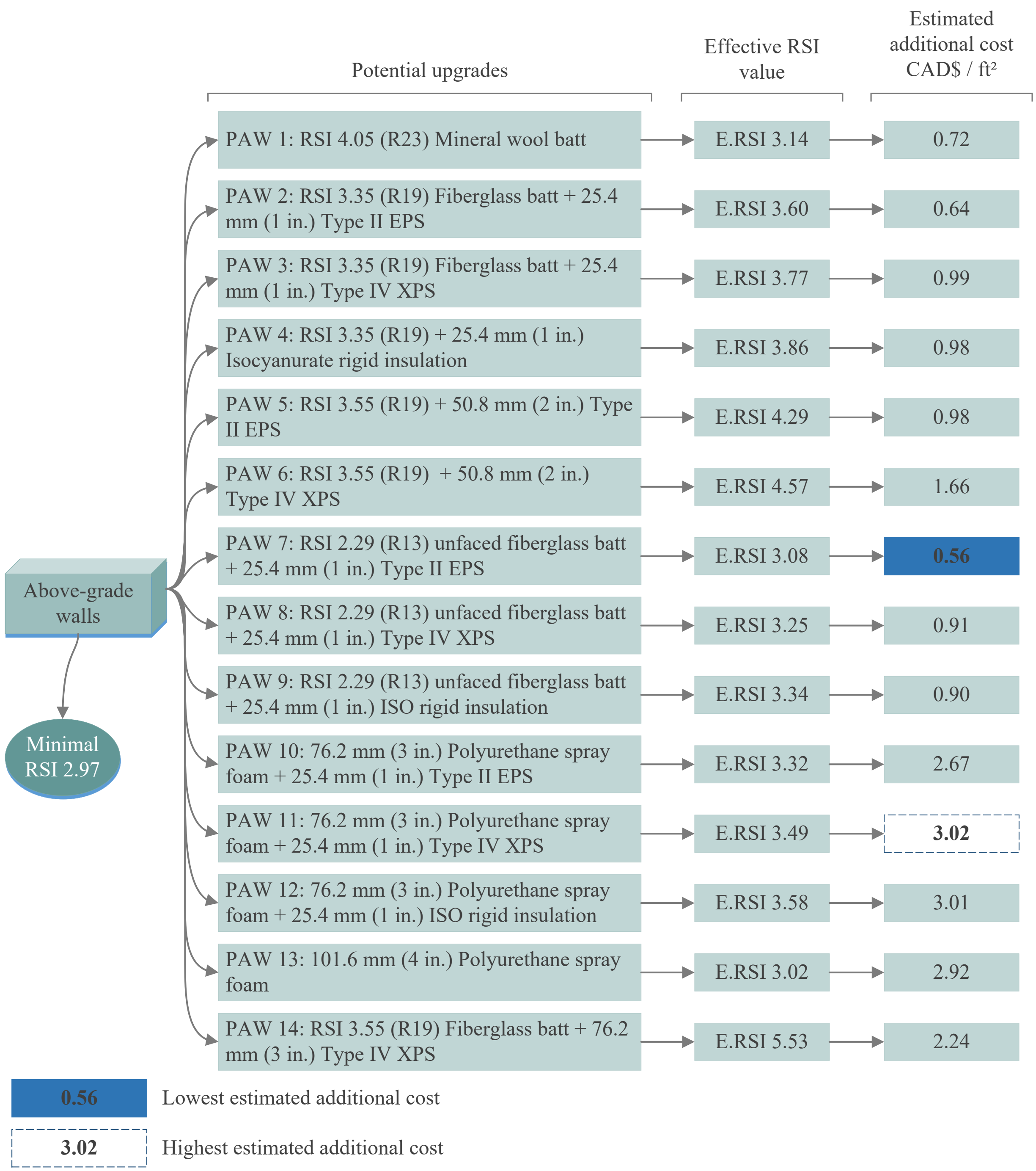


Figure B.3: Additional Information on Potential Upgrades for Above-Grade Exterior Walls.

B.2.3. Below-grade Exterior Walls

Below-grade walls → Minimal RSI 2.98

Upgrade solution	Effective RSI value	Estimated additional cost CAD$ / ft²
PBW 1: RSI 3.87 (R22) Kraft faced fiberglass batt	E.RSI 3.83	**0.45**
PBW 2: RSI 4.23 (R24) Kraft faced fiberglass batt	E.RSI 4.03	0.55
PBW 3: RSI 4.58 (R26) Kraft faced fiberglass batt	E.RSI 4.38	0.65
PBW 4: RSI 4.58 (R26) Unfaced fiberglass batt	E.RSI 4.38	0.55
PBW 5: RSI 2.64 (R15) Unfaced fiberglass batt + RSI 1.94 (R11) kraft faced fiberglass batt	E.RSI 4.21	0.66
PBW 6: RSI 5.28 (R30) Mineral wool batt	E.RSI 4.91	1.29
PBW 7: RSI 2.64 (R15) Mineral wool batt + RSI 1.94 (R11) kraft faced fiberglass batt	E.RSI 4.21	0.87
PBW 8: RSI 2.29 (R13) Unfaced fiberglass batt + RSI 2.64 (R15) unfaced fiberglass batt	E.RSI 4.33	0.71
PBW 9: RSI 2.29 (R13) Unfaced fiberglass batt + RSI 2.64 (R15) mineral wool batt	E.RSI 4.33	0.92
PBW 10: RSI 2.29 (R13) Kraft faced fiberglass batt + RSI 2.64 (R15) unfaced fiberglass batt	E.RSI 4.33	0.76
PBW 11: RSI 2.29 (R13) Kraft faced fiberglass batt + RSI 2.64 (R15) mineral wool batt	E.RSI 4.33	0.97
PBW 12: RSI 1.94 (R11) Kraft faced fiberglass batt + 50.8 mm (2 in.) Type II EPS	E.RSI 3.29	0.93
PBW 13: RSI 1.94 (R11) Kraft faced fiberglass batt + 50.8 mm (2 in.) Type IV XPS	E.RSI 3.57	1.61
PBW 14: RSI 1.94 (R11) Kraft faced fiberglass batt + 50.8 mm (2 in.) ISO rigid insulation	E.RSI 3.83	1.31
PBW 15: RSI 2.29 (R13) unfaced fiberglass batt + 50.8 mm (2 in.) Type II EPS	E.RSI 3.49	0.98
PBW 16: RSI 2.29 (R13) unfaced fiberglass batt + 50.8 mm (2 in.) Type IV XPS	E.RSI 3.77	**1.66**
PBW 17: RSI 2.29 (R13) unfaced fiberglass batt + 25.4 mm (1 in.) ISO rigid insulation	E.RSI 3.06	0.98
PBW 18: RSI 2.64 (R15) unfaced fiberglass batt + 25.4 mm (1 in.) Type II EPS	E.RSI 2.98	0.80
PBW 19: RSI 2.64 (R15) unfaced fiberglass batt + 25.4 mm (1 in.) Type IV XPS	E.RSI 3.15	1.15
PBW 20: RSI 2.64 (R15) unfaced fiberglass batt + 25.4 mm (1 in.) ISO rigid insulation	E.RSI 3.24	1.14

0.45 Lowest estimated additional cost

1.66 Highest estimated additional cost

Figure B.4: Additional Information on Potential Upgrades for Below-Grade Exterior Walls.

APPENDIX C: Additional Information on Sensitivity Analyses

Detailed information on the simulation models developed to conduct the sensitivity analyses of window sizing (Figure C.1) and least-construction-cost prescriptive upgrades (Figure C.2) are presented in this section.

C.1. Sensitivity Analyses of Window Sizing

Model Name	Description	WWR, % (Façade area)				WWR, % (Exterior wall area)			
		South	West	North	East	South	West	North	East
Baseline models									
BL	Reference house built with current construction practices	16.0	4.0	16.0	0.0	2.6	1.5	2.6	0.0
Prescriptive path ABC 2014									
CD	Reference house built with the least-cost prescriptive upgrades for building envelope	16.0	4.0	16.0	0.0	2.6	1.5	2.6	0.0
Windows' sizing: Investigation of windows' sizing per façade orientation									
W1	Study of basement windows: Quantity of windows is the same as in the reference house original design, but their orientation varied.	18.0	3.0	16.0	0.0	3.0	1.1	2.6	0.0
W2	Study of basement windows: Quantity of windows is the same as in the reference house original design, but their orientation varied.	18.0	4.0	13.0	0.0	3.0	1.5	2.2	0.0
W3	Study of basement windows: Quantity of windows is the same as in the reference house original design, but their orientation varied.	18.0	2.0	18.0	0.0	3.0	0.7	3.0	0.0
W4	Study of basement windows: Quantity of windows is the same as in the reference house original design, but their orientation varied.	18.0	2.0	13.0	2.0	3.0	0.7	2.2	0.8
W5	Study of main- and upper-floor windows: Basement of Model 2 and increased windows size on south orientation (flex room, owners suite [picture and slider], WIC)	25.0	4.0	11.0	0.0	4.1	1.5	1.8	0.0
W6	Study of main- and upper-floor windows: Basement of Model 2, Model 5 plus increased owners suite (slider) window area (south orientation)	26.0	4.0	11.0	0.0	4.3	1.5	1.8	0.0
W7	Study of main- and upper-floor windows: Basement of Model 2, Model 6 plus increased flex room	27.0	4.0	11.0	0.0	4.5	1.5	1.8	0.0
W8	Study of main- and upper-floor windows: Basement of Model 2, Model 7 plus increased flex room and owners suite (slider) windows areas (south orientation)	29.0	4.0	11.0	0.0	4.9	1.5	1.8	0.0
W9	Study of main- and upper-floor windows: Basement of Model 2, Model 8 plus increased flex room and owners suite (slider) windows areas (south orientation)	32.0	4.0	11.0	0.0	5.2	1.5	1.8	0.0
W10	Study of main- and upper-floor windows: Basement of Model 2, Model 9 changes plus increased basement window area (south orientation)	32.0	4.0	11.0	0.0	5.3	1.5	1.8	0.0
W11	Study of main- and upper-floor windows: Basement of Model 2, Model 10 plus increased flex room and basement windows areas (south orientation)	36.0	4.0	11.0	0.0	5.9	1.5	1.8	0.0
W12	Study of main- and upper-floor windows: Basement of Model 2, Model 11 plus increased owners suite (picture) and WIC windows areas (south orientation)	38.0	4.0	11.0	0.0	6.3	1.5	1.8	0.0
W13	Study of main- and upper-floor windows: Basement of Model 2, Model 12 plus increased flex room and basement windows areas (south orientation)	44.0	4.0	11.0	0.0	7.4	1.5	1.8	0.0

Figure C.1: Information on Simulation Models Developed for the Sensitivity Analyses of Window Sizing.

C.2. Sensitivity Analyses of Least-Construction-Cost Prescriptive Upgrades

Model Name	Description
Baseline models	
BL	Reference housebuilt with current construction practices
Prescriptive path ABC 2014	
CD	Reference housebuilt with the least-cost prescriptive upgrades for building envelope
Performance path: Simplest Least-Cost Upgrade to Accomplish Code-Required Energy Performance	
UEP1	Reference housebuilt with current construction practices + 2.5 ACH (minimal 2014 ABC requirement for air tightness) + tankless condensing DHW + triple pane windows (below- and above-grade floors)
UEP2	Reference housebuilt with current construction practices + 2.5 ACH (minimal 2014 ABC requirement for air tightness) + tankless condensing DHW + triple pane windows (above-grade floors) + least-cost code compliant option for walls (above-grade)
UEP3	Reference housebuilt with current construction practices + 2.5 ACH (minimal 2014 ABC requirement for air tightness) + tankless condensing DHW + least-cost identified prescriptive upgrade for walls (above- and below-grade)
UEP4	Reference housebuilt with current construction practices + 2.5 ACH (minimal 2014 ABC requirement for air tightness) + tankless condensing DHW + least-cost identified prescriptive upgrade for attic ceiling
UEP5	Reference housebuilt with current construction practices + 2.5 ACH (minimal 2014 ABC requirement for air tightness) + tankless condensing DHW + triple pane windows (above-grade floors)
UEP6	Reference housebuilt with current construction practices + 2.5 ACH (minimal 2014 ABC requirement for air tightness) + tankless condensing DHW
UEP7	Reference housebuilt with current construction practices + 2.5 ACH (minimal 2014 ABC requirement for air tightness) + least-cost identified prescriptive upgrade for attic ceiling
UEP8	Reference housebuilt with current construction practices + 2.5 ACH (minimal 2014 ABC requirement for air tightness) + (above- and below-grade)
UEP9	Reference housebuilt with current construction practices + 2.5 ACH (minimal 2014 ABC requirement for air tightness) + triple pane windows (above-grade floors) + least-cost code compliant option for walls (above-grade)
UEP10	Reference housebuilt with current construction practices + 2.5 ACH (minimal 2014 ABC requirement for air tightness) + triple pane windows (above-grade floors)
UEP11	Reference housebuilt with current construction practices + 2.5 ACH (minimal 2014 ABC requirement for air tightness) + triple pane windows (below- and above-grade floors)

Figure C.2: Information on Simulation Models Developed for the Sensitivity Analyses of Identified Least-Construction-Cost Prescriptive Upgrades.

APPENDIX D: Total Lifecycle Cost

Detailed information on calculations conduct to estimate the total lifecycle cost of the reference house (which accounts for additional construction cost, operation costs of fuel, and piece of equipment reposition) are presented in this section.

D.1. Total Lifecycle Cost of the Reference House - Current Construction Practice

Inflation rate	1.87%															
Natural gas escalation rate	5.08%															
Electricity escalation rate	1.35%															
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Construction costs	0.00															
Annual energy cost - natural gas	1,049.63	1,102.95	1,158.98	1,217.86	1,279.72	1,344.73	1,413.05	1,484.83	1,560.26	1,639.52	1,722.81	1,810.33	1,902.29	1,998.93	2,100.47	2,207.18
Annual energy cost - electricity	1,090.99	1,105.72	1,120.65	1,135.77	1,151.11	1,166.65	1,182.40	1,198.36	1,214.54	1,230.93	1,247.55	1,264.39	1,281.46	1,298.76	1,316.30	1,334.07
Replacement costs	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1,077.17	0.00	0.00	0.00	0.00	0.00
Net annual cash flow	2,140.62	2,208.67	2,279.63	2,353.63	2,430.83	2,511.38	2,595.44	2,683.19	2,774.80	2,870.45	4,047.53	3,074.72	3,183.75	3,297.69	3,416.77	3,541.24
Present value of cash flow	2,140.62	2,168.13	2,196.70	2,226.38	2,257.20	2,289.19	2,322.38	2,356.82	2,392.55	2,429.59	3,363.00	2,507.82	2,549.08	2,591.84	2,636.13	2,682.01
Lifecycle cost	**87,878.54**															

	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Annual energy cost - natural gas	2,319.30	2,437.12	2,560.93	2,691.02	2,827.73	2,971.38	3,122.32	3,280.94	3,447.61	3,622.75	3,806.78	4,000.17	4,203.37	4,416.91	4,641.28
Annual energy cost - electricity	1,352.08	1,370.33	1,388.83	1,407.58	1,426.58	1,445.84	1,465.36	1,485.14	1,505.19	1,525.51	1,546.10	1,566.98	1,588.13	1,609.57	1,631.30
Replacement costs	0.00	0.00	0.00	0.00	1,296.43	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1,560.31
Net annual cash flow	3,671.38	3,807.45	3,949.76	4,098.60	5,550.74	4,417.21	4,587.68	4,766.07	4,952.80	5,148.25	5,352.88	5,567.14	5,791.50	6,026.47	7,832.90
Present value of cash flow	2,729.53	2,778.73	2,829.68	2,882.41	3,831.99	2,993.48	3,051.93	3,112.40	3,174.97	3,239.68	3,306.62	3,375.84	3,447.42	3,521.44	**4,492.97**

Figure D.1: Additional Information on Total Lifecycle Cost – Current Construction Practice.

D.2. Total Lifecycle Cost of the Reference House - Case Study 1

Inflation rate	1.87%															
Natural gas escalation rate	5.08%															
Electricity escalation rate	1.35%															
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Construction costs	3,886.50															
Annual energy cost - natural gas	956.65	1,005.25	1,056.31	1,109.98	1,166.36	1,225.61	1,287.87	1,353.30	1,422.05	1,494.29	1,570.20	1,649.96	1,733.78	1,821.86	1,914.41	2,011.66
Annual energy cost - electricity	1,094.43	1,109.20	1,124.18	1,139.36	1,154.74	1,170.33	1,186.13	1,202.14	1,218.37	1,234.81	1,251.48	1,268.38	1,285.50	1,302.86	1,320.45	1,338.27
Replacement costs	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Net annual cash flow	5,937.58	2,114.45	2,180.49	2,249.33	2,321.10	2,395.94	2,474.00	2,555.44	2,640.41	2,729.10	2,821.68	2,918.34	3,019.28	3,124.71	3,234.85	3,349.93
Present value of cash flow	5,937.58	2,075.64	2,101.17	2,127.72	2,155.30	2,183.96	2,213.72	2,244.61	2,276.68	2,309.95	2,344.47	2,380.27	2,417.40	2,455.89	2,495.78	2,537.12
Lifecycle cost	**84,409.64**															

	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Annual energy cost - natural gas	2,113.85	2,221.23	2,334.07	2,452.64	2,577.24	2,708.16	2,845.74	2,990.30	3,142.21	3,301.83	3,469.56	3,645.82	3,831.02	4,025.64	4,230.14
Annual energy cost - electricity	1,356.34	1,374.65	1,393.21	1,412.01	1,431.08	1,450.40	1,469.98	1,489.82	1,509.93	1,530.32	1,550.98	1,571.92	1,593.14	1,614.64	1,636.44
Replacement costs	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Net annual cash flow	3,470.19	3,595.88	3,727.28	3,864.66	4,008.31	4,158.56	4,315.71	4,480.12	4,652.14	4,832.15	5,020.54	5,217.73	5,424.16	5,640.28	5,866.58
Present value of cash flow	2,579.95	2,624.33	2,670.29	2,717.89	2,767.17	2,818.19	2,871.00	2,925.67	2,982.23	3,040.76	3,101.32	3,163.96	3,228.76	3,295.78	**3,365.09**

Figure D.2: Additional Information on Total Lifecycle Cost – Case Study 1.

D.3. Total Lifecycle Cost of the Reference House - Case Study 2

Inflation rate	1.87%															
Natural gas escalation rate	5.08%															
Electricity escalation rate	1.35%															
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Construction costs	5,658.82															
Annual energy cost - natural gas	844.30	887.19	932.26	979.62	1,029.38	1,081.68	1,136.62	1,194.37	1,255.04	1,318.80	1,385.79	1,456.19	1,530.16	1,607.89	1,689.58	1,775.41
Annual energy cost - electricity	1,092.92	1,107.67	1,122.63	1,137.78	1,153.14	1,168.71	1,184.49	1,200.48	1,216.69	1,233.11	1,249.76	1,266.63	1,283.73	1,301.06	1,318.62	1,336.43
Replacement costs	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Net annual cash flow	7,596.04	1,994.86	2,054.89	2,117.40	2,182.53	2,250.39	2,321.11	2,394.84	2,471.72	2,551.91	2,635.55	2,722.82	2,813.89	2,908.95	3,008.20	3,111.83
Present value of cash flow	7,596.04	1,958.25	1,980.14	2,002.92	2,026.63	2,051.28	2,076.91	2,103.55	2,131.23	2,159.97	2,189.82	2,220.80	2,252.95	2,286.31	2,320.91	2,356.79
Lifecycle cost	**81,961.23**															

	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Construction costs															
Annual energy cost - natural gas	1,865.60	1,960.37	2,059.96	2,164.60	2,274.56	2,390.11	2,511.53	2,639.11	2,773.18	2,914.06	3,062.09	3,217.65	3,381.10	3,552.86	3,733.35
Annual energy cost - electricity	1,354.47	1,372.75	1,391.28	1,410.07	1,429.10	1,448.40	1,467.95	1,487.77	1,507.85	1,528.21	1,548.84	1,569.75	1,590.94	1,612.42	1,634.18
Replacement costs	0.00	0.00	0.00	0.00	2,296.61	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Net annual cash flow	3,220.06	3,333.12	3,451.24	3,574.67	6,000.28	3,838.51	3,979.48	4,126.88	4,281.03	4,442.27	4,610.93	4,787.40	4,972.04	5,165.28	5,367.53
Present value of cash flow	2,394.00	2,432.56	2,472.53	2,513.95	4,142.33	2,601.30	2,647.33	2,694.99	2,744.34	2,795.42	2,848.29	2,903.01	2,959.64	3,018.22	**3,078.83**

Figure D.3: Additional Information on Total Lifecycle Cost – Case Study 2.

D.4. Total Lifecycle Cost of the Reference House - Case Study 3

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Inflation rate	1.87%															
Natural gas escalation rate	5.08%															
Electricity escalation rate	1.35%															
Construction costs	690.48															
Annual energy cost - natural gas	967.88	1,017.05	1,068.71	1,123.01	1,180.05	1,240.00	1,302.99	1,369.18	1,438.74	1,511.83	1,588.63	1,669.33	1,754.13	1,843.24	1,936.88	2,035.27
Annual energy cost - electricity	1,097.14	1,111.95	1,126.96	1,142.18	1,157.60	1,173.22	1,189.06	1,205.11	1,221.38	1,237.87	1,254.58	1,271.52	1,288.69	1,306.08	1,323.72	1,341.59
Replacement costs	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Net annual cash flow	2,755.50	2,129.00	2,195.68	2,265.18	2,337.65	2,413.22	2,492.05	2,574.30	2,660.12	2,749.70	2,843.21	2,940.85	3,042.82	3,149.33	3,260.59	3,376.86
Present value of cash flow	2,755.50	2,089.92	2,115.81	2,142.71	2,170.67	2,199.71	2,229.87	2,261.18	2,293.67	2,327.39	2,362.36	2,398.63	2,436.24	2,475.23	2,515.64	2,557.51
Lifecycle cost	**83,453.01**															

	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Annual energy cost - natural gas	2,138.66	2,247.31	2,361.47	2,481.43	2,607.49	2,739.95	2,879.14	3,025.40	3,179.09	3,340.59	3,510.29	3,688.61	3,876.00	4,072.90	4,279.80
Annual energy cost - electricity	1,359.70	1,378.05	1,396.66	1,415.51	1,434.62	1,453.99	1,473.62	1,493.51	1,513.67	1,534.11	1,554.82	1,575.81	1,597.08	1,618.64	1,640.49
Replacement costs	0.00	0.00	0.00	0.00	2,296.61	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Net annual cash flow	3,498.36	3,625.36	3,758.13	3,896.95	6,338.72	4,193.94	4,352.76	4,518.91	4,692.76	4,874.70	5,065.11	5,264.42	5,473.08	5,691.54	5,920.29
Present value of cash flow	2,600.90	2,645.84	2,692.39	2,740.59	4,375.98	2,842.17	2,895.65	2,951.00	3,008.27	3,067.54	3,128.85	3,192.28	3,257.88	3,325.73	**3,395.89**

Figure D.4: Additional Information on Total Lifecycle Cost – Case Study 3.