Enhancing the Business Case for Deep Building Retrofits: A Total Cost of Building Ownership Approach

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Abstract

To achieve Canada's housing sector energy efficiency and greenhouse gas targets, deep retrofits are crucial. These retrofits aim to save energy, but it's imperative to consider associated costs like maintenance and renewal expenses. This study introduces a Total Cost of Building Ownership (TCBO) analysis, which estimates hourly energy use, greenhouse gas emissions, and lifecycle costs, integrating construction, installation, and replacement expenses over a building's lifespan. This paper includes a case study of the TCBO methodology applied to Ottawa Community Housing's Presland PEER project. Results show that within inflation rates spanning from 2% to 3.0%, no cost savings are evident when comparing existing building to the retrofitted building over a 30-year life span. However, as the inflation rate exceeds 3.5%, retrofitting shows greater cost savings throughout the building's lifespan. Moreover, with a 30% reduction in construction expenses, cost savings are evident even at the lowest inflation rate, and these savings escalate as the inflation rate rises. Despite the substantial initial investment, future projects are expected to yield significant savings through economies of scale.

Introduction

In 2021, the residential sector accounted for 13% of Canada's end-use energy demand and 8.7% of its greenhouse gas emissions [1], [2]. As Canadian jurisdictions implement carbon pricing and policies aimed at achieving a net-zero carbon housing stock, substantial investments are expected in housing energy retrofits in the foreseeable future [3].

Most decarbonization pathways entail deep retrofits. Deep retrofits involve enhancements such as highly insulated, air-tight envelopes, energy-efficient systems like heat pumps, and renewable energy generation such as photovoltaic cells, etc.

Traditionally, the economic viability of a building retrofit is evaluated based on the return on investment from energy savings alone. However, this approach provides an incomplete assessment as it overlooks the condition of the existing building and the costs associated with maintaining and replacing building components that have reached the end of their life [4]. These maintenance and renewal activities, including re-roofing, painting, siding replacement, and upgrading windows or HVAC equipment, constitute a significant portion of ownership costs over the building's lifespan. Efficiency improvements represent incremental costs when incorporated into major capital renewal projects.

A key challenge in financing high-performance buildings is the absence of a standardized method for evaluating the financial value of energy efficiency, maintenance, and renewal costs. This gap is crucial for optimized financing of high-performance homes and deep energy retrofits [4].

This study aims to develop a Total Cost of Building Ownership (TCBO) methodology to assess the overall cost of deep retrofits. This methodology considers the energy costs and GHGs associated with operating the building and the necessary construction, installation, and replacement of components and systems over the life of the building (i.e. cladding, roofing, windows).

This methodology is demonstrated using the data from Ottawa Community Housing's Presland Prefabricated Exterior Energy Retrofit (PEER) demonstration project [5]. The PEER approach involves installing prefabricated panels to retrofit above-grade walls and roof assemblies [6]. The Presland PEER project retrofit a four-unit, two-story row house built in the early 1960s, to net-zero energy performance [5]. Funding for this project included approximately $548,000 investment from NRCan's Green Infrastructure – Energy Efficient Buildings Program, matched by Ottawa Community Housing (OCH), resulting in a project total of just over $1 million [5].

Existing and retrofitted building description

This study compares the fourplex residential housing unit constructed in the 1950s to the same building retrofitted with the PEER method. Table 1 outlines the construction features of the Existing building and the Net-zero retrofitted building.

Table 1: Building description

Building component	Existing building	Net-zero retrofitted building
Above-grade wall RSI (m^2-^{o}C/W)	2.2	8.0
Attic space RSI	4.9	10.6
Below-grade wall RSI	0.2	5.7
Roof type	Rafter Frame Hip Roof	Panelized gable, rafter framed over roof, raised heel
Window type	Aluminium sliders (U-value: 4.20 W/m^2 ^{o}C)	Fiberglass triple pane (U-value: 1.0 W/m^2 ^{o}C)
Space heating system	Mid Efficiency Gas Warm Air Furnace	Centrally-ducted Air-source Heat Pump
Cooling system	None	Centrally-ducted Air-source Heat Pump
Ventilation system	Bathroom exhaust fan	Heat Recovery Ventilator
Domestic water heating system	Gas Fired	Heat Pump
Air leakage (Air Changes per Hour (ACH) at 50 pa)	10.0	2.3
Siding	Brick	Cellular PVC
Renewable energy	None	34 kW PV Array

Existing building

The existing building structure consisted of an uninsulated, concrete unit masonry foundation wall sitting atop a concrete strip footing. Above-grade walls, framed with 2"x4" (38mm x 89mm) wood studs were insulated with nominal R12, kraft-paper faced batt insulation. The building was clad with brick masonry veneer from foundation to soffit, featuring double-glazed, aluminium-framed windows (a combination of fixed and sliders). The 4:12 hip roof was rafter framed, with an asphalt shingled roof, with attic insulation consisting of nominal R-30 batts in the ceiling.

Net-zero retrofitted building

The prefabricated building envelope retrofit included new wall panels with triple-glazed fiberglass windows, a new over-roof system, and insulating and air-sealing the foundation from the exterior. For a detailed description of the envelope retrofit, please see reference [7]. The old natural gas furnaces and the gas-fired domestic hot water tanks were removed and replaced with electric air-source heat pumps. A new central heat pump provides heating and cooling via existing ducts, while heat recovery ventilators in each suite facilitate ventilation. Finally, a 34-kW solar array (expected to produce over 40,000 kWh annually) was installed to generate sufficient electricity to offset the building's annual energy consumption, achieving net-zero performance.

Methodology

The Total Cost of Building Ownership (TCBO) was evaluated over 30 years and attempts to forecast all significant expenses related to ownership including property tax, utilities, maintenance/ replacement, and labour costs.

An hourly energy model was developed in BEOpt software [8] to simulate the existing and retrofitted building performance. To address the evolving climatic conditions and offer optimal design strategies for both mitigation and adaptation, the simulation used a future-shifted weather file provided by the University of Victoria [9]. These files were generated using the Canadian Weather Year for Energy Calculation (CWEC) 2016 dataset [10]. These weather files forecast weather patterns for three distinct 30-year periods: The 2020s (representing current conditions), the 2050s, and the 2080s [9]. Each weather file is generated using the RCP8.5 concentration pathway, reflecting a relatively high emission scenario [11]. Weather files for 2020 and 2050 were specifically utilized to compare current conditions with the projected future weather conditions.

The study evaluates two methods for calculating energy costs: first, utilizing energy cost estimates from the Canada Energy Futures report [7] and second, applying energy escalation rates (ranging from 2% to 5.5%) for electricity rates from Hydro Ottawa [12] and natural gas prices from Enbridge [13].

For the first approach, the Canada Energy Futures report explores three scenarios: Global Net-zero, Canada Net-zero, and Current Measures [7]. This paper concentrates on the Canada Net-zero and Current Measures scenarios. In the Canada Net-zero Scenario, Canada attains net-zero emissions by 2050, while efforts to reduce greenhouse gas emissions in the rest of the world progress more gradually. The Current Measures Scenario assumes limited action in Canada to reduce GHG emissions beyond existing measures, without requiring net-zero emissions. This scenario also envisions minimal global climate action.

In the Canada Net-zero scenario it is assumed that space and water heating are electrified along with other improvements to the housing sector such as increasing insulation levels by 50% from 2021 to 2050. However, in Current Measures less ambitious policy measures result in slower improvements in efficiency [1]. Electricity and natural gas prices fluctuated in accordance with the Canada Net-Zero and Current Measure scenario outlined in the Canada's Energy Future 2023 report [14]. Figure 1 and Figure 2 illustrate the natural gas and electricity costs predicted within the context of the Canada Net-zero and Current Measure scenario. Under both the Canada Net-zero and Current Measure scenarios, the cost of electricity remains relatively stable. However, there is a significant increase in the cost of natural gas under the Canada Net-zero scenario. This increase can be attributed to

various factors such as industries transitioning to fully electric operations, and incentive programs supporting low-carbon technology, leading to an upward trend in natural gas prices.

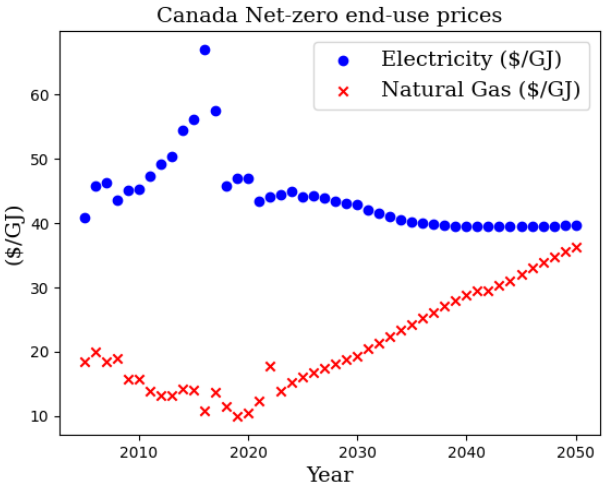

Figure 1: Electricity and natural gas costs over 30 years under Canada Net-zero scenario

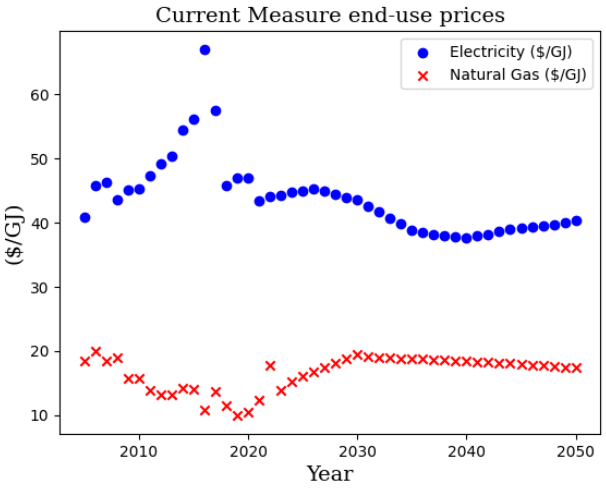

Figure 2: Electricity and natural gas costs over 30 years under Current Measure scenario

Canada's Energy Future estimates are aimed at achieving net-zero greenhouse gas (GHG) emissions by 2050 and employ their models to delineate pathways toward this objective. It is important to note that this approach is policy-driven and top-down, focusing on devising pathways to meet targeted emissions rather than estimating GHG emissions based on modelling an expanding grid infrastructure.

For the second approach, electricity and natural gas rates from Hydro Ottawa and Enbridge were taken into account. In Ontario, residential customers have three options for selecting their electricity price plan: Time-of-Use rates (TOU), Ultra-Low Overnight rates (ULO), and Tiered rates [12]. For this study, energy costs were also calculated based on TOU rates, which consist of three periods: on-peak (when energy demand and cost are high), mid-peak (when energy demand and cost are moderate), and off-peak (when energy demand and cost are low) [12]. Additionally, natural gas costs from Enbridge were considered [13] Although no TOU rates and natural gas prices were forecasted for the future, various inflation rates ranging from 2% to 5.5% were applied to assess the impact on costs over the next 30 years.

It is important to note that the energy cost projections are highly sensitive to future scenarios. According to the estimates by the Alberta Electric System Operator, load-adjusted generation costs in 2035 could be 56-66% higher in 'net-zero by 2035' scenarios compared to a technology trajectory based on current policies [15]. For Ontario, replacing expiring gas generator contracts with a mix of solar, wind, storage, and small modular reactors could potentially raise the average generation cost by around 20% in 2035 compared to renewing the gas contracts and proceeding with the current procurement plan for new resources [16]. These estimates add to the 15-20% increase in average generation costs projected in 2035 under current policy trajectories compared to 2021 in both provinces. When these higher costs are passed on directly to consumers, their impact on consumer bills would be compounded by additional expenses stemming from increased investment in transmission and distribution infrastructure due to necessary upgrades. Hydro One anticipates investing about $2.5 billion annually between 2023 and 2027 in transmission and distribution projects [17]. While numerous energy cost forecasting scenarios exist, for this study, we rely solely on estimates provided by the Canada Energy Futures report [7] and apply energy escalation rates (ranging from 2% to 5.5%) for electricity rates from Hydro Ottawa [12] and natural gas prices from Enbridge [13].

For this study it is assumed that capital is available for all upgrades and will not be borrowed. While retrofitting the house can impact property value and insurance, these costs are not included in the overall TCBO analysis for simplicity. Additionally, no incentive programs or rebates were considered for this analysis. The cost of borrowing and impact on insurance will be examined in the future.

The study compares the existing building (Scenario A) to a fully electric, net-zero building (Scenario B), and a fully electric, net-zero building with an expected 30% reduction in cost (Scenario C). Since the project was a unique pilot, it demanded considerable research and design investment. However, significant cost savings are anticipated in future projects by leveraging economies of scale. Scenario C, reflecting a 30% reduction in total costs, is included to illustrate this potential. Energiesprong, the Dutch inspiration for PEER has reported cost savings exceeding 50% after completing 5000+ prefabricated net-zero retrofits [18].

Results

Operational GHG emission

Table 2 is a comparison of the GHG emissions, energy use intensity (EUI) and required capital investment for both the existing building and the net-zero building over a 30-year time period. The PV system is estimated to generate 158 GJ annually for four units and the energy consumption for the house is estimated to be 144 GJ, leaving a net energy balance of approximately 14 GJ. The retrofit resulted in a 88% reduction in overall energy costs. Note the cost of electricity was calculated using the time-of-use energy rates in Ontario [12]. Additionally, it achieved a 94% reduction in operating GHG emissions and 80% reduction in EUI by retrofitting to a fully electric, net-zero building. The simulated solar production exceeds simulated energy demand, but without a battery storage system, the surplus electricity generated during the day cannot be stored for later use. As a result, there remains a need to draw power from the grid, particularly in the winter. Note the reported Scope 2 GHG emission factor for natural gas combustion in Ontario is 1.921 kg CO_2e/m^3 while the emission factor for electricity is 0.028 kg CO_2e/kWh [19].

Hourly Average GHG emissions

As the generation sources vary throughout the day, emission factors fluctuate in Ontario [20]. Daily average greenhouse gas (GHG) emissions for electricity were computed for both existing and retrofitted buildings using hourly average emission factors from 2020. By analyzing the hourly electricity consumption data for each building, a typical daily electricity consumption profile was derived. The retrofit building demonstrates notably reduced GHG emissions throughout the day. However, during periods when solar panels cannot fully meet the energy demand, supplementary energy is sourced from the grid. It's important to note that this analysis exclusively pertains to electricity consumption and does not include natural gas usage in the existing building.

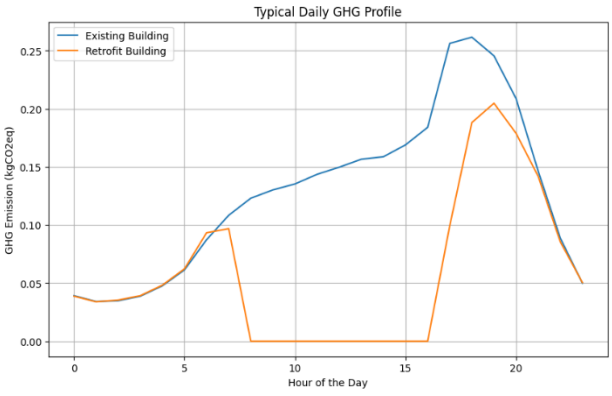

Figure 3: predicted daily GHG profile of the electricity usage for existing building vs retrofit building

Material Carbon emissions

Using the Material Carbon Emissions Estimator (MCE2) [21], the embodied greenhouse gas (GHG) emissions associated with various retrofit materials were assessed. Remarkably, triple-pane fiberglass windows exhibited the highest embodied carbon footprint compared to all other retrofit materials examined. The total embodied carbon emissions for the retrofit project amounted to 26.7 tonnes of CO_2e. It's important to note that these embodied carbon emissions calculations pertain solely to the building envelope, with the mechanical and renewable systems excluded from the analysis.

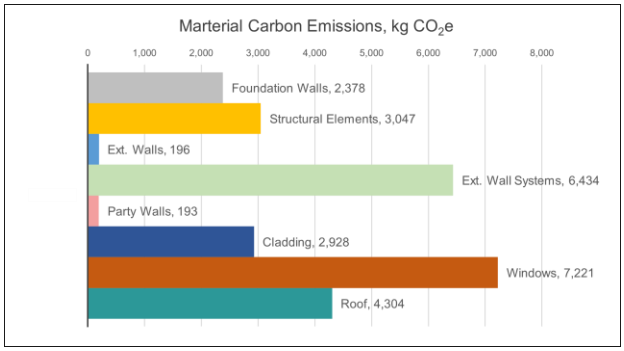

Figure 4: Embodied carbon emissions resulting from the integration of new materials during retrofitting

Capital investment cost

In the Existing building scenario in Table 2, capital costs represent the Business-as-Usual case, including expenses for repair and replacement that would be incurred over the building's lifespan even without a deep retrofit. Retrofitting to a net-zero building involved an additional investment of $15,685 beyond ongoing maintenance and renewal costs.

Table 2: Existing building vs net-zero building, comparing the GHG emissions, energy use intensity (EUI) and the capital investment cost

	Existing building- Scenario A (weather file 2020)	**Net-zero building- Scenario B (weather file 2020)**
Operational GHG (tonnes CO_2e/year)	12.2	0.671
EUI (kWh/m^2 /year)	211	45
Net energy use (GJ/year)	144	(14) - exported to grid
Annual energy cost	$8,417 - includes electricity and natural gas costs	$1051 - includes electricity cost only
Embodied carbon emissions for the first year (tonnes CO_2e)	0	26.7
Annual capital investment cost	$15,576	$31,261

(amortized over 30 years)		

Table 3, Table 4 present the Total Cost of Building Ownership (TCBO) at 30 years for both the Canada Net-zero and Current Measure scenarios. The analysis utilizes 2020 and 2050 weather forecasts for existing and net-zero buildings, respectively. The TCBO analysis was conducted by applying a 2% inflation rate to parameters such as maintenance, deployed capital, and property tax. Additionally, the total energy cost was calculated using the two climate scenarios and the future energy price forecasts under the Canada Net-zero and Current Measure scenarios. Overall, there is not a significant difference in TCBO across all scenarios.

Table 3: Existing Building TCBO at 30 years under Canada Net-zero and Current Measure scenario with different weather conditions

Weather file	**TCBO at 30 years (Canada Net-zero)**	**TCBO at 30 years (Current measure)**
2020	735,091	733,907
2050	741,686	740,454

Table 4: Net-zero Building TCBO at 30 years under Canada Net-zero and Current Measure scenario with different weather conditions

Weather file	**TCBO at 30 years (Canada Net-zero)**	**TCBO at 30 years (Current measure)**
2020	1,116,805	1,116,007
2050	1,110,884	1,110,130

Figure 5, Figure 6 and Figure 7 present the TCBO at 30 years for the Existing building (Scenario A), Net-zero building (Scenario B), and the Net-zero building with a 30% reduction (Scenario C). As shown in these figures, there is a significant drop in total energy consumption when the building is retrofitted and overall TCBO is lower for the net-zero building as the inflation rates start to go up[1].

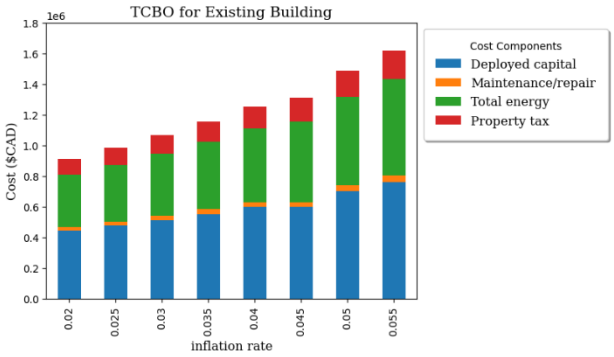

Figure 5: Total Cost of Building Ownership (TCBO) calculation at 30 years for existing buildings

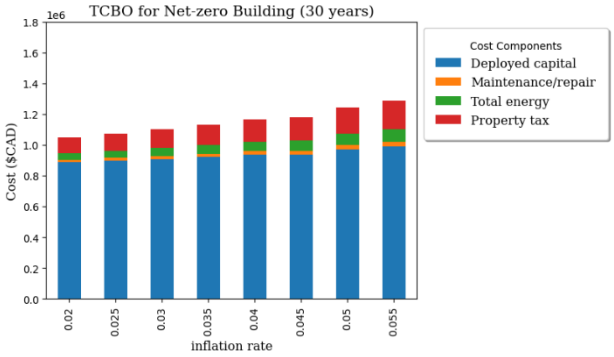

Figure 6: Total Cost of Building Ownership (TCBO) calculation at 30 years for net-zero building

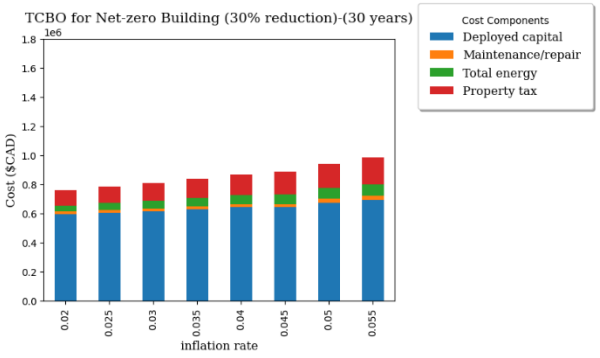

Figure 7: Total Cost of Building Ownership (TCBO) calculation at 30 years for net-zero building (at 30% reduction)

Table 5 presents a comparison of the Total Cost of Building Ownership (TCBO) between the existing building (Scenario A) and the Net-zero building (Scenario B) under various inflation rates. The energy models presented in this table were simulated using the weather file projection for 2050. As the inflation rate increases, it becomes evident that there are greater cost savings associated with retrofitting the building over its lifespan.

[1] Note the cost of electricity for TCBO calculations in Figure 5, Figure 6 and Figure 7 were calculated using the time-of-use energy rates from Hydro Ottawa [12] while the natural gas costs in Figure 5 were derived from prices provided by Enbridge[13]

Table 5: Total Cost of Building Ownership (TCBO) calculation at 30 years using weather file projection for 2050 for existing buildings vs net-zero building

Inflation rate (%)	Existing building- Scenario A (TCBO at 30 years)	Net-zero building - Scenario B (TCBO at 30 years)	Saving (going from A to B)
2.00%	$911,596	$1,049,532	-15%
2.50%	$984,981	$1,074,181	-9%
3.00%	$1,066,001	$1,101,365	-3%
3.50%	$1,155,518	$1,131,355	2%
4.00%	$1,254,489	$1,164,446	7%
4.50%	$1,311,722	$1,182,691	10%
5.00%	$1,485,182	$1,241,288	16%
5.50%	$1,619,414	$1,285,807	21%

Table 6 provides a comparison of the TCBO between the existing building (Scenario A) and the net-zero building with a 30% capital cost reduction (Scenario C) under various inflation rates. The energy models presented in this table were simulated using the weather file projection for 2050. As the inflation rate increases, it becomes apparent that there are greater cost savings associated with retrofitting the building over its lifespan.

Table 6: Total Cost of Building Ownership (TCBO) calculation at 30 years using weather file projection for 2050 for existing buildings vs net-zero building (at 30% reduction)

Inflation rate (%)	Existing building - Scenario A (TCBO at 30 years)	Net-zero building- Scenario C (30% reduction) (TCBO at 30 years)	Saving (going from A to C)
2.00%	$911,596	$760,038	17%
2.50%	$984,981	$783,518	20%
3.00%	$1,066,001	$809,454	24%
3.50%	$1,155,518	$838,113	27%
4.00%	$1,254,489	$869,793	31%
4.50%	$1,311,722	$888,038	32%
5.00%	$1,485,182	$943,571	36%
5.50%	$1,619,414	$986,441	39%

Conclusion

A Total Cost of Building Ownership (TCBO) methodology was developed to assess the overall cost of deep retrofits. To illustrate TCBO principles, the study used a real case: Ottawa Community Housing's Presland project, a panelized, net-zero retrofit of a typical Canadian social housing archetype. This methodology considered the energy use and greenhouse gas emissions associated with operating the building, as well as the necessary construction, installation, and replacement of components and systems over the life of the building.

The retrofit resulted in a 88% reduction in overall energy costs. Additionally, it achieved a 94% reduction in operating GHG emissions and an 80% reduction in EUI by retrofitting to a fully electric, net-zero building.

Results have shown that capital costs can have a significant impact on overall TCBO. Maintenance/replacement and energy cost escalation costs are the second-biggest drivers of TCBO. There are no cost savings at inflation rates ranging from 2% to 3.0%. However, as the inflation rate escalates to 3.5% and beyond, greater cost savings become associated with retrofitting the building over its lifespan. When considering the retrofit cost with a 30% reduction in construction expenses, there are cost savings at even the lowest inflation rate, however, savings increase as the inflation rate rises. Given that the retrofit project was a unique pilot involving the design and installation of prefabricated panels, substantial research and design investment was required. Nevertheless, future projects are anticipated to yield significant cost savings through economies of scale. The inclusion of a 30% reduction in costs serves to illustrate this potential. Notably, the Energiesprong program reported cost savings exceeding 50% after completing 5000+ prefabricated net-zero retrofits [18]. For this study, it is assumed that capital is available and not borrowed. Additionally, retrofitting the house can have an impact on the property value and insurance. Future studies should consider costs related to interest rates of borrowing as well as home insurance rates.

Numerous energy cost forecasts consider grid decarbonization and grid infrastructure cost and in future studies, these should be considered.

Acknowledgments

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References

[1] "CER – Canada's Energy Future 2023: CER's first long-term Outlook modeling Net-Zero by 2050." Accessed: Feb. 16, 2024. [Online]. Available: https://www.cer-rec.gc.ca/en/data-analysis/canada-energy-future/2023/

[2] N. R. C. Government of Canada, "Residential Sector Canada Table 1: Secondary Energy Use and GHG Emissions by Energy Source." Accessed: Mar. 06, 2024. [Online]. Available: https://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/sh

owTable.cfm?type=CP&sector=res&juris=ca&year=2020&rn=1&page=0

[3] P. Institute, "Reframed Initiative: Outcomes and analysis," Pembina Institute. Accessed: May 06, 2024. [Online]. Available: //www.pembina.org/pub/reframed-initiative-outcomes-and-analysis

[4] J. F. Azcarate-Aguerre, M. Conci, M. Zils, P. Hopkinson, and T. Klein, "Building energy retrofit-as-a-service: a Total Value of Ownership assessment methodology to support whole life-cycle building circularity and decarbonisation," *Construction Management and Economics*, vol. 40, no. 9, pp. 676–689, Sep. 2022, doi: 10.1080/01446193.2022.2094434.

[5] O. staff writer, "Prefabricated exterior energy retrofit pilot project promises Net Zero consumption | ontario construction report." Accessed: Feb. 29, 2024. [Online]. Available: https://ontarioconstructionreport.com/prefabricated-exterior-energy-retrofit-pilot-project-promises-net-zero-consumption/

[6] N. R. Canada, "PEER – Prefabricated Exterior Energy Retrofit." Accessed: Feb. 29, 2024. [Online]. Available: https://natural-resources.canada.ca/energy-efficiency/data-research-insights-energy-efficiency/housing-innovation/peer-prefabricated-exterior-energy-retrofit/19406

[7] Pembina institute, "Prefabricated panels & deep retrofit," 2020. [Online]. Available: https://www.pembina.org/docs/event/reframed-tech-series-1-slides.pdf

[8] "BEopt: Building Energy Optimization Tool." Accessed: Mar. 06, 2024. [Online]. Available: https://www.nrel.gov/buildings/beopt.html

[9] "Weather Files | Pacific Climate Impacts Consortium." Accessed: Feb. 28, 2024. [Online]. Available: https://www.pacificclimate.org/data/weather-files

[10] "Engineering Climate Datasets - Climate - Environment and Climate Change Canada." Accessed: Mar. 05, 2024. [Online]. Available: https://climate.weather.gc.ca/prods_servs/engineering_e.html

[11] "Representative Concentration Pathways." Accessed: Mar. 05, 2024. [Online]. Available: https://climate-scenarios.canada.ca/?page=scen-rcp

[12] H. O. Limited, "Electricity Rate Selection | Hydro Ottawa." Accessed: Mar. 07, 2024. [Online]. Available: https://hydroottawa.com/en/accounts-services/accounts/electricity-rate-selection

[13] "Residential Natural Gas Rates | Enbridge Gas." Accessed: May 15, 2024. [Online]. Available: https://www.enbridgegas.com/residential/my-account/rates

[14] C. E. R. Government of Canada, "CER – Canada's Energy Future 2023: Energy Supply and Demand Projections to 2050." Accessed: Feb. 20, 2024. [Online]. Available: https://www.cer-rec.gc.ca/en/data-analysis/canada-energy-future/2023/

[15] "Net-Zero Emissions Pathways," AESO. Accessed: Mar. 07, 2024. [Online]. Available: https://www.aeso.ca/future-of-electricity/net-zero-emissions-pathways/

[16] "The Electrification Puzzle: How to decarbonize the grid and manage rising electricity costs." Accessed: Mar. 07, 2024. [Online]. Available: https://economics.td.com/esg-electricity-costs

[17] "Hydro One Limited 2023-2027 Joint Rate Application." Aug. 10, 2021. Accessed: Mar. 07, 2024. [Online]. Available: https://www.hydroone.com/investorrelations/Documents/eventsandpresentations/Hydro%20One%20Limited%202023-2027%20Joint%20Rate%20Application.pdf

[18] A. Lamb, "Energiesprong – the Dutch system that could rescue Britain's social housing," CIBSE Journal. Accessed: Mar. 11, 2024. [Online]. Available: https://www.cibsejournal.com/case-studies/a-forward-leap-how-dutch-housing-process-energiesprong-guarantees-performance/

[19] P. S. and P. C. Government of Canada, "Emission factors and reference values : Canada's greenhouse gas offset credit system.: En84-294/2022E-PDF - Government of Canada Publications - Canada.ca." Accessed: Mar. 04, 2024. [Online]. Available: https://publications.gc.ca/site/eng/9.911206/publication.html

[20] "A Clearer View of Ontario's Electricity Emissions: Updated Electricity Emissions Factors and Guidelines." Accessed: May 09, 2024. [Online]. Available: https://taf.ca/publications/electricity_emissions_factors/

[21] N. R. Canada, "Material Carbon Emissions Estimator (MCE2)." Accessed: May 09, 2024. [Online]. Available: https://natural-resources.canada.ca/maps-tools-and-publications/tools/modelling-tools/material-carbon-emissions-estimator/24452