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ENERGY CODE-COMPLIANT HOUSING DESIGN: A COST AND ENERGY PERSPECTIVE

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Abstract: The residential sector is the third highest end-user of energy in Canada, accounting for ~17% of all energy consumed in the country. Moreover, housing in Canada consumes approximately 214 kWh/m^2 per year, and ~63% of this consumption results from space heating. Thus, in an effort to improve the energy efficiency of housing, the provincial government in Alberta, Canada, recently updated its building code, including a section dedicated entirely to energy-efficiency requirements applied to new housing and small building construction in the province. As a result, housing built in compliance with this improved energy standard will have better energy performance. On the other hand, code-compliance is also expected to lead to an increase in initial housing construction cost due to changes in construction practice. In this context, this paper investigates the impacts of code-compliance on housing construction practice and operation costs for housing in Edmonton, Alberta. Selection of least-construction-cost upgrades for building envelope (attic ceiling, above- and below-grade walls, and windows) that meet code-specified thermal insulation values is discussed. Then, a 30-year lifecycle analysis is conducted using HOT2000 simulation to estimate the energy performance and operation cost of a home built using current construction practice and using the proposed least-construction-cost upgrades. The results obtained indicate that a reduction of ~12% in energy consumption is achieved by deploying the upgrades suggested by this study in comparison to a house built according to the current construction practice.

1 INTRODUCTION

The residential building sector accounts for a substantial portion of the secondary energy consumed in the world (IEA 2008); for instance, in Canada, ~17% of the secondary energy consumed is attributed to this sector (NRCan 2016c). Moreover, Canadian housing consumes considerably more energy than housing located in other countries, such as the United States and countries within the European Union (EEA 2015; EIA 2016; NRCan 2016e). Space heating is the primary driver of this energy consumption accounting for ~64% of the energy consumed by housing in Canada (NRCan 2016a). Thus, aiming to reduce the country's energy consumption and green house gas (GHG) emissions, the Government of Canada is adopting several approaches—EnerGuide rating, ENERGY STAR homes, R-2000 homes, and restrictive energy-efficiency requirements set by buildings codes—to promote energy-efficient homes throughout the country (NRCan 2015, 2016a, 2016d, 2016b).

In regard to energy-efficiency requirements set by building codes, the Canadian model energy code for building underwent a major revision in 2011. This updated version of the code, the National Energy Code of Canada for Buildings (NECB) 2011, introduced nearly 25% more restrictive energy-efficiency requirements than the requirements specified by the previous code, the Model National Energy Code of Buildings (MNECB) 1997 (CCBFC 1997; NRC 2015). However, like any other model code in Canada, the NECB 2011 must be adopted by regulatory authorities to become effective, which in Alberta occurred on November 1, 2016, through the Alberta Building Code (ABC) 2014 (NRCan 2017; NRC 2017, 2014). Hence, currently, the energy performance of housing in Alberta is regulated by two codes: (a) the NECB 2011, and (b) the ABC 2014. The ABC 2014 regulates the design and construction of small buildings and homes, while the NECB 2011 regulates residential buildings that are greater than three stories in height and whose building area exceeds 600 m^2 (NRC 2014, 2011). Since 80% of housing in Edmonton has an area smaller than 600 m^2 and the most common structural type of residence is the single-family detached home, most of the new homes in Edmonton are required to comply with the ABC 2014 (Statistics Canada 2013; City of Edmonton 2013). It is anticipated that housing built compliant to this improved energy standard will have better energy performance. On the other hand, code-compliance is also expected to lead to an increase in initial housing construction cost due to changes in construction practice (NRCan 2016d; Alberta Munipal Affairs 2016). In this context, this paper investigates the impacts of the energy-efficiency requirements set by the ABC 2014 on current housing construction practices and operation costs in Edmonton, Alberta. This investigation is conducted by identifying least-construction-cost code-compliant upgrades for new housing in Edmonton, and by assessing the impacts of these upgrades on the current construction practice in terms of construction cost, energy consumption, and operation costs. It is important to clarify that this study focuses on identifying least-construction-cost upgrades to meet code-specified thermal insulation values defined in the ABC 2014 for the climate zone where Edmonton is located.

2 LITERATURE REVIEW

With the update of the Canadian energy model building code and subsequent reviews of provincial building codes, research is being conducted to explore the impacts of these restrictive energy-efficiency regulations on housing construction in Canada. In Ontario, the Ontario Building Code (OBC) 2012 introduced more restrictive energy-efficiency requirements for housing. In this context, Dembo (2011), Dembo and Fung (2012), and Dembo et al. (2013) identify cost-effective specifications to achieve the energy-efficiency requirements of the OBC 2012 by performing a lifecycle analysis using the brute force sequential search method. Other approaches to comply with updated energy regulations in Canada are explored by Lohonyai and Korany (2013), Di Placido et al. (2014), Dias Ferreira (2017), Hesaraki (2017), and Hesaraki et al. (2018). Performing hygrothermal analyses of nine specifications for exterior walls designed to comply with the NECB 2011 for the climate conditions of Edmonton, Lohonyai and Korany (2013) verify that the wall specification with the lowest construction cost is the most cost-effective option, regardless of the building's life time. Alternatively, Di Placido et al. (2014) explore three potential upgrades for exterior wall assemblies to surpass the energy-efficiency requirements of the OBC 2012. However, due to current utility rates, the upgrades proposed by Di Placido et al. (2014) are considered unprofitable if analyzed from the users' perspective. Dias Ferreira (2017) investigates compliance with energy building codes in terms of least impact on building envelope specifications. Hesaraki (2017) and Hesaraki et al. (2018) propose a practical methodology for achieving code compliance with near-lowest lifecycle cost by investigating market-available configurations for walls and windows as well as domestic systems.

Hence, it is noted that few studies have already explored approaches to meet energy-efficiency requirements defined by building codes. However, these studies have focused on the following aspects: (a) improvements in housing energy performance with a focus on total lifecycle analysis rather than on additional investment, e.g Dembo (2011); Dembo and Fung (2012); Dembo et al. (2013); and Hesaraki et al. (2018); (b) upgrades to surpass current energy standards, e.g., Di Placido et al. (2014); or (c) a single element—exterior wall, e.g., Lohonyai and Korany (2013). In this context, this study aims to bridge a gap in the research by identifying potential code-compliant upgrades focusing on minimizing the impacts of building codes on current housing construction practice, and, thus, lessening additional construction costs required to meet restrictive energy regulations.

3 METHODOLOGY

As mentioned in the introduction of this paper, this study explores code-compliant upgrade options for building envelope considering their additional construction cost. In this context, potential configurations for building envelope are identified based on two primary aspects: (1) compliance with the thermal resistance (RSI) values set by the ABC 2014, and (2) additional construction cost. In addition to these aspects, ease of construction, utilization of materials already familiar to the industry, and different insulation materials with distinct levels of thermal resistance are other aspects taken into consideration during the identification of code-compliant upgrades. Figure 1 provides a visual summary of the research methodology followed in this study, and a thorough description of each process is presented in this section.

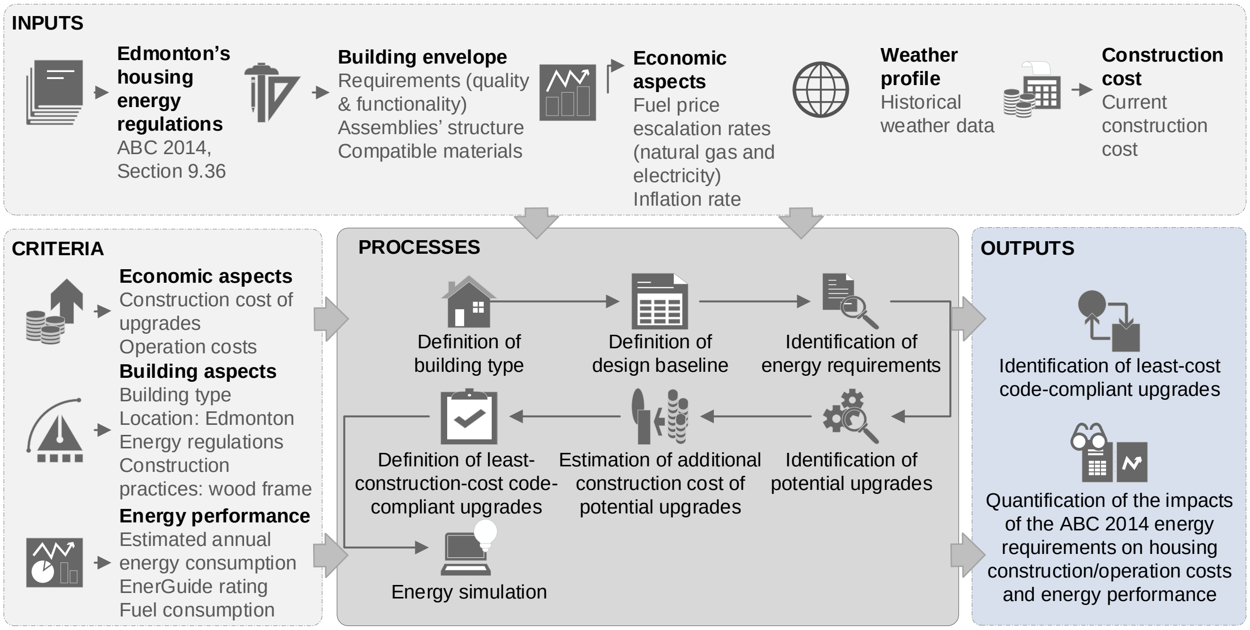

Figure 1: Overview of Research Methodology.

3.1 Definition of Building Type

To represent Edmonton's current housing market, two primary factors are analyzed in this study to define the reference house: (a) housing structural type, and (b) housing area. In terms of housing structural type, based on data from Statistics Canada (2013), the single-family detached house is the predominant structural type of housing in Canada, in Alberta, and in the metropolitan area of Edmonton. Regarding housing area, excluding basement, the area of most of the homes being built in Edmonton varies from 134.80 m^2 to 278.71 m^2 (City of Edmonton 2013). Based on this information, a single-family detached home whose area is equal to 149.57 m^2 is selected to represent a typical home in this study. This selected house is referred to herein as the "reference house".

3.2 Definition of Design Baseline

Identifying the design configurations commonly applied for new housing in Edmonton is a crucial step in determining a design baseline to which the upgrades proposed in this research will be compared, concerning construction cost, energy performance, and operation cost. Thus, for the purpose of capturing the current construction practice for housing in Edmonton, a web survey is performed to gather relevant design specifications used by major builders in the city. It is verified that most builders are no longer following the energy specifications defined by the previous building code, ABC 2006 (Table 1). Additionally, it is also noted that ~82.35% of the builders analyzed are using a nearly identical design configuration. This design configuration will be referred to herein as "current construction practice", and it will be used as the design baseline for the upgrades investigated in this study.

Table 1: 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 blown-in cellulose
Above-grade exterior walls	RSI 2.10	RSI 3.52 fiberglass batt
Exposed floors	RSI 3.50	RSI 4.93 fiberglass batt
Below-grade exterior walls	RSI 1.40	RSI 2.11 fiberglass batt
Doors	Minimal value for thermal resistance is not specified	Insulated fiberglass
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)

3.3 Identification of Energy Requirements

Based on the information regarding codes provided, the reference house must comply with the energy-efficiency requirements defined in the ABC 2014 for Edmonton's climate zone. Therefore, the upgrades proposed in this study are selected based on two criteria: (a) compliance with the ABC 2014, and (b) least additional construction cost. Also, it is essential to clarify that, rather than proposing new design solutions, this study investigates market-available materials and assembly configurations to be deployed in current construction practice for new homes in Edmonton to comply with updated energy code requirements. In this context, an assessment of the thermal characteristics of building envelope assemblies built following the current construction practice is performed. In this step, the effective thermal resistance (RSI) of each assembly is calculated by the method depicted in the ABC 2014 (NRC 2014). Then, a comparison with the energy-efficiency requirements of the ABC 2014 is conducted. Table 2 presents the results of this comparison. Since this study focuses on minimizing the impact of energy regulations on the current construction practice, upgrades are proposed exclusively for building envelope assemblies that are not compliant with the code (attic ceiling, above- and below-grade exterior walls, and windows).

Table 2: Comparison of current construction practice and ABC 2014 energy requirements.

Building Envelope & Domestic Systems	ABC 2014 Requirements (RSI in $(K \cdot m^2)/W$)	Current Construction Practice (RSI in $(K \cdot m^2)/W$)	Code-compliance
Attic ceiling	8.67	RSI 6.22	✗
Above-grade exterior walls	2.97	RSI 2.96	✗
Exposed floors	5.02	RSI 5.32	✓
Below-grade exterior walls	2.98	RSI 1.99	✗
Doors	0.63	RSI 0.98	✓
Windows	0.63	RSI 0.50	✗

3.4 Estimation of Additional Construction Cost of Potential Upgrades

The construction cost of building envelope assemblies is ascertained in this study primarily using RSMeans platform (RSMeans 2016). Given that this study focuses on improving the effective RSI values of building envelope assemblies, materials that have a low impact on these values (e.g., gypsum board, oriented strand board, house wrap, and vapour barrier) are not investigated. Hence, the estimation of the construction cost of those materials is not required. In this context, the additional construction cost in $/ft^2 of building envelope is estimated by calculating the difference between the cost of insulation materials used in the current homebuilding practice in Edmonton and the cost of insulation materials proposed as upgrades in this study. However, since RSMeans provides construction cost of windows based on their dimensions and characteristics (e.g., operation type, glazing, and coating), some assumptions are made to estimate their additional construction cost. To obtain an average cost per ft^2 of window, the cost of windows with different dimensions but identical characteristics (double-pane, Low-E, air filled, and casement vinyl frame) is collected and the average cost is calculated. As the cost of argon-filled and triple-pane windows is not covered in the RSMeans database, two assumptions are made to account for these characteristics. The calculated average cost per ft^2 is increased by 10% to account for argon-filled windows. This new average cost is defined in this study as the baseline cost for windows. To account for the extra layer of glazing pane, the baseline cost of windows is increased by 30%.

3.5 Energy Simulation

Aiming to assess the energy consumption and operational costs of the reference house built using the current construction practice and the upgrades identified in this research, simulation models are developed. HOT2000 is a free evaluation tool, developed by the Office of Energy Efficiency (OEE), housed under Natural Resources Canada (NRCan), which can accurately estimate the energy consumption of houses. In this research, HOT2000 version 10.51 is selected as the energy simulation tool.

4 ANALYSIS AND RESULTS

4.1 Determination of Upgrades for Attic Ceiling

Nine potential code-compliant upgrade configurations are suggested for attic ceiling. The application of either blown-in cellulose or blown-in fiberglass is recommended as the primary insulation material. Additionally, combinations of these materials with expanded polystyrene (EPS), extruded polystyrene (XPS), and polyisocyanurate (ISO) rigid insulation are also proposed. The effective RSI values of the configurations suggested range from 8.69 (K·m^2)/W to 11.51 (K·m^2)/W, while additional construction cost varies from \$0.50/ft^2 to \$2.40/ft^2. Among the upgrades explored, potential attic ceiling (PAC) 6 is found to have the lowest additional construction cost; therefore, it is selected as the upgrade to be deployed in current construction practice. PAC 6 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. For conciseness, Figure 2 contains the upgrade options with highest and lowest additional construction cost and effective RSI values for attic ceiling.

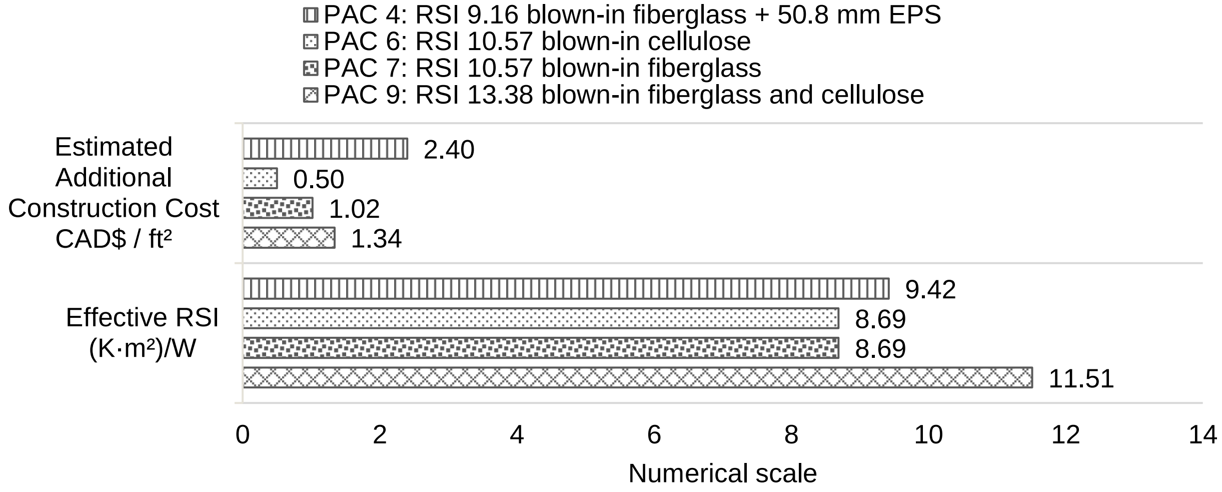

Figure 2: Estimated Additional Construction Cost and Effective RSI Value of Potential Upgrade Configuration for Attic Ceiling.

4.2 Determination of Upgrades for Above-grade Exterior Walls

Upgrades for above-grade exterior walls suggest the application of several types of insulation materials inside the wall cavity as well as the combination of these materials and EPS, XPS, and ISO rigid insulation applied to the exterior surface of the walls. As a result, the effective RSI values of potential upgrades vary from RSI 3.02 (K·m^2)/W to RSI 5.53 (K·m^2)/W. In terms of cost, the additional construction cost of potential above-grade exterior walls (PAW) varies from \$0.56/ft^2 to \$3.02/ft^2 (For conciseness, Figure 3 contains the upgrade options with highest and lowest additional construction cost and effective RSI values). In this context, consisting of one layer of unfaced fiberglass 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, PAW 7 is the configuration with the least-additional-construction cost. Hence, PAW 7, whose effective RSI value is 3.08 (K·m^2)/W, is selected as the upgrade for above-grade exterior walls.

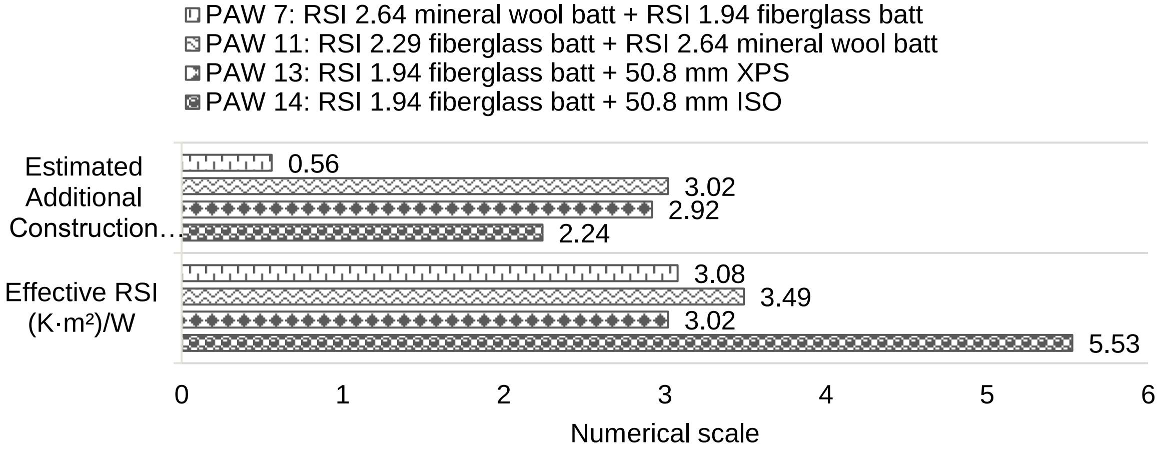

Figure 3: Estimated Additional Construction Cost and Effective RSI Value of Potential Upgrade Configuration for Above-grade Exterior Walls.

4.3 Determination of Upgrades for Below-grade Exterior Walls

The identification of potential upgrades for below-grade exterior walls follows the same approach applied to attic ceiling and above-grade exterior walls. Therefore, application of different types of batt insulation and combinations of batt insulations and different thicknesses of EPS, XPS, and ISO rigid insulation are also investigated. The additional construction cost of potential upgrades ranges from \$0.45/ft^2 to \$1.66/ft^2, and their effective RSI values range from 2.98 (K·m^2)/W to 4.91 (K·m^2)/W, as presented in Figure 4. The potential below-grade exterior wall (PBW) upgrade with the least-construction-cost is found to be PBW 1. PBW 1 has an effective RSI value of 3.83 (K·m^2)/W and consists of two layers of kraft-faced fiberglass batt RSI 1.94 (K·m^2)/W.

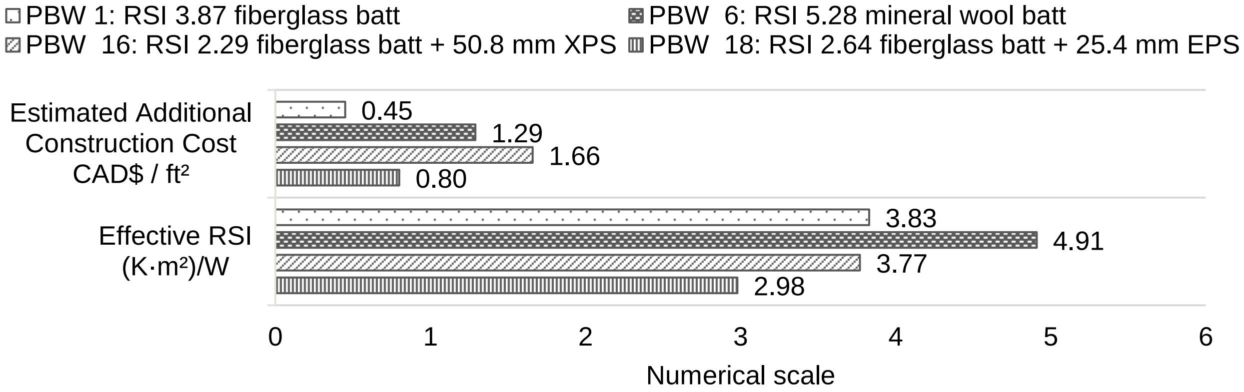

Figure 4: Estimated Additional Construction Cost and Effective RSI Value of Potential Upgrade Configuration for Below-grade Exterior Walls.

4.4 Determination of Upgrades for Windows

This research investigates triple-pane argon-filled windows with a vinyl frame as a code-compliant upgrade. The selection of this window specification is based on the fact that the industry is already familiar with this window type given that builders that focus on highly energy-efficient homes and/or net-zero homes currently use this window configuration.

4.5 Impacts of Identified Least-construction-cost Upgrade Configuration for Building Envelope on Current Construction Practice in Edmonton

To assess the impacts of the identified upgrades on construction cost, energy consumption, and operation cost of the reference house, two simulations models are developed in HOT2000 (Table 3). The first model represents the reference house built using the current construction practice, baseline model (Model BL), while the second model accounts for a code-compliant house built with the identified least-construction-cost upgrade configuration for building envelope and code-compliant design configurations of current construction practice, named herein Model CS ("CS" referring to "case study").

Table 3: Simulation Model Inputs.

House components	Model BL	Model CS
Attic ceiling	Effective RSI 6.22	PAC 6 **|** Effective RSI: 8.69
Above-grade exterior walls	Effective RSI 2.96	PAW 7 **|** Effective RSI: 3.08
Exposed floors	Effective RSI 5.28	Effective RSI: 5.28.
Below-grade exterior walls	Effective RSI 1.99	PBW 1 **|** Effective RSI: 3.83
Doors	Effective RSI 0.98	Effective RSI 0.98
Windows	Effective from RSI 0.47 to 0.51	Effective from RSI 0.67 to 0.80
Ventilation system (HRV)	Efficiency: 66% at 0°C and 60% at −25°C	Efficiency: 66% at 0°C and 60% at −25°C
Heating/Cooling system	92% high efficiency natural gas-fired furnace	92% high efficiency natural gas-fired furnace
Domestic hot water	Power direct vented with 189.27 (50 US gal) capacity and EF = 0.67	Power direct vented with 189.27 (50 US gal) capacity and EF = 0.67
Air tightness (50 Pa pressure difference)	3.57 ACH	2.50 ACH

As observed in Figure 5, from an energy perspective, Model CS performs better than Model BL. For instance, with respect to the energy consumed by space heating system, a reduction of ~17% is noted between Model BL and Model CS. This improvement is primarily attributable to the higher level of insulation and airtightness of Models CS's building envelope. On the other hand, it is also found that the energy used by Model CS's ventilation system is ~41% higher than the energy used for the same purpose in Model BL. This increase in energy consumption is primarily attributable to the improvement of the building envelope's airtightness, which results in less infiltration of natural air and, consequently, reduced air movement inside the house. Hence, to maintain a satisfactory level of air quality, the demand for ventilator usage increases in Model CS. Nevertheless, overall, a reduction of 12% in the reference house's energy consumption is obtained by deploying the identified least-construction-cost upgrades in the current housing construction practice in Edmonton.

Furthermore, because of Model CS's reduced energy consumption, a decrease of ~9% in operation cost is observed by comparing the annual operation cost of Model BL and Model CS. Thus, the present value of the 30-year savings from operation cost, determined per Equation [1] and Equation [2], is found to be ~$3,752.98. Hence, since an additional investment of ~$3,886.50 is required to deploy the identified upgrades (Table 4), this study concludes that the additional investment necessary to deploy the identified upgrades is not offset by the savings from operation costs during the analyzed 30-year period.

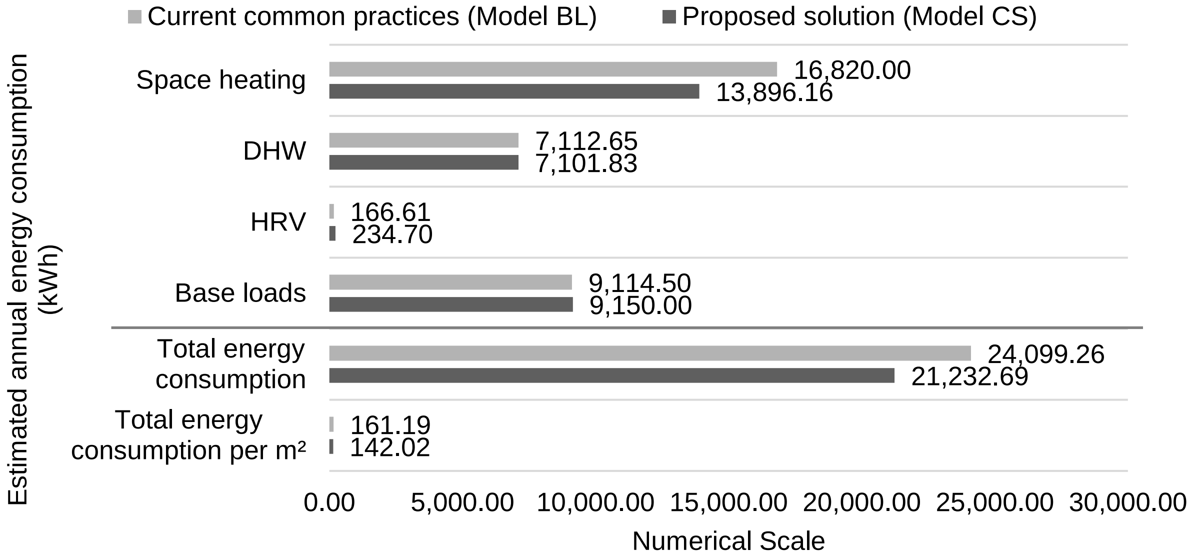

Figure 5: Comparison of Total Annual Energy Consumption of Simulation Models.

Table 4: Estimated Additional Construction Cost* of Upgrades Investigated.

	Additional ($/ft²)	Assembly area (ft²)	Total cost ($)
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

*All dollar amounts presented in this study are in Canadian dollars (CAD).

$$\text{[1]}\quad \text{AOPCS}_n\text{, Cost} = [\text{A}_{\text{CNG}} \text{ of Model BL } - \text{ A}_{\text{CNG}} \text{ of Model with Upgrade} \times (1 + \text{i}_{\text{NG}})^n] + [\text{A}_{\text{CELEC}} \text{ of Model BL} - \text{A}_{\text{CELEC}} \text{ of Model with Upgrade} \times (1 + \text{i}_{\text{ELEC}})^n]$$

where

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

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

i_{NG}: Escalation rate of natural gas, i_{NG} = 0.0508 (Dias Ferreira 2017);

i_{ELEC}: Escalation rate of natural gas, i_{ELEC}= 0.0135 (Dias Ferreira 2017); and

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

$$\text{[2]}\quad \text{PVSOPC}_{30} = \sum_{\text{i-1}}^{30}\left[\frac{\text{AOPCS}_\text{n}}{(1+\text{i}_{\text{inf}})^\text{n}}\right]$$

where

$PVSOPC_{30}$: Present value of 30-year savings from operation cost; and

i_{inf}: Canadian inflation rate, i_{inf} = 0.0187 (Dias Ferreira 2017).

5 CONCLUSION

This research identifies least-construction-cost upgrades for building envelope (attic ceiling, above- and below-grade exterior walls, and windows) to be deployed in the current housing construction practice in Edmonton to meet code-specified thermal insulation requirements. Additionally, an assessment of the impacts of these identified upgrades on current construction practice is also performed in light of construction cost, energy consumption, and operation cost. Therefore, based on the results of the developed simulation models, a reduction of ~12% and ~9% for total energy consumption and operation cost, respectively, is achieved by deploying the identified least-construction-cost code-compliant upgrades in the current construction practice. Nevertheless, in terms of economic aspects, it is concluded that, considering the analyzed 30-year period, the monetary savings achieved as a result of the higher energy performance of houses with design characteristics similar to those of the reference house fail to surpass the additional investment required during the construction phase.

6 ACKNOWLEDGEMENTS

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