Net-Positive Energy Buildings: Empirical Insights Towards Achieving the SDGs

Monika Mikhail
University of Waterloo

David Mather
University of Waterloo

Paul Parker
University of Waterloo

Buildings impact multiple United Nations (UN) Sustainability Development Goals (SDGs). Net-positive energy buildings (NPEBs) present an opportunity for the built sector to offer climate solutions and habitable environments with improved energy efficiency, responsible consumption, sustainable energy production, and sustainable communities. Case study analysis of a multi-tenant office NPEB demonstrates decisions made to realize the SDGs. Average annual energy consumption of 83 kWh/m^2 was one-third that of typical office buildings and the generation of 871 kWh of solar electricity achieved the net-positive goal. This mixed methods performance assessment used four years of energy meter data and key informant interviews to provide a holistic understanding of building energy performance and contributions to the SDGs.

Keywords: sustainable development goals, net-positive energy building, building energy performance, green office building

INTRODUCTION

Background

The built environment is responsible for 30% of global emissions through construction and operation (International Energy Agency (IEA), 2020). 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 energy, reduce their energy consumption from external sources and distribute excess solar electricity to the local grid. The United Nations urges world leaders to take action to mitigate climate change in sustainable development goal 13. One way the built environment can answer this call and work towards achieving the IPCC target of staying within 1.5 ^{o}C warming is through the construction and operation of green buildings.

Green buildings are defined as those that engage in being environmentally responsible and resource-efficient throughout a development's life cycle (US Environmental Protection Agency, 2018). Environmental effects include waste, water and air pollution, and greenhouse gas (GHG) emissions. Different aspects of the built environment that can be designed, operated, and maintained to reduce these impacts include choosing the development site and material with impacts in mind and operating the building such that energy and water consumption is responsible. Ultimately these buildings aim to reduce the harmful impacts of the built environment on human health, the environment, and natural resources.

Specific types of green buildings include zero-carbon buildings, net-zero energy buildings, and net-positive energy buildings. Zero-carbon buildings are defined by the Canada Green Building Council (CaGBC) as those that are energy-efficient and minimize greenhouse gas emissions from building materials and operations (Canada Green Building Council, 2022). These buildings aim to eliminate all emissions through operation and if they are unable to, they may use high-quality carbon offsets to reach zero carbon. Net-zero energy buildings are those that aim to generate as much energy on-site as they consume annually (Sartori, Napolitano, & Voss, 2012). This means that the overall or net energy demand from the grid is less than or equal to the net energy generation supplied to the grid by the building in the period of an average year (Nikdel, Agee, Reichard, & McCoy, 2022). 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, Rovas, Kosmatopoulos, & Kalaitzakis, 2011). A graphic representation of this definition can be seen in Figure 1.

Positive developments improve economic, social and ecological conditions during their life cycle by (Birkeland, 2008). These developments aim to leave the ecology or physical environment better than before they were built (Birkeland, 2008). This can include improving air, and water quality or generating renewable energy. 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 (Service 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).

In the 2000s, the Millennium Development Goals (MDGs) focused on global efforts to tackle poverty (United Nations, 2015). They succeeded in enabling the decline of the number of people in extreme poverty, increasing people in working for middle class, and reducing the number of undernourished people in developing nations (United Nations, 2015). Following this success, at the United Nations Conference on Sustainable Development in Rio de Janeiro in 2012, the SDGs was born to provide world leaders with a set of universal goals built on 5 main pillars known as the 5P's to be achieved by 2030 (United Nations, 2022a). These pillars are people, planet, prosperity, peace, and partnership. The 2030 agenda seeks to benefit all people while keeping environmental viability and economic prosperity in mind (United Nations, 2022b). The UN urges world leaders to form partnerships to achieve this inclusive and sustainable vision. Although the SDGs are criticized for their non-binding and open-ended nature (Bali Swain, 2017), they still serve as a framework to direct attention to global challenges that need urgent action.

The World's Green Building Council (World Green Building Council, 2022) highlights 11 SDGs that green buildings contribute to and are summarized below in Table 1. An earlier analysis of this case study building examined the stakeholder partnerships formed to support the design and development of a building with high-performance goals (e.g., net-positive energy) (Dreyer et al., 2021; Whitney, Dreyer, & Riemer, 2020; Zitars et al., 2021). Whitney et al. (Whitney et al., 2020) conducted tenant interviews that explored the relationship between building tenants and operators. They found that communication among stakeholders is vital to create engagement and alignment toward achieving operational goals (Whitney et al., 2020). Dreyer et al. (Dreyer et al., 2021) analyzed collective action integration to foster a culture of sustainability among building tenants and operators. They found that preparing a multi-year strategic plan can enable core sustainability principles incorporation (Dreyer et al., 2021). Lastly, Zitars et al. (2021) analyzed the impact of the case study building on promoting employee health, well-being and productivity.

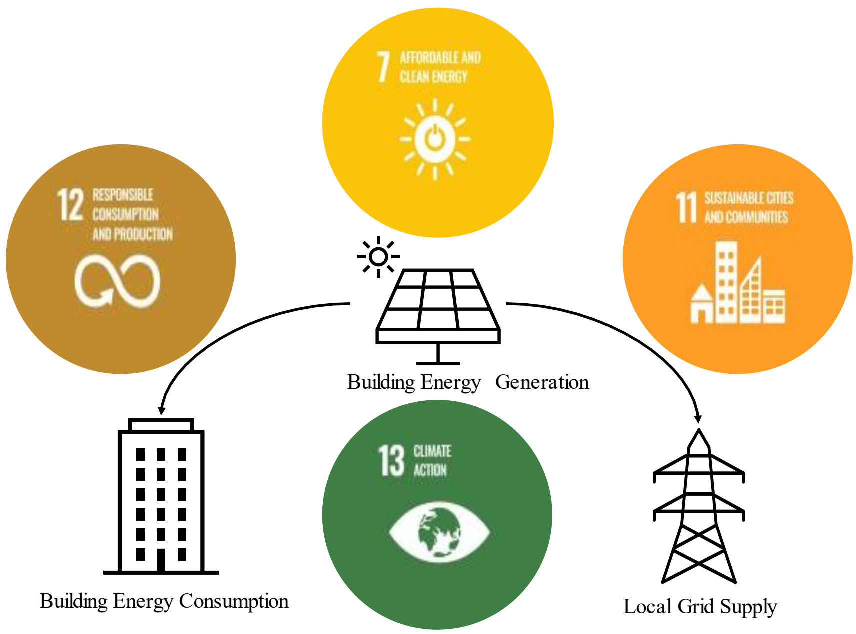
They present a framework that addresses how human psychological needs can be met from the built environment. This highlights the contributions of the case study building to many social impacts focused SDGs such as SDG 3, 8, 13, and 17. For this paper, the focus was on the energy-related SDGs, hence SDG 7, 11, and 12 were the main ones empirically analyzed while recognizing contributions to SDG 13 as the overarching goal behind building NPEBs.

TABLE 1
SUMMARY OF THE WORLD'S GREEN BUILDING COUNCIL'S CONTRIBUTION TO THE SDGS

SDG #	Description	Contribution
3	Good health and wellbeing	Encouraging healthy lifestyles and generating good social value
6	Clean water and sanitation	Providing access to clean and safe water and increasing water efficiency and reducing waste
7	Affordable and clean energy	Prioritizing energy efficiency and decreasing energy poverty to allow a just transition
8	Decent work and economic growth	Creating job opportunities to transition the carbon economy
9	Industry, innovation, and infrastructure	Providing resilient infrastructure to promote economic development and human welfare
10	Reduced inequalities	Eliminating energy poverty and ensuring power accessibility to enhance equity and resilience
11	Sustainable cities and communities	Creating safe and resilient infrastructure
12	Responsible consumption and production	Applying circular economy principles to reduce waste and support resource regeneration
13	Climate action	Decarbonizing the built sector to stay on track to meeting IPCC's 1.5 ºC climate goal
15	Life on land	Regenerating natural resources and improving biodiversity
17	Partnership for the goals	Creating collaboration opportunities to enable knowledge transfer opportunities

The United Nations identified major challenges for high-income countries' progress toward achieving the SDGs (United Nations, 2022b). 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, 2022b). 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 light on energy consumption and production to improve understanding of building operational decisions.

FIGURE 1
NET-POSITIVE ENERGY BUILDING OPERATION AND IMPACTED SDGS



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?

Overview

This paper will present a brief literature review followed by 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 four 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 conclusion.

LITERATURE REVIEW

SDGs and the Built Environment

Several studies analyzed the impact of the built environment on the SDGs (Alawneh, Ghazali, Ali, & Sadullah, 2019; Alawneh, Mohamed Ghazali, Ali, & Asif, 2018; Balali & Valipour, 2020; Di Foggia, 2018; Gade & Opoku, 2020; Lu, Chi, Bao, & Zetkulic, 2019; Omer & Noguchi, 2020; Opoku, 2019; Pogge & Sengupta, 2015; Wen et al., 2020). Although these studies analyzed the impact of the built environment on contributing to achieving the SDGs, there were no case studies focused specifically on how these sub-targets can be achieved during building operations. This paper aims to provide empirical insights from a Canadian case study building with a net-positive energy performance goal and its contribution toward achieving energy-related SDG targets.

Firstly, some studies focused on the relationship between certification programs such as Leadership in Energy and Environmental Design (LEED) and the SDG sub-targets (Alawneh et al., 2019, 2018). In these investigations, it was found that reducing energy consumption and increasing the share of renewable energy in the global mix (SDG7) were core credit prerequisites for energy credits in the LEED certification program. It was concluded that the implementation of LEED credits contributes to achieving SDGs 6, 7, 8, 9, 12, 13, and 15. This highlights the relationship between these certification programs and achieving the SDGs (Alawneh et al., 2019, 2018).

Other studies looked at the use of sustainable and smart materials in building construction to reduce energy consumption and contribute to the SDGs (Balali & Valipour, 2020; Lu et al., 2019; Omer & Noguchi, 2020). Green building materials were reported to help achieve the SDGs mentioned by (World Green Building Council, 2022), but specifically, they were found to significantly impact infrastructure resilience (SDG 9) and climate change disaster mitigation (SDG 13) (Omer & Noguchi, 2020). Selecting building façade materials was optimized to select material that decreased energy consumption and was resistant to earthquakes thus improving resilience and safety (Balali & Valipour, 2020). Additionally, integrating photovoltaics and thermochromic material was found to improve energy use intensity (Balali & Valipour, 2020). Construction waste management can be a challenge when a building's life comes to an end, hence it is important to select building construction materials appropriately (Lu et al., 2019). LEED credits awarded for material choices were also examined in their relation to sustainable development and it was found that these credits do not generally promote superior performance potentially due to a lack of incentives, bias from the developers, and limitations of the rating system's design (Lu et al., 2019).

One case study looked at integrating sustainability development goal targets in a net-positive energy building design in Canada (Goubran & Cucuzzella, 2019). This study focused on the design aspects that can be integrated into different levels by creating sustainable design visions that incorporate human needs (Goubran & Cucuzzella, 2019). For example, to achieve the highest level of protecting cultural and natural heritage (part of SDG 11), it was proposed to develop an operation plan that considered the well-being of different building occupants (Goubran & Cucuzzella, 2019). This paper aims to add empirical operational insights from a similarly designed building.

Wen et al., (2020) developed a framework for assessing green buildings' ways of contributing to the SDGs. For assessing clean energy affordability (SDG 7), they had indicators regarding systematic commissioning, reduced energy use, renewable energy generation, and facility management. Similarly, for contributing to sustainable cities and communities (SDG 11), the indicators included access to public transit, healthy, safe, and accessible services, and protection of biodiversity. Lastly, to measure responsible consumption (SDG 12), access to recycling and waste sorting facilities, adequate indoor air quality, and user participation were included as indicators. This paper aims to show how the case study NPEB applied some of these indicators in its goals to achieving sustainable operation.

Energy Performance and Commissioning

Building energy performance is impacted by many factors including the design, construction, and operation of the building. In the design phase, the building systems are conceptualized, and key decisions are made regarding the energy performance. The specific systems, control strategies, and operating set points, impact total energy consumption. Operation is the longest phase of a building's life and fine-tuning operating setpoints is essential to ensure that design goals are met during operation. Heating, ventilating, and air conditioning HVAC typically the highest energy load in a building and as such, lots of attention has been paid to reducing the heating and cooling energy demand in high-performing buildings (Deng & Chen, 2020; W. Kim, Katipamula, & Lutes, 2017; Kong, Dong, Zhang, & O'Neill, 2022). A common strategy to reduce HVAC energy consumption and ultimately improve building energy performance is by using occupant-centric controls that focus on operating to condition the space when occupants are present and reduce wasted energy for conditioning spaces when they are unoccupied (Kong et al., 2022; Park et al., 2019). Another common energy performance improvement strategy is building commissioning.

Building commissioning generally has two main types: existing building commissioning and new building commissioning (Li, Lu, Qian, Wang, & Liang, 2022). Existing building commissioning looks at improving the existing building's performance, usually focusing on solving a specific operational challenge after the building has been built for a while (Li et al., 2022). It is far less standardized and established relative to new building commissioning which has established standards and guidelines by ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), 2019). There are many benefits to both types of commissioning including managing operational costs, energy consumption, and associated greenhouse gas emissions in the built sector; however, there remains a lack of awareness about these advantages (Mills, 2011). In meta-analyses of commissioning projects, different benefits of new building commissioning were highlighted including energy savings and improved building operation performance (Crowe et al., 2020; Ruffin, Claridge, & Baltazar, 2021). To maintain the longevity of these benefits, operators may need to engage in a continuous commissioning process to maintain their performance targets. Other building commissioning activities can take place beyond the formal process if the operator wishes to continue finetuning and improving the building's energy performance.

Energy Generation

There are different design configurations proposed to integrate on-site renewable energy generation, depending on the climate of the region where the proposed net-positive or net-zero energy building is located. A design assessment of energy generation using solar photovoltaic (PV) and wind systems in different climate zones found that solar PV is a reliable and stable onsite renewable energy system not only in the present time but also into the future as the energy output is expected to increase (Shen & Lior, 2016). Another NPEB case study reports that 65% of onsite energy generation was used for building energy consumption, while the remaining 35% was used to charge electric vehicles (Zomer et al., 2020). In a techno-economic and environmental assessment for a solar PV system, it was reported that a 1MW system would meet a campus's energy needs and generate revenue by selling the energy back to the grid (Paudel et al., 2021). This study highlights the economic feasibility of solar PV systems in developing countries (Paudel et al., 2021) to ensure the global realization of the SDGs. These studies highlight the potential and successes of the built sector in generating onsite renewable energy and contributing to decarbonizing the energy mix.

METHODOLOGY

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 before its delivery into the HVAC system with increases of over 20 ºC being measured on sunny winter days (Sturla, 2022). The system is coupled with an enthalpy wheel to further reduce HVAC energy consumption. Variable frequency drives 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 (D. Kim, Cox, Cho, & Im, 2018). The three-story 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). The details of the specifications and the building features a contribution to the SDGs are summarized in Table 2.

TABLE 2
SUMMARY OF CASE STUDY BUILDING FEATURES, SPECIFICATIONS, AND CONTRIBUTION TO THE SDGS

SDG(s) #	Design Feature	Description	Contribution to SDG(s)
7, 12	Building Envelope	Window-to-wall ratio 37% with continuous glazing Rated R-30 for walls and R-40 for the roof	Improving airtightness and insulation beyond the building code reduces energy consumption
7, 11	HVAC	Variable frequency drives used for precise pump and motor control Enthalpy wheel for 81% heat recovery Dedicated outdoor air system 3-storey and 5.7m wide living wall to provide natural humidification	Using an efficient electric system to heat and cool the building reduces energy consumption and particulate pollution in cities
7	Lighting	LED lights with daylight harvesting and occupancy sensors controls Atrium lighting for the living wall Lighting power density design: 4.75 W/m^2	Reducing energy use intensity by using proactive control strategies
6, 12	Water Management	Low-flow washroom installations Rainwater harvesting for closets, washrooms, and living wall irrigation	Improving water efficiency Reducing net consumption
7, 13	Renewable Energy	825 MWh solar electricity generated from the roof top and parking lot PV Solar wall used to pre-heat outdoor air Open loop geo-exchange system providing water to regulate indoor air temperature	Increasing renewable energy share in the mix

Data Collection and Analysis

FIGURE 2
DATA COLLECTION AND ANALYSIS PROCESS

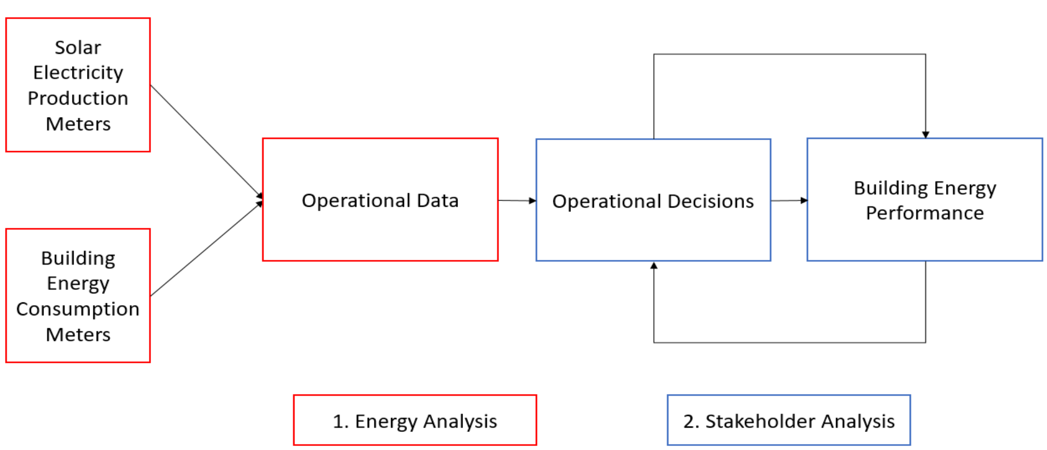


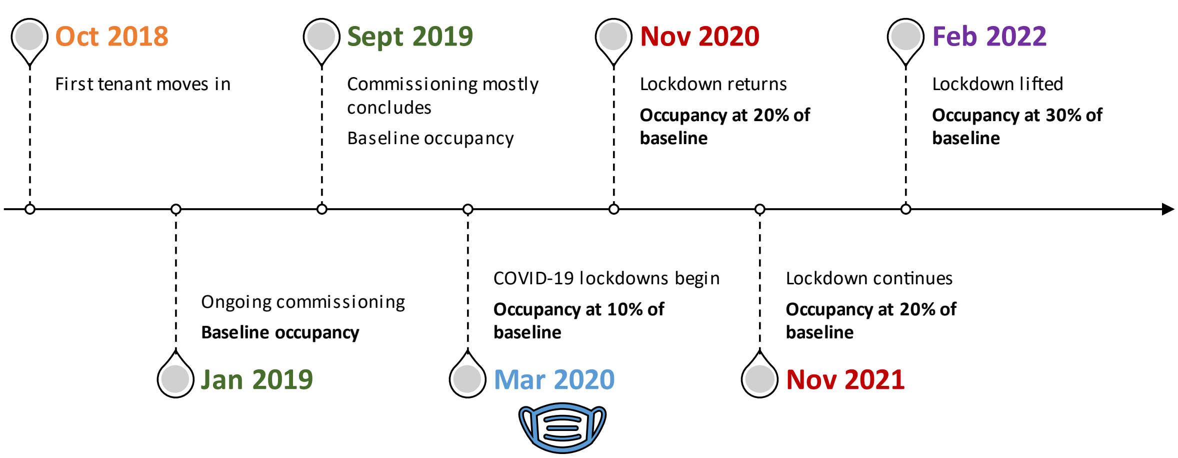
Figure 2 demonstrates the mixed methods used to provide a holistic analysis of this NPEB operation. A combination of quantitative operational energy data analysis and qualitative data collected from key informant interviews with a building operator and energy advisor were used in this study. Digital daily building energy consumption (BEC) and monthly solar electricity generation (SEG) 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. This mixed methods approach was applied to provide a holistic understanding of the observed energy performance.

Empirical data was available from January 2019 to November 2022 for analysis. To estimate December 2022 consumption and generation levels, the average of the previous 3 Decembers from 2019, 2020, and 2021 was used. All raw data was extracted from virtual databases for consumption and generation. The data was added up to aggregate hourly and daily consumption into monthly and annual consumption profiles. To estimate the monthly surplus generation, the percentage ratio of consumption to generation was calculated. The ratio percentages below 100% indicate a deficit where the building could not meet its demand and borrowed energy from the grid. When the ratio is greater than 100%, the on-site energy generation exceeded the building energy demand, and the building was able to contribute the excess to the grid.

Timeline and Key Events

Three main events took place over the analysis period. Firstly, there were commissioning activities taking place in the first 9 months of operation (from January to September 2019). Then COVID-19 lockdown began in Ontario in mid-March and to reduce the spread of the virus, the majority of occupants began working remotely. There was a slight increase in occupancy during the November months of the lockdown as some tenants returned to work from the office due to the increased volume of work for the season. Lastly, the lockdown was lifted in February of 2022 and a few more occupants returned, while most continued to work remotely. A detailed summary of the key events and occupancy levels at various stages is shared in the timeline below.

FIGURE 3
SUMMARY OF KEY EVENTS AND TIMELINE TAKING PLACE DURING CASE STUDY BUILDING OPERATION



RESULTS

Building Energy Consumption

FIGURE 4
BUILDING ENERGY CONSUMPTION IN EUI FROM 2019-2022 RELATIVE TO THE 2018 MEDIAN CANADIAN OFFICE EUI

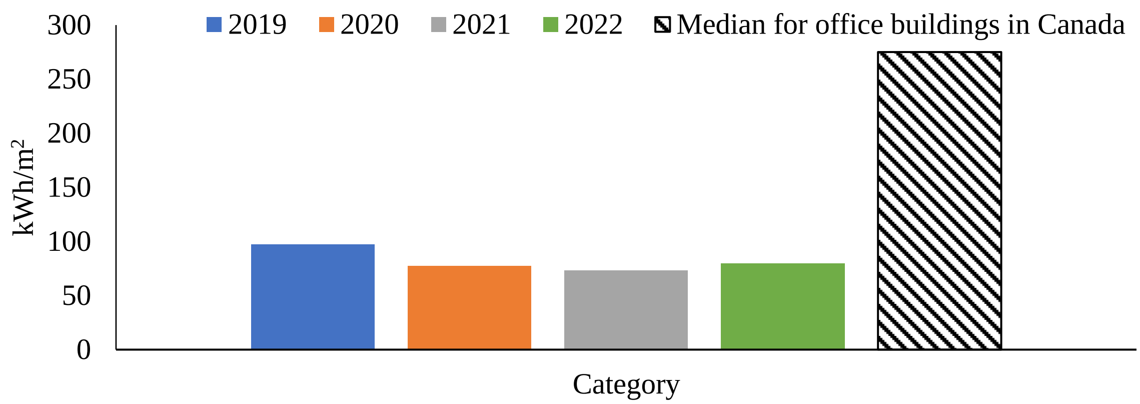
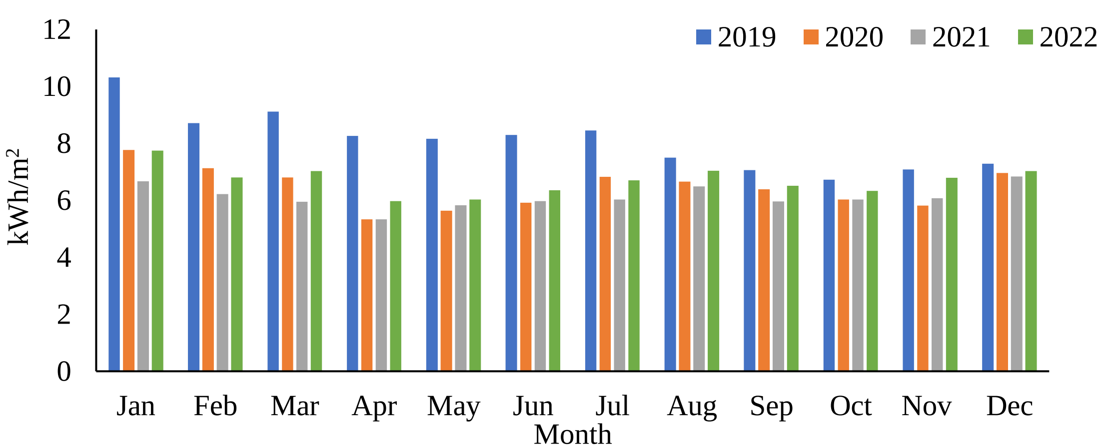


Figure 3 summarizes the BEC in 2019, 2020, and 2021 as 97 kWh/m^2, 77 kWh/m^{2,} and 74 kWh/m^2 respectively, averaging 83 kWh/m^2 over the three years. A survey of Canadian national median values of EUI in office buildings revealed a median operational EUI of 275 kWh/m^2 (Energy Star, 2018). Comparing 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. Energy consumption increased by 9.6% after occupants began returning to the office in 2022. This shows that although 30% of occupants returned to work from the office, the building is using less than 10% more energy than when it was minimally occupied. This shows a low sensitivity to the number of occupants in a building and highlights the importance of setting accurate operating schedules for equipment to reduce consumption during unoccupied times.

FIGURE 5
MONTHLY BUILDING ENERGY CONSUMPTION IN EUI, 2019-2021

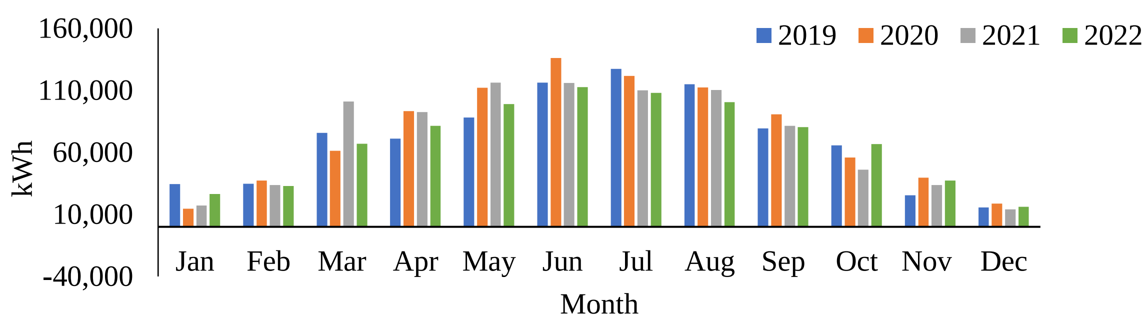


Commissioning typically takes 12-18 months to understand the building operation and make modifications to finetune energy consumption and occupant comfort. Initially, there were occupant requests to adjust the temperature due to the positioning of thermostats. After construction, the room thermometers 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.

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 5 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. Starting in February 2022, the lockdown was lifted in Ontario and occupants began returning to work in the office, however, there were reduced levels of occupancy observed (30%), indicating lasting impacts from the COVID-19 pandemic. This indicates that office buildings are being used differently with increased teleworking.

Solar Electricity Generation

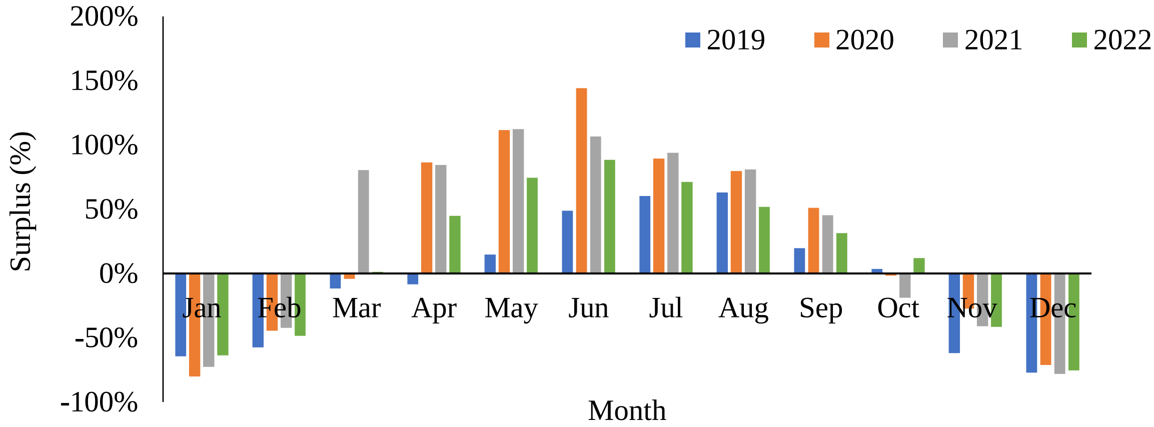
FIGURE 6
MONTHLY SOLAR ENERGY GENERATION, KWH, 2019-2022



Several factors contribute to the SEG of the NPEB. The building has a south-easterly orientation that provides a good direction to maximize SEG. The PV system utilizes inclination angles to maximize summer solar radiation capture. These design strategies contribute to the performance demonstrated by the monthly SEG displayed in Figure 6. The results show peak production months start in March and end in September, followed by reduced production from October to February. Variations in the electricity production of particular months can be attributed to variations 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 SEG than other years. Annual SEG of 848 MWh, 893 MWh, 872 MWh, and 829 MWh in 2019, 2020, 2021, and 2022 respectively, result in average annual production of 861 MWh and demonstrate exceeding the PV system's design target of 825 MWh/yr.

Solar Electricity Grid Contribution

FIGURE 7
MONTHLY SURPLUS GENERATION RELATIVE TO CONSUMPTION, 2019-2022



From Figure 7 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 6 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. Starting in February 2022, building energy consumption levels increased due to increased occupancy; however, the levels were not back to baseline consumption in terms of the more tenant-impacted loads such as lighting and plug loads. The building operation team did not change any setpoints in terms of building heating, cooling, or ventilation that may reduce building energy consumption. More details on the impact of COVID-19 and occupant-centric loads (lighting and plug loads) can be seen in (Mikhail, 2022).

Overall, the NPEB produced 93%, 123%, 127%, and 115% of its energy demand on-site in 2019, 2020, 2021, and 2022 respectively. 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 COVID-19 impacts considered, the results suggest that the building achieved net-positive energy status. A more detailed analysis of the impacts of COVID-19 on building operations can be found in (Mikhail, Mather, Parker, & Kapsis, 2022).

DISCUSSION

From its conception, this case study building has been about taking action against climate change (SDG 13) and adapting the built environment and increasing its resilience in the face of adversity. The NPEB brought together many key stakeholders and governments to realize the feasibility of achieving sustainable development (Riemer, Reimer-Watts, Whitney, & Leitan-Claymo, 2021; Whitney et al., 2020). This investigation looked at four years of measured building energy consumption and generation data and the NPEB's contribution to three energy-related SDGs. As described by the World Green Building Council (2022), sustainable buildings can contribute to 11 out of the 17 SDGs as summarized in Table 2.

In this investigation, empirical contributions to affordable and clean energy (SDG 7), sustainable cities and communities (SDG 11), and responsible consumption (SDG 12) were analyzed. A summary of the contribution areas and the specific SDG sub-targets can be found in Table 3.

Building Energy Performance and the SDGs

The potential to contribute to achieving the SDGs begins in the built environment's design phase. Several design elements contribute to building energy consumption such as the thermal performance of the building envelope (Zhou & Zhao, 2013). This includes interior and exterior walls, windows, and the roof which all contribute to the energy performance and comfort of the building (Zhou & Zhao, 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 most of the area. The solar air heater contributed to reducing the heating load, coupled with an energy-efficient enthalpy wheel for heat recovery, a 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. Combining these strategies led to a reduced energy use intensity as demonstrated by 4 years of operation compared to the median office building in Canada, summarized in Figure 4.

In this study, the energy consumption and impact of the commissioning of an NPEB was described. As described by earlier studies, systematic commissioning and reducing energy consumption are ways of achieving access to clean and affordable energy (SDG7) (Wen et al., 2020). Similar to the findings of another NPEB Canadian case study, most of the contributions to the SDGs in this investigation were found to be product focused. That is the integration of systems such as variable frequency drives, dedicated outdoor air systems, living walls, solar PV and solar air preheaters mainly focused on reducing energy use intensity, and managing indoor air quality and emissions using technology. Although there have been interventions to engage with the NPEB occupants (Zitars et al., 2021) and apply more of the human aspects to achieving the SDGs, there are opportunities for growth in this area.

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. Reducing energy intensity is essential, as rising populations need more buildings to provide shelter. The transition to a sustainable energy future will require not only converting to sustainable energy sources but also changing our behavior around how energy is consumed (Niamir, Filatova, Voinov, & Bressers, 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.

Onsite Energy Generation and the SDGs

SEG in the built sector is needed to reach net-zero energy consumption and to directly address 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 (Service Canada, 2021), one option is to have buildings generate their renewable energy so that they can become more independent and less reliant on natural gas for heating and grid electricity. 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.

Energy generation through onsite solar PV systems has been commonly applied to help the built sector offset its emissions and contribute to increasing the mix of renewables in the grid (Paudel et al., 2021; Shen & Lior, 2016; Zomer et al., 2020). In this case study, energy generation was used to meet the demand of the building and contribute to the local grid, similar to findings reported from other Canadian case studies (Zomer et al., 2020). Additionally, this empirical data support earlier design assessments of the reliability and stability of onsite solar PV as a method of energy generation (Shen & Lior, 2016).

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 net 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.

Limitations and Future Research

As the scope of this research was focused on energy, it did not provide a comprehensive view of the contributions that the case study building made to other SDGs such as safe water and sanitation (SDG 6). In future research, it is recommended to examine the water consumption levels to assess the efficiency of the water systems and their potential contribution to SDG 6 sub-targets. Furthermore, there is uncertainty associated with allocating contributions to specific SDG sub-targets since the sub-targets are usually applied to a broader context. In this case, the authors aimed to highlight potential areas of contributions from a case study building to encourage future research into NPEB design and operation. Lastly, there are opportunities for future research to expand more on building relationships between occupants and the building operators to collaborate more towards achieving the SDGs.

CONCLUSION

A mixed methods case study analysis of a southwestern Ontario multi-tenant office NPEB highlights the impact of design and operational decisions on achieving SDGs 7, 11, 12, and 13. BEC analysis demonstrates an average EUI of 82 kWh/m^2 which is one-third of the 2018 Canadian office median EUI. Design decisions such as higher insulation levels, window-to-wall percentage, and window triple glazing contributed to reducing energy consumption, achieving sustainable consumption, and reducing EUI. SEG analysis demonstrates the PV system's capability to produce an average of 861 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 natural gas for heating. Surplus generation analysis for four 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%, 110% of its load in 2020 and 2021 respectively. In 2022, the building generated 115% of its load, showing a 15% excess renewable electricity shared with the local grid. NPEBs thereby contribute to creating sustainable cities with an increased mix of distributed electricity generation using renewable energy sources to replace fossil fuels. Ultimately, this case study highlights a feasible example for the built sector to improve its resilience and take action against climate change.

TABLE 3
SUMMARY OF SDGS, APPLICABLE TARGETS AND INDICATORS, AND THE CASE STUDY NPEB CONTRIBUTION TO ACHIEVING THE TARGETS BY 2030

SDG	Applicable Target	Applicable Indicator	Example of NPEB Contribution
7 – Ensure access to affordable, reliable, sustainable and modern energy for all	7.2 – increase share of renewable energy in global energy mix	7.2.1 renewable energy share in total final energy consumption	Distributing excess solar electricity produced during May to September months
	7.3 – double the rate of improvement in energy efficiency	7.3.1 energy intensity measured in terms of primary energy and GDP	Reduced energy use intensity during operation by using proactive management approaches and energy efficient technologies
11 – Make cities and human settlements inclusive, safe, resilient and sustainable	11.3 – inclusive and sustainable urbanization and capacity for settlement planning and management	11.3.2 proportion of cities with a direct participation of civil society in planning and management	Location beside a light rail transit station for access to public transportation
	11.6 – reduce adverse per capita environmental impact of cities by considering air quality management	11.6.2 annual mean levels of fine particulate matter in cities	Shifting away from using fossil fuels for heating and using renewable electricity
12 – Ensure sustainable consumption and production patterns	12.2 – sustainable management and use of natural resources	12.2.1 material footprint per capita and material footprint per GDP	As a zero-carbon certified building the NPEB offsets its embodied carbon during operation
	12.8 – ensure that people have relevant information and awareness for SD and lifestyles in harmony with nature	12.8.1 extent to which global citizenship education and education for sustainable development are mainstreamed	Operator communication with occupants about goals fosters sustainability culture Community and student education events held in classroom
13 – Climate	13.1 – strengthen resilience and adaptive capacity to climate-related disasters	13.1.3 proportion of local governments that adopt and implement local disaster risk reduction strategies in line with national reduction strategies	The City of Waterloo was a supporter of this building’s ambition and goals and helped fund some of the costs to make it feasible (Riemer et al., 2021), thus forming partnerships to adapt the City’s infrastructure

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