# Net-positive energy buildings: towards achieving the SDGs and carbon neutrality

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**Abstract**

Building design and operational decisions directly impact multiple United Nations (UN) Sustainability Development Goals (SDGs) (e.g., SDGs 7, 11 and 12). Net-positive energy buildings (NPEBs) present an opportunity for the built sector to offer habitable environments with improved energy efficiency and can contribute to responsible consumption, sustainable energy production, and sustainable cities and communities. Case study analysis of a multi-tenant office NPEB demonstrates the impact of operational decision making to realize the SDGs. The case study building consumed an annual average of 83 kWh/m$^2$ and produced an annual average of 871 kWh of solar electricity. Over three years of operation, the building solar electricity production to building energy consumption ratio was 93%, 123% and 127% in 2019, 2020 and 2021 respectively. This mixed methods performance assessment used three years of energy meter data and key informant interviews to provide a holistic understanding of operational decisions contributing to the case study building's energy performance. Analysis of the case study NPEB's performance in relation to the SDG goals demonstrates areas of contribution that can help achieve a sustainable future.

## 1. Introduction

Decarbonization of the built sector in Canada presents opportunities to achieve multiple sustainable development goals (SDGs), especially responsible consumption, sustainable energy access, and sustainable cities. The integration of renewable energy technologies such as solar photovoltaic (PV) systems, solar air heaters and geothermal pumps as part of building energy production allows buildings to produce their own energy, reduce their energy consumption from external sources and distribute excess solar electricity to the local grid.

Net-positive energy buildings (NPEBs) refer to buildings that produce more energy than they consume and typically distribute the excess clean energy to the surrounding grid (Kolokotsa et al., 2011). NPEBs empower the built sector to provide habitable environments with improved energy efficiency and distribution potential. Canadian homes and buildings account for 18% of greenhouse gas (GHG) emissions due to the combustion of fossil fuels in space and water heating ( Environment and Natural Resources Canada, 2021). Despite ongoing efforts to improve building energy use intensity (EUI) the increases in building area led to increased total energy demand in commercial buildings since there is more building space to heat, cool and maintain good air quality (Galvez & MacDonald, 2018). EUI is typically measured in kWh/m$^2$ as the ratio of building energy consumption to building floor area (Energy Star, 2022).

The United Nations identified major challenges for high income countries' progress toward achieving the SDGs (United Nations, 2022). Progress on increasing the share of renewable energy in the global energy mix and reducing the total GHG emissions per year from fossil fuel combustion is part of the energy decarbonatization challenges (United Nations, 2022). Statistics Canada identifies several data gaps in measuring the progress toward the SDG indicators (Government of Canada, 2018a, 2018b). Collaborations between building operators and researchers are needed to address missing data and work towards meeting the SDG targets. Empirical data from this study can shed a light on energy consumption and production to improve understanding of building operational decisions.

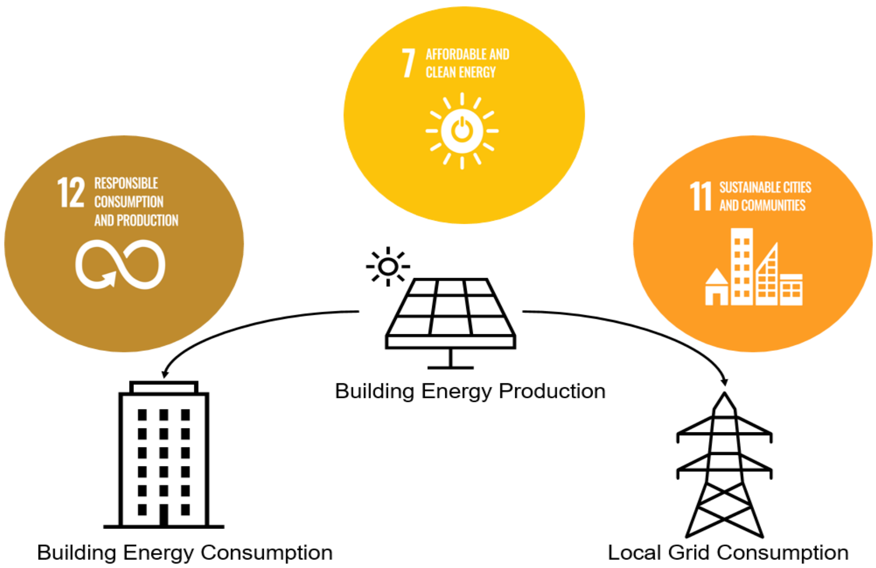


*Figure 1: Net-positive energy building operation and impacted SDGs*

### 1.1 Research Questions

Research questions explored in this analysis were (1) can building energy consumption be reduced and how does the case study building compare to other Canadian office buildings? (2) can clean, onsite energy be produced to eliminate the conventional reliance on fossil fuels? (3) is net-positive energy performance achievable and how does excess solar electricity production contribute to city sustainability?

### 1.2 Overview

This paper will present the results of an analysis of the trends in building energy consumption and key informant interviews to highlight the operational decisions made during commissioning that contributed to the improved building energy performance (reduced consumption). Then a quantitative analysis of the monthly building solar electricity production over three years of operation will be conducted and the net monthly surplus (solar electricity production to building energy consumption ratio) of the case study building will be investigated. In the discussion, the contribution to specific SDG targets and indicators will be summarized, followed by a brief conclusion.

## 2. Methodology

### 2.1 Design Features

The southwestern Ontario multi-tenant office NPEB is 110, 000 sq ft with four tenants including university/incubator space, technology and analytics companies and a consulting firm. It features a 220 kW AC/ 264kW DC roof-mounted photovoltaic array and 400 kW AC/504kW DC ground mount array to provide 825 kWh energy, designed to produce 105% of the building's annual energy demand (Canada Green Building Council, 2019). A solar wall is also used to increase outdoor air temperature prior to its delivery into the HVAC system with increases of over 20°C being measured on sunny winter days (Sturla, 2022). The system is coupled with an enthalpy wheel to further reduce heating, ventilating and air-conditioning (HVAC) energy consumption. Variable frequency drivers and variable refrigerant flow (VRF) are used for precise pump and motor control to meet variable demand in the different zones of the building. Previous studies found that design strategies such as using VRF can provide high energy savings and improve indoor thermal comfort (Kim et al., 2018). The three-storey building features a 5.7m living green wall to improve air quality by using natural humidification (Canada Green Building Council, 2019). These design features earned the building a platinum leadership in energy and environmental design (LEED) rating and zero-carbon building certification (Canada Green Building Council, 2019).

### 2.2 Data Collection and Analysis

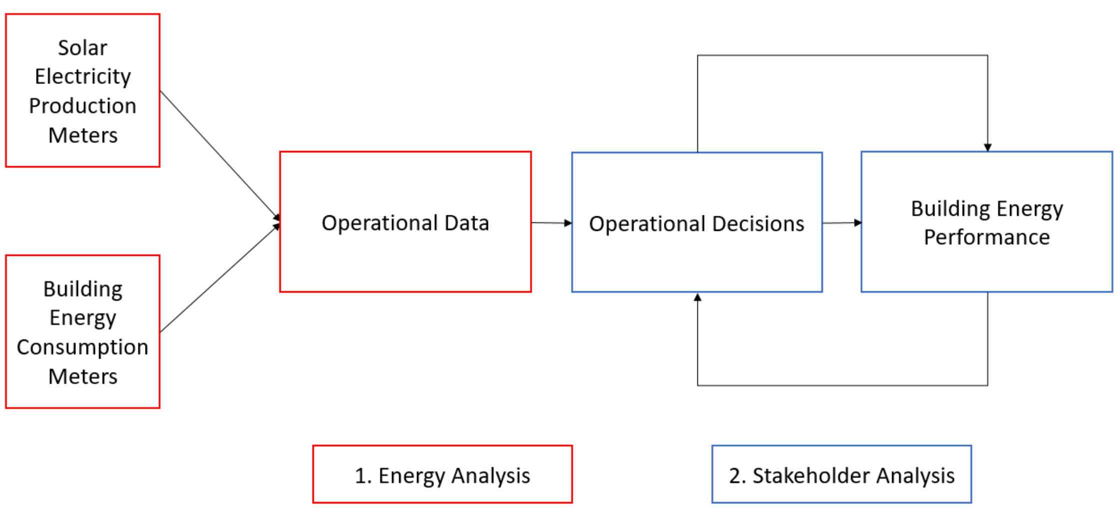


*Figure 2: Data collection and analysis process*

Figure 2 demonstrates the mixed methods used to provide a holistic analysis of this NPEB operation. A combination of quantitative operational energy data analysis and qualitative data collected from key informant interviews with a building operator and energy advisor were used in this study. Digital daily building energy consumption (BEC) and monthly solar electricity production (SEP) were collected from different databases to quantify the net-positive operation. Key informant interviews with a building operator and energy advisor provided insights into decisions made during the commissioning period that led to current building operation arrangements. Information from the interviews was integrated with the quantitative analysis to explain the various observed trends.

## 3. Results and Discussion

### 3.1 Building Energy Consumption

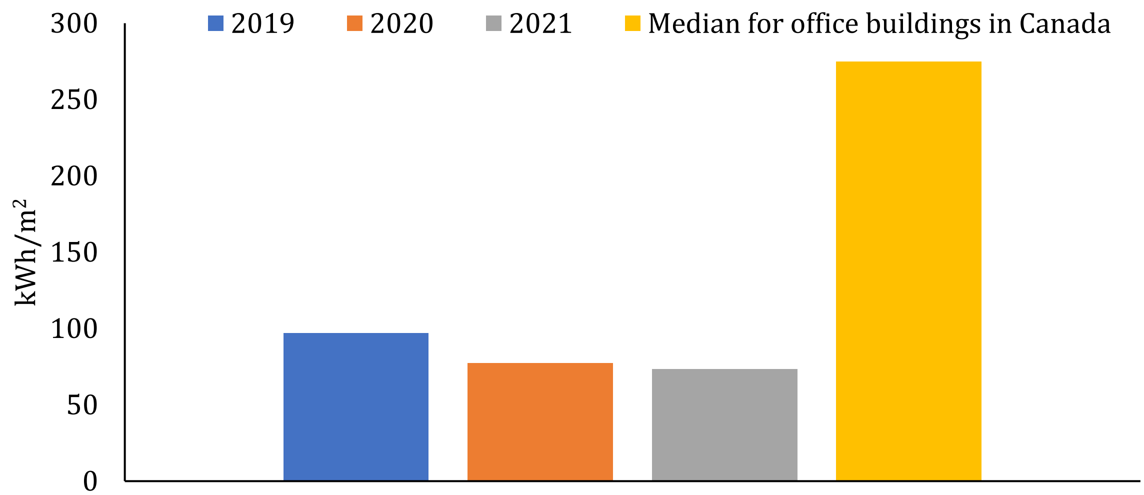


*Figure 3: Building energy consumption in EUI from 2019-2021 relative to the 2018 median Canadian office EUI*

Figure 3 summarizes the BEC in 2019, 2020 and 2021 as 97 kWh/m$^2$, 77 kWh/m$^2$ and 74 kWh/m$^2$ respectively, averaging 83 kWh/m$^2$ over the three years. A survey of Canadian national median values of EUI in office buildings revealed a median operational EUI of 275 kWh/m$^2$ (Energy Star, 2018). Comparing the case study building to the median Canadian office building reveals that even during commissioning, with ongoing finetuning, the BEC is 65% less than the 2018 median. Various factors contribute to the decrease in BEC over the first three years of operation, including operational decisions, COVID-19 occupancy impacts and weather variation. Ultimately, a difference of 73% was measured between the median EUI and the case study building EUI during 2021.

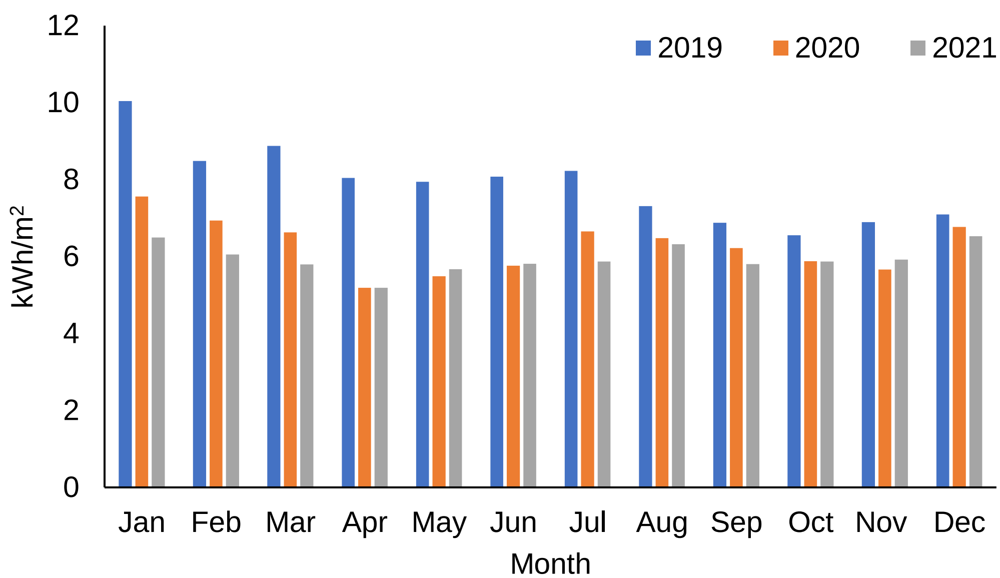


*Figure 4: Monthly building energy consumption in EUI, 2019-2021*

Building commissioning typically takes 12-18 months to understand the building operation and make modifications to finetune energy consumption and occupant comfort. Initially, there were occupant requests to adjust the temperature due to the positioning of thermostats. After construction, the room thermometers remained on the perimeter of the rooms and did not get moved to central walls where they could better match occupant perceptions. As a result, there were several changes to find the optimal operating temperatures. Other modifications to the HVAC building controls were completed by collaborating with the building mechanics and electricians to reduce the excessive operation of pumps and finetune the control parameters.

Building operators' close monitoring of the energy performance demand curves inspired several finetuning changes to reduce EUI. The building's HVAC system underwent several start-up modifications to reduce the peak demand when the building comes out of the set-back schedule. During office hours, from 8 am to 6 pm, the building is set to maintain a comfortable environment, however, during unoccupied hours, the building goes into a set-back mode to reduce energy use. The decrease in energy consumption can be seen in Figure 4 when comparing January to March 2019 with January to March 2020 when occupancy levels in the building were similar, and COVID-19 had not impacted the BEC. From April 2020 onwards the building was minimally occupied and was mainly on an unoccupied schedule daily. The variation observed between months is due to operator decisions, COVID-19 impact and weather variation.

Several design factors contribute to building energy consumption such as the thermal performance of the building envelope (Zhou and Zhaou, 2013). This includes interior and exterior walls, windows, and the roof which all contribute to the energy performance and comfort of the building (Zhou and Zhaou, 2013). In this case study NPEB, design strategies that contributed to the reduced EUI include the high-performance building envelope with R-30 walls, R-40 roofing insulation, triple glazed windows to reduce heat escaping during the winter months and tight sealing to reduce air leaks. Additionally, the building window-to-wall percentage is 37%, designed to provide natural lighting while also maintaining energy savings from continuous wall insulation over a majority of the area. The solar air heater contributed to reducing the heating load, coupled with an energy efficient enthalpy wheel for heat recovery, ground source heat pump and advanced HVAC controls. The space heating and cooling were optimized in the design and commissioning processes to facilitate responsible energy consumption.

The design strategies and operational management decisions contribute to the NPEB working towards achieving responsible consumption (SDG 12) and ensuring access to reliable and sustainable energy (SDG 7). Achieving zero-carbon status contributes to sustainably managing and using natural resources by reducing the material footprint per capita, in line with SDG target 12.2. It is important to reduce the material footprint to reduce greenhouse gas emissions resulting from building construction and operation. Additionally, the low EUI demonstrates a reduction of energy intensity measured in terms of primary energy, in line with SDG target 7.3. Reducing energy intensity is significant as with continued rising populations, we will need more buildings to provide shelter and our energy demand will continue to increase. The transition to a sustainable energy future will require not only converting to sustainable energy sources but also changing our behaviour around how energy is consumed (Niamir et al., 2018). Part of this transformation is to become more aware of our consumption patterns and work to reduce excessive energy consumption (Niamir et al., 2018). Therefore, efforts to reduce BEC and EUI are needed to achieve SDGs 7 and 12 by 2030.

### 3.2 Solar Electricity Production

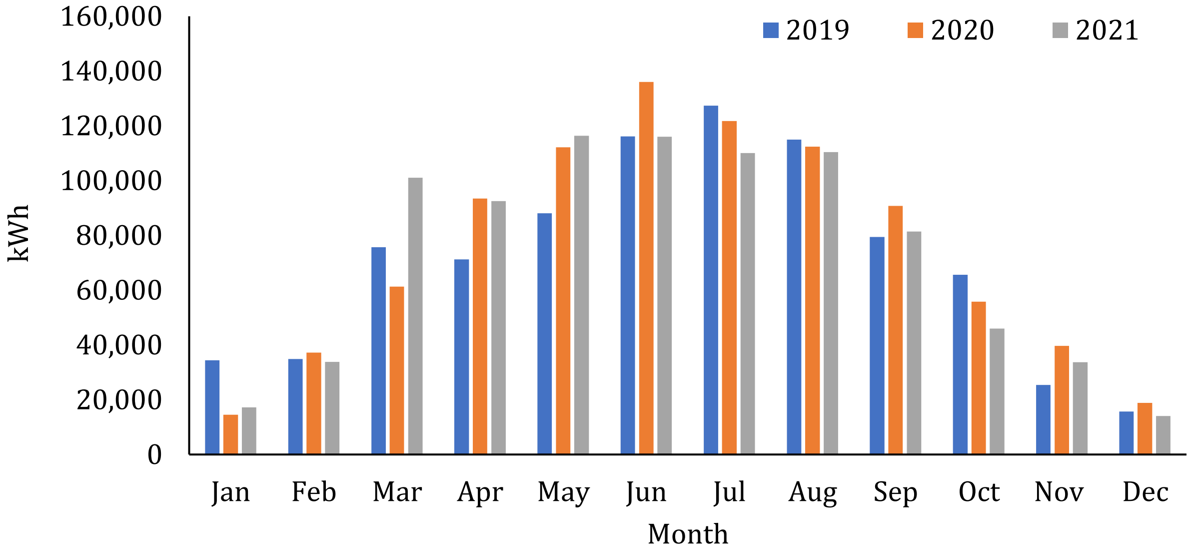


*Figure 5: Monthly SEP in kWh 2019-2021*

Several factors contribute to the SEP of the NPEB. The building has a south-easterly orientation that provides a good direction to maximize SEP. The PV system utilizes inclination angles to maximize summer solar radiation capture. These design strategies contribute to the performance demonstrated by the monthly SEP displayed in Figure 5. The results show peak production months to start in March and end in September, followed by reduced production in October to February. Variation in the electricity production of particular months can be attributed to variation in solar irradiance between those years, which is to be expected. The results suggest that January 2019 had more hours of sunlight than January 2020 and 2021. Similarly, March 2021 and June 2020 had higher SEP than other years. Annual SEP of 848 kWh, 893 kWh and 872 kWh in 2019, 2020 and 2021, respectively, result in average annual production of 871 kWh and demonstrate exceeding the PV system's design target of 825 kWh/yr.

SEP in the built sector is needed to reach net-zero energy consumption, mainly addressing the UN's call to increase renewable energy share in the global energy mix (target 7.2). To reduce the built sector's growing energy demand, which currently accounts for 18% of Canadian GHG emissions (Canada, 2021), one option is to have buildings generate their own renewable energy so that they can become more independent and less reliant on the grid while we transition towards more renewable energy sources to replace fossil fuels. This case study NPEB demonstrates that it is possible to generate energy on-site and decrease reliance on fossil fuels even during peak demand winter months.

### 3.3 Solar Electricity Grid Contribution

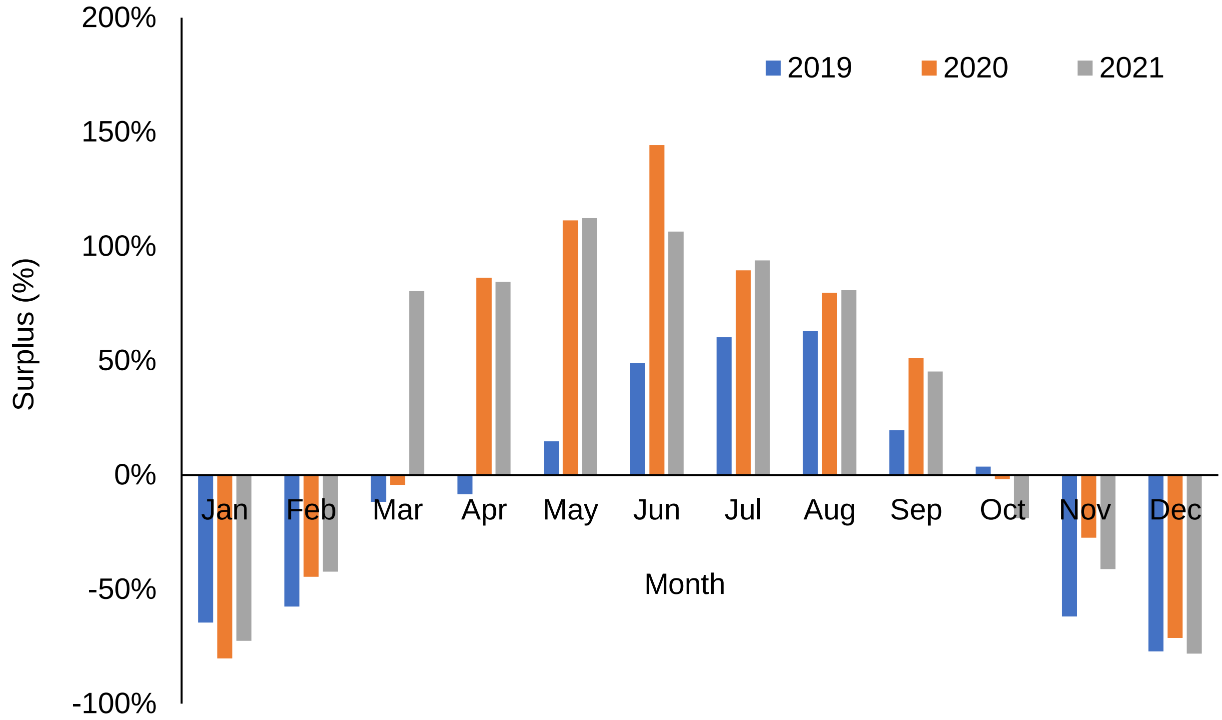


*Figure 6: Monthly surplus generation for operation, 2019-2021*

The performance of the NPEB was assessed using an energy balance comparing monthly energy use in the building to monthly energy generation by the parking lot and rooftop solar PV systems for three years of operation. The surplus percentage is 100% from the ratio of SEP to BEC. When the surplus percentage is negative, this means that the building needed to draw additional energy from the grid. When the surplus is 0% this means that the building is achieving net-zero energy operation, producing as much energy as it is using over the month. When the surplus is positive, the excess energy is sold to the local utility and net-positive energy performance is achieved.

From Figure 6 it can be seen that the building relies on the local grid during the winter months (November to February), borrowing 30% to 80% of its energy from the grid, but from May to September it can produce a monthly energy surplus up to an excess of 144% solar electricity to sell to the local utility. The difference in the surplus generation between the three years of operation can be attributed to differences in outdoor air temperature, COVID-19 impacts, as well as operational HVAC energy improvements. The difference between January to March 2019 and 2020 demonstrates the HVAC energy improvements and weather effects. January 2019 was colder than January 2020 on a heating degree days (HDD) basis (Environment and Climate Change Canada, 2022) and as suggested by Figure 5 sunnier, thus contributing to the observed decrease in energy borrowed from the grid even during the first month of regular building operation. In February and March, the control improvements of the HVAC system from 2019 are seen more clearly in the reduced surplus while the building was still mainly occupied. Starting in April 2020 the building occupancy decreased, and the building operator used an unoccupied building schedule, maintaining lower temperatures than if the building were occupied. This led to a further decrease in energy borrowing from the grid and resulted in an increased surplus generation.

Overall, the NPEB produced the equivalent of 93% of its own energy demand in 2019, 123% in 2020 and 127% in 2021. If 2019 tenant lighting and plug loads were substituted in 2020 and 2021 to minimize the impact of COVID-19, the solar electric generation would be 113% and 110% of building energy consumption respectively. Therefore, even with minimal COVID-19 impacts considered, the results suggest that the building may still achieve net-positive energy status.

Sharing surplus energy generation with the local grid further contributes to ensuring access to sustainable energy and making cities more resilient and sustainable. Solar electricity produced by this NPEB reduces its reliance on the grid and decreases energy demand. These contributions ensure access to reliable sustainable modern energy and make cities safer and more resilient by decentralizing power generation so that in the case of a power outage from extreme weather events, the NPEBs can maintain their own generated power. Additionally, this NPEB's SEP increases the share of renewable energy in the Canadian grid mix, addressing SDG target 7.2. Furthermore, shifting away from using fossil fuels for heating and relying on electric heating all year round contributes to reducing the adverse environmental impacts of cities in the form of GHG emissions, helping to achieve SDG target 11.6. Lastly, the planning decisions considered in the design phase, such as using the building roof and parking lot for solar arrays, demonstrate a way to sustainably urbanize and plan for settlement, addressing SDG target 11.3. Therefore, the SEP by the NPEB works towards achieving SDG targets 7.2, 11.3 and 11.6.

## 4. Conclusion

A mixed methods case study analysis of a southwestern Ontario multitenant office NPEB highlights the impact of design and operational decisions on achieving SDGs 7, 11 and 12. BEC analysis demonstrates an average EUI of 83 kWh/m$^2$ which is one-third of the 2018 Canadian office median EUI. Design decisions such as insulation, window-to-wall percentage and window triple glazing contributed to reducing the energy consumption, achieving sustainable consumption and reducing EUI. SEP analysis demonstrates the PV system's capability to produce an average of 871 kWh/yr, further contributing to increasing the renewable energy mix in Ontario and reducing levels of combustion related emissions of fine particulate matter and gases in cities by eliminating reliance on fossil fuels. Surplus generation analysis for three years of building operation demonstrates the NPEB's ability to meet its design goal of generating at least 105% of its energy consumption and exceeding that goal, even when adjusted for COVID-19 impact, by generating 113% and 110% of its load in 2020 and 2021 respectively. NPEBs thereby contribute to creating sustainable cities with an increased mix of distributed generation using renewable energy sources to replace fossil fuels.

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