Topic: Low / Zero Carbon Emission Buildings and Communities

Climate Zone-Based Energy Retrofits – Residential Buildings in Canada

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SUMMARY

This research considers open low-rise residential buildings in two of Canada's Building Climate Zones, Vancouver and Toronto. Each Climate Zone has different weather conditions and vegetation, which lead to different building code requirements. Inputting these requirements and weather conditions into the Vertical City Weather Generator (VCWG) model, one can determine what energy saving solutions should be incorporated into residential buildings for each Climate Zone, while also making the building more affordable and reducing CO_2e emissions. The results of a 30-year analysis show that increasing vegetation from one to two trees, decreasing infiltration from 1.2 to 0.4 Air Changes per Hour (ACH), and incorporating a photovoltaic system that covers 69% of the residential roof may lead to cost savings of 37.3% and 36.6% for Vancouver and Toronto, respectively. CO_2e emissions savings could be reduced to 257 and 204 [Tonnes] for Vancouver and Toronto, respectively, if an R-value increase was also incorporated into the most cost-efficient case. However, this would reduce total cost savings.

INTRODUCTION

Implementing energy saving retrofits into residential buildings would reduce space heating and cooling demands, leading to a decrease in Canada's Greenhouse Gas (GHG) emissions.

Low roof albedos contribute to positive Urban Heat Islands (UHIs) by storing more incident shortwave solar energy. Most of the roofs in Canada use asphalt as the key ingredient, which have low albedos (~0.125). Baniassadi et al. [1] studied the direct and indirect effects of cool roofs (increasing albedo from 0.2 to 0.5) on three building types with varying Air Exchange Rates (AER) in Los Angeles. The results showed a decrease in uncomfortable hours for all building types as well as a decrease in cost.

Vegetation impacts UHI. Trees reduce heat and temperature in the area through shading because building materials will absorb and store less solar radiation [2, 3]. Zhao et al. [4] analysed the influence of street tree density and layout on the outdoor microclimate and found that an increase in trees compared to no trees offered 10.6 [ºC] cooling.

Adding photovoltaic panels to convert the sun's radiative energy into electricity that can be used for cooling and domestic electricity demands, can reduce grid electricity demand. Pearce and Sommerfeldt [5] found a reduction in grid electricity demand when adding PV panels that meet 100% of the electricity demand of a residential building leading to an investment return of 4.3% over a 25-year period.

There is a substantial amount of research that details energy saving retrofits but a lack of research, as far as the authors of this paper are aware, of energy retrofits that are Climate Zone specific in Canada. This research aims to retrofit a house in a residential neighbourhood in Climate Zones 4 and 5 [6, 7], for Vancouver and Toronto, respectively, by increasing vegetation, adding PV systems, increasing insulation, decreasing infiltration, and adding a cool roof. An analysis is performed to determine which combination of retrofits is best for each Climate Zone by comparing the annualized cost savings and the CO_2e emission reduction of each retrofit system to a base system. Although embodied emissions are an important area of research when investigating overall CO_2e emissions, it is beyond the scope of this paper.

METHODS

Simulation Platform

The Vertical City Weather Generator (VCWG) is an urban microclimate weather model that can simulate building energy flows while considering urban environmental factors [3] by forcing weather data from a rural site. The European Centre for Medium-Range Weather Forecasts (ECMWF) produces climate reanalysis data known as ERA5. Forced weather files used in VCWG modelling are taken from ERA5 files for an entire year in 2000 for both Vancouver and Toronto. VCWG has been validated against observed urban climate variables in both Basel and Vancouver [2, 3].

Retrofit Parameters

To establish a base house in Zones 4 and 5, the National Energy Code of Canada for Buildings (NECB) [8] was used along with ASHRAE Standards. Using Stewart and Oke's [6] local Climate Zone urban area classification system, a street was found for each city (Vancouver and Toronto) in an open low-rise neighbourhood ($LCZ6_B$): Longitude and Latitude Vancouver: -123.127356, 49.212288, Longitude and Latitude Toronto: -79.581630, 43632580. Google maps was used to determine the house and neighbourhood geometric and morphometric dimensions. Each building resembles a two-story house. A summary of retrofit options are provided in Table 1.

In VCWG, Leaf Area Density (LAD) [m^2 m^{-3}] is used to show tree abundance. Vancouver is in the Coast Forest region of Canada while Toronto is in the Carolina Forest region [9]. It was decided that an increase of one tree would be equivalent to an increase Leaf Area Index (LAI) of 0.5 [m^2 m^{-2}], that is, one tree: $0 < LAI \leq 0.5$ [m^2 m^{-2}], two trees: $0.5 < LAI \leq 1.0$ [m^2 m^{-2}], and three trees: $1.0 < LAI \leq 1.5$ [m^2 m^{-2}], see Figure 1. To account for vegetation in the economic analysis, an initial tree planting cost and annual Operation and Maintenance (OM) cost were considered for each additional tree, see Table 2. For the CO_2e emissions savings calculations, an average value from The United States Environmental Protect Agency (USEPA) – Greenhouse Gas Equivalency Calculator [10] was used.

Air leakage is modelled as infiltration/exfiltration in VCWG, infiltration/exfiltration values are used from ASHREA standards 90.1 [7]. The cost of sealing air-leakage of an existing building is adapted from a report written by Proskiw Engineering Ltd. [11]. It was assumed that two air-tightness tests were conducted over the 30-year period.

Insulating the walls will reduce heating loss by decreasing thermal conduction through the walls of the building. R-4 foam insulation was chosen with a thickness of 1 [in]. The cost of insulation was per unit of R-value added and per wall area [m^2 K W^{-1} m^{-2}].

The authors have chosen a Liquid Applied Cool Roof (LACR) coating because of its high albedo, easy application, and low cost [12]. Two coats of paint and OM are accounted for in the economic analysis to maintain a constant albedo of 0.8 [2]. Values can be found in Table 2.

The economic analysis used in this study comes from Aliabadi et al. [13], which provides the global cost method to determine how cost effective each retrofit is compared to the base case. This method considers all the costs associated with the retrofit: initial investment costs, OM, and gas and electricity costs. The analysis compares the cost of each retrofit system with a base house and calculates the marginal annualized cost. Values used for the cost analysis can be found in Table 2.

In this analysis, CO_2e emissions is quantified from gas consumption increase/decrease, electricity increase/decrease, and the addition of trees for CO_2e uptake. The natural gas consumption for each retrofit case is subtracted from the base case and multiplied by the fraction of CO_2e emission from natural gas, see Equation 3. CO_2e emission savings related to electricity factors in consumption for cooling, consumption for domestic demand, savings from PV, and emissions from grid electricity, see Equation 5.

RESULTS

An analysis was conducted to determine which configuration of retrofits: PV system, cool roof, decreased infiltration, increased insulation, and increased vegetation could decrease CO_2e emissions while increasing homeowner savings, see Figures 2, 3. Results for individual retrofits for Vancouver and Toronto can be seen in Figure 2a, 3a, respectively. In Vancouver and Toronto increasing vegetation from one tree (VegL) to two trees (VegM) will increase gas consumption but decrease electricity demand giving small percent cost savings <2%. Increasing vegetation further to three trees (VegH) will have a similar energy consumption trend but the increase in gas consumption leads to negative cost savings. Both cases led to an increase in CO_2e emissions. Increasing insulation decreased both gas and electricity consumption but the high cost of insulation lead to negative cost savings. Having the highest fraction of roof area covered with PV panels gave the largest amount of electricity production, the largest percent cost savings, and the largest CO_2e reduction in emissions. Increasing the albedo by adding a cool roof can increase both the electricity and gas consumption in Vancouver. In Toronto, adding a cool roof increased gas consumption but decreased electricity consumption. Both cases resulted in negative cost savings and negative CO_2e emissions savings. Decreasing infiltration to 0.4 [ACH] was the most cost-effective single retrofit with cost savings of 8.6% and CO_2e emissions savings of 228 [Tonnes] in Vancouver. The results for Toronto showed similar trends.

Once single retrofits were analysed the best performing retrofits were combined to observe further cost savings and CO_2e emissions savings. Results for Vancouver and Toronto can be seen in Figures 2b, 3b, respectively. A combination of increasing vegetation to two trees, high PV panel system, and a decrease in infiltration to 0.4 [ACH] gave the largest overall cost savings of 37.3% for Vancouver and 36.6% for Toronto. Increased vegetation to two trees, high PV panel system, a decrease in infiltration to 0.4 [ACH], and an increase in R-value gave the greatest amount of CO_2e emissions savings of 257 [Tonnes] for Vancouver and 204 [Tonnes] for Toronto.

Tables and Figures

Table 1. Values for retrofit buildings in Zones 4 and 5

Description	Vancouver				Toronto			
	Base	Retrofit1	Retrofit2	Retrofit3	Base	Retrofit1	Retrofit2	Retrofit3
Albedo base [-], CR_{Base}	0.125	0.8	-	-	0.125	0.8	-	-
Infiltration base [ACH], Inf	1.218	0.7	0.4	-	1.218	0.7	0.4	-
Insulation R-value base [m^2 K W^{-1}], Rval	3.175	7.175	-	-	3.597	7.597	-	-
Vegetation Base – [tree]	1	2	3	-	1	2	3	-
PV Coverage Base [%], PV	0	0.23	0.35	0.69	0	0.23	0.35	0.69

Table 2. Economic analysis

Variable	Sources	Values
Price of PV Panels, P_{PV} [$ m^{-2}]	Company pricing	377
Price of CR, P_{CR} [$ m^{-2}]	Company pricing	8
Price of Insulation, P_{Ins} [$ m^{-2}]	Company pricing	32.29
Price of Air-tightness Test and Sealing, P_{AirT} [$]	[11]	1500 × 2
Price of Tree Additions, P_{Tree} [$ $Tree^{-1}$]	Company pricing	200
OM Price for PV, OM_{PV} [$ m^{-2}]	Assumed	$0.01 \times P_{PV}$
OM Price for CR, OM_{CR} [$]	Assumed	75
OM Price for Tree, OM_{Tree} [$ $Tree^{-1}$]	Company pricing	130
Marginal Initial Cost of Base System, C_B [$ m^{-2}]	Assumed	5
Marginal OM Cost of Base System, OM_B [$ m^{-2}]	Assumed	1
Price of Electricity, P_E [$ kW^{-1} hr^{-1}]	[13]	0.127
Inflation Rate of Electricity, j_E	[13]	0.045
Price of Gas, P_G [$ m^{-3}]	[13]	0.137
Inflation Rate of Gas, j_G	[13]	0.01
Inflation Rate, j	[13]	0.0109
Nominal Interest Rate, i_n	[13]	0.0138
Salvage Factor for Base System, F_{SB}	Assumed	0.03
Salvage Factor for System, F_S (PVL, PVM, PVH)	Assumed	0, 0.03, 0.04, 0.05
Government Rebate for PV Panels, ITC_{PV} [$]	[14]	3000
Government Rebate for Air-tightness sealing, ITC_{AirT} [$ $test^{-1}$]	[14]	550
Government Rebate for Insulation, ITC_{Ins} [$ m^{-2}]	[14]	8.60
Number of years for economic analysis	-	30

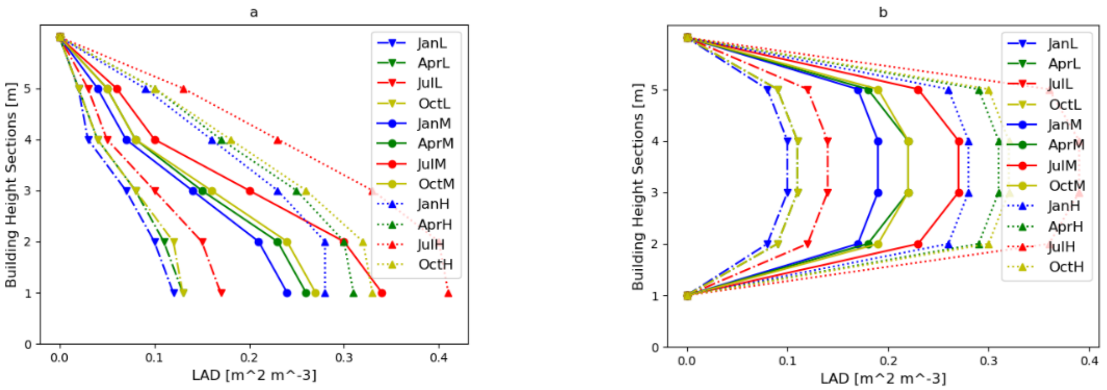

Figure 1. LAD profiles for Low, Medium, and High vegetation during the months of January, April, July, and October for a) Vancouver and b) Toronto.

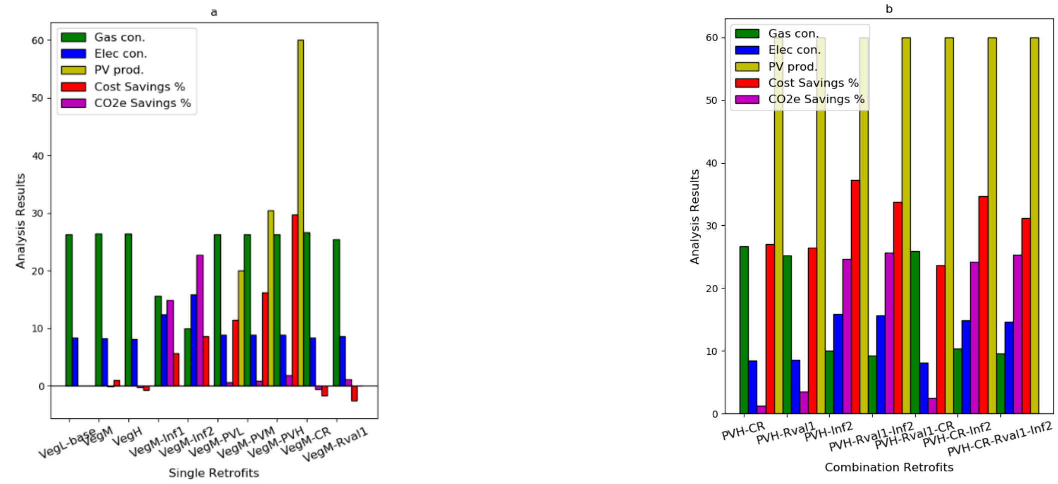

Figure 2. Vancouver results of: Annual total gas consumption [m^3 m^{-2}], annual total electricity consumption [kW-hr m^{-2}], annual total electricity production from PV system [kW-hr m^{-2}], total percent cost savings [%], and total CO$_2$e savings [Tonnes]$\times 10^{-1}$ for a) individual solutions and b) multiple combinations.

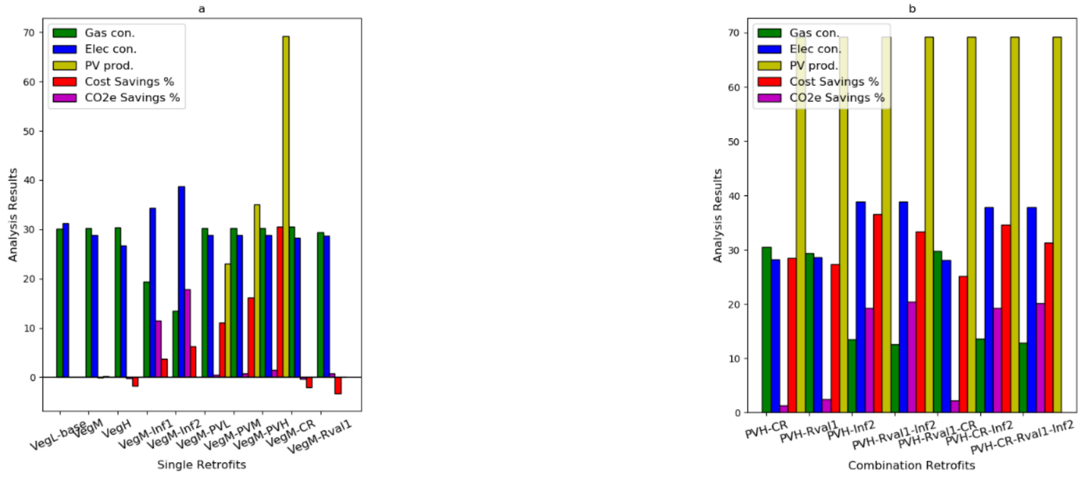

Figure 3. Vancouver results of: Annual total gas consumption [m^3 m^{-2}], annual total electricity consumption [kW-hr m^{-2}], annual total electricity production from PV system [kW-hr m^{-2}], total percent cost savings [%], and total CO$_2$e savings [Tonnes]$\times 10^{-1}$ for a) individual solutions and b) multiple combinations.

Equations

Total CO$_2$e savings is

$$TCO_{2_{Sav}} = VegCO_{2_{Sav}} + GasCO_{2_{Sav}} + ElecCO_{2_{Sav}} , \tag{1}$$

where $VegCO_{2_{Sav}}$ is the total CO2e savings associated with planting trees [kg], $GasCO_{2_{Sav}}$ is the total CO2e savings associated with natural gas savings [kg], and $ElecCO_{2_{Sav}}$ is the total CO2e savings associated with electricity savings [kg]. Vegetation CO2e savings is

$$VegCO_{2_{Sav}} = N_{Tree} \times \left(\frac{13.88}{10}\right) \times N, \tag{2}$$

where N_{Tree} is the number of additional trees and N is number of years. Gas CO2e savings is

$$GasCO_{2_{Sav}} = (TGCH_b - TGCH_s) \times A_H \times N \times \rho_{CH4} \times \frac{MW_{CO2}}{MW_{CH4}}, \tag{3}$$

where $TGCH_b$ is the total gas consumption for heating for the base system [m^3 m^{-2}], and $TGCH_s$ is the total gas consumption for heating for the retrofit system [m^3 m^{-2}]. Electricity CO2e savings is

$$ElecCO_{2_{Sav}} = ((TECD_b + TEDD) - (TECD_s + TEDD - TEP_{PV})) \times A_H \times N \times EEI, \tag{4}$$

where $TECD_b$ is the total electricity consumption for cooling of the base system [kW hr m^{-2}], $TEDD$ is the total domestic electricity demand [kW hr m^{-2}], $TECD_s$ is the total electricity consumption for cooling for the retrofit system [kW hr m^{-2}], TEP_{PV} is the total electricity produced by the PV panels [kW hr m^{-2}], and EEI is the CO2e emissions from grid electricity production [kgCO2e kW^{-1} hr^{-1}].

DISCUSSION

The results for Climate Zone 4 and 5 show similar trends with each retrofit addition except for the decrease in electricity consumption with a cool roof for Toronto. This decrease in electricity was a result of higher peak temperatures in Toronto requiring more electricity for air-conditioning. However, the savings in electricity consumption was not enough to offset the increase in gas consumption during the winter months as well as the cost of a cool roof retrofit. These results were not always consistent with findings form Baniassadi et al. [1] for multiple reasons. First, most studies focus on few technologies under specific seasons and climate conditions, while we have a comprehensive approach, considering combinations of solutions over longer term assessments. Second, the discrepancy could be due to the chosen albedo value. Most studies have cool roof values ranging from 0.5-0.7 [1, 2]. A lower albedo might produce lower gas consumption costs.

Increasing insulation was able to save on gas consumption by reducing heat loss during the winter months. During the summer months the extra insulation increased the cost of electricity because there was no heat loss, and the air conditioning unit would have to meet the cooling demand. The cost of increasing insulation was too high and resulted in negative cost savings but the reduction in gas consumption resulted in an increase in CO2e emissions savings.

In every retrofit that included a PV system there were CO2e emissions savings and cost savings. With a smaller PV system, the electricity produced was able to meet 100% and 80% of the electricity associated with cooling demand in Vancouver and Toronto, respectively. Once the electricity need for cooling was met, the PV produced electricity was able to offset the electricity demand for domestic use. A large PV system accounted for the largest cost savings and the largest CO2e emissions savings. These findings were consistent with Pearce and Sommerfeldt [5].

Reducing infiltration/exfiltration decreased gas consumption (winter heating) but increased electricity consumption (summer cooling) for similar reasons stated above. The model assumed that there were no windows or doors open but if the analysis was performed with windows open during the summer months at night there might be a decrease in electricity consumption for cooling. Of all the individual retrofit runs, increased infiltration/exfiltration produced the second greatest cost savings (PV system was the greatest) and the greatest CO_2e emissions savings.

Increasing the number of trees increased gas consumption but decreased electricity consumption. In Vancouver, coniferous trees would provide shade for a house during the winter, reducing the amount of solar radiation that could be used to heat the house but also decreasing the amount of solar radiation that would have resulted in an increase in cooling demand. These results are consistent with findings from Zhao et al. [4]. The low cost of adding a tree plus the decrease in electricity consumption resulted in small cost savings for both Vancouver and Toronto. A trees' ability to uptake CO_2e was not enough to compensate for the increase in CO_2e production from the increase in natural gas consumption, leading to a negative CO_2e emissions savings.

Combining retrofits showed that some combinations were able to produce even larger cost savings and CO_2e emissions savings. Coupling the PV system with a decrease in infiltration/exfiltration produced the greatest cost savings. Decreasing infiltration/exfiltration decreased gas consumption and the PV system was able to provide 100% of the electricity needed for cooling demand increase. In fact, coupling the PV system with any other retrofit option resulted in cost savings and CO_2e savings.

The similarities between Climate Zone 4 and 5 could be a result of similar climate and vegetation. Although the dominant vegetation in Toronto is deciduous, there is an abundance of coniferous trees. Toronto also has more heating degree days but from the ERA5 data used for the year 2000, it seems that this year was abnormally warm, resembling the Vancouver climate.

CONCLUSIONS

This study investigated the cost savings and CO_2e emissions reductions for retrofitting a house in two of Canada's six Climate Zones over a 30-year period. The retrofits include installing a PV system, adding a cool roof, decreasing air leakage, increasing insulation, and increasing outdoor vegetation. The results can show which retrofits have the greatest impact on reducing CO_2e emissions while also decreasing building retrofit and operation costs. Increasing vegetation from one to two trees, decreasing infiltration from 1.2 to 0.4 Air Changes per Hour (ACH), and using a photovoltaic system covering 69% of half the residential roof may lead to cost savings of 37.3% and 36.6% for Vancouver and Toronto, respectively. Additionally, increasing the wall R-value in a building, is costly, but it will result in CO_2e emissions savings of 257 and 204 [Tonnes] for Vancouver and Toronto, respectively. The results are meant to give general information on possible retrofits for each Climate Zone, which is why a common neighborhood type ($LCZ6_B$) was chosen with house dimensions averaged out.

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