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Efficacy of government incentivized residential building retrofits in Canada

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This study evaluates the efficacy of government-incentivized residential building retrofit programs across ten diverse Canadian cities from economic and environmental perspectives. We modeled retrofit strategies using the Vertical City Weather Generator (VCWG v1.4.9) software. We assessed their financial and environmental viability under various jurisdictions with different economic incentive programs and future energy price inflation rates for electricity and fossil fuels. Our findings reveal city-specific variability in retrofit effectiveness, emphasizing the need for tailored approaches. Increasing electricity rates enhances Photovoltaic (PV) systems benefits but diminishes Heat Pump (HP) financial returns. Higher energy costs make retrofits more financially viable and shorten investment payback periods. While most strategies reduce Greenhouse Gas (GHG) emissions, PV systems are particularly environmentally effective when the electricity grid GHG emissions intensities are high. Building Envelop (BE) upgrades benefit all cities with a short payback period. Despite the economic incentives, HP may offer limited financial or environmental benefits. This study underscores the nuanced considerations necessary for effective retrofit policy formulation adapted to local contexts.

According to the Intergovernmental Panel on Climate Change (IPCC), buildings are responsible for approximately 32% of global energy consumption and 19% of energy-related CO_2e emissions. Retrofitting existing buildings to improve energy efficiency is one of the most effective measures to reduce GreenHouse Gas (GHG) emissions[1]. This is particularly crucial in Canada, where the built environment contributes significantly to the nation's energy consumption and GHG emissions. In Canada, buildings account for 13% of national Greenhouse Gas (GHG) emissions from direct fossil fuel combustion for space and water heating. When electricity use for cooling, lighting, and appliances is included, the total rises to 18% of national emissions. Retrofitting existing buildings can significantly reduce these emissions by improving energy efficiency and shifting to cleaner energy sources[2]. As the country strives to meet its ambitious climate targets, the need to enhance the energy efficiency of existing buildings becomes paramount[3]. The integration of renewable energy systems, such as PhotoVoltaic (PV), Solar Thermal (ST) and Wind Turbine (WT) systems, alongside energy storage (such as Building Integrated Thermal Energy Storage (BITES)) or heat pump (HP) technologies, can enhance the environmental benefits of retrofits by reducing reliance on fossil fuels and strengthening energy supply resilience. Studies have indicated that a combination of economic, social, and environmental incentives is crucial in overcoming barriers to adopting energy-efficient technologies, making retrofitted homes more attractive in the real estate market. While financial benefits and market transformation play significant roles in driving consumer behavior, other factors such as environmental concerns, policy support, and social norms also influence the decision to invest in home energy improvements. Cost-effectiveness analyses across various regions have shown that the long-term savings and indirect economic benefits of energy efficiency investments often outweigh initial costs, but these decisions are also shaped by broader motivations beyond economic considerations[4–7]. However, the rebound effect associated with such improvements and the necessity of government support to overcome financial barriers have also been noted[8–11].

Although research underscores the effectiveness of residential building retrofits in reducing energy consumption and GHG emissions, gaps remain in understanding their impact across Canada's diverse climate zones and economic incentive programs. Most studies focus on single climate zones, neglecting the need for tailored retrofit strategies across regions with varying energy costs, climate conditions, and government incentives[12–14]. The effectiveness of retrofits also hinges on factors like the electricity grid GHG emissions

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intensities and the anticipated rise in energy prices, which could affect the long-term economic viability and accessibility of these measures. This study aims to bridge these gaps by evaluating the cost-effectiveness and environmental impact of government-supported residential retrofits across Canada, examining how benefits such as energy and cost savings, financial returns, and GHG emissions reductions vary with regional factors and incentive programs.

Methodology

Vertical city weather generator (VCWG v1.4.9)

In this study, a single detached residential two-storey building with a footprint area of $A_{bld} = 130 \, \mathrm{m}^2$ is used as the model[15]. The Vertical City Weather Generator (VCWG v1.4.9) software is used as an Urban Physics Model (UPM), to investigate the implementation of various retrofit strategies across diverse urban settings in Canada. VCWG is an open-access, micro-scale, and multi-physics model designed to predict urban climate and building performance by parameterizing essential physical processes. It integrates system-level models to simulate the exchange of momentum, heat, humidity, and water across soil, urban surfaces, and the atmosphere, with the optional inclusion of alternative energy systems. VCWG employs various modeling approaches, including the Resistance-Capacitance (RC) thermal network, Navier-Stokes transport equations in the vertical direction, Monin-Obukhov Similarity Theory (MOST), and bulk energy modeling paradigms[16]. VCWG comprises multiple sub-models, such as the rural MOST model, urban vertical transport model, radiation model, building energy model, and rural/urban soil and surface energy balance models. Detailed descriptions of these components can be found in previous studies[3,17–20]. Weather boundary conditions for VCWG are generated using the Vatic Weather File Generator (VWFG v1.0.0), which derives data from the ERA5 dataset provided by the European Centre for Medium-Range Weather Forecasts (ECMWF). VWFG produces EnergyPlus Weather (EPW) files at an hourly resolution, which are essential inputs for VCWG. The forcing weather files correspond to a rural site near each modeled city[21]. VCWG's output for a reference building has been validated against measured gas and electricity consumption in London, Ontario, Canada, over the full year of 2019[22]. The economic analysis in VCWG v1.4.9 considers capital investment for implementing retrofit alternatives, government rebates, changes in operational fuel and electricity costs, operation and maintenance costs, loan payments, revenue from salvaging used equipment, and social cost of carbon. It considers electricity produced by PV and WT. The time horizon for this analysis is 20 years, and the analysis calculates the annualized marginal cost: net cost difference for an owner who implements various retrofit strategies compared to a base case scenario with no retrofits. Time value of money is accounted for using historical nominal interest and inflation rates. Further, various scenarios for inflation in energy prices are considered. In addition, a GHG emissions analysis is conducted in VCWG v1.4.9, which considers the implications of the changes in operational GHG emissions due to retrofit strategies. This analysis considers emissions from net grid electricity usage and net fossil fuel consumption. In this study VCWG v1.4.9 is run for an entire year in 2020, for which extensive weather data was already available (Supplementary Fig. S1).

Selected cities and climate zones

Figure 1 shows cities in different climate zones (4–8) across Canada based on the classifications of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE)[23]. Generally lower zones (e.g. 4) are warmer than higher zones (e.g. 8). Further, sub-zone A represents more humid conditions than sub-zone B, which signifies less humid and drier conditions. This study selects ten cities from different climate zones and provinces/territories. It was attempted to cover all climate zones to study the feasibility and potential benefits of different retrofitting strategies. Base building parameters are adjusted based on building standards and codes in their respective climate zones (Supplementary Table S1)[24–26].

Energy price rates and inflation

The study examines the varying electricity and fossil fuel pricing structures across Canadian provinces and territories. Ontario (electricity) and Alberta (electricity and gas) use time-based pricing systems, with Ontario employing on-peak, off-peak, and mid-peak rates, while Alberta having monthly price variations. Other regions like Quebec, British Columbia, and Manitoba utilize basic and step charges for electricity (Supplementary Fig. S2). Gas pricing structures vary by city, with Toronto, Vancouver, Calgary, Halifax, Winnipeg, Saskatoon, and Montreal all employing different combinations of basic, delivery, and commodity charges (Supplementary Table S2). In Canada's territories, diesel fuel is primarily used for residential heating due to extreme climates and limited alternative fuels, with prices ranging from 1.805 L^{-1} in Yellowknife to 1.899 L^{-1} in Whitehorse. The study also explores how energy price inflation impacts the cost-effectiveness of building retrofits, considering scenarios with varying inflation rates for electricity and fossil fuels. Seven annual inflation scenarios were analyzed, combining low, medium, and high inflation rates (1, 5 and 10%) for electricity and fossil fuel prices, to determine the economic viability of retrofit strategies under different future price conditions (Supplementary Fig. S3)[27–43]. Note that the previous Canadian government policy on carbon tax resulted in a net zero impact on household finances, as this carbon tax was typically offset by rebates under federal and provincial policies. Present and future carbon pricing is implicitly reflected in our energy price inflation assumptions because we assume many inflation scenarios in the future.

Electricity grid GHG emission intensity

The emissions intensity of electricity generation in Canada varies widely across provinces and territories, reflecting diverse energy sources. Ontario (ON), British Columbia (BC), Quebec (QC), Manitoba (MB), and Newfound Land (NL) exhibit lower values of 25, 12, 1.5, 1.1, and 24 $\mathrm{g_{CO_2e}} \, \mathrm{kW\text{-}hr}^{-1}$ (as of 2020), indicating a commitment to cleaner energy sources such as nuclear or hydro. Conversely, Nova Scotia (NS), Alberta (AB)
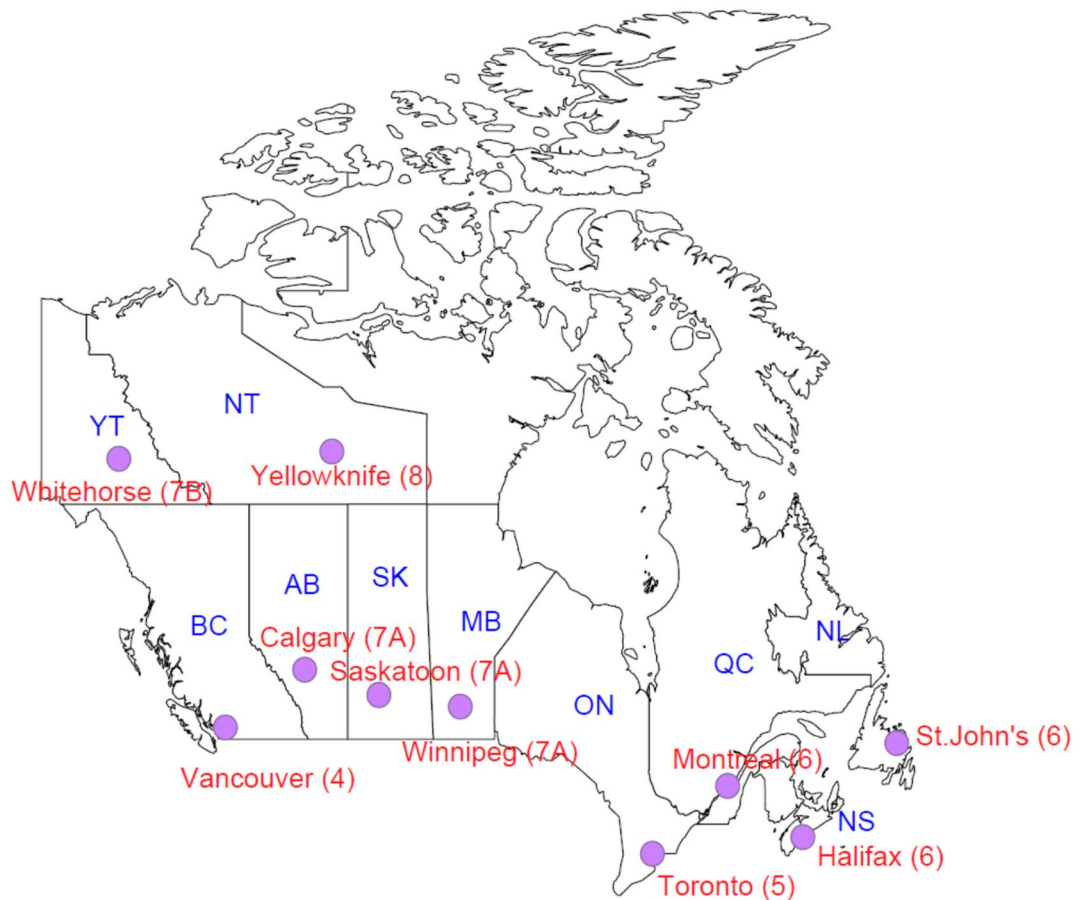
Fig. 1. Cities in different climate zones (4–8) across Canada; map generated using python 3.10 and various libraries: geopandas 1.0.1, matplotlib 3.9.0, and unidecode 1.4.0

and Saskatchewan (SK) report higher emission intensities of 670, 560 and 580 g_{CO_2e} kW-hr^{-1}, respectively, suggesting a greater environmental impact due to use of fossil fuels for generating electricity. The Yukon Territories (YT) and Northwest Territories (NT) have emission intensities in the middle range of 100 and 180 g_{CO_2e} kW-hr^{-1}, respectively (Supplementary Fig. S4)[44]. Note: in Yellowknife (NT) hydro electricity is available, so the actual grid GHG emission intensity may be lower than the territorial average. From 2020 to 2040, we assume a 70% reduction in emissions intensity of electricity generation for all provinces and territories[45].

Government economic incentive programs

Figure 2 outlines various financial incentives available for homeowners to improve energy efficiency and integrate alternative energy solutions. Supplementary Fig. S5 and Table S3 provide details of the government economic incentive programs, and the associated text in the supplementary material provides explanations of these programs.

Retrofit strategies

The selection of retrofit strategies across various cities is driven by federal, provincial, and territorial incentives, along with local climate conditions. Common strategies include PhotoVoltaic (PV) and Building Envelop (BE) improvements, which are prevalent due to energy efficiency incentives. Heat Pumps (HP) are often selected in colder climates like Saskatoon, Winnipeg, and Montreal, while Cool Roofs (CR) are seen in Toronto. Coastal areas like Halifax also include Solar Thermal (ST), and Wind Turbines (WT) are utilized in Whitehorse. These strategies are tailored to local climate conditions, energy needs, and available financial incentives. Refer to Supplementary Fig. S6, Table S4, and the associated text for more details.

Economic analysis

The equations in this section are adapted from reference[3]. For calculating the annual marginal cost of residential building retrofits, the following equation is used,

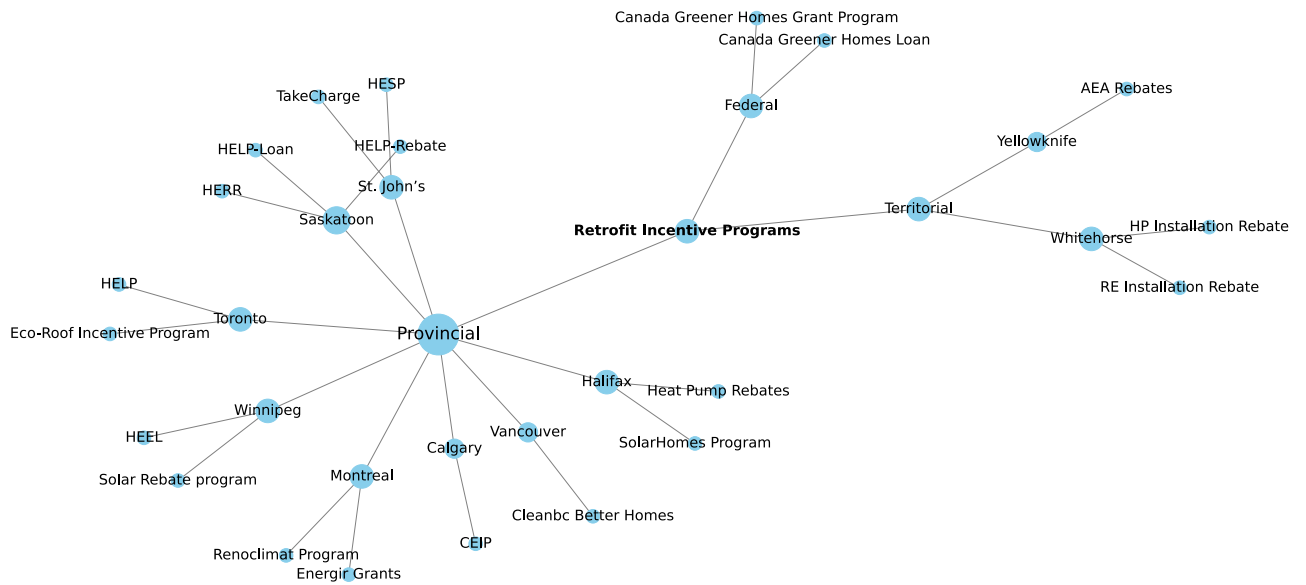$$C = C_I + C_F + C_E + C_{OM} + L - C_S - SCC_S, \tag{1}$$

Fig. 2. Federal and provincial/territorial government building retrofit economic incentive programs across Canada; network diagram generated using python 3.10 and various libraries: networkx 3.3 and matplotlib 3.9.0

where C_I is the annualized initial investment (net cost involving capital investment minus rebates), C_F is the annual fossil fuel cost, C_E is the annual grid electricity consumption cost, C_{OM} is the annual operation and maintenance cost, L is the annual loan cost, C_S is the annual income from alternative energy system salvage, and SCC_S is the annual cost savings considering the social cost of carbon, all in [\$]. Supplementary Eqn. S1 to S14 and Table S5 and Table S6 provide details pertaining to discounting, interest rate, inflation rate, social cost of carbon, and other variables for the calculation of each annualized term.

Environmental analysis

The environmental analysis involves the calculation of potential GHG emissions savings (CO_2e), or lack thereof, achieved through various building retrofit strategies, including BE, HP, PV, ST, WT, and CR systems. The GHG emissions saving is a summation of GHG saving through a reduction of electricity and fossil fuel consumption. The fuel usage reduction is computed as,

$$F_{\text{save}} = [F_{hB} + F_{whB} - (F_h + F_{wh})]A_{bld}N, \tag{2}$$

where F_{hB}, F_{whB}, F_h and F_{wh} [m^3 m^{-2}] are the fossil fuel usage for the base and retrofitted buildings for space and water heating, respectively. Then, the GHG emissions reduction potential in CO_2e associated with fossil fuel saving is estimated by,

$$GHG_{F_{\text{save}}} = F_{\text{save}}\rho_F \frac{MW_{CO_2}}{MW_F}, \tag{3}$$

where ρ_F [kg$_F$ m^{-3}] is the density of fossil fuel (for natural gas or diesel), MW_{CO_2} [g$_{CO_2}$ mole^{-1}] is the molecular weight of CO_2, and MW_F [g$_F$ mole^{-1}] is the molecular weights of the fossil fuel. The electricity usage reduction is computed by,

$$E_{\text{save}} = [E_{cB} + E_{dB} - (E_c + E_h + E_d - E_{pv} - E_{wt})]A_{bld}N, \tag{4}$$

where $E_{cB}, E_{dB}, E_c, E_h,$ and E_d [kW-hr m^{-2}] are the electricity usage for space cooling/heating and domestic appliance in base/retrofitted buildings, and E_{pv} and E_{wt} [kW-hr m^{-2}] are electricity generated by PV and WT, respectively, in the retrofitted building. Then, the GHG emissions reduction potential in CO_2e associated with electricity saving is found as,

$$GHG_{E_{\text{save}}} = E_{\text{save}}EI_E, \tag{5}$$

where EI_E [kg$_{CO_2e}$ kW-hr^{-1}] is the electricity grid GHG emissions intensities in each province or territory.

Results
Retrofit costs
Figure 3 visualizes the results for annualized marginal cost savings due to retrofits. For brevity, the results in this section are discussed for Vancouver and Toronto (climate zones 4 and 5), Halifax, Montreal, and St. John's
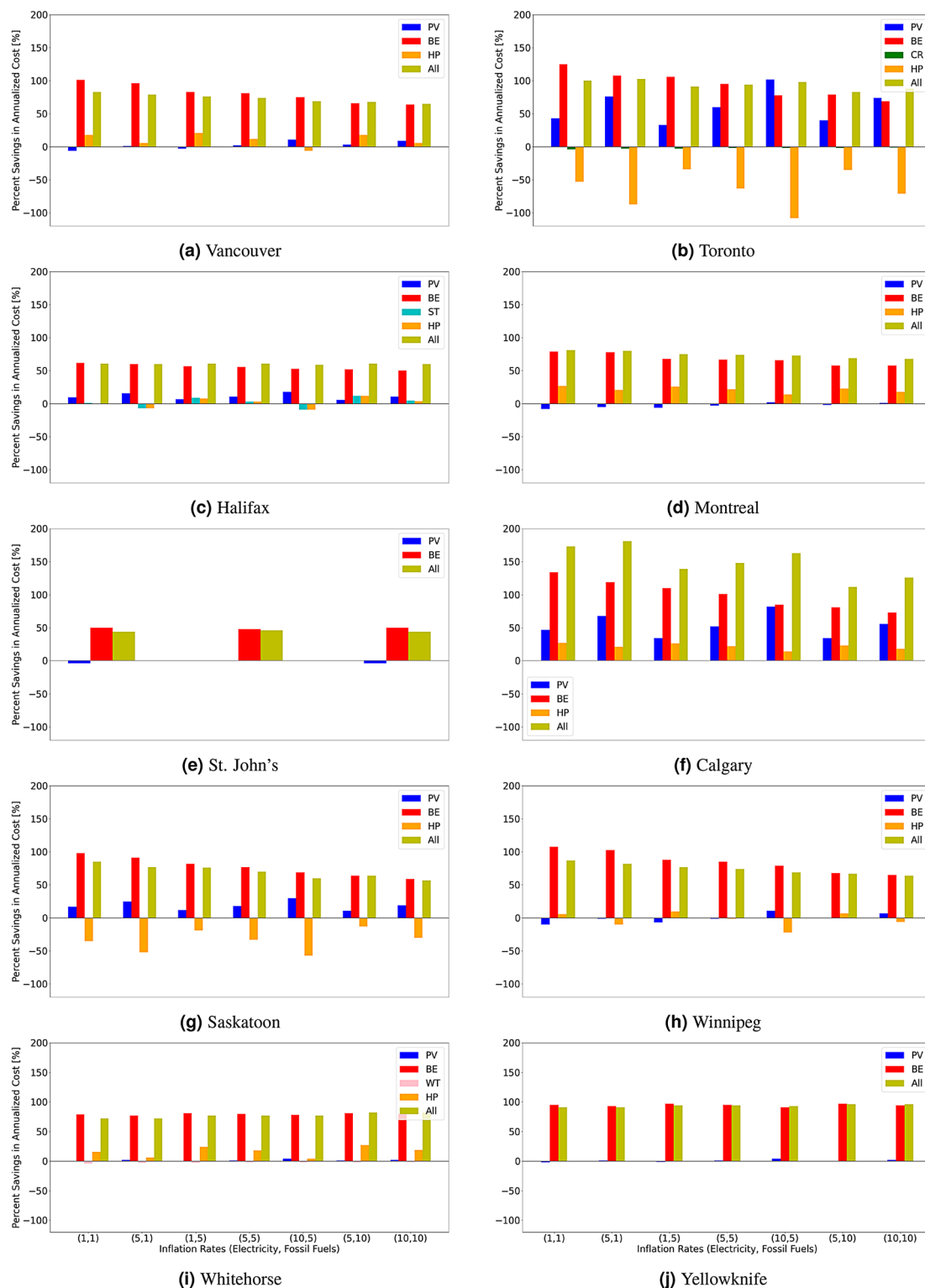
Fig. 3. Percent savings in marginal annualized cost using building retrofits associated with different energy price inflation rates across various Canadian cities (The comparison is against a house with no retrofits, which is built per codes and standards); (a) Vancouver, (b) Toronto, (c) Halifax, (d) Montreal, (e) St. John's, (f) Calgary, (g) Saskatoon, (h) Winnipeg, (i) Whitehorse, and (j) Yellowknife.

(climate zone 6), Calgary, Saskatoon, and Winnipeg (climate zone 7A), and Whitehorse and Yellowknife (climate zones 7B and 8).

Climate zones 4 and 5

In Vancouver (4), the economic viability of retrofit measures varies significantly. PV installations show mixed results, with savings ranging from −17 to 5%, suggesting limited effectiveness possibly due to suboptimal solar conditions. BE improvements, however, demonstrate substantial savings between 65% and 100%, indicating their strong potential for cost reduction in Vancouver's climate. HP strategies also show varied outcomes, with savings from −15 to 20%, reflecting mixed cost-effectiveness. In contrast, Toronto (5) benefits more from PV installations, with substantial savings between 40% and 100%, especially under higher electricity price inflation. BE improvements also offer significant savings ranging from 60 to 130%. However, cool roofs and HP strategies show negative savings, suggesting higher costs and reduced economic viability for these measures. Overall, while combined retrofits in both cities can be effective, careful planning and consideration of specific measures are essential to achieve economic benefits, with Vancouver showing stronger results for BE improvements and Toronto for PV/BE installations. Note: achieving savings of 100% or more is possible due to additional income or savings from the social cost of carbon and electricity generation by PV/WT.

Climate zone 6

In climate zone 6, retrofit scenarios for Halifax, Montreal, and St. John's reveal varying cost implications. Halifax shows potential savings with PV systems ranging from 10 to 20%, significant reductions in BE retrofits (∼50%), and mixed results for HPs and ST installations (−10 to 10%), influenced by price inflation trends. Montreal's PV systems offer minor changes (−10 to 5%) due to low electricity prices, while BE retrofits are highly effective (60 to 80%), and HP retrofits provide savings from 15 to 30%. St. John's sees modest savings from PV retrofits (−10 to 5%) and significant improvements from BE enhancements (45% to 55%). Combined retrofit options across all cities demonstrate a broad range of savings, highlighting the varying effectiveness of different measures under regional economic conditions.

Climate zone 7A

In climate zone 7A, retrofit scenarios for Calgary, Saskatoon, and Winnipeg reveal distinct insights into energy savings and cost implications. In Calgary, PV retrofits show substantial savings ranging from 30 to 90%, especially with higher electricity price inflation rates. BE retrofits offer 60 to 120% cost difference at moderate inflation rates, while combined PV and envelop retrofits can yield savings from 120 to 180%. Saskatoon presents mixed results for PV retrofits, with savings varying from 20 to 30%, influenced by electricity price inflation. BE retrofits offer notable savings from 70 to 100%, whereas HP retrofits generally lead to cost increases, with savings ranging from −60 to −20%. Combined retrofit options show promising cost reductions up to 60%. Winnipeg's PV retrofits demonstrate variable outcomes, with some scenarios showing notable savings and others slight negative impacts. BE retrofits provide substantial reductions, from 60 to 110%, while HP retrofits are generally inefficient, with cost savings from −20 to 20%. Overall, combined retrofit scenarios in Winnipeg show cost-effectiveness, with cost reductions up to 80% as energy prices rise.

Climate zone 7B and 8

In the distinct climates of Whitehorse (7B) and Yellowknife (8), retrofit scenarios reveal varied impacts on energy savings and costs. In Whitehorse, PV retrofits show minimal changes in savings, ranging up to 5%, likely due to limited solar radiation. Wind Turbine (WT) retrofits exhibit mixed outcomes, with savings from −5 to −1%. Conversely, BE retrofits demonstrate substantial potential, with cost savings ranging from 75 to 85%, and HP retrofits offer minimal savings from 5 to 30%. Combined retrofit scenarios show significant improvements, with cost savings ranging from 70 to 85%. In Yellowknife, PV retrofits also show limited cost impact, with savings from −2 to 2%. BE retrofits provide substantial savings, ranging from 90 to 95%. Integrating multiple retrofit measures results in significant cost efficiency improvements, with cost savings from 85 to 90%, highlighting the effectiveness of a comprehensive approach in both locations.

In summary, the variation in retrofit cost savings across cities under different energy price inflation scenarios was analyzed. A key trend emerges when examining the impact of higher inflation rates (e.g., 10% electricity, 5% fossil fuels). Cities with higher initial electricity prices and carbon-intensive grids, such as Halifax, show diminishing cost and emissions savings potential for HP systems. Cities with high electricity prices, but with greener grids, show environmental benefits with cost disadvantages for HP systems (e.g. see Supplementary Fig. S7 for Toronto). This is primarily due to the increasing cost of electricity outpacing the operational cost savings of these retrofits. BE improvements show consistently high cost savings for most cities, regardless of inflation rates. Moreover, the observed drop in savings for some cities under specific inflation scenarios, such as in Montreal and Whitehorse, may be attributed to the interplay between electricity price escalation and the cost-effectiveness of PV installations. In these regions, PV systems become less viable when electricity price inflation is moderate but fossil fuel inflation remains relatively low, as the comparative advantage of on-site electricity generation diminishes. Meanwhile, cities like Toronto and Calgary, where electricity prices are already higher, continue to benefit from PV retrofits under these conditions, as the avoided cost of grid electricity offsets the installation costs more effectively. These regional variations highlight the importance of considering both local energy pricing structures and inflation trajectories when assessing the long-term financial viability of retrofit investments.

Payback period

Figure 4 shows the cost difference of retrofit strategies relative to the no retrofit case versus time for each city, which provides an estimate of payback period for the retrofit investment. The payback period quantifies the number of years required for an initial investment in retrofitting a building to be recovered given operational savings in energy costs. In our analysis, we considered the impact of energy price inflation rate on the payback
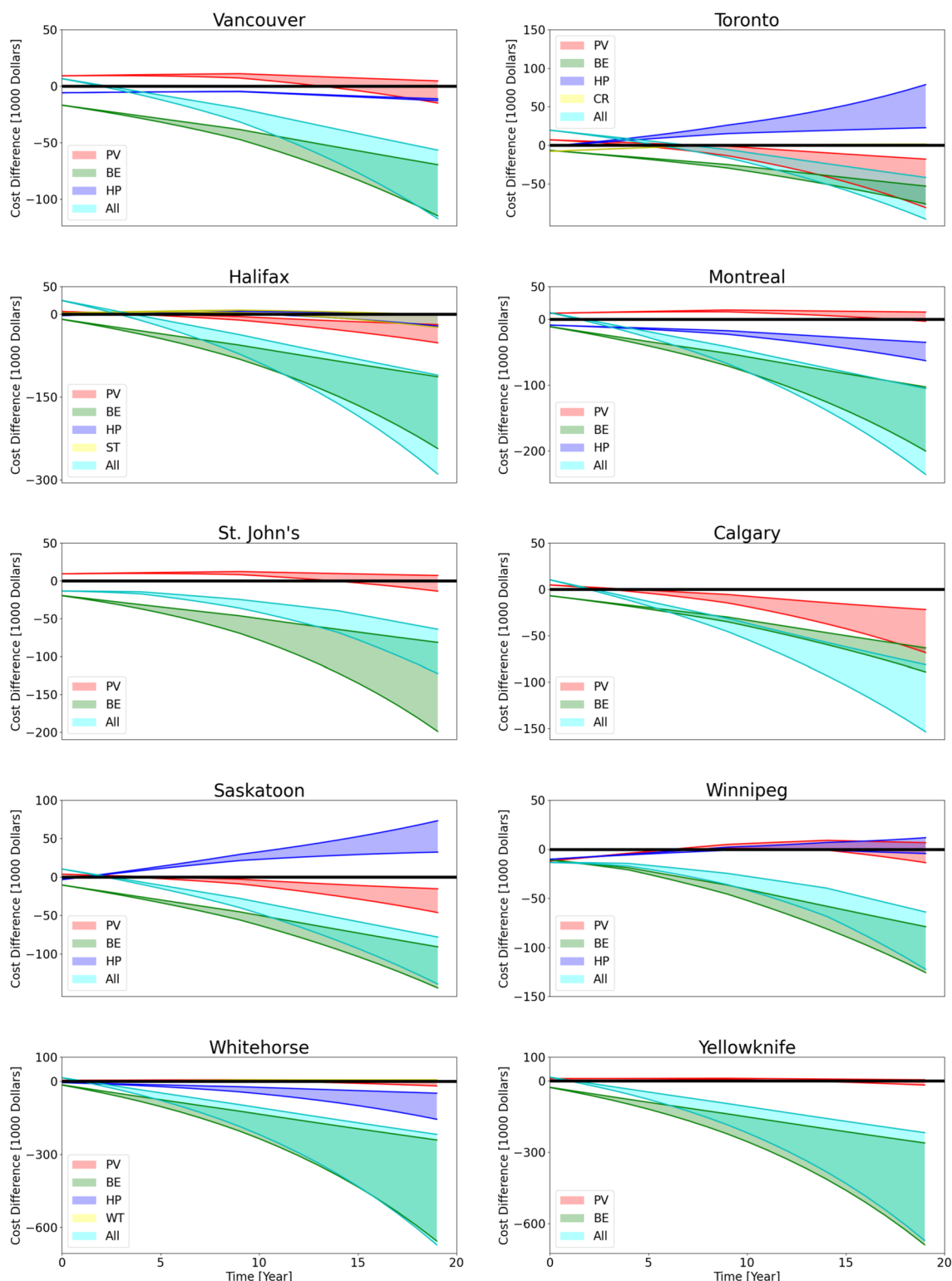

Fig. 4. Cost difference of retrofit strategies relative to the no retrofit case versus time for each city; the horizontal solid line at zero represents the point of cost parity; the payback period occurs where each curve crosses this line. Shaded areas reflect inflation scenarios: (1%, 1%) and (10%, 10%).
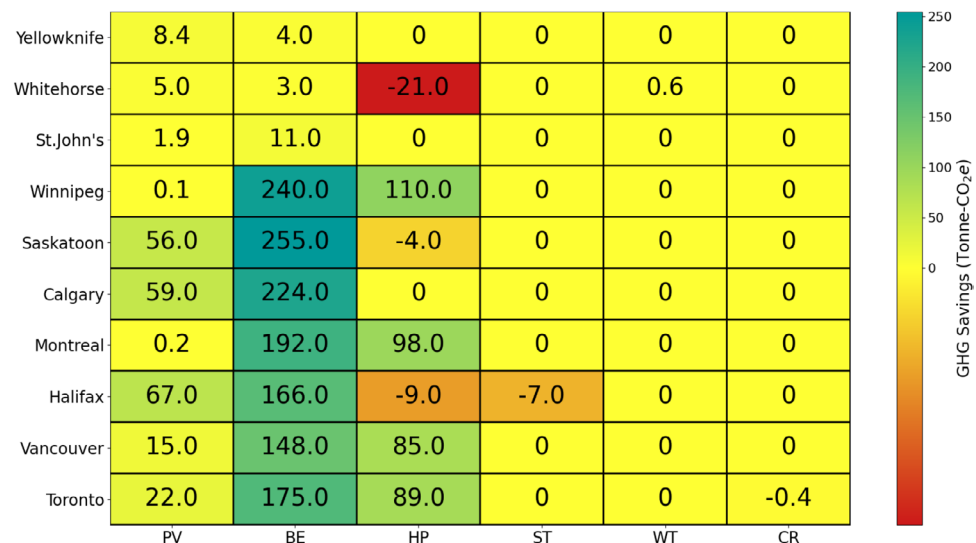
Fig. 5. GHG emissions savings potential color map by retrofit type and city over 20 years [Tonne-CO$_2$e].

period, and we will discuss the nuances below. The estimated range for the payback period is based on low energy price inflation (1% electricity, 1% fossil fuels) and high energy price inflation rate (10% electricity, 10% fossil fuels).

In both Vancouver (climate zone 4) and Toronto (climate zone 5), BE improvements offer the quickest financial returns, with payback periods of less than 1 year. In Vancouver, PV systems generally have payback periods exceeding 20 years, though they become more viable under high energy price inflation rate scenarios, reducing to 15 years. Comprehensive retrofits in Vancouver face economic challenges, with payback periods ranging from 5 to 6 years depending on energy price inflation rates. In Toronto, PV systems have shorter payback periods of 6–7 years as energy price inflation rate increases, while HP and cool roofs lack defined payback periods, indicating higher costs for homeowners. Comprehensive retrofits in Toronto typically have about 8–9 years in payback time.

In Halifax, St. John's, and Montreal (all in climate zone 6), the economic feasibility of various retrofit strategies varies significantly. In Halifax, PV installations have payback periods ranging from 5 to 6 years, with HPs and Solar Thermal (ST) systems showing uniformly long payback periods exceeding 20 years, indicating substantial upfront costs and the need for long-term investment. In St. John's, PV systems also demonstrate extended payback periods of 15–20 years, while BE improvements offer immediate returns with payback periods of less than 1 year. Comprehensive retrofits in St. John's have a short payback period (1 year), underscoring the impact of economic conditions on investment feasibility. In Montreal, PV installations exhibit payback periods exceeding 20 years across all scenarios, contrasting with the immediate payback periods of less than 1 year for BE improvements and HP installations. Implementing all retrofit strategies together in Montreal yields payback periods of 3–6 years, highlighting moderate to relatively short-term returns depending on energy price inflation rates. Overall, BE improvements offer rapid financial returns across these cities, while other strategies like PV, HP, and ST require longer-term investment horizons.

In Calgary, Winnipeg, and Saskatoon (climate zone 7A), BE improvements offer the quickest payback periods, typically under 1 year in Saskatoon, Calgary, and Winnipeg, reflecting their effectiveness in offsetting initial costs through energy savings. In Calgary and Saskatoon, PV installations and comprehensive retrofits have payback periods ranging from 4 to 6 years, indicating moderate returns on investment. Conversely, Winnipeg faces longer payback periods for PV installations, exceeding 12 to over 20 years. While for comprehensive retrofits in Saskatoon, the payback period is under 3 years, HP installations in Saskatoon and Winnipeg have payback periods exceeding 20 years, suggesting high initial costs and limited short-term viability. Overall, while BE improvements show rapid returns, other retrofit strategies in these cities present extended payback periods, highlighting the long-term nature of energy efficiency investments in climate zone 7A.

In Whitehorse (climate zone 7B) and Yellowknife (climate zone 8), PV installations have long payback periods of over 17–20 years due to high upfront costs and less solar radiation, while BE improvements show immediate payback (less than 1 year). Also, HP for Whitehorse indicates a very short payback period. In both regions, combining all retrofit strategies results in shorter payback periods of 2–4 years, indicating quicker economic returns compared to PV investments alone.

GHG emissions savings potential

The study, illustrated in Figure 5, shows that BE improvements are the most effective retrofit strategy for GHG emissions reduction across Canadian cities. Saskatoon leads with the greatest GHG emissions savings potential using BE retrofits, followed by Winnipeg and Calgary. HP and PV systems also provide notable benefits, though their impact varies by city. Halifax faces challenges with HP and ST systems due to high electricity grid GHG emissions intensities but still achieves notable savings from PV and BE. Overall, Winnipeg, Calgary, and

Saskatoon are the top performers in GHG reductions, with Figure 5 highlighting the broad regional variations and effectiveness of different retrofit strategies. Supplementary Fig. S8 shows the overall GHG emissions savings potential for each province or territory in Canada.

Discussions

The study evaluated government-incentivized residential building retrofits across ten Canadian cities with diverse climates using the Vertical City Weather Generator (VCWG v1.4.9) software for performance estimation. The analysis examined the economic and environmental viability of key retrofit strategies, including PhotoVoltaic (PV) installations, Building Envelop (BE) improvements, and Heat Pump (HP) systems, supplemented by city-specific programs such as Wind Turbines (WT) and Solar Thermal (ST) collectors. The findings highlight the importance of region-specific policy adjustments to enhance the effectiveness of retrofit programs. PV installations are financially viable in cities with high electricity rates, such as Toronto and Vancouver, where expanding net metering, feed-in tariffs, or the integration of battery storage–an emerging alternative that reduces electricity grid impacts–could further encourage adoption. In cities with lower electricity grid GHG emission intensities, such as Calgary, increasing rebates or tax credits could help incentivize the adoption of low-carbon technologies and drive significant emissions reductions. It has been shown that that well-targeted financial incentives can effectively overcome upfront cost barriers and promote cleaner energy choices[46–48].Given their short payback periods and high cost-effectiveness, BE improvements could be effectively promoted through low-interest loans and performance-based incentives, rather than direct subsidies. Additionally, stringent retrofit codes could help ensure widespread implementation. However, HP systems were not consistently favorable financially or environmentally. Their environmental benefits can be limited in cases where 1) electric heating is already in place and electricity grid GHG emission intensity is low (e.g. St. John's) or 2) electricity grid GHG emission intensity is high (e.g. Saskatoon). On the other hand, HP systems are not financially beneficial in cities where electricity price is high (e.g. Toronto). As a result, HP incentives should be targeted primarily in regions where they replace gas- and oil-based heating systems or where electricity price is low.

To improve retrofit program design, governments should adopt regionally adjusted incentives that reflect electricity pricing, heating demand, and emissions reduction potential. Performance-based subsidies, rewarding homeowners based on actual energy savings and emissions reductions rather than flat-rate incentives, would enhance cost-effectiveness. Integrated support programs bundling BE improvements with PV or HP incentives could encourage comprehensive retrofits, maximizing financial and environmental benefits. Expanding zero-interest loans and property-assessed financing models would reduce financial barriers, particularly for low-income and vulnerable populations. Additionally, targeted HP subsidies should focus on regions heavily reliant on fossil-fuel heating, while reducing emphasis in cleaner-grid provinces with limited impact. Future research should explore integrated optimization techniques, climate scenario modeling, and behavioral adoption patterns to refine policy recommendations. By aligning incentive programs with localized economic and environmental realities, governments can enhance energy cost savings, accelerate decarbonization, and maximize public investment impact.

Availability of code and data

The Atmospheric Innovations Research (AIR) Laboratory at the University of Guelph provides the model source code and forcing data. For access, contact Amir A. Aliabadi (aaliabad@uoguelph.ca), visit http://www.aaa-scientists.com/, or visit https://github.com/AmirAAliabadi/VCWGv1.4.9).

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A.A.A.: Software, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Supervision, Funding acquisition, Writing original draft, Writing—review & editing. A.M.: Conceptualization, Software, Data curation, Investigation, Methodology, Writing original draft, Writing—review & editing. B.G.: Funding acquisition, Writing—review & editing. K.S.: Supervision, Funding acquisition, Writing original draft, Writing—review & editing.

Declarations

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The authors declare no competing interests.

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