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BUILDING RETROFITS AND ECONOMIC ANALYSIS ACROSS CANADA: NATURAL VENTILATION AND PHOTOVOLTAIC SYSTEMS

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***Abstract*—Buildings significantly contribute to climate change through energy consumption and Greenhouse Gas (GHG) emissions. Therefore, building retrofitting is crucial. In this study, two retrofit scenarios—Photovoltaic (PV) systems and Natural Ventilation (NV)—were investigated across 10 Canadian cities. GHG emissions and cost savings were calculated for each retrofit strategy. Results indicated that NV yields significant financial benefits in all cities. On the other hand, cost saving of PV systems can vary due to differing electricity rates across provinces. Cities with higher electricity rates are more suitable for implementing PV systems in buildings. Both retrofit strategies were found to contribute to GHG emissions reduction albeit with variations depend on each city's emission intensity factor. Additionally, the payback period analysis for PV system installation revealed differences among cities, with Toronto exhibiting the shortest payback period among all Canadian cities.

***Keywords*—Building Retrofit; Economic Analysis; Natural Ventilation; Photovoltaic Systems**

I. INTRODUCTION

Building energy consumption constitutes a significant contributor to Greenhouse Gas (GHG) emissions, making it a important aspect in the pursuit of sustainable urban development. The importance of identifying optimal retrofit strategies lies in their potential to enhance energy efficiency, lower operational costs, and mitigate environmental impacts [9]. For instance, two retrofit strategies include the integration of Photovoltaic (PV) systems [1] and Natural Ventilation (NV) [14] in buildings. The effect of weather and climate zones on retrofit strategies plays a crucial role in determining the success of these strategies in reducing GHG emissions and achieving cost savings. Additionally, the economic viability of these retrofits is closely tied to the local cost of energy and available incentives for renewable energy adoption.

A. Objectives

In this study, we aim to evaluate the economic and environmental advantages associated with building retrofitting—a proactive strategy designed to reduce energy consumption and GHG emissions in different climate zones and provinces of Canada.

We seek to explore the potential benefits of two specific retrofitting scenarios: PV systems and NV in different Canadian cities. By investigating these strategies, we aim to shed light on their effectiveness in curbing energy use and their associated economic implications.

Additionally, we aim to examine how the energy efficiency and cost-effectiveness of PV systems and NV may vary across different Canadian cities. Our objective is to identify patterns and considerations that could inform future retrofitting initiatives in diverse urban contexts.

II. METHODOLOGY

A. Vertical City Weather Generator (VCWG v1.4.8)

In this study we use the Vertical City Weather Generator (VCWG v1.4.8) software as an urban physics model to study the implementation of PV and NV in different cities across Canada. Previous versions of the VCWG have the same submodels as rural model, building energy model, rural surface energy balance model, 1-D vertical diffusion model, radiation model, soil energy balance models [3], [10], [11], while

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VCWG v1.4.8 has an additional module to analyze economics and GHG emissions of various retrofit strategies.

B. Selected Cities and Their Climate Zones

Figure 1 indicates that Canada has various climate zones (4 to 8). In this article, ten cities from different climate zones and provinces were selected (I). It was attempted to cover all of Canada to study the feasibility and potential benefits of PV and NV as retrofitting strategies. Also,the weather files for each city are created for the year 2020 using the ERA5 reanalysis data product [2]. Building parameters are adjusted based on building standards and codes in their climate zones [4], [6], [12] that are presented in Table II.

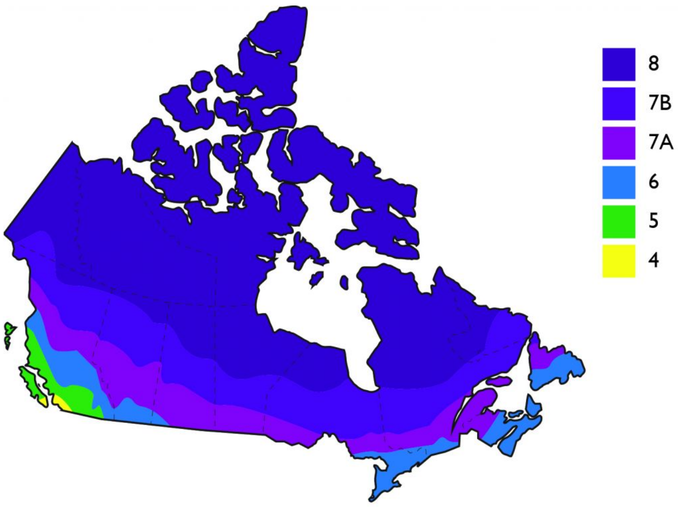

Figure. 1. Different Climate Zones of Canada [5].

TABLE. I
Selected cities across Canada from different climate zones.

City	Zone
Vancouver	4
Toronto	5
Halifax	6
St. John's	6
Montreal	6
Winnipeg	7A
Saskatoon	7A
Calgary	7A
Whitehorse	7B
Yellowknife	8

TABLE. II
Building Parameters in Different Climate Zones [12]

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 Value [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

C. Residential Electricity Rates

The electricity billing systems in different provinces of Canada vary and each province employs a specific method (Figure 2). Notably, provinces like Ontario and Alberta adopt a time-based charging system, where electricity prices fluctuate during different times. In Ontario, three rates—on-peak, off-peak, and mid-peak—vary in winter and summer. Alberta, on the other hand, witnesses monthly variations in electricity prices among different providers.

In contrast, some provinces implement a structure comprising a basic charge and an energy charge based on electricity consumption. Quebec does not have a basic charge but employs a two-step charging process. British Columbia and Manitoba utilize a combination of basic charges and step charging procedures.

D. Emissions Intensity of Electricity Generation

The emissions intensity of electricity generation in Canada varies widely across provinces, reflecting diverse energy sources. As shown in Figure 3 Ontario (ON) and British Columbia (BC) exhibit lower values of 25 and 12 $\mathrm{g}_{\mathrm{CO}_2 e}$ kWh^{-1}, indicating a commitment to cleaner energy. Conversely, Nunavut (NU), Nova Scotia (NS), Alberta (AB) and Saskatchewan (SK) report higher emissions intensities of 770, 670, 590 and 580 $\mathrm{g}_{\mathrm{CO}_2 e}$ kWh^{-1}, suggesting a greater environmental impact. Some provinces, like Prince Edward Island (PE), show zero emissions intensity, reflecting a reliance on clean or renewable sources. Quebec (QC) and Manitoba (MB) have emissions intensities of 1.5 and 1.1 $\mathrm{g}_{\mathrm{CO}_2 e}$ kWh^{-1}, respectively, indicating environmentally friendly practices.

III. RESULTS AND DISCUSSION

A. Base Cost

Figure 4 presents the marginal annualized cost for the base cases (no retrofits), measured in Dollars, providing valuable insights into the economic considerations associated with energy consumption in various cities across Canada. The data reveals significant disparities among cities, shedding light on the varying financial implications for residents. To calculate marginal annualized cost we use the equation 1

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

where C_I is annualized initial investment for the systems' acquisition, C_G is the annualized cost of gas consumption, C_E is the annualized cost of electricity consumption, C_{OM} is the annualized cost of operation and maintenance, and C_S is the annualized income of discarding the systems (salvage).

Vancouver and St. Johns's, with a marginal annualized cost base of \$5243.66 and \$5109.85, respectively, emerge as the cities with the lowest associated energy costs. Toronto, on the other hand, shows a substantially higher marginal annualized cost base of \$17650.10. This considerable difference emphasizes the financial burden associated with energy prices (particularly electricity) in Toronto, potentially influenced by factors such as local energy sources and rates, infrastructure,

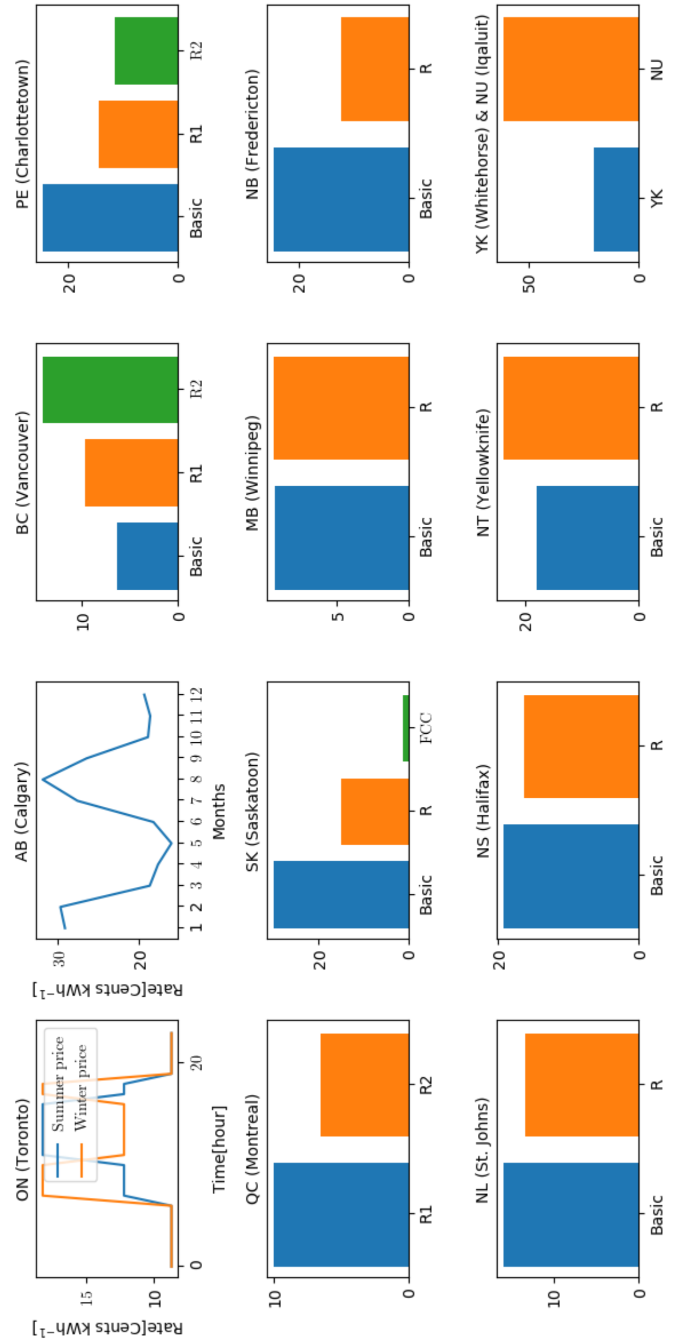

Figure. 2. Residential Electricity Rates (M: Month, R: Rate [Cent kWh^{-1}], Basic: Basic Charge [CAD kWh^{-1}], FCC: Federal Carbon Charge [Cents kWh^{-1}])

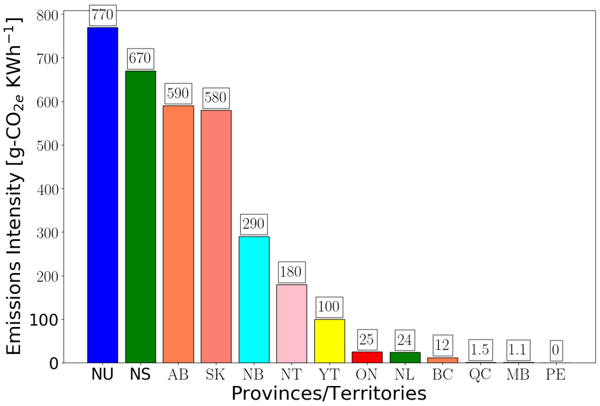

Figure. 3. Emissions Intensity of Electricity Generation [8].

and consumption patterns. Montreal, Calgary, Saskatoon, and Winnipeg exhibit marginal annualized cost bases ranging from \$9209.28 to \$10489.26. These cities share relatively similar cost considerations, potentially reflecting comparable energy infrastructures, prices, and consumption habits.

The marginal annualized cost base data provides a nuanced perspective on the economic aspects of energy consumption in Canadian cities. The disparities observed among cities underscore the importance of understanding local energy dynamics and adopting region-specific retrofit strategies for energy efficiency and cost savings.

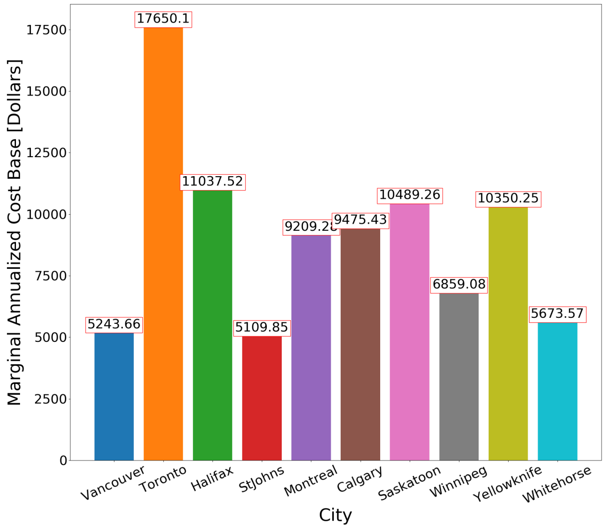

Figure. 4. Marginal Annualized Base Cost.

B. Cost Saving of NV

Figure 5 represents the percent reduction in marginal annualized cost after applying NV as a retrofit strategy in various Canadian cities. This retrofit strategy aims to enhance energy efficiency and reduce costs associated with building operations.

Analyzing the data reveals notable differences in the effectiveness of NV retrofit strategies across these cities. Vancouver demonstrates the highest reduction at 9.14%, indicating a substantial improvement in cost efficiency. St. John's closely follows with an 8.36% reduction, suggesting successful implementation of NV measures.

Meanwhile, cities like Halifax and Yellowknife exhibit more conservative reductions at 4.62% and 4.21%, respectively. This may suggest that the impact of NV retrofit strategies in these locations is comparatively less pronounced.

Comparing the mid-range reductions, Toronto, Montreal, Calgary, Saskatoon, Winnipeg, and Whitehorse fall within a relatively close range, showcasing reductions between 5.44% and 7.60%. This suggests a moderate but impactful improvement in cost efficiency across these cities.

Figure 5 highlights the diverse outcomes of implementing a natural ventilation retrofit strategies in different cities, emphasizing the importance of considering local climate conditions and building characteristics in optimizing energy efficiency measures.

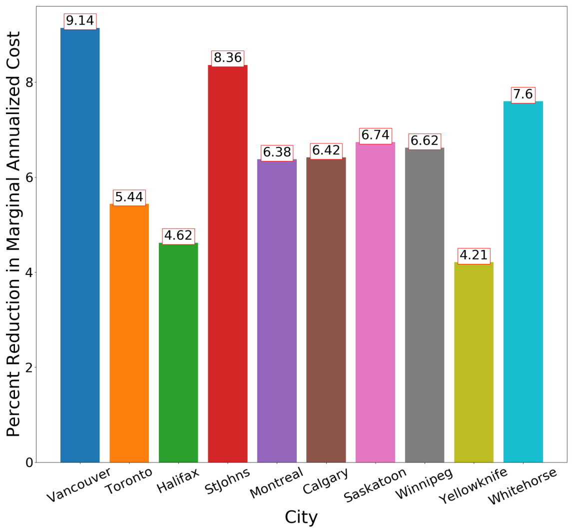

Figure. 5. Percent Reduction in Marginal Annualized Cost of NV

NV strategies, influenced by climate zones, can impact energy consumption by optimizing indoor/outdoor air exchange. In temperate climates, effective NV can reduce the reliance on mechanical cooling systems, contributing to energy savings and lowering GHG emissions associated with electricity consumption for air conditioning [7].

C. GHG Saving of NV

The retrofitting strategy of NV in various cities across Canada has demonstrated diverse impacts on CO_{2e} savings from electricity consumption. The data in Figure 6 showcases the tangible environmental benefits associated with the implementation of NV as a retrofitting measure. To calculate GHG emission saving we use the equations 2 and 3

$$E_{save} = [E_{cB} + E_{dB} - (E_c + E_h + E_d - E_{pv})]A_{bld}N, \quad (2)$$

$$GHG_{E_{save}} = 0.001 * E_{save}EI_E, \quad (3)$$

where E is electricity [kW-hr m^{-2}], B is Base building (no retrofit), c is space cooling, h is space heating, d is domestic use, pv is photovoltaic, A_{bld} is footprint area [m^2], N is number of years, EI_E is grid electricity emissions intensity [$g_{CO_{2e}}$ kWh^{-1}]

In Vancouver, the application of NV has resulted in CO_{2e} savings of 149 kg. Toronto follows substantial savings of 5384 kg, indicating a considerable reduction in the carbon footprint of electricity consumption. Halifax stands out with the highest CO_{2e} savings among the cities, amounting to 87169 kg. St. John's and Montreal also report noteworthy savings of 889 kg and 291 kg, respectively.

Calgary, Saskatoon, Winnipeg, Yellowknife, and Whitehorse exhibit varying degrees of CO_{2e} savings, contributing to environmental sustainability. The comparative analysis reveals that the application of NV retrofit strategies yields substantial benefits in terms of reducing carbon emissions associated with electricity consumption across these diverse Canadian cities.

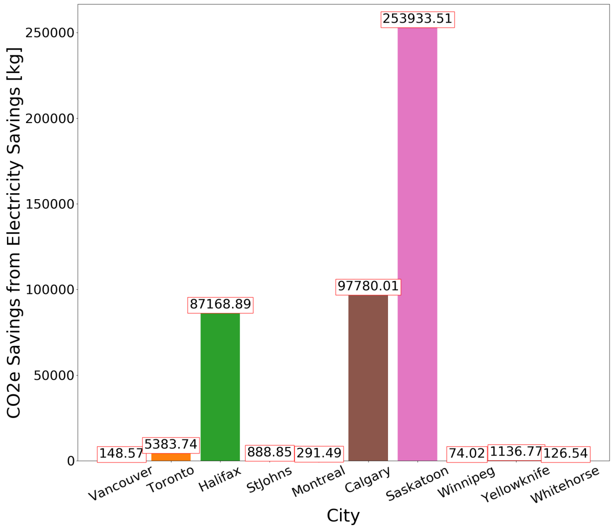

Figure. 6. CO_{2e} Savings from Electricity Savings of NV

D. Cost Saving of PV

The analysis of retrofit strategies involving the application of PV systems in various Canadian cities reveals substantial variations in the percent reduction in marginal annualized cost (Figure 7). Among the cities considered, Toronto stands out with the highest reduction, showing a significant 54% decrease in the marginal annualized cost after implementing PV retrofit strategies. This indicates a considerable economic benefit and underscores the effectiveness of solar energy solutions in the Toronto context.

On the contrary, Vancouver experiences a reduction of -25%, signifying a unique scenario where the application of photovoltaic systems has a negative impact on the marginal annualized cost. This unusual result may be attributed to specific characteristics of Vancouver's energy infrastructure or the local economic context.

Other cities such as Halifax, St. John's, Montreal, Calgary, Saskatoon, Winnipeg, Yellowknife, and Whitehorse demonstrate varying degrees of reduction in marginal annualized costs, ranging from 2% to 28%. These differences highlight the city-specific considerations and potential effectiveness of PV retrofit strategies in optimizing energy costs across diverse urban landscapes.

In comparing the cities, Toronto's remarkable 54% reduction underscores the potential for significant economic gains through PV retrofit strategies. The negative reduction in Vancouver may warrant further investigation into the factors influencing the effectiveness of PV applications in that particular city. The remaining cities show moderate reductions, reflecting a range of outcomes influenced by local energy infrastructure, climate, and economic conditions. This data emphasizes the need for tailored approaches when implementing solar energy solutions based on the unique characteristics of each city.

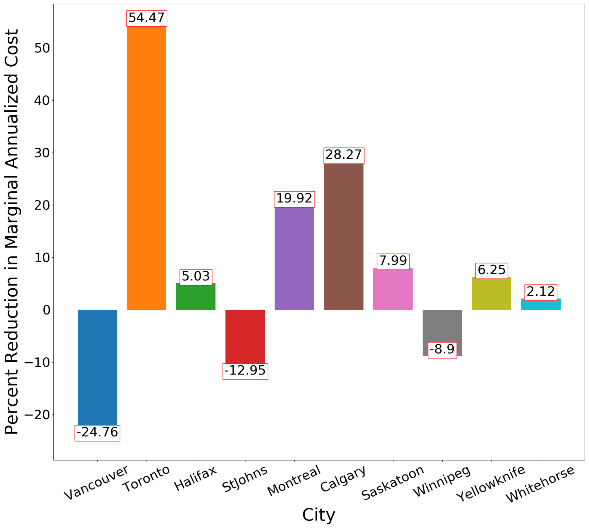

Figure. 7. Percent Reduction in Marginal Annualized Cost of PV.

E. GHG Saving of PV

The CO_{2e} savings from the implementation of photovoltaic systems (PV) as retrofit strategies in various Canadian cities provide valuable insights into the environmental impact of adopting renewable energy solutions. As shown in Figure 8, Vancouver stands out with a notable reduction of 5161 kg of CO_{2e}, emphasizing the city's commitment to sustainability. Toronto follows with a substantial CO_{2e} savings of 158,835 kg, showcasing the potential impact of PV systems on larger metropolitan areas. Halifax demonstrates a remarkable environmental impact, leading with CO_{2e} savings of 3,722,893 kg, underscoring the efficacy of renewable energy strategies in significantly reducing carbon emissions.

St. John's, Montreal, and Calgary exhibit varying but considerable CO_{2e} savings of 109,223 kg, 9,039 kg, and 3,676,930 kg, respectively. These cities showcase the adaptability of PV systems across different urban landscapes. Saskatoon and Winnipeg contribute to the environmental cause with CO_{2e} savings of 3,551,775 kg and 7,168 kg, respectively, further illustrating the positive impact of renewable energy implementation.

In the northern territories, Yellowknife and Whitehorse demonstrate noteworthy CO_{2e} savings of 706,816 kg and 391,870 kg, respectively. These results underscore the potential for renewable energy strategies to make a significant difference even in more remote regions.

The data presents a comprehensive view of the environmental benefits associated with the application of PV systems in diverse Canadian cities, emphasizing the need for widespread adoption of renewable energy solutions to mitigate climate change.

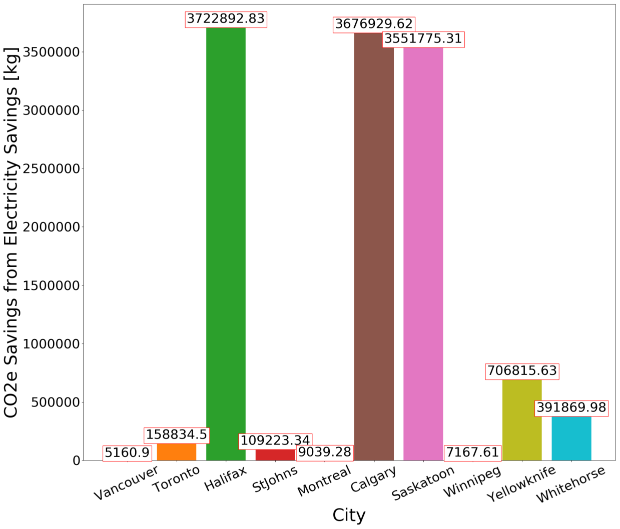

Figure. 8. CO_{2e} Savings from Electricity Savings of NV

F. Payback Period of PV

As depicted in Figure 9, the payback periods for installing PV systems vary significantly. Toronto, with a payback period of less than 6 years, stands out as particularly economically viable. This indicates that the initial investment in PV systems in Toronto can be recovered in a relatively short time, making it an attractive option for building owners.

Calgary, with a payback period of around 11 years, is still within a reasonable range, suggesting a moderate but acceptable duration for the investment to pay off. Montreal, Saskatoon, and Yellowknife have payback periods ranging from 17 to 18 years, indicating a more extended period for the initial investment to be recovered.

Halifax, with a payback period of around 20 years, and other cities with payback periods exceeding 20 years, may face longer timelines for realizing financial returns. Vancouver, with the longest payback period among the cities studied, suggests that the initial investment in PV systems would take the most extended time to recover in this location.

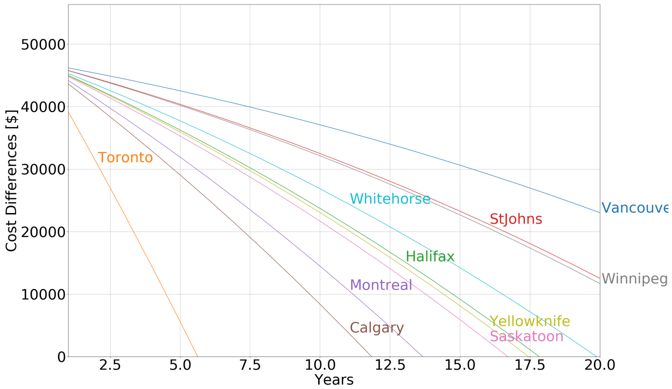

Figure. 9. Payback Period of PV in Different Cities (Initial Investment Minus Cumulative Cost Savings over 20 Years)

In the context of PV systems, the effectiveness of solar energy generation is highly dependent on local weather patterns and the amount of sunlight a region receives. Climate zones with abundant sunlight can optimize the performance of PV systems, leading to higher energy production and, consequently, greater GHG emission reductions. On the other hand, regions with frequent cloud cover or limited sunlight may experience lower efficiency, affecting the overall environmental and economic benefits [13].

The selection and design of retrofit strategies must be tailored to the specific weather and climate conditions of a region to maximize their impact. Additionally, the economic viability of these retrofits is closely tied to the local cost of energy and available incentives for renewable energy adoption. In regions with higher energy costs, the financial benefits of PV systems may be more pronounced, enhancing the cost-saving potential.

IV. CONCLUSIONS

In our study, we found that implementing NV in urban areas can lead to substantial cost savings across all cities. Notably, NV significantly reduces GHG emissions, demonstrating heightened effectiveness in cities such as Halifax, Calgary, and Saskatoon. Additionally, exploring PV systems revealed diverse cost-saving potentials, with Toronto, Montreal, and Calgary experiencing over 20% reduction in marginal costs. The environmental impact of PV is considerable, especially in cities with high GHG intensity emissions. Examining the payback periods of PV installations revealed variations across different cities, with Toronto boasting the shortest payback period among Canadian cities (less than 6 years).

Looking ahead, our future work involves the exploration of additional retrofit strategies, including wind turbines, solar thermal collectors, energy storage, and heat pumps. We aim to determine the optimal retrofit strategy for different provinces using optimization techniques. Furthermore, our investigation extends to economic instruments such as carbon pricing/tax and financial incentives (rebates, loans, etc.) seeking to identify cost-effective and environmentally-friendly solutions for reducing GHG emissions from buildings.

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