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Net-Zero Retrofit of Commercial Buildings in Cold Climates: A Case Study from Canada

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ABSTRACT

The Canadian government has committed to achieving net-zero emissions by 2050. In response, many organizations committed to exploring and implementing necessary measures and technologies to achieve net-zero buildings. By 2050, majority of Canada's building stock will already exist. Therefore, in addition to designing and constructing new net-zero buildings, it's crucial to develop effective approaches for retrofitting existing buildings. This task can be particularly challenging in colder climates due to the high heating load, primarily met by natural gas, and reduced solar generation during the heating season. Hence, efforts need to focus on significantly reducing overall energy use, maximizing the use of renewables, and electrifying end uses through the integration of appropriate building technologies. In this paper, we outline a recent net-zero retrofit carried out in a commercial building located in Ontario, Canada. The building under study incorporates three types of solar panels, a closed-loop ground-source heat exchange system, a highly efficient lighting system, and dynamic smart windows. We analysed two years of hourly electricity end-use and utility billing data to verify the energy performance of the building and provide insights into the lighting, plug, and heating and cooling electrical loads during pre- and post-retrofit periods. Additionally, we presented the performance of the solar electrical system and its impact on achieving net-zero performance in colder climates. The post-retrofit heating and cooling loads emerged as the largest electrical end-use, accounting for over 70% of the building's total electricity use. We also compared the pre- and post-retrofit energy performance against benchmark values and studied the cost and environmental impacts of the retrofit. The results showed that the building's pre-retrofit energy use intensity was nearly twice as high as the benchmark values. It is essential to consider this when applying the findings to similar commercial buildings undergoing net-zero retrofits. Ultimately, we determined this building achieved savings of more than $148,000 and 120 tonnes of CO_{2e} *for utility cost and operational carbon emissions per year, respectively.*

INTRODUCTION

The Pan-Canadian Framework on Clean Growth and Climate Change (Government of Canada, 2016) describes Canada's plan to meet the objectives of the 2015 Paris Agreement. Heating and cooling the existing building stock in Canada accounts for approximately 17% of the national greenhouse gas (GHG) emissions (Natural Resources Canada, 2017). Hence, reducing emissions from buildings is a major component of meeting Canada's commitment to GHG reductions. The Pan-Canadian Framework outlines four approaches to reducing emissions in the building sector: (1) make new buildings more energy efficient, (2) retrofit the existing building stock, (3) improve energy efficiency of building appliances and equipment, and (4) support building codes and energy efficient housing in indigenous communities. Considering that 75% of the 2050 Canadian building stock will already exist, retrofitting the existing building stock needs to be prioritized to achieve the 2015 Paris Agreement goals. In response to these requirements for zero carbon emission for existing and new buildings, a number of organizations committed to exploring the most efficient ways to retrofit aging buildings, and to implementing the required measures and technologies supporting net-zero operations. These retrofits usually involve major upgrades to a building's mechanical and electrical systems, use of renewable sources and technologies, changes to a building's envelope, replacements of windows and roofs, as well as upgrades or reconfigurations of the interior design. Despite the broad range of available retrofit technologies and practices, methods to determine the most suitable set of retrofit actions for specific projects are still a practical challenge.

The majority of the research on net-zero buildings has focused primarily on new construction (Ahmed et al., 2022; Aram, Taherkhani, & Šimelytė, 2022; Idrissi Kaitouni, Pfafferott, Jamil, Ahachad, & Brigui, 2023; Le, Nguyen, Bui, Teodosio, & Ngo, 2023; Luo, 2022). In the net-zero retrofitting studies, most studies have analyzed the feasibility, and retrofit options and their performance using energy simulation. Ferrari et al. (Ferrari & Beccali, 2017) studied various retrofitting options for an existing office building in Italy using TRNSYS (University of Wisconsin--Madison. Solar Energy Laboratory, 1975). The retrofitting target was to achieve better energy performance and reduce primary operating energy demand close to zero. The investigated retrofit options included improving the thermal insulation of the envelope, replacement of the air conditioning system, and installation of advanced controls for lighting systems and photovoltaic (PV) panels. The results showed that it was possible to reduce primary energy demand and associated emissions by up to 40%. A near net-zero energy performance was achievable by exploiting on-site renewable energy sources. Alkhateeb et al. (Alkhateeb & Abu-Hijleh, 2019) assessed the feasibility of converting an existing office building toward net-zero operating electricity consumption. They used a commercially available building energy simulation software to test several passive and active measures in order to achieve net-zero goal including the envelope insulation improvement and integration of a grid-connected PV system. The simulation results showed that the implementation of active measures proved to be more effective in reducing energy demand than passive ones. The passive strategies reduced electricity demand by 15%, while active measures reduced electricity demand by 63%. A PV system was able to cover the reduced energy demand resulting in a net zero electricity building. Net-zero energy retrofit in colder climates was studied by Rabani et al. (Rabani, Bayera Madessa, & Nord, 2021). They developed an optimisation method for minimising energy use in a simulated office building in Norway. Their method coupled an indoor climate and energy simulation software and a generic optimization tool to optimize the retrofit process. They achieved net-zero energy use through improving the building envelope and fenestration system, and integrating PV panels. Oh and Gardner (Oh & Gardner, 2022) analyzed measured end-use and utility bill data from a retrofitted net-zero energy building in a cold climate. The building under study was an administration and maintenance facility in Idaho, U.S. (climate zone 5B and 6B). They analyzed 10 months of sub-hourly electricity use data during the post-retrofit period. The pre-retrofit data was limited to monthly utility bills. They showed that the HVAC system load was the most sensitive to the outside air temperature. The PV electricity generation was higher than the building electricity use, except from the winter season, and the building was net-positive from an energy perspective. In Canada, net-zero retrofit studies have been mainly focused on residential stock. Asaee et al. (Asaee, Ugursal, & Beausoleil-Morrison, 2019) conducted a techno-economic analysis of using renewable/alternative energy technologies in the Canadian housing stock. They showed that substantial energy and GHG emission savings are techno-economically feasible for residential buildings in cold Canadian climates through careful selection of retrofit options. Wills et al. (Wills, Beausoleil-Morrison, & Ugursal, 2021) proposed a hybrid statistical and engineering-based model to analyze community-scale energy retrofits in residential building stock in Canada. The modeling included envelope and mechanical retrofits, as well as district renewable energy systems. Using energy simulations, they showed that deep envelope retrofits and fuel switching from natural gas to electric heat pump systems reduce community energy demand by 69%. Saturating the available roof area with photovoltaics was able to achieve a net-zero performance.

This paper presents the details of a recent real-world net-zero energy retrofit of an office building located in Ontario, Canada. The effects of various retrofit measures were studied using two years of hourly sub-metered electricity use data and utility bills. The main motivation of this study is to highlight the critical points that affect the energy performance of a net-zero energy retrofitted building using real-world data from an occupied building. First, we discuss the formal definitions of "net-zero" and "nearly net-zero" buildings. Then we provide a detailed description of the initial state of the building and the retrofit process including the building envelope and heating and cooling, and lighting systems improvements. Finally, we quantify the pre- and post- retrofit energy performance of the building using sub-metered electricity use and utility bills data.

NET-ZERO ENERGY BUILDINGS

U.S. Department of Energy (Deru & Torcellini, 2007) described four well-documented definitions of a net-zero building: net-zero site energy, net-zero source energy, net-zero energy emissions and net-zero energy costs. Site net-zero considers the use and export of energy at the building site and does not consider the energy carriers. Therefore, it is the most generalizable definition that can be adopted and calculated across various jurisdictions. The main disadvantage of this definition is overlooking the time-varying costs of energy. Source net-zero has a broader scope to account for electric generator inefficiencies, transmission and distribution. In this definition, onsite energy generation is balanced with imported energy as measured at the source. Although this definition may provide a more comprehensive overview of the building energy performance, the transmission and distribution data may not always be publicly available. In a net-zero energy emissions building, the onsite emission-free renewable energy generation balances (or exceeds) the building energy use from emissions-emitting sources. Intuitively, a building connected to a clean grid, such as a hydro or nuclear-powered grid, would benefit from this definition. Energy cost net-zero is an economically driven definition that seeks to balance the total cost of importing energy to the building with the revenue generated from exporting onsite energy generation. Due to varying utility costs, a building with consistent energy performance may achieve the energy cost net-zero one year and not the next. In this work, we adopt the net-zero site energy definition to assess the energy performance of the building under study. This helps to generalize the results for future cross-comparison with similar retrofits in various geographical locations with different grid cleanliness and utility costing paradigms. Similar to the site net-zero definition, in this work, a near net-zero building is considered as one where onsite energy generation is nearly balanced with imported energy as measured at the source, resulting in a very low net energy use in the building.

BUILDING CASE STUDY

In this section, we provide a high-level description of the building properties before and after the retrofit. The building under study was built in Toronto, Ontario (climate zone 5A) in 1991 as a two-storey office building. The building has a gross floor area of 2,071 m^2 (22,297 ft^2) and a height of 13.1 m. The original design of the building consisted of multiple offices and meeting rooms. Other spaces were used for services (for example kitchen and toilets), technical rooms and common areas. The building was built to R2000 which is a voluntary national standard in Canada to encourage energy efficiency in buildings (Natural Resources Canada, in press). The building faces south and is located close to a green space that minimizes the shadow from other buildings or trees. Therefore, the original roof design anticipated the addition of solar panels in the future. The building originally used a natural gas boiler and an air-cooled chiller for heating and cooling while lighting was mostly provided by strip fluorescents. The building's deep net-zero energy retrofit started in 2017. The retrofit measures include envelope, and mechanical and lighting systems improvements as well as onsite renewable generation. Thermal bridging was reduced by adding insulation to soffits. The R-values of the external walls were improved from R-10 to a new R-30 value where possible. Windows were replaced with triple-pane glass with dynamic electrochromic coatings and redirecting films. These thin plastic films were applied to external windows to redirect the incoming light upwards. This provides more even illumination throughout the deeper sections of the room. A blower door test was conducted before the start of the retrofit process with a reported value of 0.9 L/s/m^2 @75Pa. The results are based on total envelope surface area which was measured to be 4149 m^2. The test was not repeated after the retrofit process, therefore the post-retrofit value is not available. The old natural gas boiler and the chiller were replaced with water to water heat pumps which allowed natural gas to be eliminated for space heating and domestic hot water. A set of renewable energy systems were also installed. The new geothermal system is composed of a double circular field of 15 wells that are 180 m deep. In addition to the geothermal system, two types of solar panels, namely a thermal and a PV system, were installed on the roof. The solar thermal energy system is composed of an overall collector area of 83 m^2 and two storage tanks. The solar electrical system includes around 600 m^2 of PV panels. The main retrofit measures are presented in Table 1.

Table 1. Retrofit process highlights

Measure		Pre-retrofit status	Post-retrofit status
Envelop	Exterior wall	R-10	R-30
	Windows	double-glazed	Tripled glazed with dynamic glass and redirecting coating
	Air infiltration	0.9 L/s/m^2 @75Pa	Not measured
Heating and cooling	Heating	Natural gas boiler	Replaced with heat pump

	Cooling	Chiller	Replaced with heat pump
	Domestic hot water	Natural gas boiler	Replaced with solar thermal system and heat pump
Lighting system	Internal lighting	Mostly fluorescents	Occupancy triggered LED lighting
	External lighting	Mostly fluorescents	LED lighting with timer
Renewables	Geothermal system	N/A	15 wells, 180 m deep
	Solar system	N/A	Thermal: 83 m2 , PV: 600 m2

ENERGY USE DATA

In this study, we employed two sources of energy use data: utility bills and sub-metered electricity end-use data. For each data category, we collected a year of pre-retrofit and a year of post-retrofit data. The retrofit started in late 2017 and concluded in mid-2019. However, the post-retrofit occupancy was disturbed amid the Covid-19 pandemic in February 2020. Consequently, we used a year of data from December 2021 onwards as the post-retrofit dataset. The pre-retrofit natural gas use was not metered, as a result, we relied on utility bills for its evaluation. In the case of electricity use, 14 sub-meters were installed to measure electricity end-uses and PV generation. Sub-meters measured hourly electricity use of lighting, plugs, heating and cooling, and main incoming loads during both pre- and post-retrofit periods as well as PV generation during the post-retrofit period. Table 2 summarizes the data used in this analysis.

Table 2 Data categories used in this study

Data category	Duration	Available data
Pre-retrofit	December 2016 – December 2017	Utility bills: whole building natural gas and electricity use Sub-metered: hourly electricity end uses
Post-retrofit	December 2021 – December 2022	Utility bills: electricity Sub-metered: hourly electricity end uses and PV generation

End-use electrical loads

To provide insights into sub-metering and end-use electrical loads, Figure 1 shows the breakdown of pre- and post-retrofit electricity use. As shown in Figure 1(a) the heating, ventilation, and air conditioning (HVAC) load consumed the largest portion (57%) of the building's total electricity during the pre-retrofit period. This component is composed of the chiller, fans, pumps, and electric baseboard heater loads. The lighting load includes both internal and external components. The summation of all submeters was compared with the main meter and it was determined that sub-meters captured 89% of the total load, leaving 11% not sub-metered. Consequently, additional sub-meters were installed during the retrofit process to account for previously untracked end uses, including house services (e.g., janitor rooms), kitchen, washrooms, sprinkler room, and fire panels. The combined readings of these meters are presented in Figure 1(b) under the category of "services". Figure 1(b) shows that the HVAC load remains the most substantial component of total electricity use. A higher percentage of heating and cooling load is expected as the use of natural gas was eliminated. The plug load ratio remains consistent, while there is a notable decrease in the lighting load percentage. In the rest of this section, we provide a detailed analysis of pre- and post-retrofit end-uses.

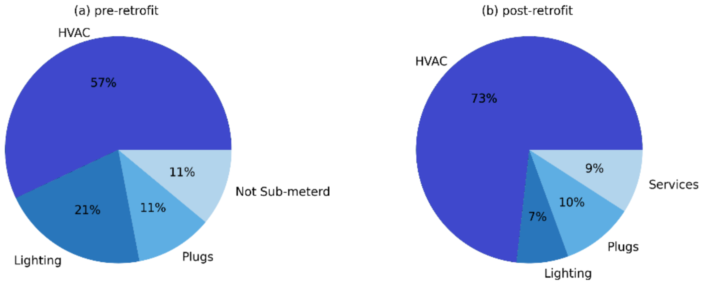

Figure 1 Electricity use breakdown by sub-meters. (a) pre-retrofit and (b) post retrofit.

Pre- and post-retrofit end uses

We used the hourly data to calculate the daily electricity end-uses. Table 3 compares the unnormalized daily values of electricity uses during pre- and post-retrofit electricity end uses. The normalized electricity use analysis is presented in the next section. The post-retrofit plug loads are significantly lower than pre-retrofit values. The lower usage can be attributed to modern workspaces with energy-efficient IT equipment, energy-efficient large screens in the common areas, and the elimination of the use of personal heating/cooling devices in the offices. The post-retrofit values of lighting loads are significantly lower due to the highly efficient lighting and glazing systems used in the building. The dynamic electrochromic window glass allows for adjustment of the visible light transmittance to optimize natural lighting. Similarly, the post-retrofit HVAC loads are significantly lower than pre-retrofit values. Specifically, the post-retrofit load profile demonstrates an average reduction of 43%, 75%, and 74% during winter, summer, and shoulder seasons, respectively, in comparison to the pre-retrofit values. The most modest reduction occurs in the winter season, which is expected due to higher heating demand met by electricity and lower PV generation. As presented in Table 1, the building is equipped with 600 m2 of PV panels with a nominal capacity of 100 MWh annually. The PV generation varies from a minimum of only 0.3 kWh/day in January to a maximum value of 721.7 kWh/day in July 2022.

Table 3 Daily mean and standard deviation (std) of major end uses and PV generation

Load	Pre-retrofit, kWh	Post-retrofit, kWh	Change in mean, %
Plugs	mean: 131, std: 17	mean: 48, std: 11	63
Lighting	mean: 213, std: 89	mean: 34, std: 10	84
HVAC	mean: 721, std: 210	mean: 237, std: 124	67
PV generation	N/A	mean: 312, std: 192	N/A

MONTHLY BILL DATA ANALYSIS

The pre-retrofit natural gas use was not metered, therefore, we used monthly utility bill data to compare the pre- and post-retrofit total energy use. Based on the periods defined in Table 2, two years of billing data was collected. The pre-retrofit data consists of both natural gas and electricity bills while post-retrofit data is composed of electricity use only. The post-retrofit monthly bills included the net electricity use and the net electricity return to the grid. Figure 2 shows the monthly energy use and average outdoor dry-bulb temperature for both periods. During the pre-retrofit period, the sensitivity of natural gas use on outdoor temperature is evident. Figure 2(b) shows a clear mismatch between the electricity use and return to grid on a monthly level. In particular, in the coldest months, when heat pump consumption rises because of heating loads and PV generation is at its minimum, and for April–June, when maximum PV generation happens.

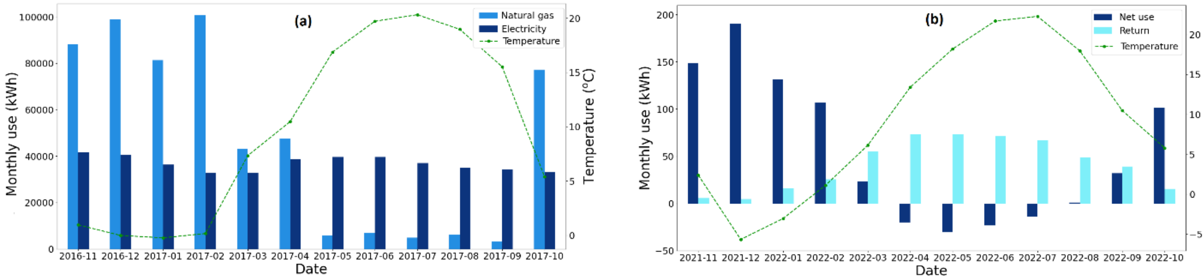

Figure 2 Monthly energy flow in the building for (a) pre-retrofit, and (b) post-retrofit period from utility bills.

This figure shows that the building did not achieve the net-zero energy. However, the post-retrofit net energy use was 647 kWh/year (equivalent to 0.06% of pre-retrofit total energy use) which indicates a near net-zero energy operation. Table 4 summarizes the post-retrofit monthly net electricity use characteristics.

Table 4. Characteristics of the post-retrofit net electricity use

Energy flow	Maximum, kWh	Mean, kWh	Minimum, kWh	Summation, kWh
Net use	190	54	-31	647

Avoided energy use

We used various linear change-point models (Kissock, Haberl, & Claridge, 2003) to estimate the building's avoided energy use. Following the guidance of ASHRAE Guideline 14 (American Society of Heating Refrigerating and Air-Conditioning Engineers, 2014), the coefficient of variation of root mean squared error (CV-(RMSE)) and coefficient of determination (R^2) were used to assess the performance of the models, as follows:

$$R^2 = \frac{\sum_i (y_i - \bar{y})^2 - \sum_i (y_i - \hat{y}_i)^2}{\sum_i (y_i - \bar{y})^2} \quad (1)$$

$$CV(RMSE) = \frac{\sqrt{\frac{\sum_i (y_i - \hat{y}_i)^2}{(n-p)}}}{\bar{y}} \quad (2)$$

where n is the number of samples, p is the number of model parameters, and y and $\bar{y}$ are the real and predicted energy use, respectively.

Figure 3 shows the change point models for the pre-retrofit period. The data from natural gas and electricity bills were used to develop these models. For each utility, different models were tested and the model with the best R^2 and CV(RMSE) was selected. The monthly natural gas usage is significantly sensitive to outdoor temperature during the heating season while it remains fairly constant during the cooling season. This part shows the natural gas use for domestic hot water in the building. As shown in Figure 3(b), at outdoor temperatures lower than 1.9°C, monthly electricity use decreases with increase in outdoor temperature. In sub-zero temperatures, electric heaters were used in the sprinkler room and stairways which may explain this trend. The electricity use remains relatively constant at moderate temperatures and starts to increase at higher temperatures. This increase can be attributed to the electrical cooling demand.

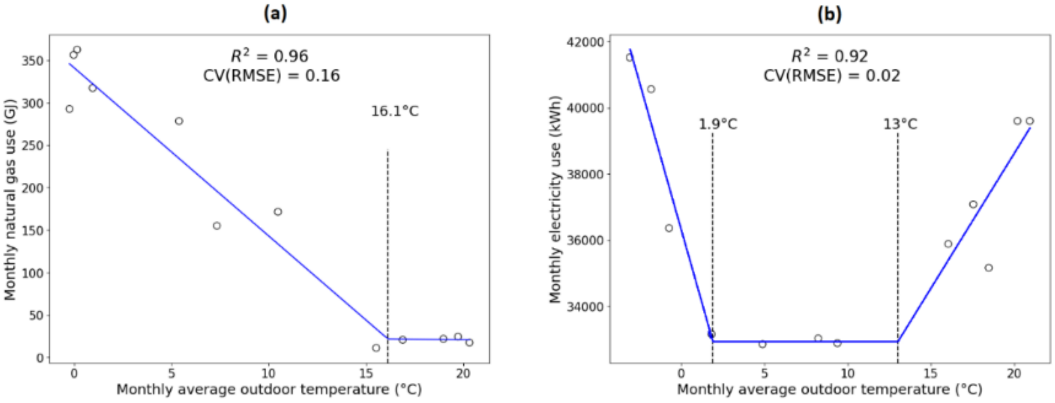

Figure 3 Pre-retrofit change point models for (a) monthly natural gas use, and (b) monthly electricity use

The post-retrofit net electricity use is shown in Figure 4. This figure illustrates the best performing change point model for the post-retrofit net electricity use. The net electricity use is considerably sensitive to temperature during the heating season. The post-retrofit HVAC load is the major end-use in the building and it constitutes more than 90% of the total electricity use during winter. Further, the PV generation is lower during the heating season. These factors may explain the higher sensitivity of net electricity use to outdoor temperature during the heating season.

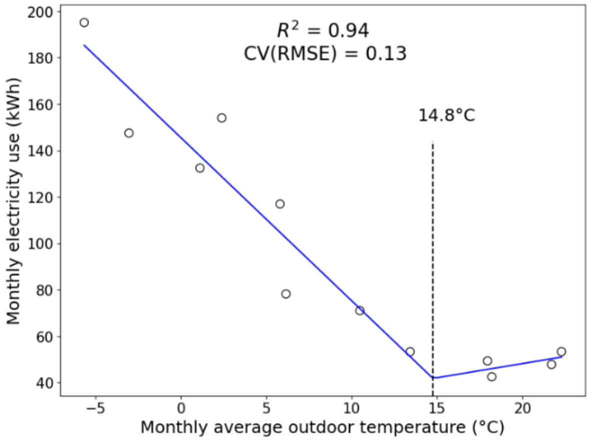

Figure 4 Post-retrofit change point model for electricity use

We used the pre-retrofit models, along with post-retrofit average monthly outdoor temperature, to estimate the avoided energy use as follows:

Avoided energy use = Adjusted pre-retrofit (baseline) energy use – Post-retrofit (reporting period) energy use (3)

where adjusted pre-retrofit energy use is the baseline value projected to post-retrofit conditions. This was calculated by using the pre-retrofit change point models along with post-retrofit average monthly outdoor temperatures. The avoided energy use was converted to avoided CO_{2e} emissions and utility cost savings. The estimated natural gas and electricity costs were calculated based on the average rates from the utility companies and the Ontario Energy Board (Board, in press). The CO_{2e} emissions were estimated based on Ontario's average emission factors from the Government of Canada (Government of Canada, in press). The avoided cost estimations are shown in Table 5. In this table, the real cost is obtained from the post-retrofit utility bills while the estimated cost is based on the values obtained from the change point models. The total utility cost savings is around $148,000 per year while more than 87% of the savings is associated with the reduction in net electricity use. In Ontario, all electricity customers pay a Global Adjustment (GA) fee based on their electricity use during the province's peak electrical load hours. For commercial buildings, GA costs can consist more than 60% of the total electrical costs. The reduction in the building's post-retrofit GA fees plays an important role in the substantial reduction in the real electricity cost reflected in this table.

Table 5 Annual real and estimated utility costs during the post-retrofit period

Utility	Real cost ($)	Estimated cost ($)	Avoided cost ($)
Natural gas	0	19,100	19,100
Electricity	551	129,600	129,049
Total	551	148,700	148,149

Similarly, the CO_{2e} emissions are presented in Table 6. The real CO_{2e} values are based on the utility use from the bills along with the average emission factors for Ontario (Government of Canada, in press). The estimated emissions are calculated based on energy use from the change point models. More than 90% of the total CO_{2e} emission reduction is associated with the elimination of natural gas use in the building. Ontario's electrical grid is relatively clean as most generation is from hydro and nuclear sources. Therefore, the substantial reduction in electricity use contributes to only 10% of the total CO_{2e} reduction. However, the net-zero retrofit is crucial for lowering the net electricity use and unburdening the electrical grid.

Table 6 Annual real and estimated CO_{2e} emissions during the post-retrofit period

Utility	Real CO2e emission (tonnes)	Estimated CO2e emission (tonnes)	Avoided CO2e emission (tonnes)
Natural gas	0	114	114
Electricity	0.03	12.25	12.22
Total	0.03	126.26	126.23

Energy use intensity

The pre- and post-retrofit building's energy use intensity (EUI) was used to compare the performance of the building to that of similar properties. Energy use values, obtained from utility bills, were used to estimate the pre- and post-retrofit EUI values. The pre-retrofit EUI value is 1.73 GJ/m^2 while, based on the data from the Energy Star Portfolio Manager (Arjunan, Poolla, & Miller, 2019) benchmark, the median EUI for the Canadian office buildings is 0.87 GJ/m^2. Despite the building being built to a high standard of its time, namely R2000 standard, the results indicate the poor energy performance of the 25-year-old building before the retrofit. However, the post-retrofit EUI is 0.001 GJ/m^2 which is significantly lower than the benchmark value indicating the near net-zero energy performance of the building.

Conclusions and Future Work

This paper analyzed the energy performance of the net-zero energy retrofit of a commercial building in Ontario, Canada using two years of hourly sub-metered electricity use and monthly utility bill data. The results showed that the building achieved a near net-zero performance during the studied period. This was achieved due to the highly efficient building envelope and systems along with the PV and geothermal systems. The building was net-positive during the cooling season due to higher PV generation while higher heating load and low PV generation during the heating season led to a net-negative performance. The monthly bill analysis showed that the building's post-retrofit electricity use is significantly sensitive to the outdoor temperature during the heating season. Further, the electricity generation from the PV system tends to be lower during this period. Therefore, the building should be carefully operated during the heating season to achieve net-zero energy performance. End-use data analysis showed that the three main end-use types (i.e., HVAC, lighting, and plug loads) accounted for 91% of the total annual energy use in the building. The results suggest that the implemented lighting system, i.e. high-efficiency lights and windows with dynamic electrochromic and redirecting films, resulted in a substantial reduction of 84% in the lighting load compared to pre-retrofit values. It was shown that the retrofit resulted in avoided utility costs and CO_{2e} emissions of $149,000 and 126 tonnes per year, respectively. Finally, the EUI analysis showed that the building's EUI was about two times higher than the median EUI value for office buildings in Canada. This should be noted when extending the results of this study to similar buildings in Canada. Moreover, such deep retrofit may change the perceived indoor environments and organizational productivity. In our future work, we will present the results of the physical measurements of the indoor environment and occupant surveys during both pre- and post-retrofit periods. The human factor and user-centric analysis may improve our understanding of the human factor impacts caused by net-zero energy retrofit practices. Moreover, we plan to conduct a comparative analysis of the costs associated with deep retrofits versus those of basic HVAC and lighting system retrofits, to provide a cost-benefit assessment of this project. Electricity use sub-metering will continue beyond the scope of this study. In future works, we will use the collected data for the long-term analysis of the building's energy performance."

REFERENCES

Ahmed, A., Ge, T., Peng, J., Yan, W. C., Tee, B. T., & You, S. 2022. Assessment of the renewable energy generation towards net-zero energy buildings: A review. *Energy and Buildings*, 256: 111755.

Alkhateeb, E., & Abu-Hijleh, B. 2019. Potential for retrofitting a federal building in the UAE to net zero electricity building (nZEB). *Heliyon*, 5(6): e01971.

American Society of Heating Refrigerating and Air-Conditioning Engineers. 2014. *ASHRAE Guideline 14-2014: Measurement of Energy, Demand, and Water Savings*.

Aram, K., Taherkhani, R., & Šimelytė, A. 2022. Multistage Optimization toward a Nearly Net Zero Energy Building Due to Climate Change. *Energies*, 15(3).

Arjunan, P., Poolla, K., & Miller, C. 2019. EnergyStar++: Towards more accurate and explanatory building energy benchmarking. Retrieved from http://arxiv.org/abs/1910.14563

Asaee, S. R., Ugursal, V. I., & Beausoleil-Morrison, I. 2019. Development and analysis of strategies to facilitate the conversion of Canadian houses into net zero energy buildings. *Energy Policy*, 126(October 2018): 118–130.

Board, O. E. in press. Historical natural gas rates. Retrieved March 1, 2023, from https://www.oeb.ca/consumer-information-and-protection/natural-gas-rates/historical-natural-gas-rates#enbridge

Deru, M., & Torcellini, P. 2007. *Source Energy and Emission Factors for Energy Use in Buildings*. *National Renewable Energy Laboratory*.

Ferrari, S., & Beccali, M. 2017. Energy-environmental and cost assessment of a set of strategies for retrofitting a public building toward nearly zero-energy building target. *Sustainable Cities and Society*, 32: 226–234.

Government of Canada. in press. Emission Factors and Reference Values. Retrieved from https://www.canada.ca/en/environment-climate-change/services/climate-change/pricing-pollution-how-it-will-work/output-based-pricing-system/federal-greenhouse-gas-offset-system/emission-factors-reference-values.html#toc14

Government of Canada. 2016. *Pan-Canadian Framework on Clean Growth and Climate Change: Canada's plan to address climate change and grow the economy*. *Government of Canada*. Retrieved from http://publications.gc.ca/collections/collection_2017/eccc/En4-294-2016-eng.pdf%0Ahttps://www.canada.ca/content/dam/themes/environment/documents/weather1/20170113-1-en.pdf%0Ahttps://www.canada.ca/en/services/environment/weather/climatechange/pan-canadian-

Idrissi Kaitouni, S., Pfafferott, J., Jamil, A., Ahachad, M., & Brigui, J. 2023. A holistic digital workflow methodology to shifting towards net zero energy urban residential buildings in a semi-arid climate. *Solar Energy*, 263(August): 111959.

Kissock, J. K., Haberl, J. S., & Claridge, D. E. 2003. Inverse modeling toolkit: Numerical algorithms. *ASHRAE Transactions*, 109 PART 2: 425–434.

Le, S. T., Nguyen, T. N., Bui, D.-K., Teodosio, B., & Ngo, T. D. 2023. Comparative life cycle assessment of renewable energy storage systems for net-zero buildings with varying self-sufficient ratios. *Energy*, 290(October 2023): 130041.

Luo, X. J. 2022. Retrofitting existing office buildings towards life-cycle net-zero energy and carbon. *Sustainable Cities and Society*, 83(April): 103956.

Natural Resources Canada. in press. R-2000 Standard. Retrieved January 22, 2024, from https://natural-resources.canada.ca/energy-efficiency/homes/professional-opportunities/become-energy-efficient-builder/details-the-r-2000-standard/20588

Natural Resources Canada. 2017. Build Smart Canada's Buildings Strategy. *Energy and Mines Ministers' Conference St. Andrews by-the-Sea, New Brunswick*, (August): 20. Retrieved from https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/emmc/pdf/Building_Smart_en.pdf%0Ahttp://www.nrcan

.gc.ca/sites/www.nrcan.gc.ca/files/emmc/pdf/Building_Smart_en.pdf

Oh, S., & Gardner, J. F. 2022. Energy Consumption Analysis Using Measured Data from a Net-Zero Energy Commercial Building in a Cold and Dry Climate. *Sustainability (Switzerland)*, 14(16).

Rabani, M., Bayera Madessa, H., & Nord, N. 2021. Achieving zero-energy building performance with thermal and visual comfort enhancement through optimization of fenestration, envelope, shading device, and energy supply system. *Sustainable Energy Technologies and Assessments*, 44(January): 101020.

University of Wisconsin--Madison. Solar Energy Laboratory. 1975. *TRNSYS, a transient simulation program*. Madison, Wis.: The Laboratory, 1975. Retrieved from https://search.library.wisc.edu/catalog/999800551102121

Wills, A. D., Beausoleil-Morrison, I., & Ugursal, V. I. 2021. A modelling approach and a case study to answer the question: What does it take to retrofit a community to net-zero energy? *Journal of Building Engineering*, 40(February): 102296.