

# Perspectives on Policy, Economic, and Environmental Aspects of Building Retrofits in Canada

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**Abstract.** Building retrofits are essential for improving the durability, affordability, and environmental performance of the existing building stock, particularly under changing climate conditions. However, optimal retrofit outcomes depend on the complex interactions among building technologies, economic conditions, and policy instruments. In this study, the Vertical City Weather Generator (VCWG v1.6.1), an urban physics based model, is coupled with a micro-genetic optimization algorithm (MGA) to identify optimal retrofit strategies. The optimization considers 14 key decision variables, including building retrofit measures alongside policy and economic parameters such as loan amounts, rebate levels, loan interest rates, and electricity and fuel consumption taxes. Multiple objective functions are evaluated, including marginal annual cost savings for homeowners, government, and total greenhouse gas (GHG) emission reductions, accounting for both operational and embodied emissions over a 20-year time horizon. Future climate conditions are represented using weather projections from 2025 to 2050 at five-year intervals under SSP2-4.5 and SSP5-8.5 socioeconomic pathways. Results indicate that optimal strategies favor photovoltaic (PV) deployment, solar heat gain coefficient (SHGC) and thermal energy storage, while envelope upgrades align closely with current building code levels. Substantial rebates combined with low-interest loans emerge as the most effective policy instruments. Despite sustained public investment requirements, optimized retrofits deliver persistent cost savings for homeowners and significant GHG reductions across both climate scenarios, highlighting the importance of adaptive and policy-aware retrofit planning under future uncertainty.

**Keywords:** Building retrofit optimization · Future climate informed urban modeling · Policy-economic analysis.

## 1 Introduction

The existing residential building stock plays a central role in achieving long term climate mitigation, energy affordability, and durability objectives, particularly in countries such as Canada. A large proportion of Canadian dwellings were constructed prior to the adoption of modern energy and durability standards, resulting in high operational energy demand, aging envelopes, and increased vulnerability to future climate stresses. Building retrofits, therefore, represent a critical intervention for extending service life, improving environmental performance, and reducing greenhouse gas (GHG) emissions across the building lifecycle [1, 2].

While extensive research has examined the technical performance of individual retrofit measures such as envelope upgrades, renewable energy systems, and mechanical improvements, retrofit decision making in practice is shaped by a broader socio-technical context. Economic constraints, policy instruments, financing mechanisms, and energy pricing structures strongly influence the feasibility and uptake of retrofit solutions. In many cases, technically effective measures fail to achieve large scale adoption due to misalignment concerning upfront costs, long-term benefits, and policy support frameworks. Consequently, there is a growing need for integrated approaches that simultaneously evaluate building performance, economic outcomes, and policy effectiveness [3, 4].

Climate change further complicates retrofit planning by altering future weather conditions, heating and cooling demands, and long-term building durability. Retrofit strategies optimized for historical climate

conditions may under-perform or lose economic attractiveness under future climate change scenarios. Incorporating climate projections into retrofit analysis is therefore essential for identifying resilient and cost effective solutions over the expected service life of building components [6].

This study addresses these challenges by developing an integrated modeling and optimization framework that links urban climate physics, building retrofit technologies, and policy economic parameters. The Vertical City Weather Generator (VCWG) is employed to represent future urban weather conditions across multiple time horizons, while a micro-genetic optimization algorithm (MGA) is used to identify optimal retrofit configurations. By applying this framework to future climate scenarios of Toronto under different Shared Socioeconomic Pathways (SSPs), this work provides a systematic assessment of how policy design, economic incentives, and environmental conditions jointly shape optimal retrofit pathways. The findings aim to support policymakers, practitioners, and researchers in developing durable, affordable, and climate responsive retrofit strategies for the Toronto’s residential sector.

## 2 Methodology

### Vertical City Weather Generator (VCWG v1.6.1)

In this study, the Vertical City Weather Generator (VCWG v1.6.1) is employed as an urban physics model to simulate the energy performance and carbon emissions of residential buildings in Toronto (ASHRAE Climate Zone 5) [2,5]. VCWG integrates localized weather data, detailed building parameters, and energy consumption patterns to produce high-resolution, hourly simulations of building energy performance under varying retrofit scenarios. The analysis explicitly targets the use of future climate informed weather data for Toronto, considering two contrasting Shared Socioeconomic Pathways (SSP2-4.5 and SSP5-8.5) over the period from 2025 to 2050 at five-year intervals.

### Micro-Genetic Algorithm (MGA)

The MGA is employed to search for optimal retrofit solutions [6]. MGA is a computationally efficient version of traditional genetic algorithms, designed to solve problems involving multiple conflicting objectives. The algorithm operates by evolving a population of potential solutions (population of 5) (representing different retrofit strategies) over a series of generations (up to 100), selecting the best individuals based on the lowest fitness according to the defined objective functions. The primary goal of this study is to identify retrofit strategies that maximize the owner’s annualized marginal cost saving ( $C_{Os}$ ), the government’s annualized marginal cost saving ( $C_{Gs}$ ), and life cycle GHG emissions savings ( $\text{GHG}_s$ ) over  $N = 20$  years of each retrofit strategy (Eqn. 1). These objectives are considered simultaneously in the optimization process using a weighted sum approach, which is to be minimized.

$$F = -w_{GHG} \frac{\text{GHG}_s}{\text{GHG}_{0s}} - w_O \frac{C_{Os}}{C_{0s}} - w_G \frac{C_{Gs}}{C_{0s}}. \quad (1)$$

We assign specific weights to each sub-objective function, such that  $w_{GHG} = w_G = 0.2$  and  $w_O = 0.6$ . The sub-objective functions are normalized using  $\text{GHG}_{0s}$  [kg-CO<sub>2</sub>e] and  $C_{0s} = |C_{0Os}| + |C_{0Gs}|$  [\$], representing the total GHG emissions savings and the overall absolute value of annualized cost savings, respectively. These values are derived from the solution of the first iteration of the optimization process.

Using the multi-objective optimization framework, we determine the nearly global optimum values for 14 key retrofit variables (outlined in Table 1) under 4 projected energy price inflation rates scenarios.

### Economic analysis

The equations in this section are adapted from [2,6]. For the retrofitted case, the annualized cost for the owner is given by

$$C_{\text{Retrofit}} = C_I + C_F + C_E + C_{OM} + L + \text{Tax}_F + \text{Tax}_E - \text{Rebate} - \text{Loan} - C_S - SCC_S, \quad (2)$$

Table 1: Optimization variables with minimum value, maximum value, and variation interval: Building Integrated Thermal Energy Storage (BITES), Solar Thermal (ST), PhotoVoltaic (PV); note: the ranges are informed by building codes and standards in each climate zone

Category	Variables	Minimum	Maximum	Interval
<b>Building Parameters</b>	Volume of BITES ( $V_{\text{bites}}$ ) [ $\text{m}^3\text{m}^{-2}$ ]	0.05	0.25	0.04
	Roof Albedo ( $\alpha_R$ )	0.1	0.7	0.05
	Collector Area for ST ( $A_{\text{st}}$ ) [ $\text{m}^2\text{m}^{-2}$ ]	0.2	0.6	0.05
	Roof Thermal Resistance ( $R_{\text{roof}}$ ) [ $\text{m}^2\text{K W}^{-1}$ ]	5.46	11.5	0.5
	Infiltration Rate ( $V_{\text{inf}}$ ) [ACH]	0.5	1.5	0.25
	Wall Thermal Resistance ( $R_{\text{wall}}$ ) [ $\text{m}^2\text{K W}^{-1}$ ]	3.6	7	0.5
	Glazing Ratio ( $GR$ )	0.1	0.4	0.05
	Solar Heat Gain Coefficient ( $SHGC$ )	0.1	0.7	0.1
	Collector Area for PV ( $A_{\text{pv}}$ ) [ $\text{m}^2\text{m}^{-2}$ ]	0.1	0.6	0.1
<b>Economic Parameters</b>	Rebate [\$]	20000	50000	5000
	Loan [\$]	0	10000	2000
	Loan Interest Rate [%]	0.25	1.5	0.25
	Fuel Tax [%]	0	10	2
	Electricity Tax [%]	0	10	2

where  $C_I$  is the annualized initial investment,  $C_F$  is the annualized fossil fuel cost,  $C_E$  is the annualized grid electricity consumption cost,  $C_{OM}$  is the annualized operation and maintenance cost,  $L$  is the annualized loan cost,  $\text{Tax}_F$  is tax that owners pay for their fuel consumption,  $\text{Tax}_E$  is tax that owners pay for electricity consumption,  $C_S$  is the annualized cost savings by salvaging the equipment, and  $SCC_S$  is annualized cost savings due to reduction of the social cost of carbon, all in [\$]. The marginal annualized cost saving is given by

$$C_{Os} = C_{\text{Base}} - C_{\text{Retrofit}}, \quad (3)$$

where  $C_{\text{Base}} = C_F + C_E + C_{OM} + \text{Tax}_F + \text{Tax}_E - C_S$  is the annualized cost for the base case without any retrofits in [\$]. More detailed calculations of the marginal annualized cost are provided in our recently published paper [2]. The government's annualized marginal cost saving is calculated as follows:

$$C_{Gs} = L + \text{Tax}_F + \text{Tax}_E - \text{Loan} - \text{Rebate}. \quad (4)$$

## Environmental analysis

The environmental analysis involves the calculation of potential operational GHG emissions savings ( $\text{GHG}_{o,s}$ ) and the potential embodied GHG emissions savings ( $\text{GHG}_{e,s}$ ), which will be negative in our analysis. The embodied GHG emission, for various building retrofit technologies, is the summation of embodied GHG emissions for each retrofit technology

$$\begin{aligned} \text{GHG}_e = & A_{\text{pv}}\text{EEF}_{\text{pv}} + V_{\text{BITES}}\text{EEF}_{\text{BITES}} + \text{EEF}_{\text{HP}} \\ & + A_{\text{st}}\text{EEF}_{\text{st}} + \Delta R_{\text{wall}}A_{\text{wall}}\text{EEF}_{\text{Insulation}} \\ & + \Delta R_{\text{roof}}A_{\text{roof}}\text{EEF}_{\text{Insulation}} + A_{\text{roof}}\text{EEF}_{\text{CoolRoof}} \end{aligned} \quad (5)$$

where  $A_{\text{pv}}$ ,  $A_{\text{st}}$ ,  $A_{\text{wall}}$ , and  $A_{\text{roof}}$ , are PV, ST, wall, and roof areas, all in [ $\text{m}^2$ ],  $V_{\text{BITES}}$  is the BITES volume in [ $\text{m}^3$ ]; embodied GHG emissions factor (EEF) for PV systems ( $\text{EEF}_{\text{pv}}$ ) is  $150 \text{ kg CO}_2\text{em}^{-2}$ , for the BITES system ( $\text{EEF}_{\text{BITES}}$ ) is  $30 \text{ kg CO}_2\text{em}^{-3}$ , for Heat Pump (HP)  $\text{EEF}_{\text{HP}}$  is  $600 \text{ kg CO}_2\text{e}$ , and for solar thermal systems ( $\text{EEF}_{\text{st}}$ ) is  $40 \text{ kg CO}_2\text{em}^{-2}$ . Additionally, the embodied GHG emissions factor for insulation materials ( $\text{EEF}_{\text{Insulation}}$ ) is  $10 \text{ kg CO}_2\text{em}^{-2}\text{Wm}^{-2}\text{K}^{-1}$ . Here  $\Delta R_{\text{wall}}$  and  $\Delta R_{\text{roof}}$  [ $\text{m}^2\text{K W}^{-1}$ ] are changes made to the building envelop to achieve a new thermal resistance. For the cool roof, the embodied GHG emissions factor ( $\text{EEF}_{\text{CoolRoof}}$ ) is  $5 \text{ kg CO}_2\text{em}^{-2}$  [7–10].

The potential operational GHG emissions saving is the summation of GHG emissions saving through a reduction of electricity and fossil fuel consumption. The fuel usage reduction is computed as

$$F_s = [F_{hB} + F_{whB} - (F_h + F_{wh})]A_{\text{bld}}N, \quad (6)$$

where  $F_{hB}$ ,  $F_{whB}$ ,  $F_h$  and  $F_{wh}$  [ $\text{m}^3 \text{m}^{-2}$ ] are the fossil fuel usage for the base and retrofitted buildings for space and water heating, respectively. Here  $N = 20$  is the number of years for the retrofit time horizon.  $A_{\text{bld}} = 130 \text{ [m}^2\text{]}$  is the building footprint area. Then, the GHG emissions reduction potential in  $\text{CO}_2\text{e}$  associated with fossil fuel saving is estimated by,

$$GHG_{F,s} = F_s \rho_F \frac{MW_{\text{CO}_2\text{e}}}{MW_F}, \quad (7)$$

where  $\rho_F$  [ $\text{kg}_F \text{m}^{-3}$ ] is the density of fossil fuel (for natural gas or diesel),  $MW_{\text{CO}_2\text{e}}$  [ $\text{g}_{\text{CO}_2\text{e}} \text{mole}^{-1}$ ] is the molecular weight of  $\text{CO}_2\text{e}$ , and  $MW_F$  [ $\text{g}_F \text{mole}^{-1}$ ] is the molecular weight of the fossil fuel. The electricity usage reduction is computed by,

$$E_s = [E_{cB} + E_{dB} - (E_c + E_h + E_d - E_{pv})]A_{\text{bld}}N, \quad (8)$$

where  $E_{cB}$ ,  $E_{dB}$ ,  $E_c$ ,  $E_h$ , and  $E_d$  [ $\text{kW-hr m}^{-2}$ ] are the electricity usage for space cooling/heating and domestic appliance in base/retrofitted buildings, and  $E_{pv}$  [ $\text{kW-hr m}^{-2}$ ] is electricity generated by PV, in the retrofitted building. Then, the GHG emissions reduction potential in  $\text{CO}_2\text{e}$  associated with grid electricity saving is found as,

$$GHG_{E,s} = E_s EI_E P_E, \quad (9)$$

where  $EI_E$  [ $\text{kg}_{\text{CO}_2} \text{kW-hr}^{-1}$ ] presents the electricity grid emissions intensity for different cities in 2020, and  $P_E$  [%] denotes the projected percentage reduction in this intensity over the next 20 years [11, 12]. Finally, the potential operational GHG emissions savings is given by

$$GHG_{o,s} = GHG_{F,s} + GHG_{E,s}, \quad (10)$$

and the total GHG emission savings over  $N = 20$  years is given by:

$$GHG_s = GHG_{o,s} - GHG_e. \quad (11)$$

### 3 Results and discussion

#### 3.1 Optimized variables

Table 2 presents the optimized economic policy parameters (mean  $\pm$  standard deviation) for different combinations of energy and fuel price inflation under SSP2-4.5 and SSP5-8.5 climate change scenarios, averaged over years (2025 to 2050) and optimization series. Across all runs and scenarios, the optimization consistently favors substantial rebates (\$28,000–31,000) combined with moderate loan amounts (\$4,000–5,400), highlighting that direct financial incentives and access to capital are the primary drivers for enabling building retrofits. Loan interest rates remain low (generally below 1%), indicating the importance of concessional financing in maintaining affordability, particularly under high-inflation cases. Electricity and fuel taxes emerge as complementary instruments, with electricity tax rates typically ranging from about 4.5% to 5.5% and fuel tax rates from roughly 3.8% to 6.1%. Notably, SSP5-8.5 systematically results in higher loan values and higher fuel and electricity taxes compared to SSP2-4.5, reflecting the need for more aggressive economic instruments in high-emissions futures to offset higher baseline emissions and stronger decarbonization pressures. The relatively large standard deviations observed for rebates and loans indicate meaningful temporal variability in optimal policy levels, underscoring that adaptive and time-responsive economic strategies are more effective than static policies for balancing

Table 2: Optimized economic parameters (Mean  $\pm$  Std over years of average over series) for different energy price inflation rates under SSP2-4.5 and SSP5-8.5 scenarios; E: annual electricity price inflation in percent; F: annual fossil fuel price inflation in percent.

SSP	Run	Loan [\$]	Rebate [\$]	Loan Interest Rate [%]	Electricity Tax [%]	Fuel Tax [%]
SSP2-4.5	1E1F	4867 $\pm$ 1539	28167 $\pm$ 3578	0.83 $\pm$ 0.18	4.87 $\pm$ 1.87	5.00 $\pm$ 0.89
	5E1F	4467 $\pm$ 709	30667 $\pm$ 3300	0.66 $\pm$ 0.16	5.13 $\pm$ 1.88	4.93 $\pm$ 1.21
	1E5F	4333 $\pm$ 1374	30833 $\pm$ 4810	1.02 $\pm$ 0.16	4.53 $\pm$ 2.02	3.80 $\pm$ 1.66
	5E5F	4200 $\pm$ 825	28833 $\pm$ 4598	0.81 $\pm$ 0.15	5.53 $\pm$ 2.01	4.07 $\pm$ 2.10
SSP5-8.5	1E1F	4400 $\pm$ 1424	29000 $\pm$ 2309	0.87 $\pm$ 0.25	5.20 $\pm$ 1.15	4.47 $\pm$ 1.12
	5E1F	4000 $\pm$ 952	29667 $\pm$ 1247	0.81 $\pm$ 0.23	4.67 $\pm$ 1.07	6.00 $\pm$ 1.11
	1E5F	5133 $\pm$ 1093	30833 $\pm$ 3578	0.91 $\pm$ 0.15	4.93 $\pm$ 1.77	6.07 $\pm$ 1.85
	5E5F	5400 $\pm$ 1562	30833 $\pm$ 2478	0.91 $\pm$ 0.30	5.00 $\pm$ 0.89	5.53 $\pm$ 1.12

cost savings, emissions reduction, and household affordability under long-term climate and energy price uncertainty.

Table 1 defines the parameter intervals used as the feasible search space for the optimization, while Table 3 presents the optimized retrofit outcomes obtained after the completion of the multi-objective optimization runs. Comparing these tables provides insight into how the optimization algorithm navigates the predefined decision space and identifies cost and climate-effective retrofit strategies. The results show that the optimized Building Integrated Thermal Energy Storage (BITES) volume consistently converges toward the upper bound of the allowable range under both climate scenarios, indicating that maximizing thermal energy storage provides substantial operational and economic benefits over the analysis horizon. This reflects the strong role of seasonal energy shifting in reducing heating and cooling demands in Toronto’s climate. The Solar Thermal (ST) collector area also stabilizes around the middle of the defined range, indicating that moderate solar thermal deployment provides an optimal trade-off between capital cost and thermal energy contribution. For envelope performance, the optimized roof and wall thermal resistances cluster near the lower end of the allowed range, closely aligning with current Ontario building code requirements. This suggests that deeper insulation levels beyond code minimums do not provide sufficient economic or environmental returns within the modeled time horizon. The Glazing Ratio (GR) converges near 0.2, approximately the midpoint of the allowable range, balancing daylight access, solar gains, and heat losses. Similarly, the optimized infiltration rate centers around 1 ACH within the 0.5–1.5 range, reflecting a compromise between air-tightness improvements and retrofit feasibility in existing buildings. In contrast, the Solar Heat Gain Coefficient (SHGC) consistently converges toward its upper bound, indicating the importance of passive solar gains in offsetting heating demand. Finally, Photovoltaic (PV) area consistently reaches the upper limit of the defined interval, driven by high electricity prices in Toronto, favorable solar availability, and the increasing value of on-site electricity generation under future climate and economic conditions. Overall, the results demonstrate that the optimization does not simply favor extreme solutions across all variables but instead identifies differentiated strategies where some parameters are minimized, others maximized, and several balanced at intermediate levels to achieve robust, cost-effective, and climate-responsive retrofit outcomes.

### 3.2 Objective functions

Fig. 1 compares the evolution of owners’ annual cost savings under SSP2-4.5 and SSP5-8.5 future climate scenarios across different combinations of energy and fuel price inflation rates. Across all cases, positive cost savings are observed throughout the analysis period, indicating that the optimized retrofit strategies remain economically attractive under both moderate and high emissions futures. Under the low energy and fuel inflation scenario (1E1F), SSP2-4.5 yields slightly higher and more stable savings over time, while SSP5-8.5 exhibits greater variability and a gradual decline toward later years. In contrast, scenarios with higher energy price inflation (5E1F and 5E5F) generally result in increased owner savings, reflecting stronger economic incentives for efficiency improvements as operating costs rise. The 1E5F case

Table 3: Optimized building parameters (Mean  $\pm$  Std over years of average over series) for different energy price inflation rates under SSP2-4.5 and SSP5-8.5 scenarios.

SSP	Run	$V_{bites}$	$\alpha_R$	$A_{st}$	$R_{roof}$	$R_{wall}$	$GR$	$V_{inf}$	$SHGC$	$A_{pv}$
SSP2-4.5	1E1F	0.24 $\pm$ 0.01	0.34 $\pm$ 0.12	0.36 $\pm$ 0.08	5.56 $\pm$ 0.10	3.65 $\pm$ 0.11	0.22 $\pm$ 0.04	0.88 $\pm$ 0.12	0.69 $\pm$ 0.01	0.58 $\pm$ 0.03
	5E1F	0.24 $\pm$ 0.01	0.41 $\pm$ 0.05	0.35 $\pm$ 0.04	5.53 $\pm$ 0.07	3.67 $\pm$ 0.05	0.25 $\pm$ 0.04	0.84 $\pm$ 0.07	0.68 $\pm$ 0.02	0.60 $\pm$ 0.01
	1E5F	0.24 $\pm$ 0.01	0.44 $\pm$ 0.10	0.34 $\pm$ 0.07	5.69 $\pm$ 0.52	3.75 $\pm$ 0.21	0.24 $\pm$ 0.03	1.01 $\pm$ 0.13	0.69 $\pm$ 0.02	0.55 $\pm$ 0.06
	5E5F	0.24 $\pm$ 0.01	0.44 $\pm$ 0.07	0.33 $\pm$ 0.08	5.61 $\pm$ 0.13	3.70 $\pm$ 0.22	0.27 $\pm$ 0.04	1.12 $\pm$ 0.07	0.69 $\pm$ 0.01	0.59 $\pm$ 0.03
SSP5-8.5	1E1F	0.24 $\pm$ 0.01	0.35 $\pm$ 0.07	0.38 $\pm$ 0.07	5.49 $\pm$ 0.05	3.72 $\pm$ 0.09	0.29 $\pm$ 0.06	1.04 $\pm$ 0.20	0.70 $\pm$ 0.01	0.55 $\pm$ 0.07
	5E1F	0.23 $\pm$ 0.01	0.47 $\pm$ 0.08	0.31 $\pm$ 0.09	5.56 $\pm$ 0.08	3.62 $\pm$ 0.04	0.24 $\pm$ 0.03	1.13 $\pm$ 0.09	0.70 $\pm$ 0.01	0.60 $\pm$ 0.00
	1E5F	0.23 $\pm$ 0.01	0.36 $\pm$ 0.09	0.33 $\pm$ 0.09	5.61 $\pm$ 0.21	3.67 $\pm$ 0.11	0.27 $\pm$ 0.05	1.02 $\pm$ 0.24	0.69 $\pm$ 0.02	0.58 $\pm$ 0.04
	5E5F	0.23 $\pm$ 0.02	0.44 $\pm$ 0.10	0.36 $\pm$ 0.06	5.51 $\pm$ 0.05	3.62 $\pm$ 0.04	0.20 $\pm$ 0.04	1.10 $\pm$ 0.06	0.67 $\pm$ 0.03	0.60 $\pm$ 0.00

shows pronounced inter annual variability under SSP2-4.5, particularly around 2030, highlighting sensitivity to fuel price assumptions when energy prices remain low. Shaded regions representing  $\pm 1\sigma$  across multiple MGA runs indicate that uncertainty in savings increases under more aggressive price inflation assumptions, especially for SSP2-4.5 in the 5E5F scenario.

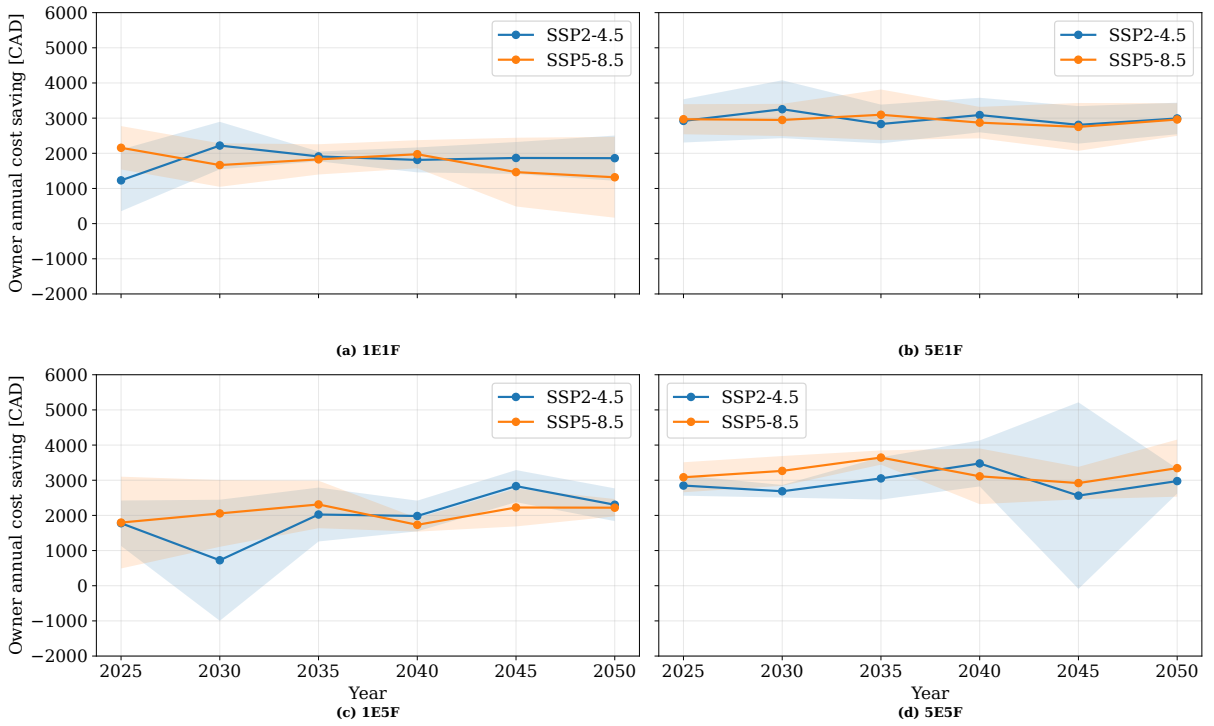


Fig. 1: Comparison of owner annual cost savings under SSP2-4.5 and SSP5-8.5 across different economic scenarios. Shaded regions represent  $\pm 1\sigma$  variability across five MGA runs.

Fig. 2 illustrates the evolution of governments' annual cost savings under SSP2-4.5 and SSP5-8.5 future climate scenarios across different combinations of electricity (E) and fuel (F) price inflation rates. In contrast to owners' savings, government cost savings remain predominantly negative across all scenarios and years, indicating sustained public expenditures associated with incentives, subsidies, and policy support mechanisms required to enable building retrofits. Under the low electricity and fuel inflation scenario (1E1F), both SSPs exhibit relatively stable and moderate fiscal burdens, with SSP5-8.5 generally associated with slightly higher government costs. As electricity or fuel price inflation increases (5E1F,

1E5F, and 5E5F), the magnitude and variability of government costs become more pronounced, reflecting stronger reliance on public financial support to maintain retrofit attractiveness under higher economic uncertainty. The 1E5F and 5E5F scenarios show notable temporal fluctuations, particularly under SSP2-4.5, highlighting sensitivity to fuel price dynamics and evolving policy requirements over time. Shaded regions representing  $\pm 1\sigma$  across multiple MGA runs indicate increasing uncertainty in government expenditures under more aggressive price inflation assumptions, especially for SSP5-8.5. Overall, the figure demonstrates that while higher energy prices can enhance private economic benefits, they also impose greater and more uncertain fiscal demands on governments, underscoring the importance of carefully balancing public investment, long-term emissions reduction goals, and budgetary sustainability.

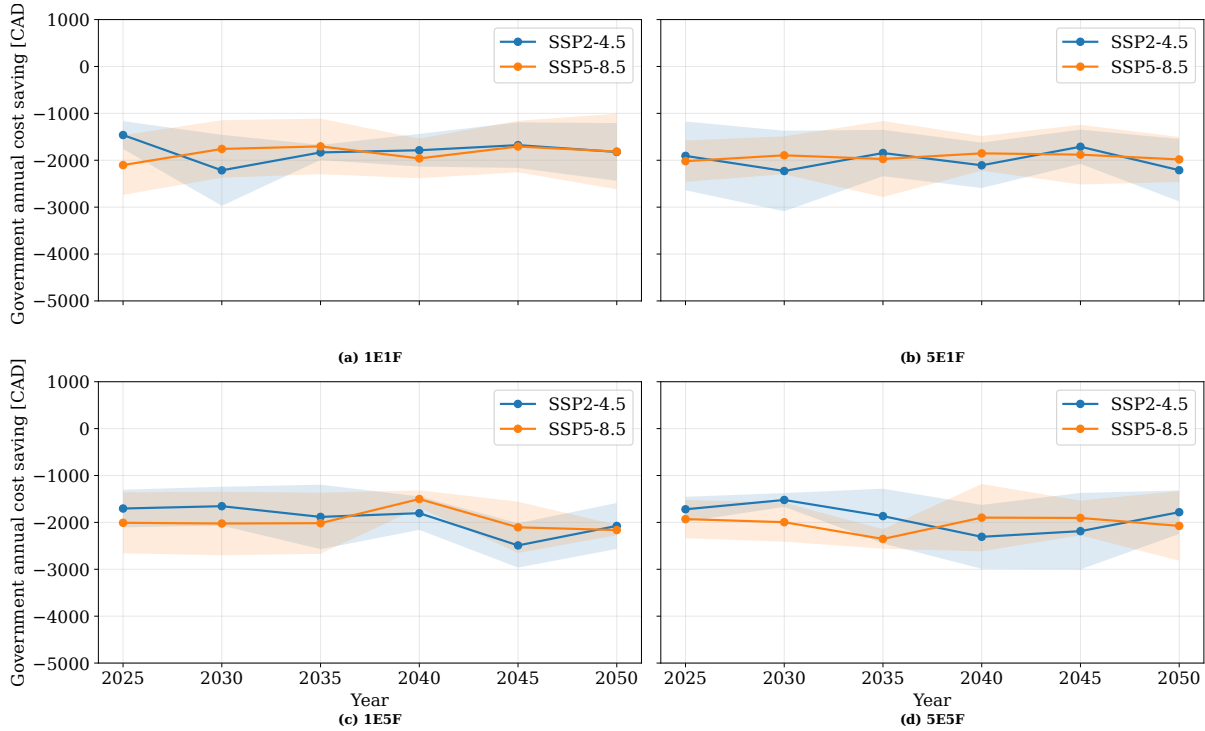


Fig. 2: Comparison of owner annual cost savings under SSP2-4.5 and SSP5-8.5 across different economic scenarios. Shaded regions represent  $\pm 1\sigma$  variability across five MGA runs.

Fig. 3 compares total GHG emission savings under SSP2-4.5 and SSP5-8.5 across different combinations of electricity (E) and fuel (F) price inflation scenarios. Across all cases, the optimized retrofit strategies deliver substantial and persistent emission reductions, with total GHG savings generally ranging between approximately 50 and 65 tonne CO<sub>2</sub>e over the analysis period. For most scenarios, SSP2-4.5 yields consistently higher GHG savings than SSP5-8.5, reflecting the combined influence of cleaner electricity grids and more favorable marginal abatement efficiencies under lower-emissions pathways. Under low energy price inflation conditions (1E1F), both SSPs exhibit relatively stable emission savings over time, whereas scenarios with higher electricity or fuel price inflation (5E1F, 1E5F, and 5E5F) show increased temporal variability, particularly in earlier years. Shaded regions representing  $\pm 1\sigma$  across multiple MGA runs reveal that uncertainty in emission outcomes increases under 1E5F price inflation assumptions, where emission savings tend to decline more noticeably toward mid-century. Overall, the figure highlights that while economic conditions influence the stability of emission reductions, optimized retrofit strategies con-

sistently achieve meaningful GHG savings across scenarios, with SSP2-4.5 providing more robust and resilient decarbonization outcomes under long-term uncertainty.

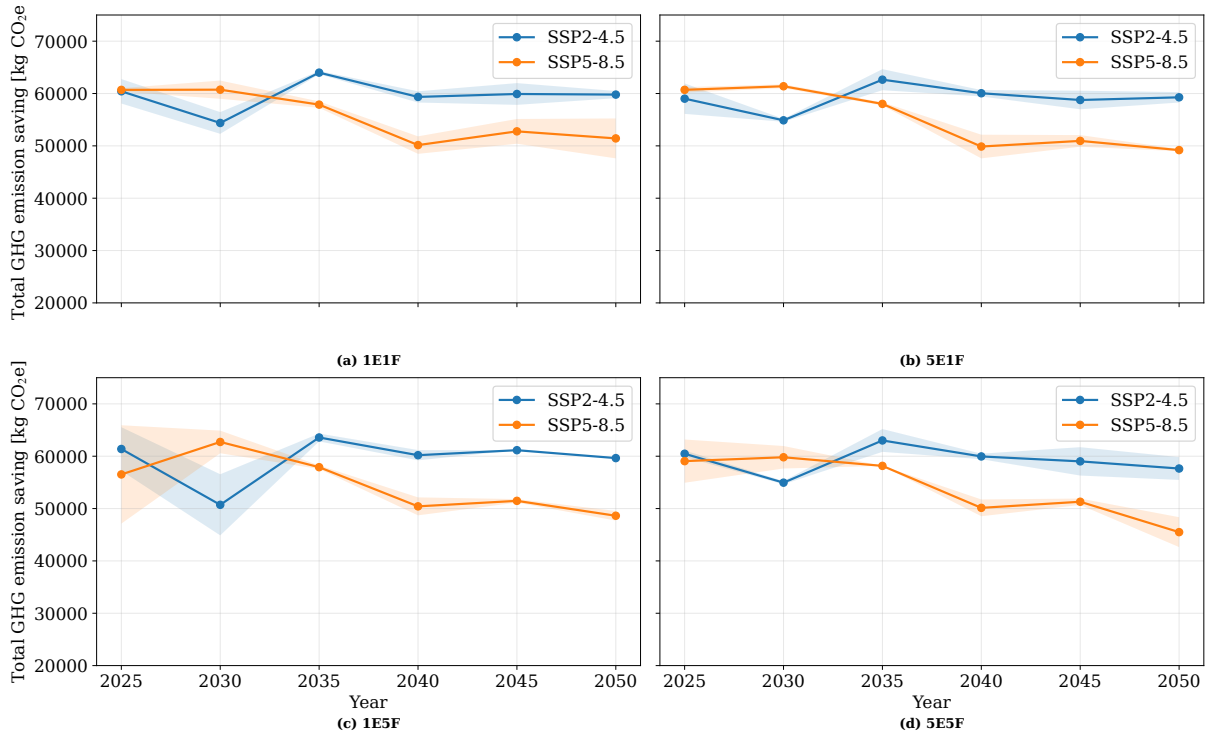


Fig. 3: Comparison of owner annual cost savings under SSP2-4.5 and SSP5-8.5 across different economic scenarios. Shaded regions represent  $\pm 1\sigma$  variability across five MGA runs.

## 4 Conclusion

This study presents an integrated, climate-informed optimization framework for identifying cost-effective and low-carbon building retrofit strategies in Toronto by jointly considering building physics, economic conditions, and policy instruments. By coupling the VCWG v1.6.1 with the MGA, the analysis captures the interactions among future climate dynamics, retrofit technologies, and long-term economic and environmental objectives under SSP2-4.5 and SSP5-8.5 future climate scenarios.

The optimization results show that effective retrofit deployment relies primarily on direct financial incentives and concessional financing, rather than high levels of private debt. Across all scenarios, substantial rebates combined with relatively modest loan amounts and low interest rates consistently emerge as optimal, underscoring the importance of affordability-focused policy design. Electricity and fuel taxes act as complementary instruments, particularly under SSP5-8.5, where higher baseline emissions and stronger decarbonization pressures require more aggressive economic signals. The observed temporal variability in optimal rebate and loan levels further highlights that adaptive and time-responsive policy frameworks are more effective than static instruments in managing long-term uncertainty.

The results demonstrate that optimal retrofit solutions do not necessarily correspond to uniformly maximizing all building performance parameters. Instead, the optimization converges toward targeted and balanced strategies. Thermal energy storage and photovoltaic deployment consistently reach the upper

bounds of their feasible ranges, reflecting their strong contribution to both emission reductions and economic savings under Toronto’s electricity pricing structure and solar availability. In contrast, envelope insulation levels align closely with current Ontario building code requirements, indicating diminishing marginal benefits of deeper insulation when evaluated alongside other retrofit options. Intermediate values of roof albedo, ST collector area, GR, and infiltration rate further highlight the importance of balancing seasonal performance, capital costs, and operational benefits.

From a private perspective, optimized retrofit strategies remain economically attractive across all scenarios, with homeowners experiencing positive annual cost savings under both moderate and high emissions futures. In contrast, government cost savings remain predominantly negative, reflecting sustained public investment required to enable large-scale retrofit adoption. While higher energy prices enhance private benefits, they also increase fiscal burdens and uncertainty for governments, particularly under aggressive inflation scenarios. Despite economic and policy uncertainties, the optimized retrofit strategies consistently deliver substantial and persistent GHG emission reductions across all scenarios. Emission savings are generally more stable and resilient under SSP2-4.5, indicating that earlier and cleaner decarbonization pathways improve marginal abatement effectiveness over time. Overall, the results confirm that climate-informed and policy-aware optimization can identify retrofit strategies that simultaneously support affordability, durability, and emissions reduction, providing actionable insights for designing resilient retrofit policies in Canadian cities under future climate uncertainty.

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