UBC Sustainability Scholar Report:

Lifecycle cost analysis of new single-family building construction and electrification on Musqueam First Nation reserve

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Disclaimer

This report was produced as part of the UBC Sustainability Scholars Program, a partnership between the University of British Columbia and various local governments and organizations in support of providing graduate students with opportunities to do applied research on projects that advance sustainability across the region.

This project was conducted under the mentorship of Musqueam Indian Band staff. The opinions and recommendations in this report and any errors are those of the author and do not necessarily reflect the views of the University of British Columbia or the Musqueam Indian Band.

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Executive summary

Energy upgrades and retrofits have been identified as key measures to reduce energy consumption and associated greenhouse gas emissions from the building sector in Canada. On a path to move towards becoming a more sustainable community, Musqueam First Nation is looking for ways to reduce greenhouse gas (GHG) emissions from energy consumption in on-reserve homes. Although most of the existing homes use natural gas for space and water heating, there is an opportunity to electrify the new buildings being constructed on the Musqueam reserve. This study aims to assess the cost-effectiveness and environmental impacts of energy-efficient new build construction on Musqueam Indian Reserve #2 located within the geographical boundaries of the City of Vancouver, British Columbia.

This study employs HOT2000 to examine the energy performance of different energy upgrade measures for a typical single-family detached house (SFDH) located on the Musqueam reserve. The author uses HOT2000 energy simulation software to evaluate the energy performance of the selected single-family detached house (SFDH) considering envelope and mechanical system upgrades. The energy simulation results were combined with cost and emission impact data to evaluate the economic and environmental performance of the selected energy upgrade measures.

The results of this study show that the proposed upgrades have the potential to reduce the annual energy consumption and GHG emissions in the studied SFDH by 17.71 GJ and up to 1.41 tonnes of CO_{2e}, respectively.

In terms of economic performance, mechanical system upgrades (the installation of air source heat pumps and water heating heat pumps) could lead to a life cycle cost savings of 2,279 CAD. However, envelope upgrades will increase the life cycle cost of the building by 6,183 CAD.

1 Introduction

Extensive use of fossil fuels and associated greenhouse gas (GHG) emissions have been identified as catalysts for climate change and associated environmental impacts [1]. In response to the increasing concerns about climate change impacts, the government of Canada has established an ambitious emission reduction target to reduce carbon emissions by 80% by 2050 compared to the 2005 levels [2]. It is suggested that stationary combustion, transportation, and fugitive sources constitute 82% of the GHG emissions in Canada [3]. As a result, Canada aims to reduce energy use in multiple sectors to reduce associated GHG emissions [2].

In recent years, the building sector in Canada has gained attention for the need to reduce GHG emissions. According to the national GHG inventory, Canadian buildings accounted for 12% of the total national GHG emissions. Moreover, the residential building sector accounted for 11% of national energy use in 2017 [2]. Recognizing the importance of reducing energy use and emissions associated with the building sector, all levels of government have introduced policies, standards, and design guidelines to improve building energy performance. For instance, the British Columbia Energy Step Code (BCESC) is introduced as a tool to enable meeting the provincial target to make all new buildings "net-zero energy ready" by 2032 [4].

As part of their plan to move towards a sustainable emission-free community, Musqueam First Nation is looking for ways to reduce GHG emissions from on-reserve homes. Although most of the existing homes use natural gas for space and water heating, there is an opportunity to electrify the new buildings being constructed in Musqueam. This project aims to assess the cost-effectiveness and environmental impacts of energy-efficient new build electrification on Musqueam Reserve, City of Vancouver, British Columbia. The cost-effectiveness will be determined based on the upfront cost, maintenance cost, and utility bill cost of using heat pumps to provide space heating and cooling, and water heating. The electrification scenarios will be compared to a baseline where natural gas is used in new homes in high-efficiency space and water heating equipment. The baseline case will be the current new construction on the Musqueam Reserve that meets Step 2 of the BCESC.

2 Building energy upgrades

Building energy upgrades can be classified under three categories, including demand side solutions, supply side solutions, and transformation of energy consumption patterns (i.e., human factors) [12,14]. Demand side solutions include strategies to reduce building heating and cooling load and other end-uses with energy upgrades. Upgrades in building envelop insulation, airtightness, windows, heating, ventilation, air-conditioning (HVAC) systems, hot-water unit, and appliances are focus areas in demand-side management [15,16]. Supply side solutions consist of renewable energy technologies such as solar photovoltaics and wind energy, which are recognized as alternative energy systems to generate electricity for buildings [17]. Supply side solutions have received much attention in recent years with the increasing pressures to reduce the environmental impacts associated with energy use [15,16]. Transformation of energy consumption patterns generally applies advanced control techniques or provides homeowners with building operation strategies to facilitate energy efficiency through behavior changes. This section discusses possible upgrade options, including the improvement of building envelope components, HVAC systems, occupant behaviors, lighting systems, and renewable energy systems.

2.1 Upgrades in building envelope components

Heat loss or gain through building envelopes affects energy consumption and the indoor condition of a house and produces a significant amount of energy depletion [1]. Therefore, upgrading the external walls and fenestrations has a considerable impact on reducing energy consumption. Depending on the upgrade objectives of each project, various energy saving, and GHG emission reduction results could be achieved. Several factors must be considered in developing upgrade scenarios, including budget, upgrade methods, and building envelope materials and components [3]. Both building envelope and mechanical system upgrades are investigated in this study.

The selection of building envelope materials and methods is case-dependent and is based on factors including cost, implementation performance, and environmental impact. All building envelope components (e.g., insulation, glazing, fenestration, window frames, sealants, finishing, and cladding) should be considered when planning for a building envelope upgrade [4].

2.2 Upgrades in mechanical systems

Previous research has shown that substantial energy saving can be achieved by improving the building service systems and the energy source [7]. Due to the gap between energy modeling predictions and actual measurements of the energy performance of buildings, more studies focus on the effect of mechanical systems on buildings' energy consumption [8]. Building mechanical systems include HVAC (heating, ventilation, and air conditioning) and water heating systems. In recent years, heat pumps for space heating and water heating have garnered greater attention to reduce building energy use because of their high coefficient of performance (COP) [9].

3 Building energy modeling

This research uses a typical single-family detached house (SFDH) located on the Musqueam Indian Reserve #2 as a case study. The author uses the energy simulation software (HOT2000) to evaluate the operational energy performance of the selected SFDH with and without proposed building upgrades. HOT2000, developed by Natural Resource Canada, is the most popular energy simulation and design tool for buildings in Canada. HOT2000 employs long-term monthly weather data in a bin-based method to analyze energy performance for a given building.

3.1 Base building energy model

The selected building is a two-story single-family detached house. The selected SFDH has three bedrooms, three washrooms, one living room, one kitchen, and one dining room. The main floor area and top floor area are 648.41 square feet and 734.22 square feet, respectively.

The building sketch for the case study single-family home is shown in Figure 1. The building characteristics are shown in Table 1.

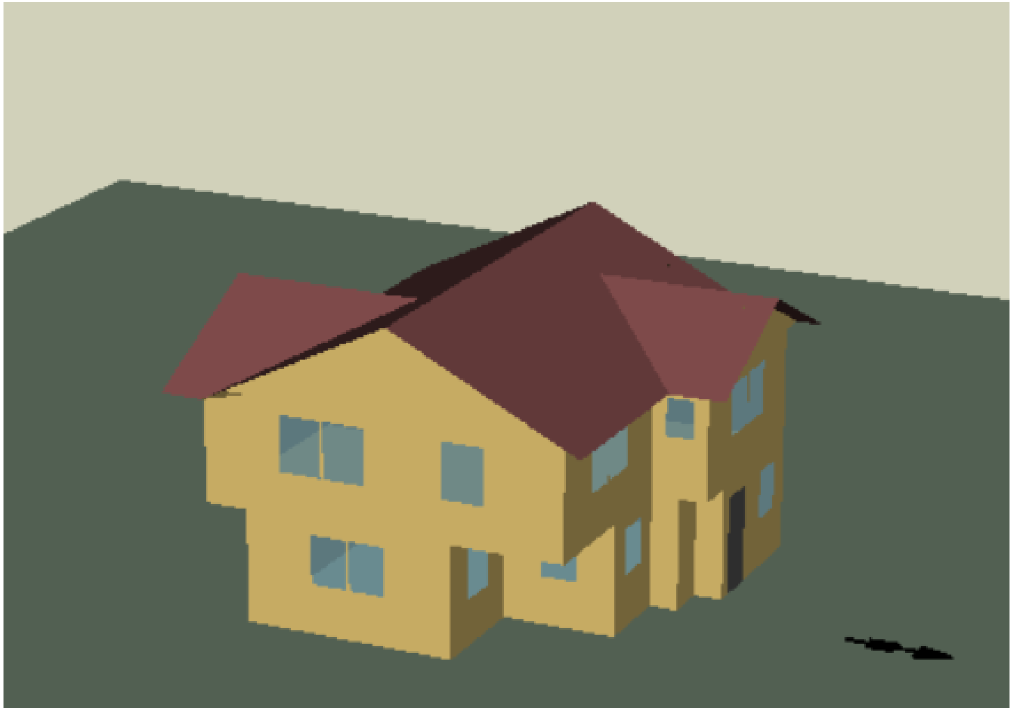

Figure 1. The 3D model of the case study building

Table 1. Base building model characteristics

Base building characteristics		
Specifications	Data	
HVAC System	Combi tankless natural gas direct vent boilers for heating, efficiency: 95%	
Domestic hot water	Combi tankless natural gas direct vent boilers, Delivery temperature: 66 °C, efficiency: 95%	
Thermostat	Heating: 22 °C	
Infiltration	3.0 ACH @50Pa	
Exterior Wall	Stucco, Wire mesh on building paper, Plywood, Studs, R-22 batt insulation, Drywall	
Door	Solid core	
Roof	Ceiling under Attic	Roofing, Joists, R-40 batt insulation, Drywall
Windows	U - value	3.57 W/m^2.K
	Type	Double glazed, Vinyl Sash
	SHGC: 0.760	

3.2 Proposed energy upgrade measures

The proposed building envelope and mechanical system upgrade measures are presented in this section. This study investigates the effect of such upgrades on the energy consumption, GHG emissions, and operational cost of the case study building.

3.2.1 Envelope components

Roof insulation: Upgrade to R49 batt insulation

Wall insulation: Upgrade to R30 batt insulation

Windows: Upgrade to Triple pane, Argon Filled (U value: 1.03 $W/m^2.K$; SHGC: 0.5 to 0.4)

Exterior Door: Upgrade to Steel Medium density spray foam core

3.2.2 Mechanical systems

Space heating system: Upgrade to Air Source Heat Pump (coefficient of performance: COP~2.5)

Water heating system: Upgrade to Electric heat pump water heater (Uniform energy factor: UEF~3.43)

3.3 Scenario development

This research uses three scenarios to evaluate the energy, emission, and cost performance of building energy upgrades. Scenario 1 (S1) consists of upgrades in building envelope components, while Scenario 2 (S2) includes upgrades only in building mechanical systems. Finally, Scenario 3 (S3) considers upgrades in both building envelope components and mechanical systems. The three scenarios are listed in Table 2, Table 3, and Table 4.

Table 2. Scenario 1 (Building envelope upgrades)

Building envelope upgrades		
Specifications	Data	
HVAC System	Combi tankless natural gas direct vent boilers for heating, efficiency: 95%	
Domestic hot water	Combi tankless natural gas direct vent boilers, Delivery temperature: 66 °C, efficiency: 95%	
Thermostat	Heating: 22°C	
Air infiltration	3.0 ACH @50Pa	
Exterior Wall	Stucco, Wire mesh on building paper, Plywood, Studs, R-30 batt insulation, Drywall	
Door	U – Value: 1.0, SHGC: 0.01	
Roof	Ceiling under Attic	Roofing, Joists, R-49 batt insulation, Drywall
Windows	U - value	1.03 $W/m^2.K$
	Type	Super spacer, Argon Filled

Table 3. Scenario 2 (Mechanical system upgrades)

Mechanical system upgrades		
Specifications	Data	
HVAC System	Air source heat pump, COP: 2.5, 12 kW	
Domestic hot water	Water heater heat pump, UEF: 3.43	
Thermostat	Heating: 22°C	
Air infiltration	3.0 ACH @50Pa	
Exterior Wall	Stucco, Wire mesh on building paper, Plywood, Studs, R-22 batt insulation, Drywall	
Door	Solid core	
Roof	Ceiling under Attic	Roofing, Joists, R-40 batt insulation, Drywall
Windows	U - value	3.57 $W/m^2.K$
	Type	Double glazed, Vinyl Sash- 0.760

Table 4. Scenario 3 (Building envelope and mechanical system upgrades)

Building envelope and mechanical system upgrades		
Specifications	Data	
HVAC System	Air source heat pump, COP: 2.5, 12 kW	
Domestic hot water	Water heater heat pump, UEF: 3.43 Bradford White RE2H50S10 electric heat pump water heater	
Thermostat	Heating: 22°C	
Air infiltration	3.0 ACH @50Pa	
Exterior Wall	Stucco, Wire mesh on building paper, Plywood, Studs, R-30 batt insulation, Drywall	
Door	U – Value: 1.0, SHGC: 0.01	
Roof	Ceiling under Attic	Roofing, Joists, R-49 batt insulation, Drywall
Windows	U - value	1.03 $W/m^2.K$
	Type	Super spacer, Argon Filled

3.4 Energy simulation process

This study employs HOT2000 to create building energy models to evaluate the annual building energy performance. To evaluate the effectiveness of different upgrade measures, the performance of the upgraded house is compared against the original plan. After creating the base building model, the author inputs the selected energy upgrade measures in the base building energy models and evaluates the post-upgrade building energy performance. The energy simulation was carried out on a computer with an Intel Core i7-12700 CPU and 32 GB RAM (DDR-4), with Windows 11 operating system. The pre and post-upgrade energy performance is discussed in Section 5.

4 Life cycle costing analysis

The upfront cost of an upgrade project is an essential consideration for homeowners and project managers. Homeowners and project managers may opt to select lower-cost equipment or material to reduce the upfront cost and stay within the project budget. However, purchasing equipment or material with low market prices without considering the operational performance might increase the life cycle cost (LCC) of the building. The LCC accounts for all cost elements associated with an upgrade project. Depending on the conditions, an upgrade package with a higher upfront cost may lead to better LCC performance due to higher energy cost savings [4].

Life cycle cost analysis (LCCA) is an evaluation method for an existing asset or a potential investment and accounts for immediate and long-term expenses. LCC is the "cost of an asset or its parts throughout its lifecycle while meeting the performance requirements" [11]. In the building and construction sector, ISO 15686–5 was issued for the financial evaluation of "Buildings and constructed assets". In this study, the considered LCC includes the upfront cost and the operational cost.

4.1 Upfront cost

The upfront cost is a combination of the cost of equipment and installation. In this study, RSMeans Building Construction Costs database and literature were used to identify the upfront costs of the identified upgrades. For a given energy upgrade scenario, upfront costs (UC) associated with building envelope and mechanical system upgrades can be calculated by the following equation.

$$UC = cc_{envelope,i} \times A_{envelope,i} + CC_{system,j}$$

Where,

- $cc_{envelope,i}$ = The unit capital cost of the ith building envelope material
- $A_{envelope,i}$ = The area of the ith building envelope component
- $CC_{system,j}$ = The capital cost of the jth energy systems

4.2 Operational energy cost

The operational cost of a building energy upgrade has three main components including operational energy cost (utility bills), maintenance costs, and replacement costs. The maintenance costs of residential energy system components are significantly lower compared to operational energy costs associated with the energy system due to energy use and were not included in the study. The energy cost savings and replacement costs were calculated in comparison to the base (existing plan) building using building energy simulations. Energy simulation results can be used to determine the annual operational cost savings of a given upgrade strategy.

$$\Delta AOCS = (EE_{base} - EE_{upgraded}) * EP + (NE_{base} - NE_{upgraded}) * NP + CTS$$

Where,

- $\Delta AOCS =$ The annual operational cost savings (CAD)
- $EP =$ The local grid electricity price (CAD/GJ)
- $NP =$ The local grid natural gas price (CAD/GJ)
- $\Delta CTS =$ The annual carbon tax cost savings (CAD)

The net present value (NPV) of the operational cost savings are considered in LCC calculations to account for the time value of money. The NPV of the operational cost savings is calculated using the following equation.

$$\Delta OCS = \sum_{t=0}^{T} \frac{\Delta AOCS}{(1+r)^t}$$

Where,

- $\Delta OCS =$ The net present value of operational cost savings
- $r =$ The discounted rate (%)
- $T =$ The project's lifetime

The BC carbon tax is also included in this study. While the current carbon tax cost in BC is $65 per tonne of CO_{2e}, the carbon tax is estimated to increase by $15 per year, reaching $170 per tonne in 2030. According to the literature [12], the carbon tax will increase to $300 by 2050. In this study, a linear increase of carbon tax after 2030 until it reaches $300 by 2050 is assumed.

$$\Delta CTS = [(EE_{base} - EE_{upgraded}) * EF + (NE_{base} - NE_{upgraded}) * NF] * CT$$

Where,

- $\Delta CTS =$ The annual carbon tax cost savings (CAD)
- EE_{base} = The annual electricity consumption of the base building model (GJ)
- NE_{base} = The annual natural gas consumption of the base building model (GJ)
- $EE_{upgraded}$ = The annual electricity consumption of the upgraded building model (GJ)
- $NE_{upgraded}$ = The annual natural gas consumption of the upgraded building model (GJ)
- $EF =$ The local grid electricity emission factor (tonne of CO_{2e}/GJ)
- $NF =$ The local grid natural gas price (tonne of CO_2e /GJ)
- CT = The carbon tax (CAD/ tonne of CO_2e)

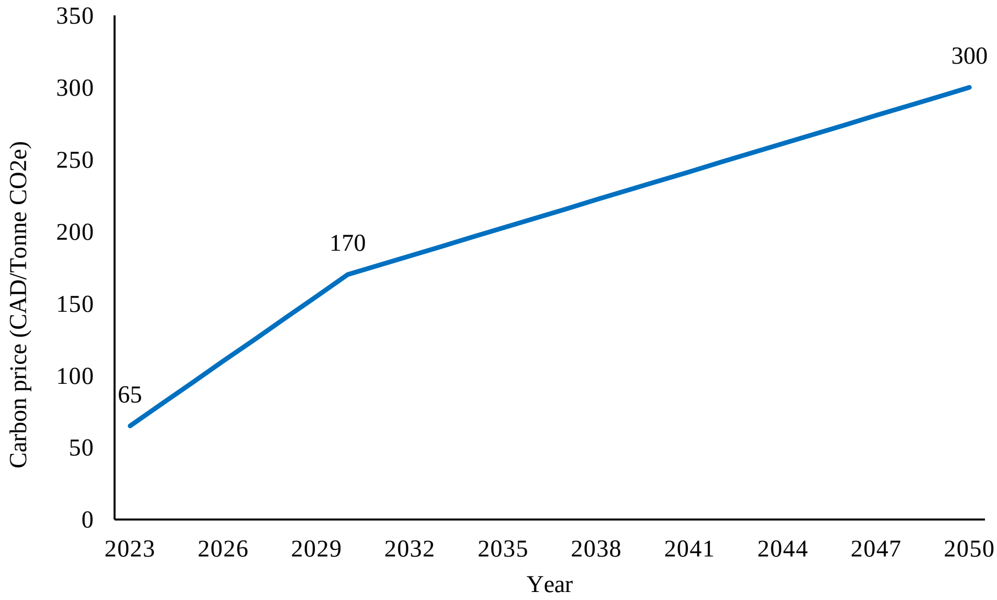

Figure 2. BC carbon tax assumed in this study

The total life cycle cost of an upgrade measure can be determined by the following equation.

$$LCC = UC - \Delta OCS$$

5 Results

5.1 Energy simulation results

This section presents the per- and post-upgrade energy performance of the case study building. The annual energy consumption, cost, and emission performance of the base building model and the developed three scenarios are presented in the following table.

Table 5. Annual energy and emission impacts

Parameter	Base-model	Scenario 1 (Envelope upgrades)	Scenario 2 (Mechanical upgrades)	Scenario 3 (Envelope and mechanical upgrades)
Annual Electricity consumption (GJ)	26.72	26.63	40.29	37.66
Annual natural gas consumption (GJ)	28.69	21.84	0	0
Annual GHG emission (tonne of CO_{2eq})	1.52	1.18	0.13	0.12

As can be seen in Table 5, the electricity consumption in Scenario 2 and Scenario 3 increased compared to the base model due to the electrification of the space heating and hot water equipment in the house. Total energy consumption, however, is reduced in all scenarios.

Figure 3 depicts the annual energy reduction compared to the base building model. S3 (envelope and mechanical system upgrades) has the highest annual energy consumption reduction potential by 17.77 GJ, followed by S2 (15.14 GJ), and S1 (6.95 GJ).

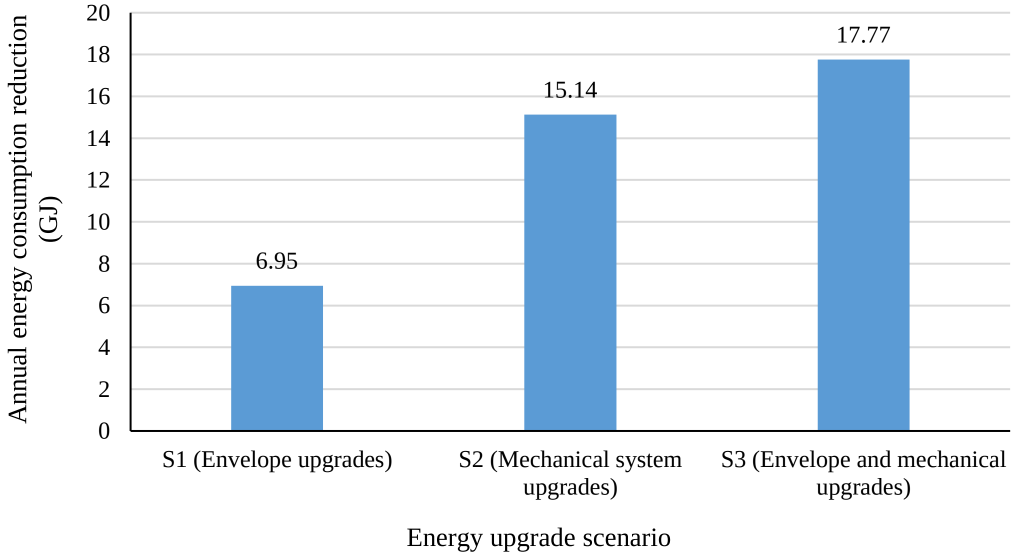

Figure 3. Annual energy reduction compared to the base building model

Figure 4 depicts the annual utility cost compared to the base building model. S1 (envelope upgrades) presents the greatest utility bill saving potential (86.21 CAD/year), while S2 (mechanical system upgrades) could increase the house's annual utility bills by 7.04 CAD per year (hence the negative number in the figure). Finally, S3 could deliver an annual utility bill savings of 62.38 CAD.

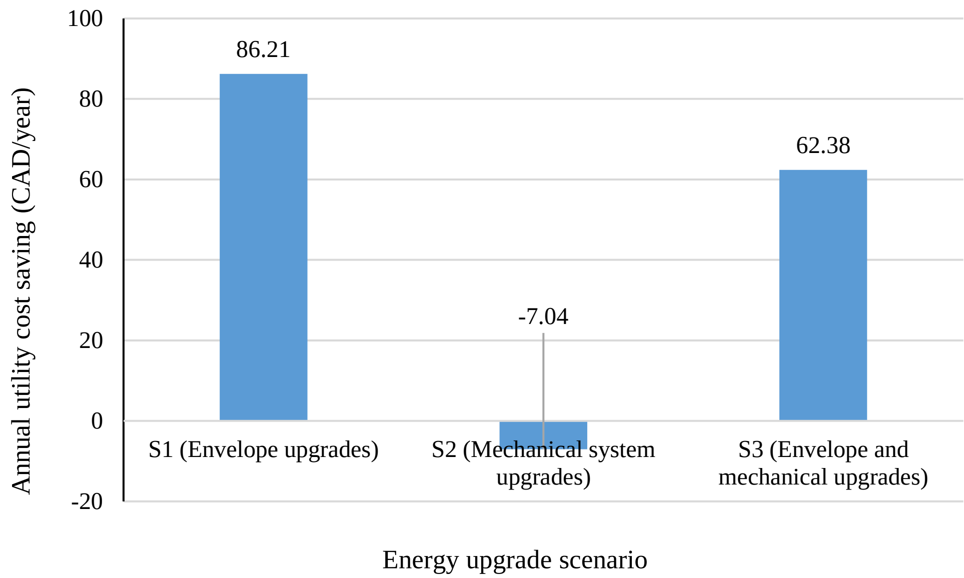

Figure 4. Annual utility cost saving compared to the base building model

Figure 5 shows the annual GHG emission reduction compared to the base building model. The mechanical system upgrades scenario (1.4 tonne of CO_{2e}) has a much higher GHG emission reduction potential compared to the envelope upgrade scenario (0.35 tonne of CO_{2e}). S3 (envelope and mechanical system upgrades) could reduce annual GHG emissions by 1.41 tonnes of CO_{2e}.

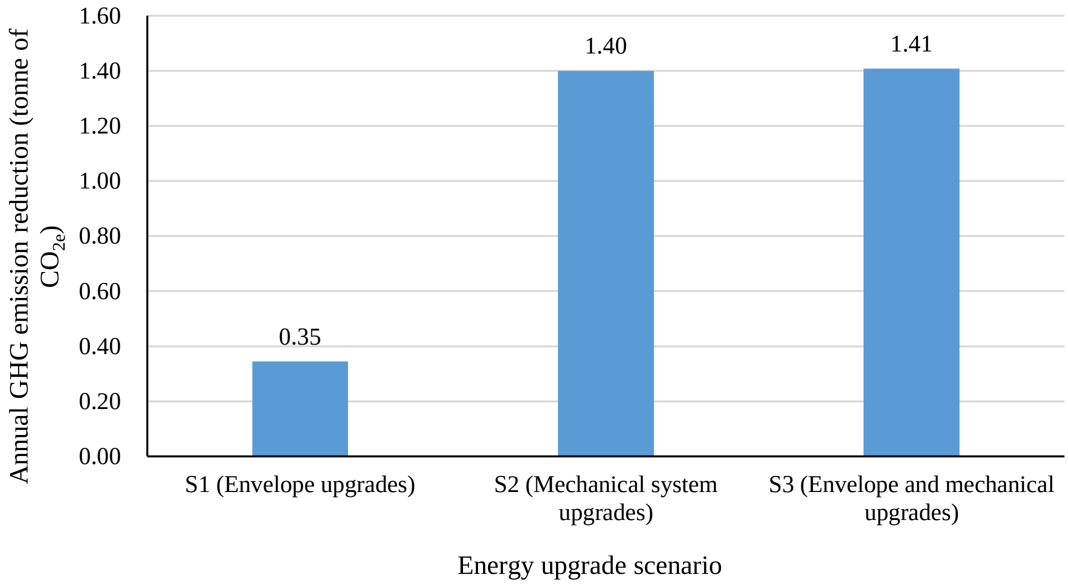

Figure 5. Annual emission reduction compared to the base building model

5.2 Life cycle cost analysis

According to the above-mentioned analysis, the life cycle cost of an energy upgrade consists of the upfront cost and the operational energy cost. The life cycle cost of the three scenarios is presented in Figure 6. S1 (envelope upgrades) has the highest life cycle cost (6,183 CAD) compared to S2 (mechanical system upgrades) and S3 (envelope and mechanical system upgrades). The life cycle cost of mechanical system upgrades is negative (-2,279 CAD), which indicates that the utility bill savings are greater than the upfront cost. Thus, mechanical system upgrades are more economical than other energy retrofit measures.

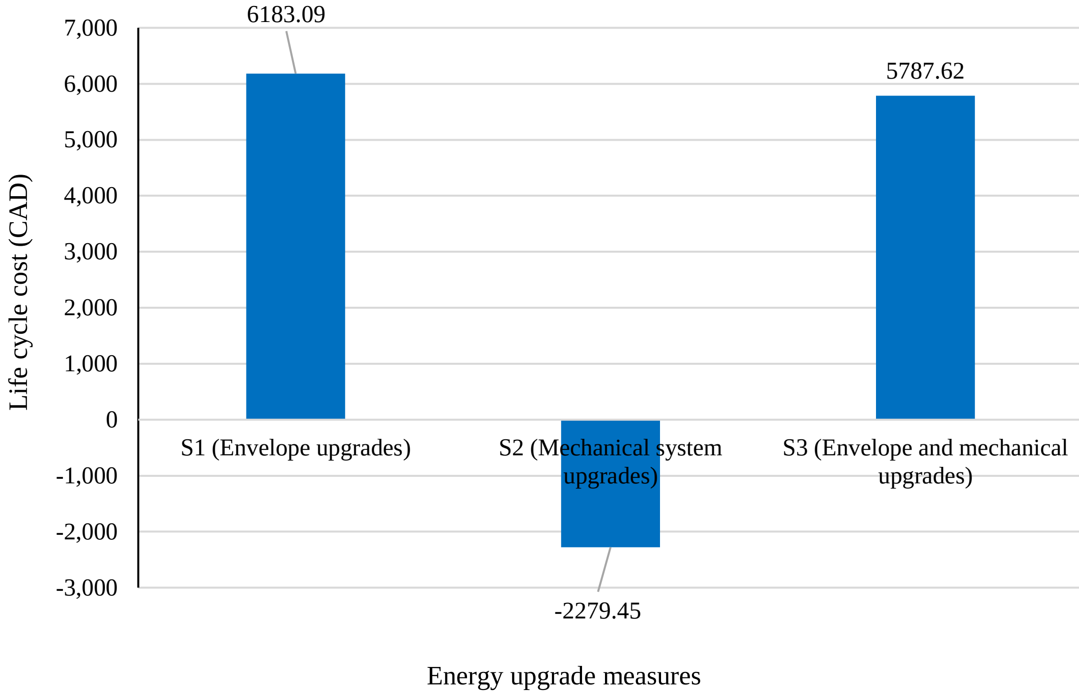

Figure 6. Life cycle cost of energy and mechanical system upgrades

6 Conclusion

Energy upgrades have been identified as key measures to improve building energy efficiency and reduce associated GHG emissions. In British Columbia, Musqueam First Nation aims to reduce GHG emissions from on-reserve homes. While most of the existing homes use natural gas for space and water heating, there is an opportunity to electrify the new buildings being constructed on the Musqueam Reserve. This study evaluated the energy, cost, and emission performance of envelope and mechanical system upgrades for a typical single-family detached house located on the Musqueam Reserve. This study investigates three scenarios where the building envelope and mechanical systems are upgraded for single-family home construction. Scenario 1 considers envelope upgrade measures, while Scenario 2 investigates mechanical system upgrades. Scenario 3 consists of both building envelope and mechanical system upgrades.

The results indicate that mechanical system upgrades (Scenario 2) by installing an air source heat pump and electric heat pump water heater could lead to significant annual energy savings (15.14 GJ) and GHG emission reductions (1.4 tonnes of CO_{2e}). Additionally, the life cycle cost of the mechanical system upgrades is -2,279 CAD, which means that the operational cost saving is higher than the upfront cost. The annual energy saving and GHG emission reduction of building envelope upgrades (Scenario 1) are 6.95 GJ and 0.35 tonnes of CO_{2e}, respectively. The life cycle cost of the envelope upgrades is 6,183 CAD, which is much higher than the mechanical system upgrades scenario. Therefore, mechanical system upgrades are more economical than other energy upgrade measures when the lifecycle cost of the system is considered. For Scenario 3 (building envelope and mechanical system upgrade), the annual energy saving is 17.77 GJ, and the annual GHG emission reduction is 1.41 tonnes of CO_{2e}. In terms of economic performance, the life cycle cost of Scenario 3 is 5,787 CAD. While the annual energy saving and GHG emission reduction potential of Scenario 3 is a bit higher than that of Scenario 2, Scenario 2 is a more economical choice due to a lower life cycle cost.

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