Efficacy of Government Incentivized Residential Building Retrofits in Canada

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Supplementary information

Vertical City Weather Generator (VCWG v1.4.9)

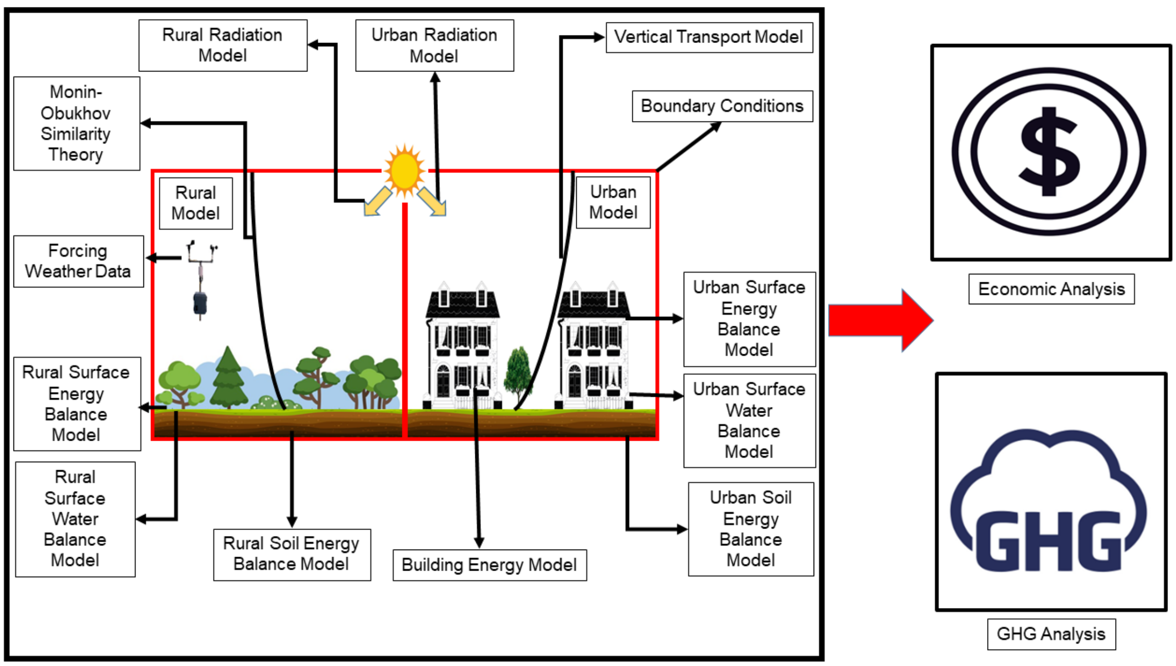


Figure S1. Vertical City Weather Generator (VCWGv1.4.9) software and the associated sub-models.

Selected cities and climate zones

Table S1. Building parameters in different climate zones[1–3]; *: Solar Heat Gain Coefficient (*SHGC*)

Parameter	Zone 4	Zone 5	Zone 6	Zone 7A	Zone 7B	Zone 8
R_{roof} [m^2 K W^{-1}]	4.41	5.46	5.46	6.17	6.17	7.04
R_{wall} [m^2 K W^{-1}]	3.17	3.60	4.05	4.76	4.76	5.46
Infiltration rate [ACH]	3	3	3	3	3	3
Ventilation rate [L s^{-1} m^{-2}]	0.3	0.3	0.3	0.3	0.3	0.3
Glazing ratio [-]	0.4	0.4	0.38-0.35	0.33-0.27	0.27-0.20	0.2
U_{window} [W m^{-2} K^{-1}]	2.4	2.2	2.2	2.2	2.2	1.6
$SHGC^*$ [-]	0.4	0.4	0.4	0.45	0.45	0.45

Energy price rates and inflation

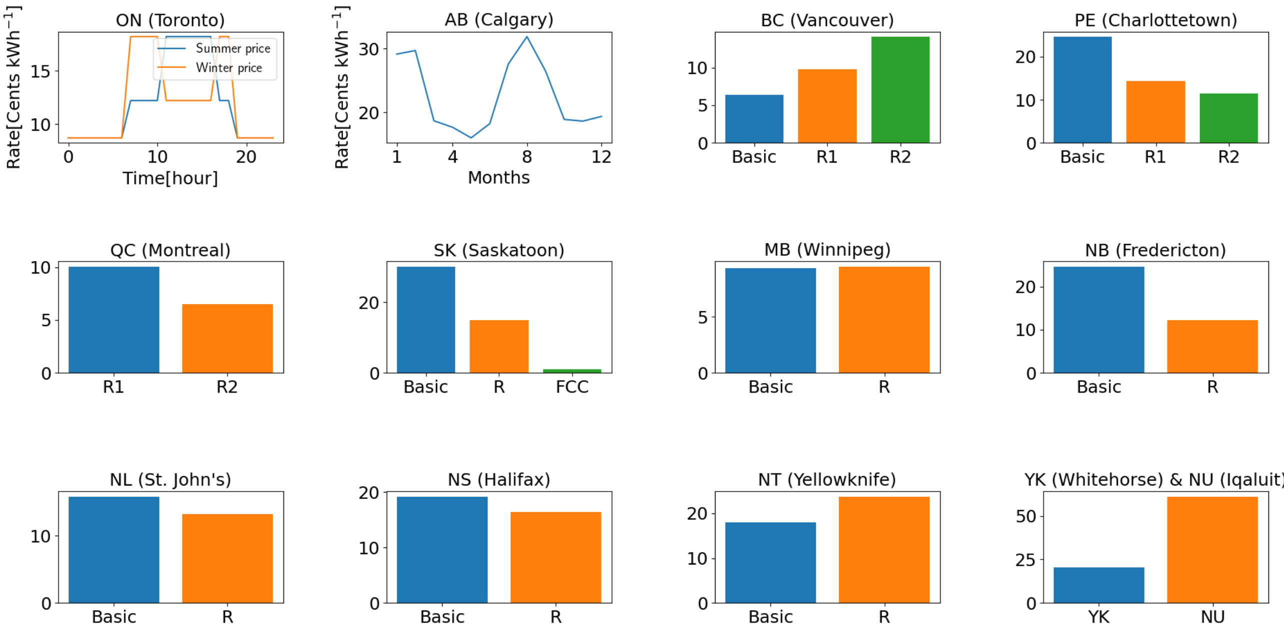


Figure S2. Residential electricity rates (R: rate [Cent kW-hr^{-1}], Basic: basic charge [$], FCC: Federal Carbon Charge [Cents kW-hr^{-1}])

Table S2. Gas prices in various cities

City	Description	Value	Unit
Toronto	Cost of gas	0.118	\$ m^{-3}
	Gas supply cost adjustment	0.020	\$ m^{-3}
	Effective gas supply	0.138	\$ m^{-3}
Vancouver	Basic charge	12.648	\$ $month^{-1}$
	Delivery charge	0.2631	\$ m^{-3}
	Storage and transport charge	0.0094	\$ m^{-3}
	Cost of gas	0.0875	\$ m^{-3}
Calgary	January	6.446	\$ GJ^{-1}
	February	3.715	\$ GJ^{-1}
	March	2.222	\$ GJ^{-1}
	April	3.381	\$ GJ^{-1}
	May	2.415	\$ GJ^{-1}
	June	2.452	\$ GJ^{-1}
	July	2.273	\$ GJ^{-1}
	August	3.368	\$ GJ^{-1}
	September	2.724	\$ GJ^{-1}
	October	2.522	\$ GJ^{-1}
	November	2.85	\$ GJ^{-1}
	December	2.902	\$ GJ^{-1}
Halifax	Basic charge	26.00	\$ $month^{-1}$
	Variable charge	9.833	\$ GJ^{-1}
	Commodity charge	10.10	\$ GJ^{-1}
	Other fees	3.897	\$ GJ^{-1}
Winnipeg	Basic charge	14.00	\$ $month^{-1}$
	Delivery charge	0.1241	\$ m^{-3}
	Cost of gas	0.1021	\$ m^{-3}
Saskatoon	Basic charge	26.5	\$ $month^{-1}$
	Delivery charge	0.1113	\$ m^{-3}
	Storage and transport charge	0.0094	\$ m^{-3}
	Cost of gas	0.1264	\$ m^{-3}
Montreal	Basic charge	14.00	\$ $month^{-1}$
	Delivery charge	0.1241	\$ m^{-3}
	Cost of gas	0.1021	\$ m^{-3}

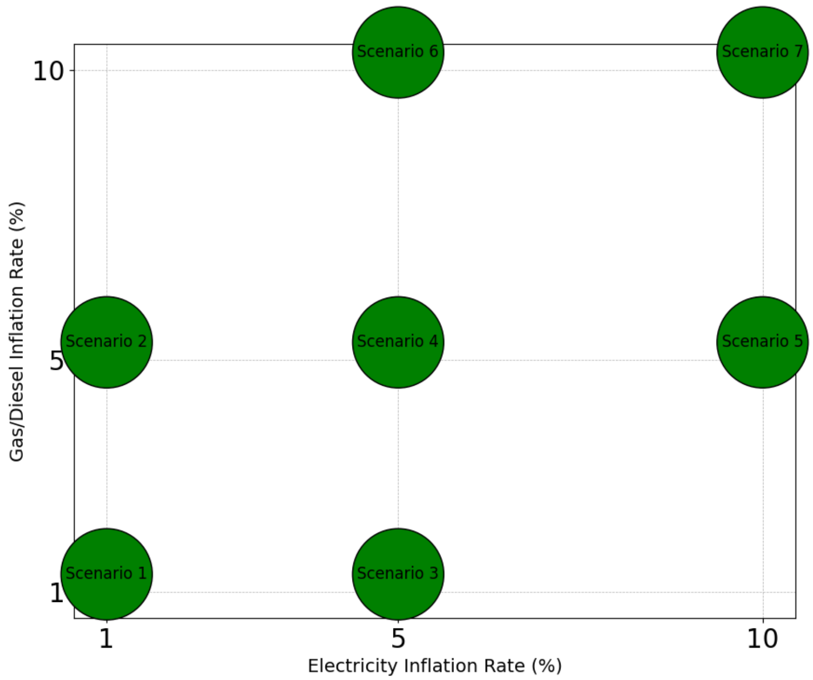


Figure S3. Future energy price inflation rate scenarios.

Electricity grid GHG emission intensity

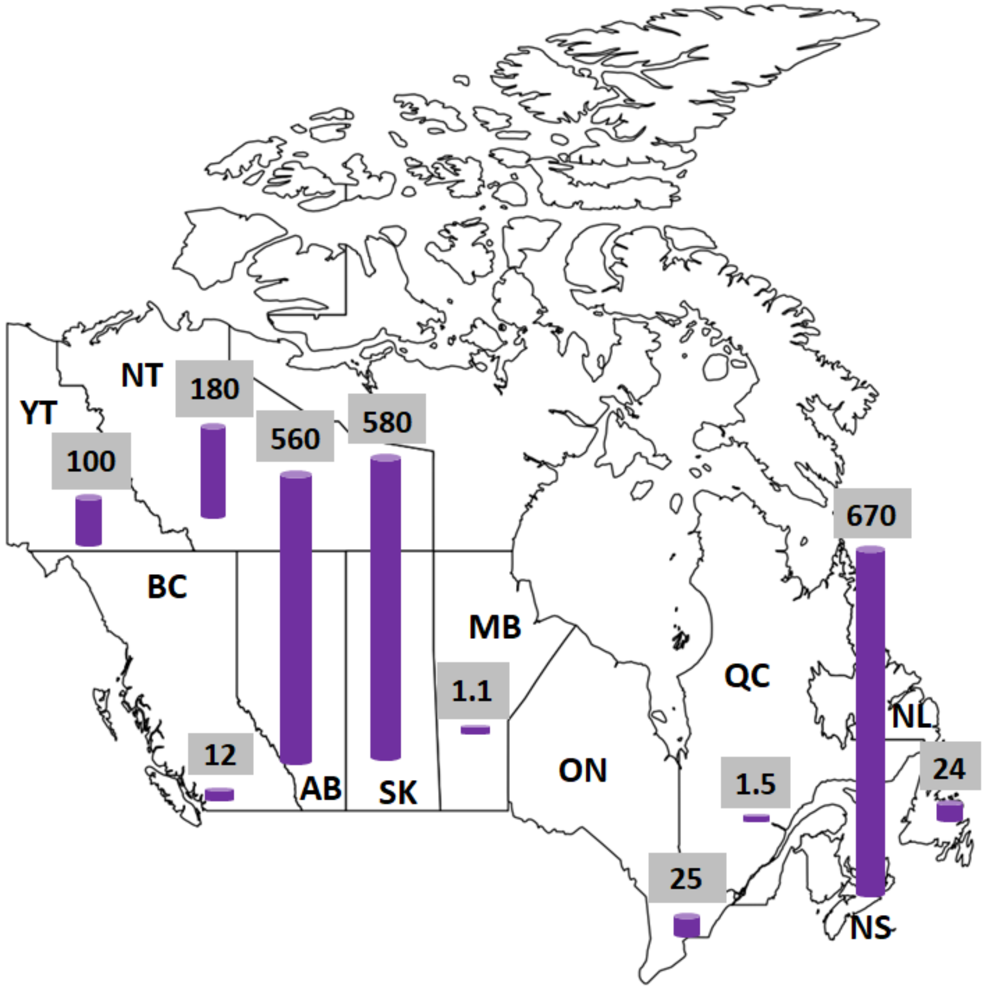


Figure S4. Electricity grid GHG emission intensity [$g_{CO_{2}e}$ kW-hr^{-1}] as of 2020[4]; note: in Yellowknife (NT) hydro electricity is available, so the actual grid GHG emission intensity may be lower than the territorial average; map generated using python 3.10 and various libraries: geopandas 1.0.1, matplotlib 3.9.0, and unidecode 1.4.0 (https://www.python.org/).

Government economic incentive programs

The federal programs include the Canada Greener Homes Grant Program, which offers grants up to $5,000 for home insulation, windows and doors replacement, space and water heating equipment upgrades, and solar PV system installations, and up to $1,000 for air-sealing. Additionally, the Canada Greener Homes Loan provides loans ranging from $5,000 to $40,000 for major home retrofits[5].

At the provincial and territorial level, specific cities offer targeted programs. In Toronto, the Eco-Roof Incentive Program provides rebates for green and cool roofs[6], while the Home Energy Loan Program (HELP) offers rebates for rooftop solar PV and HPs[7]. Vancouver's CleanBC Better Homes program offers rebates for HPs and improving windows, doors, ventilation, and insulation[8]. Calgary's Clean Energy Improvement Program (CEIP) provides rebates for major home retrofits[9]. Halifax offers rebates for PV systems, HPs, ST, and water heaters[10]. Saskatoon's Home Energy Loan Program (HELP)[11] and Home Efficiency Retrofit Rebate (HERR)[12] provide various rebates and loans for air sealing, window glazing, rooftop PV, insulation, and HPs. Winnipeg's programs include loans for PV systems, HPs, windows and doors, natural gas furnaces, and boilers, along with a solar rebate program[13,14]. St. John's offers the Home Energy Savings Program (HESP)[15] for insulation and air sealing, and the Take CHARGE Residential Rebate Program[16] for insulation and air sealing. Montreal's Renoclimat Program[17] and

Energir Grants[18] offer rebates for insulation, air sealing, windows and doors, and HPs. Yellowknife's Arctic Energy Alliance (AEA) Rebates[19] provide substantial support for insulation, windows, air sealing, and furnaces or boilers. Whitehorse offers rebates for PV systems, HPs, and WTs. Fig. S5 and Table S3 provide more details of the incentives. This comprehensive overview highlights the wide range of government incentives available to promote energy efficiency and renewable energy adoption across Canada[20]. These programs will be utilized in subsequent analysis to investigate their effectiveness in reducing home owners' retrofit costs and GHG emissions.

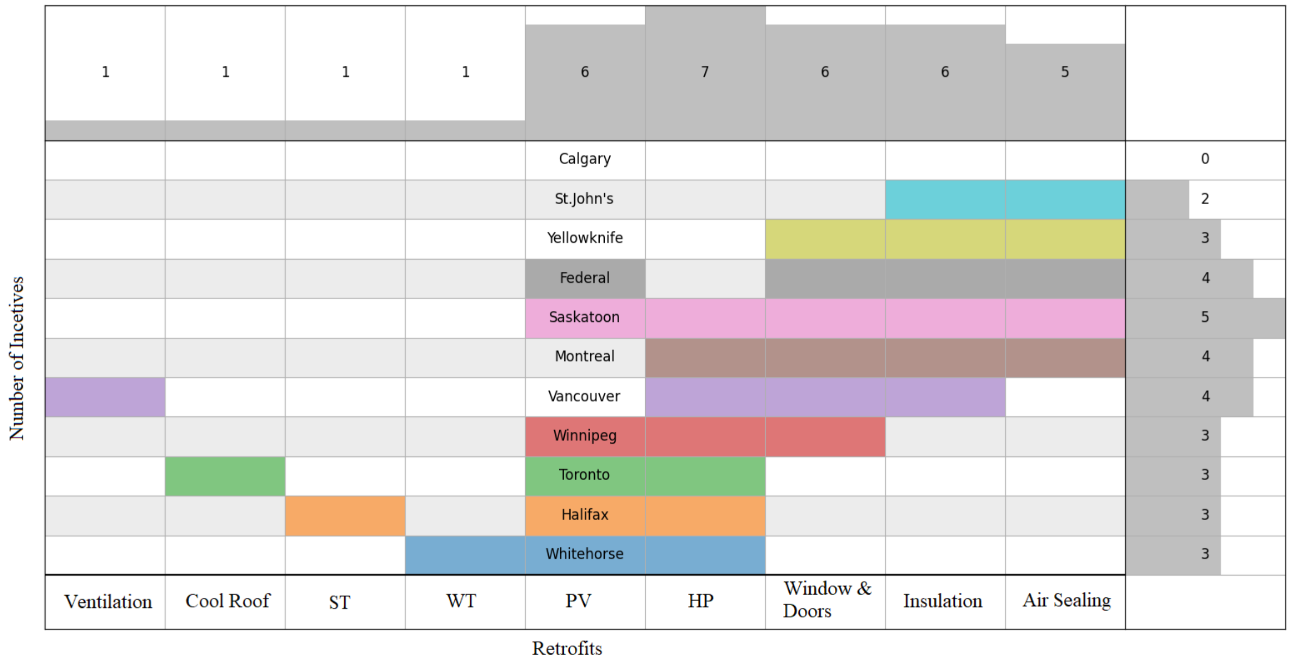


Figure S5. Federal and provincial/territorial government building retrofit economic incentive programs counted for each strategy and city; note: the low-interest loan programs are not shown; diagram generated using python 3.10 and various libraries: supervenn 0.5.0 and matplotlib 3.9.0 (https://www.python.org/).

Table S3. Federal and provincial/territorial government building retrofit incentive programs across Canada; *: incentive not used in this study

Program Type	Program Name	Retrofit Type	Amount [$]
Federal	Canada Greener Homes Grant Program	Home insulation	5,000
		Air-sealing	1,000
		Windows and doors replacement	5,000
		Space and water heating equipment upgrade	5,000
		Solar photovoltaic system installation	5,000
	Canada Greener Homes Loan	Major home retrofit	5,000-40,000
Toronto	Eco-Roof Incentive Program	Green roof incentives*	100 m^{-2}
		Cool roof incentives	2-5 m^{-2}
	Home Energy Loan Program (HELP)	Rooftop solar PV	1,000
		Heat pumps	1,250-2,500
Vancouver	CleanBC Better Homes	Heat pumps	1,000-6,000
		Windows and doors	2,000
		Ventilation rebate	1,600
		Insulation rebate	5,500
Calgary	Clean Energy Improvement Program (CEIP)	Major home retrofit	3,000
Halifax		PV	2,000
		Heat pump	200-2,000
		Solar thermal	400-1,000
		Water heater	400-650
Saskatoon	Home Energy Loan Program (HELP) - Loan		1,000
	Home Energy Loan Program (HELP) - Rebate	Air sealing	900
		Window glazing	130
		Rooftop solar	3,500
		Insulation	1,000
		Heat pump	4,000
		Solar water heater	1,000
	Home Efficiency Retrofit Rebate (HERR)	Air sealing	300
		Insulation	1,500
		Windows	75 $window^{-1}$
		Doors	50 $door^{-1}$
Winnipeg	Home Energy Efficiency Loan (HEEL)	PV	20,000
		Heat pump	10,000
		Windows and doors	7,500
		Natural gas furnace*	5,500
		Natural gas boilers*	5,500
	Solar Rebate Program	PV	5,000
St. John's	Home Energy Savings Program (HESP)	Insulation and air sealing	5,000
	Take CHARGE Residential Rebate Program	Insulation	2,000
		Air sealing	500
Montreal	Renoclimat Program	Insulation	2,000
		Air sealing	245
		Windows and doors	300
	Energir Grants	Heat pump	6,000
Yellowknife	The Arctic Energy Alliance (AEA) Rebates	Insulation	13,000
		Windows	1,000
		Air sealing	1,000
		Furnaces and boilers	4,000
Whitehorse		PV	5,000
		Heat pump	1,500
		Wind turbine	5,000

Retrofit strategies

For Toronto, the PV, Building Envelope (BE) improvements, HP, and Cool Roof (CR) are selected, leveraging incentives for energy efficiency. Vancouver's strategies include PV, BE, and HP, supported by the city's moderate climate and substantial incentives. Calgary's selections are PV and BE, benefiting from high solar potential and energy efficiency incentives. In Saskatoon and Winnipeg, we opted for PV, BE, and HP, supported by their cold climates and significant provincial incentives. Montreal follows a similar selection with PV, BE, and HP, justified by its variable climate and provincial incentives. Halifax includes PV, BE, HP, and Solar Thermal (ST), due to its coastal climate and provincial support. St. John's' strategies are PV, BE, and HP, suited for the city's climate and provincial incentives. Whitehorse includes PV, BE, HP, and Wind Turbine (WT), taking advantage of territorial incentives for renewable energy. Lastly, Yellowknife's retrofit strategies are PV and BE, backed by its extreme climate and territorial incentives (Fig. S6 and Table S4). Note, in our study we assume a ground source HP, given Canada's cold climate in the winter.

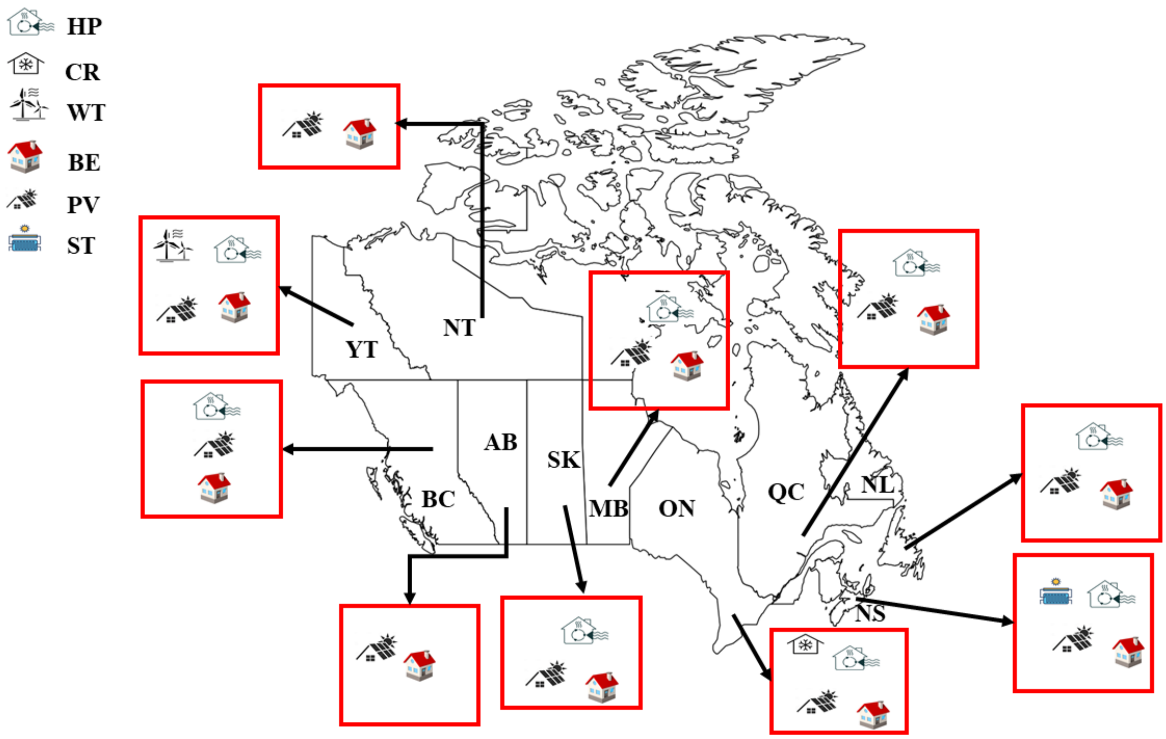


Figure S6. Selected building retrofit strategies in each city; map generated using python 3.10 and various libraries: geopandas 1.0.1, matplotlib 3.9.0, and unidecode 1.4.0 (https://www.python.org/).

Table S4. Building retrofit values for different climate zones: A_{pv}: photovoltaics area, A_{wt}: wind turbine area, V_{bites}: building integrated thermal energy storage volume, A_{st}: solar thermal area, A_{cr}: cool roof area, R_{wall}: wall thermal resistance, R_{roof}: roof thermal resistance, GR: glazing ratio; note: building integrated thermal energy storage system is coupled to the heat pump and solar thermal collector; the heat pump is assumed to be ground source, exchanging heat with the building integrated thermal energy storage system.

Parameter	Climate Zone	Value	Units
A_{pv}	4-8	0.5	$m^2\ m^{-2}$
A_{wt}	4-8	0.1	$m^2\ m^{-2}$
V_{bites}	4-8	0.1	$m^3\ m^{-2}$
A_{st}	4-8	0.3	$m^2\ m^{-2}$
A_{cr}	4-8	1	$m^2\ m^{-2}$
R_{wall}	4	8.82	$m^2\ K\ W^{-1}$
	5	10.92	$m^2\ K\ W^{-1}$
	6	10.92	$m^2\ K\ W^{-1}$
	7A	12.34	$m^2\ K\ W^{-1}$
	7B	12.34	$m^2\ K\ W^{-1}$
	8	14.08	$m^2\ K\ W^{-1}$
R_{roof}	4	6.34	$m^2\ K\ W^{-1}$
	5	7.20	$m^2\ K\ W^{-1}$
	6	8.10	$m^2\ K\ W^{-1}$
	7A	9.52	$m^2\ K\ W^{-1}$
	7B	9.52	$m^2\ K\ W^{-1}$
	8	10.92	$m^2\ K\ W^{-1}$
GR	4	0.2	-
	5	0.2	-
	6	0.2	-
	7A	0.1	-
	7B	0.1	-
	8	0.1	-

Economic and environmental analysis

The initial cost per building footprint area for a base case is C_B [\$ m^{-2}], and the annualized cost for this building is,

$$C_{IB} = C_B A_{bld} \times CRF(i,N), \tag{S1}$$

where A_{bld} [m^2] is building footprint area and $CRF(i,N)$ is known as the capital recovery factor, which computes the annualized payment needed to form a total present value of an amount given a discounting rate (in our case the annual effective interest rate i) and the time horizon for financial calculation (in our case $N = 20$ years),

$$CRF(i,N) = \frac{i}{1-(1+i)^{-N}}. \tag{S2}$$

To calculate the capital recovery factor, the nominal interest rate i_n and the inflation rate j are considered to compute the effective interest rate[21,22],

$$i = \frac{i_n - j}{1+j}. \tag{S3}$$

The annual initial cost for building retrofits is the summation of initial costs and subtraction of the federal and provincial/territorial incentives,

$$
\begin{aligned}
C_I = [& \underbrace{(S_{pv}A_{pv}P_{pv} + S_{wt}A_{wt}P_{wt} + S_{cr}A_{cr}P_{cr} + S_{st}A_{st}P_{st} + S_{bites}V_{bites}P_{bites} + S_{hp}A_{bld}P_{hp} + S_{env}P_{env} + S_{inf}P_{inf})}_{\text{Capital Expenditures}} \\
& - \underbrace{(L_{gov} + S_{pv}Reb_{pv} + S_{inf}Reb_{inf} + S_{st}Reb_{st} + S_{env}Reb_{env} + S_{hp}Reb_{hp} + S_{wt}Reb_{wt} + S_{cr}A_{cr}Reb_{cr})]}_{\text{Loans and Economic Incentives}} \\
& \times CRF(i,N),
\end{aligned}
\tag{S4}
$$

where variables S_{pv}, S_{wt}, S_{cr}, S_{st}, S_{bites}, S_{hp}, S_{env}, S_{inf} [-] are switches (zero or one) to indicate if a retrofit is present for the city of interest; A_{pv}, A_{wt}, A_{st}, A_{cr}, A_{bld} [m^2] are areas associated with PV, WT, ST, CR, and building footprint; V_{bites} [m^3] is the volume associated with the BITES system; P_{pv}, P_{wt}, P_{st}, P_{cr}, P_{hp} [\$ m^{-2}] are the installation costs for PV, WT, ST, CR, and HP; P_{bites} [\$ m^{-3}] is the installation cost for the building concrete foundation to serve the BITES system; P_{env} and P_{inf} [\$] are the costs for building envelop and infiltration retrofits; L_{gov} [\$] is the government loan; Reb_{pv}, Reb_{inf}, Reb_{st}, Reb_{env}, Reb_{hp}, and Reb_{wt} [\$] are government rebates for PV, infiltration, ST, envelop, HP, and WT retrofits; and Reb_{cr} [\$ m^{-2}] is the government rebate for CR. Note that in Table S4, some of these terms were specified per building footprint area (A_{pv}, A_{wt}, A_{st}, A_{cr}, and V_{bites}). The annual fossil fuels costs for the base case and retrofitted building are calculated by,

$$
C_{FB} = \left(\sum_{k=1}^{N} A_{bld}(F_{hB} + F_{whB})P_F(1+j_F)^k PWF(i,k) \right) CRF(i,N), \tag{S5}
$$

$$
C_F = \left(\sum_{k=1}^{N} A_{bld}(F_h + F_{wh})P_F(1+j_F)^k PWF(i,k) \right) CRF(i,N), \tag{S6}
$$

$$
PWF(i,k) = \frac{1}{(1+i)^k}, \tag{S7}
$$

where F_{hB}, F_{whB}, F_h, and F_{wh} [m^{3}m^{-2}] are yearly natural gas/diesel consumption for space and water heating of the base case and retrofitted building per building footprint area, P_F [\$m^{-3}] is the current natural gas/diesel price, and j_F is the assumed annual fossil fuel inflation rate (Figure S3). The annual electricity costs for the base case and retrofitted building are given by,

$$
C_{EB} = \left(\sum_{k=1}^{N} A_{bld}(E_{cB} + E_{dB})P_E(1+j_E)^k PWF(i,k) \right) CRF(i,N), \tag{S8}
$$

$$
C_E = \left(\sum_{k=1}^{N} A_{bld}(E_h + E_c + E_d - E_{pv} - E_{wt}) \times P_E \times (1+j_E)^k \times PWF(i,k) \right) CRF(i,N). \tag{S9}
$$

where E_{cB} and E_{dB} [kW-hr m^{-2}] are the base case annual cooling and domestic electricity consumption per building footprint area, E_h [kW-hr m^{-2}] is the retrofitted building's annual electricity consumption by HP per building footprint area, E_c and E_d [kW-hr m^{-2}] are the retrofitted building's annual cooling and domestic electricity consumption per building footprint area, E_{pv} and E_{wt} [kW-hr m^{-2}] are the retrofitted building annual electricity production by PV and WT per building footprint area, P_E [\$ kW-hr^{-1}] is the electricity price, and j_E is the assumed annual inflation rate for electricity price (Figure S3). The annual operation and maintenance cost for the retrofitted building is calculated by,

$$
C_{OM} = S_{pv}A_{pv}OM_{pv} + S_{wt}A_{wt}OM_{wt} + S_{st}A_{st}OM_{st} + S_{hp}A_{hp}OM_{hp} + S_{cr}A_{cr}OM_{cr} + S_{bites}V_{bites}OM_{bites}, \tag{S10}
$$

where OM_{pv}, OM_{wt}, OM_{st}, OM_{hp}, OM_{cr} [\$ m^{-2}] are operation and maintenance costs for PV, WT, ST, HP, and CR systems, and OM_{bites} [\$ m^{-3}] is the operation and maintenance costs for the BITES system. The annual income by salvaging the energy system components can be calculated by,

$$C_{SB} = F_{SB} \times C_{IB}, \tag{S11}$$

$$C_S = F_S \times C_I, \tag{S12}$$

where F_{SB} or F_S are salvage factors of base and retrofitted buildings over $N = 20$ years. The financial saving associated with Social Cost of Carbon (SCC) is provided by

$$SCC_S = \left(\sum_{k=1}^{N} SCC(k) \times GHG_{\text{save}} \times PWF(i,k) \right) CRF(i,N), \tag{S13}$$

$$GHG_{\text{save}} = GHG_{E_{\text{save}}} + GHG_{F_{\text{save}}}, \tag{S14}$$

where $SCC(k)$ [\$ $\text{kg}^{-1}_{\text{CO}_2e}$] represents the social cost of carbon for each year from 2020 to 2040, and GHG_{save} [kg_{CO_2e}] is the annual emissions savings. Table S5 presents the SCC values for CO_2e in Canada over the period 2020-2040. Table S6 indicates the parameters for finding the economic efficacy of retrofit strategies.

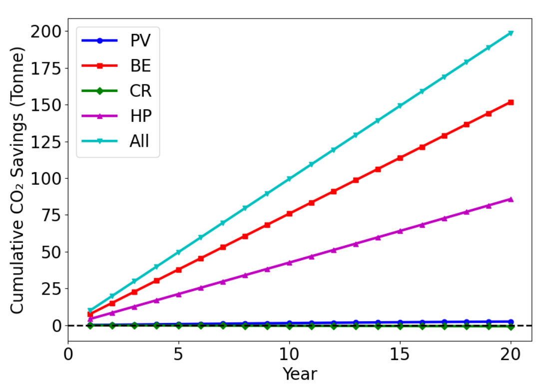
Table S5. Social Cost of Carbon (SCC) for CO_2e in Canada (2020–2040) [\$ tonne^{-1}][23].

Year	SCC [\$ $\text{tonne}^{-1}_{\text{CO}_2e}$]
2020	247
2021	252
2022	256
2023	261
2024	266
2025	271
2026	275
2027	280
2028	285
2029	289
2030	294
2031	299
2032	303
2033	308
2034	313
2035	317
2036	322
2037	327
2038	331
2039	336
2040	341

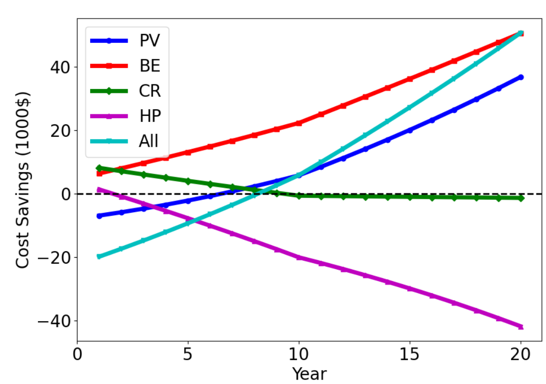
Table S6. Variables used in economic evaluation[22,24,25]; note: some prices were obtained from local manufacturers, suppliers, and contractors.

Parameter	Units	Description	Value
i_n	%	Nominal interest rate	3.78
j	%	Inflation rate	1.83
P_{pv}	\$m^{-2}	Price of PV	377
P_{wt}	\$m^{-2}	Price of WT	490 × 2
P_{st}	\$m^{-2}	Price of ST	340
P_{bites}	\$m^{-3}	Price of BITES	200
P_{hp}	\$m^{-2}	Price of HP	25 × 2
P_{cr}	\$m^{-2}	Price of CR	8 × 2
P_{env}	\$	Price of increasing envelop thermal resistance	36,000-60,000
P_{inf}	\$	Price of reducing building infiltration	1,500 × 2
C_{OMB}	\$m^{-2}	Base model operation and maintenance cost	1
OM_{pv}	\$m^{-2}	PV operation and maintenance cost	$0.01P_{pv}$
OM_{wt}	\$m^{-2}	WT operation and maintenance cost	$0.02P_{wt}$
OM_{st}	\$m^{-2}	ST operation and maintenance cost	$0.01P_{st}$
OM_{bites}	\$m^{-3}	BITES operation and maintenance cost	$0.01P_{bites}$
OM_{hp}	\$m^{-2}	HP operation and maintenance cost	$0.05P_{hp}$
OM_{cr}	\$m^{-2}	CR operation and maintenance cost	$0.1P_{cr}$
F_{SB}	-	Base model salvage factor	0.03
F_S	-	Retrofit model salvage factor	0.05
C_B	\$m^{-2}	Base model initial cost	5

Figure S7 shows cumulative CO_2e emissions savings and cost savings in Toronto over a time horizon of 20 years as a result of implementing various retrofit strategies for a typical residential building. Here the electricity and gas inflation rates are assumed to be 5% annually. As shown most retrofit strategies (except for CR) result in emissions savings. The greatest savings result from BE, followed by HP and PV. CR does not result in emissions savings because, while in the summer it helps reduce building cooling loads, in the winter, it increases the heating demand[26]. Interestingly, PV does not result in a lot of emissions savings becasue grid electricity has low carbon emissions in Ontario. As shown in the figure, to the contrary, the greatest cost savings result from PV and BE, while CR and HP do not contribute to cost savings. Rather they impose high costs. For example, HP needs electricity, which is expensive in Ontario, resulting in further costs. On the other hand, PV saves electricity needs from the grid, so it is financially desirable.



(a) Cumulative CO_2e Savings over 20 Years



(b) Cost Savings over 20 Years

Figure S7. CO_2e savings and cost savings (5% of electricity and gas inflation rate) in Toronto.

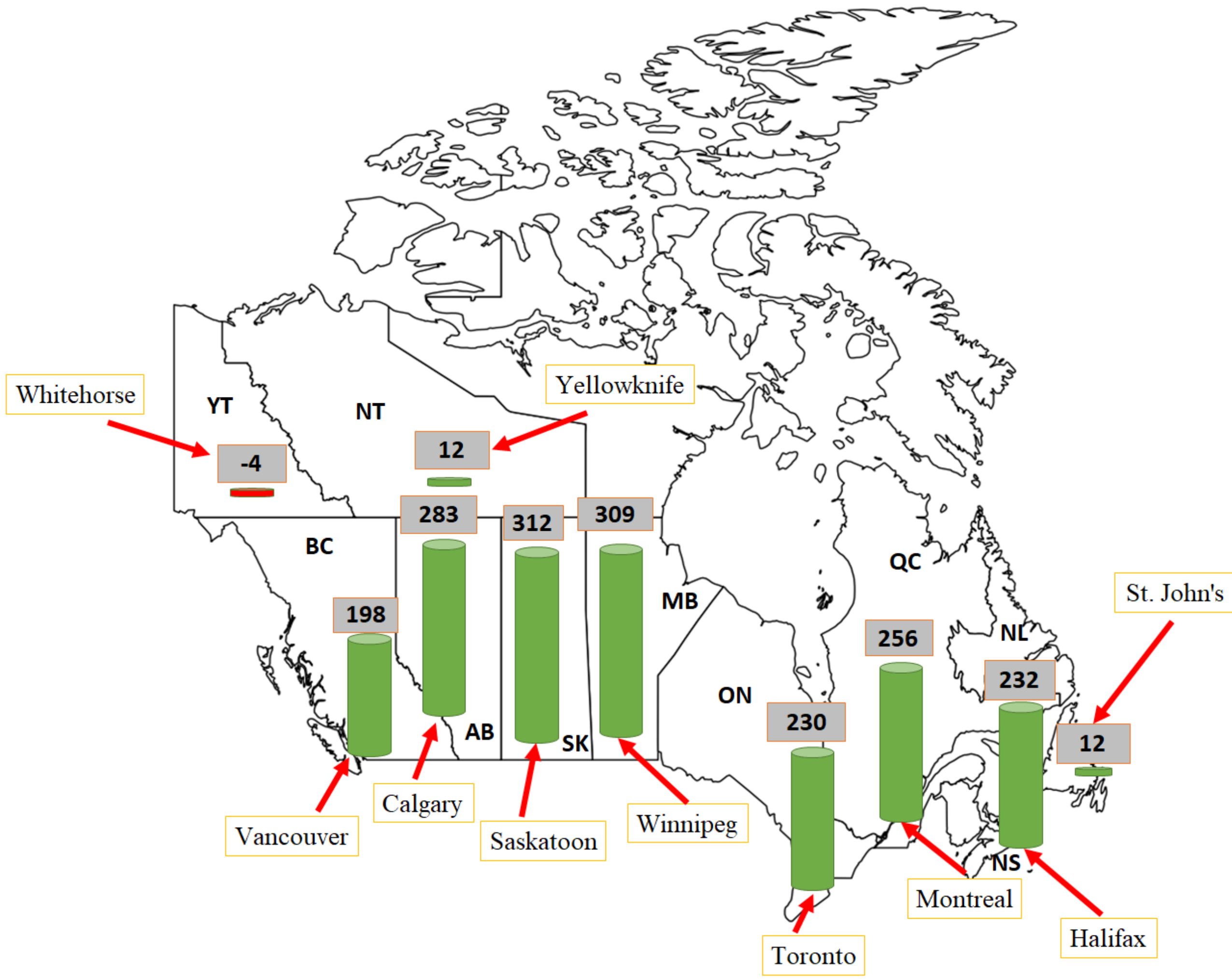


Figure S8. GHG emissions savings potential [Tonne-CO_2e] over 20 Years by implementing all government-incentivized retrofits for residential buildings; map generated using python 3.10 and various libraries: geopandas 1.0.1, matplotlib 3.9.0, and unidecode 1.4.0 (https://www.python.org/).

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