A net-positive energy building assessment: commissioning and COVID-19 insights

by

Monika Mikhail

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

The built sector is responsible for 30% of global greenhouse gas emissions, which inspired solutions including net-zero energy buildings to reduce environmental impacts. Several factors impact energy consumption including finetuning activities that take place after construction and how occupants interact with different building components. Many building energy studies take a simulation approach to estimate energy performance. There are limited studies looking at empirical office operations, especially in Northern climates. This study investigated a case study building in Waterloo, Ontario, using quantitative energy data from three and a half years of building operation and qualitative data from key informant interviews to gain a holistic understanding of building operations. The investigation was divided in two main parts, answering questions related to the performance gap, building commissioning and COVID-19. Firstly, the difference between predictions of energy consumption from the design phase and measured energy consumption was investigated. Actions taken by the building operator to close the difference between measured and predicted heating, ventilating and air conditioning energy consumption and work towards meeting the design intent were analyzed. In the second portion of the study, the focus shifted towards more occupant impacted loads such as lighting and plug loads (e.g., computers, fridges, personal space heaters). Energy consumption from 2019 was considered as the baseline and it was compared to minimal occupancy in 2021 and medium occupancy due to increased remote working during 2022. Statistical analysis was completed to test the significance of the differences in the energy consumption levels between the three modes of occupancy. Lastly, hourly profiles were analyzed to estimate occupant presence and schedules during typical work and nonwork days. Highlights of the results show that building commissioning reduced total energy consumption by 15%, while reduced occupancy led to a 10% decrease. Low sensitivity to outdoor conditions (e.g., irradiance and outdoor temperature) on energy consumption was also observed. Future research can consider investigating commissioning projects' energy savings from other Canadian offices with similar design goals (e.g., net-zero energy) and uncovering a relationship between occupancy (i.e., uncovered through occupant sensor data) and energy consumption.

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List of Abbreviations

Acronym	Meaning
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BEC	Building energy consumption
BB	Base building
DOAS	Dedicated outdoor air system
EUI	Energy use intensity
HVAC	Heating, ventilation and air-conditioning
MAU	Make-up air unit
NPEB	Net-positive energy building
LEED	Leadership in Energy and Environmental Design
LED	Light-emitting diode
PL	Plug load
SEG	Solar electricity generation
VFD	Variable frequency drive
VRF	Variable refrigerant flow

Chapter 1 Introduction

1.1 Background

The built sector is responsible for 30% of total global energy consumption and 27% of greenhouse gas emissions (1). Energy demands for constructing and operating buildings continue to rise with rising populations and more extreme weather conditions. The need for safe and affordable shelter continues to persist as the United Nations encourage world leaders to generate inclusive sustainability solutions (2). These goals encourage developments that are affordable to people of all socio-economic statuses such that new solutions do not exacerbate economic inequalities (2). The IPCC outlines that the electricity share of energy demand in buildings would be 55-75% in 2050 for a 1.5 ^{o}C scenario, compared with 50-70% for a 2 ^{o}C scenario (3). They outline adaptation options to mitigate emissions and cost of operating buildings, including designing efficient cooling systems (3). To build on this, the Paris agreement outlined key goals to decarbonize the economy by 2050 (3). From these agreed upon goals, different global governing bodies generate their own policy plans to mitigate and adapt to climate change. The European Commission outlines key-building related policies in four main areas (4). First, is tan energy performance of buildings directive that aims to harmonize building performance calculation methodology and minimum performance requirements (4). Then, there are energy efficiency and renewable energy directives that aims to increase energy efficiency and renewable energy generation by 2030 (4). Lastly, there are governance regulations to ensure the implementation of these goals (4). In Canada, this adds pressure to decrease GHG emissions by 40-45% below 2005 levels by 2030 (5). The pan-Canadian Framework aim to bring Canada's 2030 emissions to 31% less than 2005 levels (4). These ambitious goals challenge building designers and operators to come up with creative solutions.

1.2 Net-zero Energy Buildings

One of the climate change mitigations solutions from the built sector is the idea of net-zero energy buildings (NZEBs). NZEBs are a type of high performance building that is energy-efficient and aims to generate as much energy on-site as it consumes over the period of one year(6). Different definitions have the import and export boundaries in different locations. For a building that is net-zero energy on a source energy basis, the energy consumed and lost in extraction, processing, transport, power generation and distribution is accounted for on an annual basis (6). Going one step beyond net-zero are NPEBs which aim to generate enough renewable energy on-site to meet their total operations demands and transfer any excess energy to other users of the grid (6). During months where the on-site energy generation is less than the building consumption, the building can import energy from the grid; however, during months of excess on-site energy generation, that energy can be exported with the local grid to contributing to reaching net-zero energy overall. To go a step beyond net-zero, buildings can generate more energy than they consume on an annual basis, allowing them to reach net-positive energy buildings (NPEB) (7). However, to achieve this goal, NPEBs need to optimize their energy consumption so that they are within design goals.

Defining and disclosing the energy consumption and generation is needed to reach a consistent definition of net-zero or net-positive energy buildings (8). Sartori et al. (2012) introduce an energy balance framework that was adapted and applied to this study on a monthly and yearly import and export basis (8). Here, we refer to net-positive buildings, as those who can produce more energy than they consume on an annual basis (7) as seen in Figure 1.

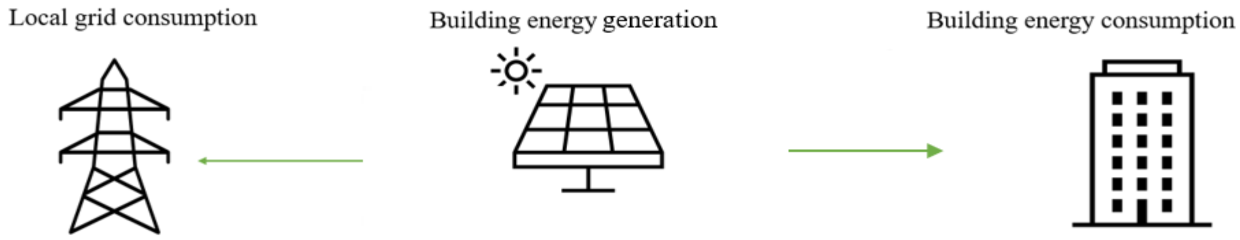


Figure 1: Net-positive energy building energy generation and consumption

1.3 Performance Gap and Commissioning

High performance buildings are those that go beyond conventional design to meet specific performance goals such as net-zero or zero carbon. These buildings can face challenges in meeting design goals, and may consume more energy than predicted (9–11). The difference between measured and predicted energy consumption is known as the performance gap. This can be due to several factors including optimistic design targets, ineffective building operation and limited building commissioning (12). The performance gap contributes to net-zero energy buildings failing to meet their design goals (13) and, as such, insights from high performance building operations can help uncover lessons learned to improve future building operation.

To close the performance gap in new buildings, operators can make decisions during the commissioning period to reduce energy consumption. Commissioning is the process of verifying and observing building equipment in operation to ensure that the design intent is being met (14). These activities do not only reduce operating costs and energy consumption (15), but they can also contribute to occupant comfort (12). This study aims to highlight effective and practical operational strategies applied during commissioning activities.

1.4 COVID-19, Occupancy, Lighting and Plug Loads

COVID-19 created an opportunity to investigate building energy consumption under minimal occupancy conditions which may not have been possible before. Lighting and plug loads are impacted by occupant behaviour and building operation schedules. HVAC energy consumption usually makes up around 60% of building energy consumption (16) and it can get a lot of attention from designers, researchers and operators. Of the remaining 40%, lighting and plug loads use approximately 30% of energy consumption, with plug loads seeing increases of over 50% over the last 18 years (16). Many studies in the literature take a simulation approach to approximating energy savings from lighting control improvements (17–20) or occupant behaviour interventions to reduce plug load consumption (21,22); however, there were limited empirical studies found demonstrating the impact of applying such controls strategies (e.g., daylighting). Hence, this case study aims to provide empirical data to provide insights on how occupants consumed lighting and plug load energy during different occupancy periods while the case study building operated.

1.5 Case Study Building

The case study building is a NPEB, leadership in energy and environmental design (LEED) platinum office building in Waterloo called evolv1. It has features such as tripled glazed windows, a high-performance building envelope and a light emitting-diode (LED) lighting system with occupancy and daylight sensors(23) which creates a uniquely sustainable environment for occupants and researchers to investigate. The office building is a three-storey, 110, 000 sq. ft commercial, multi-tenant building (23). Further details about the building design, specifications and features will be discussed in section 4.3.2.

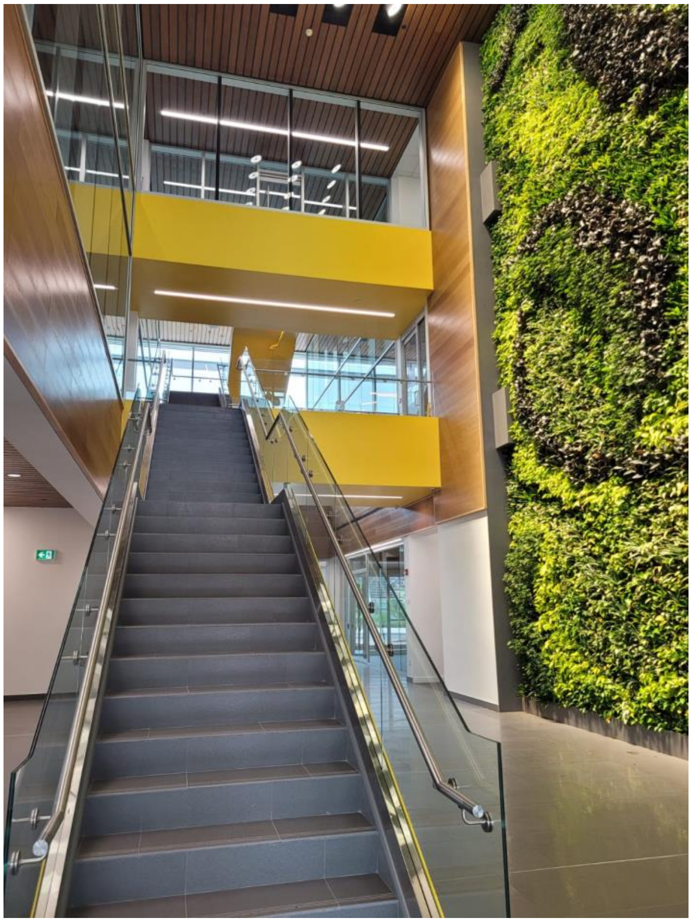


Figure 2: Case study building interior featuring central staircase and living wall used for natural humidification

1.6 Sustainable Development Goals

Canadian homes and buildings account for 18% of greenhouse gas (GHG) emissions due to the combustion of fossil fuels in space and water heating (24). The United Nations identified major challenges for high income countries' progress toward achieving the sustainable development goals (SDGs) (2). The applicable SDGs to NPEB operation can be seen in Figure 4. 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 (2). Statistics Canada identifies several data gaps in measuring the progress toward the SDG indicators (25–27). 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. Examples of how NPEBs can contribute to specific SDG targets and indicators can be seen in Table 1. Further analysis on the SDGs and how they are connected to building operations can be found in Appendix C.

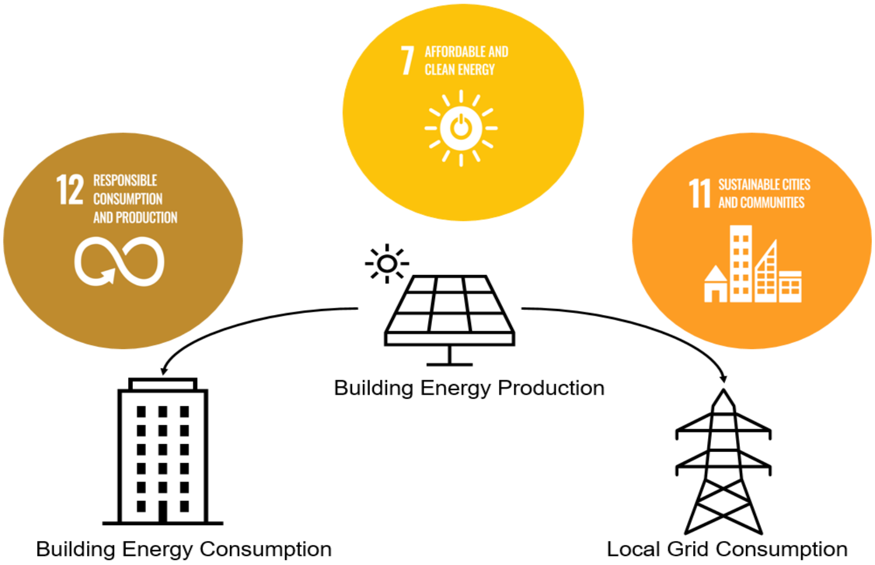


Figure 3: Net-positive energy building operation and impacted SDGs

Table 1: 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 efficiency 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 near a railway to highlight 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 all year round
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 tenants and occupants about energy performance goals fosters a sustainability culture

1.7 Research Objectives and Questions

The research objectives for this investigation were to understand how a net-positive building perform and to share empirical insights with the operation, design, and research communities. This was accomplished by collaborating with industry partners from building operations and design to uncover real-world insights on the challenges and opportunities available with new, high performance building design. Ultimately, this research aimed to increase awareness to the net energy generation potential of the built sector and the opportunities to reduce greenhouse gas emissions associated with building operation.

This research focused on answering two main questions regarding energy performance. The first was an investigation related to building commissioning and the performance gap and the second was related to COVID-19 and the impact of occupancy on building energy consumption. In the first investigation, building commissioning activities were analyzed for their impact on HVAC and pump energy consumption. The total building energy consumption and lighting and plug loads were compared to the design model to uncover the performance gap. In the second study the focus shifted more on occupant impacted loads such as lighting and plug loads. In this study, operational data from pre, during and post COVID-19 were investigated to understand the impact of baseline occupancy (2019), minimal occupancy (2021) and occupancy resulting from the hybrid work from home and return to the office mode of operation (2022) on building energy consumption. Statistical analysis was completed on the loads to understand the difference between the three occupancy levels.

Specifically, the questions were the following:

i) What were the commissioning decisions and how did they impact energy consumption?

ii) How did evolv1 perform in comparison to energy design targets?

iii) How did reduced occupancy due to COVID-19 impact evolv1's energy consumption?

1.8 Road Map

This thesis investigated the impact of commissioning and occupancy in two papers. The structure will be as follows: a literature review of the studies contributing to both papers, then the papers will include a separate introduction including a more concise review of the literature, followed by the methodology, results and analysis sections and a discussion and conclusion. The thesis will have another concluding chapter to highlight the main findings of both studies combined. The conference paper in appendix D has been submitted for proceedings (28) and the re-edited paper with additional data in Appendix E will be submitted for journal publication.

A few notes regarding the specific chapters and appendices. Chapter 4 was submitted for publication and has been accepted (29). Appendix C has been published as a part of the International Conference for Sustainable Development proceedings (28). Lastly, chapter 5 will be submitted to the Journal of Energy and Buildings for publication.

Chapter 2 Literature Review

2.1 Overview

In this literature review, four main areas of literature were assessed as they were found to be the most relevant to the two investigations conducted. Frist, the broad literature on the building energy performance gap was investigated highlighting the impact of occupancy and occupant behaviour on building energy performance. Then commissioning studies were analyzed for their findings of energy savings and other impacting factors that lead to effective commissioning. Furthermore, COVID-19 literature from residential and office buildings were explored to understand the findings and methods of other studies under this unique circumstance. Lastly, lighting and plug load studies were reviewed to provide insight on approaches used to reduce consumption. Figure 4 demonstrates a visual representation of the different literature pieces. Table 2 provides a summary of key studies and their major findings.

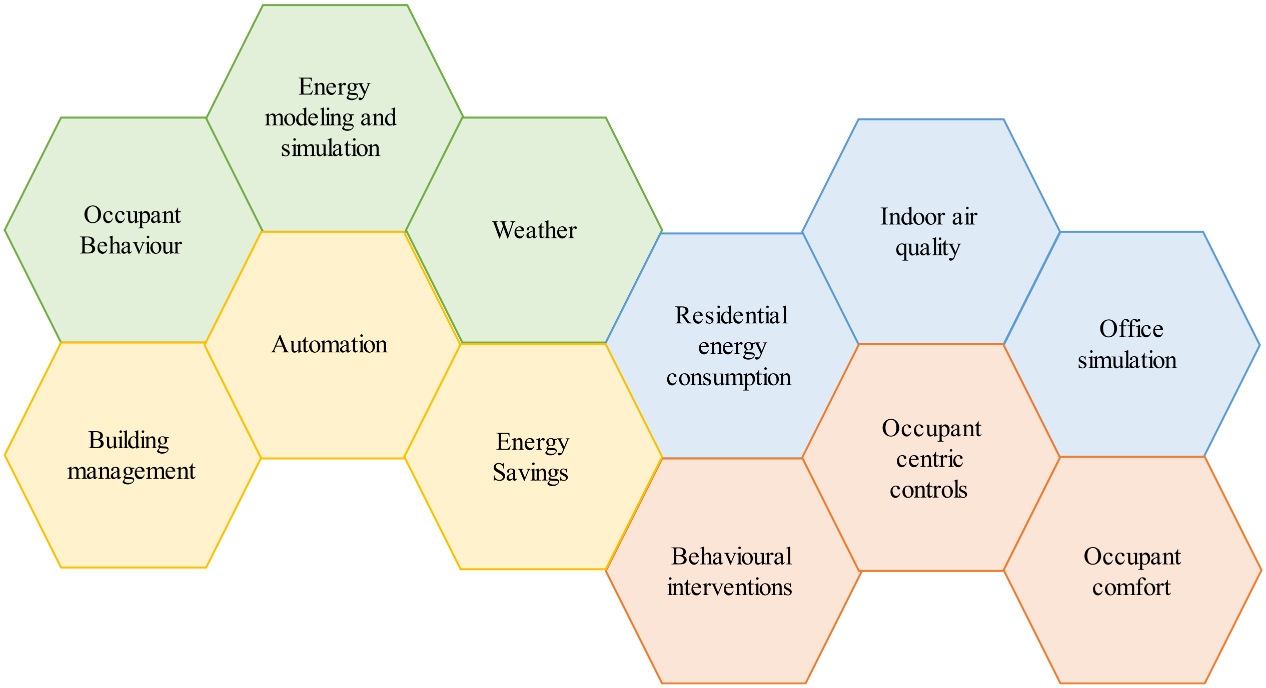


Figure 4: Graphical summary of topics found in the literature

Performance gap, commissioning, COVID-19, lighting and plug loads

Table 2: Summary of key studies and major findings in the literature

Performance gap, commissioning, COVID-19, lighting and plug loads

Study	Ref #	Summary
de Wilde (2014)	(10)	Investigated university building operation compared to design predictions, finding a 30% underprediction in electricity use from the simulations. A coordinated approach among stakeholders to close the performance gap is recommended.
Jain et al. (2020)	(11)	Calibrated simulation found higher office building occupancy, extended operation hours, higher temperature setpoints contributed to the performance gap.
Jradi et al. (2018)	(12)	Building performance monitoring and evaluation tool is presented to bridge the performance gap by highlighting continuous commissioning opportunities through preventative fault detection and diagnostics.
Crowe et al. (2020)	(15)	Building owners implement commissioning projects to qualify for specific financial rebate programs, extend equipment life, comply with policy and ensure system performance. Most energy savings measurements are related to HVAC with offices achieving a median of 6% savings in existing commissioning projects.
Kang et al. (2021)	(30)	Big data analysis of national energy consumption in different regions of South Korea found that average office electricity consumption decreased by up to 3% when comparing 2019 with 2020.
Cortiços et al. (2021)	(31)	Building energy simulation of high-rise US offices to estimate the impact of COVID-19 operating guidelines (e.g., increasing airflow rate, keeping indoor relative humidity between 50-60%) on energy consumption. The results anticipate an average of 22% increase in subarctic climates if they were to continue operating under COVID-19 guidelines after the pandemic.
Gandhi et al. (2016)	(21)	An energy game intervention was used to engage office occupants and increase their plug load energy consumption awareness. Examining loads during unoccupied periods showed that desktops tend to be left on overnight more than laptops, suggesting that occupants take their laptops home and that reduced some of the phantom load (power draw from devices that are not being used).
de Bakker et al. (2018)	(17)	Statistical analysis of a controlled occupant study examining comfort and satisfaction with different illumination conditions. Varying lighting levels (i.e., dimming) in different parts of an open floor office was evaluated as comfortable by the majority of participants. Energy savings potential were estimated at 27% if dimming was applied.

2.2 Definitions

Depending on the boundaries, net-zero energy building accounting can be completed on a site basis or on a source basis. If the building energy consumption and generation balance is completed on a site basis, then the energy losses due to transportation are not accounted for; however, when performing the balance on a source a basis, these losses need to be taken into account (32). To go beyond net-zero energy, a building may generate more energy than it consumes in a year and that excess can be exported to the local grid. When a building is contributing positively to the surrounding community as in the form of sharing renewable energy, it is a net-positive energy building (33).

Other types of high performance buildings, include zero-carbon, life cycle zero energy buildings and off-grid zero energy buildings (34). Canada green building council defines a zero-carbon building as one that is "highly energy-efficient and minimizes greenhouse gas emissions from building materials and operations" (35). Carbon offsets can be used to counterbalance emissions until the building operation can support the zero-carbon performance goal (35). Going one step beyond zero-carbon are the life cycle zero energy buildings which include embodied energy of the building and its components (32,36). Lastly, off-grid zero energy buildings produce all of their energy through renewable sources without relying on any external grid support (34).

2.3 Performance Gap

There are several factors in design and operation contributing to the performance gap including building operation and maintenance, and occupant behaviour (37). In the design phase, there can be assumptions made about occupant schedules and heating needs that are not as representative of the end-use of the building which impacts the performance gap (9,38,39). In a modelling study, it was reported that occupant presence can increase energy savings so investigating occupant schedules is of interest (40). Occupant behaviour, fine-tuning, and calibration can contribute positively or negatively to the gap during operation (9) (e.g., reducing energy consumption in some end-uses like lighting but increasing in others like heating).

This study performed a post-occupancy investigation of the impacts of building commissioning and occupancy on energy consumption.

During operation, the interaction between people and building components can have a negative or positive impact on energy use (41). Since studies usually use modelling, this makes them more context-specific (i.e., dependant on the type of building, tenants, and geographical location). It remains difficult to generalize the results and apply findings to improve building operation. The emerging theme from the literature suggests that a better understanding of the occupant related factors that contribute to increased energy consumption can identify recommendations to decrease energy consumption (9,41–43). There is a need to use mixed methods approach to get a deeper understanding of occupant perceptions and motivations (44). Mixed methods provide qualitative insight from surveys or interviews to explain the ‘how’ and ‘why’ certain modifications were made (i.e., an increase in thermostat temperature because of occupants feeling cold) which would explain the differences between the model prediction and real life operation (44).

Occupant-related modelling studies demonstrate a variety of factors impacting the difference between measured and predicted energy consumption. In a review of studies on occupant behaviour and buildings, it was reported that occupant control over building components, such as thermostats, and lighting, had a significant impact on building energy use (41). This brings attention to building areas to be considered however, it is unclear from model-based studies how occupancy play a role since there is often no empirical data supporting the findings. Similarly, a recent study on a UK office building reported a 15% gap due to increased occupancy, operation, and heating setpoints, however, there were also technical challenges with the building operation (i.e., sensor malfunction) which may have contributed to inaccuracy in the collected measured data (11). In a different review, the gap reported in various global studies was related to occupant experience, comfort, knowledge, and skills (9) which can be culture-dependent and therefore may not be generalizable to this study’s context. These studies highlight the significance of understanding occupant preferences and integrating that into building energy modelling.

Examining the difference between measured and predicted energy consumption in green buildings due to occupant behaviour was confirmed to be impacted by variation in occupancy numbers and patterns, and nonstandard hours of operations (45). Hours of operation differ depending on building type and may be impacted by specific industry seasons (i.e., tax season as a factor in increasing operation in accounting firms). In a German NZEB, a modelling-based study found variation due to occupant control over windows, lighting, ventilation, and temperature setpoint (46). However, this study used modelling to compare measured data and arrive at the conclusion of occupant behaviour leads to these differences which do not consider occupant perception and other needs that may be obtained from qualitative data. Interviewing building occupants or management can provide a new dimension of understanding where the gap between design intent and occupant understanding, or perception lies. In another NZEB, it was found that occupancy heat gains (from presence and appliances) significantly impacted the performance gap, however, this study was in residential buildings where norms and practices differ from offices (47). Closely examining these contributing factors of the performance gap is crucial to understanding the differences between model and design intent that impact energy consumption.

Understanding occupant perception is a complex topic that remains a key element to building energy performance analysis. There are different motivations contributing to these interactions, mainly internal and external drivers (41,48,49). Internal factors are related to how the occupants feel (e.g., warm, or cold) in a building and how they adapt to these physiological responses (e.g., opening or closing a window) (41,48). Further, these internal factors can be psychological, habitual or based on knowledge or lack thereof (49). Internal factors are considered a strong barrier to adopting effective measures and properly using building systems (49). External factors, on the other hand, can include architecture pertaining to building design, economic factors such as occupant income, energy prices, regulations and, policies (50). This project will focus on investigating the internal factors contributing to occupant behaviour to better optimize occupant comfort and building energy use in an office building.

Passive design such as using natural ventilation to leverage mild weather can reduce the cooling load, however, it can have adverse effects such as increasing energy use if occupants are not aware of the design intention (51). A significant difference between occupant satisfaction (31% were dissatisfied with no training reported or reported that training was not helpful) indicating that receiving training for the building systems was correlated with higher satisfaction in a survey study of ten office buildings in the US with interviews with over 40 occupants (51). There is a need for building designers to better understand occupant related interactions to incorporate them into the design and energy conservation targets (48,52). Therefore, an improved understanding of the interactions between occupants and building components can improve the designer's understanding of occupant needs, such as the desire for control over surroundings which is sometimes eliminated by some designs including fixed windows (41) and enhance occupant understanding of design intent by providing training (51).

Using different energy profiles is one way to distinguish between the variances in occupant interactions with building components(50). Different studies categorize occupant actions in descriptive profiles such as "energy frugal", "energy indifferent", and "energy profligate"(53) where energy frugal represents a conservative consumer and energy indifferent behaviour may lead to overconsumption of energy due to lack of awareness of environmental and economic consequences.

Another approach looked at improving building operators' communications with occupants to increase energy savings potential (54). The study reported an energy consumption gap of approximately 17% between different user profiles by using statistical modelling of a green office building in China. This highlights the importance of improved communication between building management and occupants which this project will investigate by interviewing building management to better understand operational decisions. Another study had three profiles, "actual", "compliance" and "standard" (47). The actual profile was using measured data in case study residential buildings in Denmark, the compliance refers to the profile generated from regulations and the standard profile was based on average data for buildings of similar sizes collected through surveys. They reported significant differences between the three occupancy profiles, compliance used about 60% more than actual and 30% more than the standard profile. This confirms a link between the performance gap and occupant presence and the use of extra appliances. These various user profiles provide different ways of comparing occupant behaviour to better understand the magnitude between different levels and highlight the need for improved communication between designers, building management and occupants.

A common factor impacting building energy consumption and also contributing to the performance gap is weather (55). Differences between measured heating and cooling degree days and the historical data used in energy modeling can contribute to the HVAC performance gap (55). Using outdoor air temperature, a case study building model was calibrated, it was found that energy consumption varies more with outdoor conditions depending on the system efficiency (i.e., a low efficiency system might consume more energy as it gets colder outside) (55). This suggests that in more efficient HVAC systems and building envelope, energy consumption variation based on outdoor conditions may decrease.

Performance gap studies are context, methodology and geography dependent. In this case study, NZEB is the first Canadian office certified zero-carbon building (23), there were no prior studies to our knowledge in Canadian offices. Additionally, most studies use a quantitative approach to analyze and model the impacts which focus on the ‘what’ and ‘how’ behind the performance gap (44). There is a need for using a mixed-methods approach to understand the ‘why’ and ‘how’ behind the results found in performance gap assessments (44). The proposed exploratory mixed-method study for comparison is a unique opportunity for Canadian researchers to contribute to the occupant behaviour performance gap conversation.

One way to address the performance gap can be through commissioning activities (12) used to investigate and learn more about equipment operations. Typically, the building operator spends time post-construction learning about the building equipment such as the HVAC and fine-tuning operational setpoints (e.g., temperature and pressure settings). This process typically takes 12-18 months; however, new innovations in building management systems can help reduce this time by efforts to be more targeted.

2.4 Commissioning

In building commissioning literature, there were three main types of studies found. First there were those that analyzed ways to improve the efficiency of building commissioning which proposed automated fault detection to improve performance. Then there were those that focused on operator experience and the access to data tools that empower targeted actions. Lastly, there were meta-analyses that compared different commissioning projects and their energy savings.

Building commissioning generally has two main types: existing building commissioning and new building commissioning (56). Existing building commissioning looks at improving existing building's performance, usually focusing on solving a specific operational challenge after the building has been built for a while(56). It is far less standardized and established relative to new building commissioning which has established standards and guidelines by ASHRAE (57). 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 (14). 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 reducing the performance gap and energy consumption.

Factors that impact commissioning effectiveness and efficiency include access to building management tools (12) and operator experience (54,58). Interviews with building operators found that data-driven insights can inform control strategies to optimize building operation; however, the operators need some familiarity with these tools to act on their insights (58). To experience the long term and continued benefits of commissioning, it was suggested that building owners monitor and maintain the operational systems continuously (59). Lack of information integrity and insufficient knowledge and experience of operators and other stakeholders were identified as core challenges associated with the building energy performance gap in a social network study (60). Strategies proposed to overcome these obstacles include establishing a platform for collaboration to engage with all stakeholders throughout a building's life cycle, this may allow for efficient problem solving throughout design, construction and operation (60). Thus, accessing building management tools coupled with collaboration among stakeholders including the occupants, operator, design and maintenance teams can improve commissioning efficacy.

Automated building commissioning using building management systems is proposed to improve efficiency and continuity. One study provides an automated tool to allow building operators to estimate the potential savings from specific commissioning projects (56). Another develops tools to automate energy audits and commissioning in collaboration with industry and research partners (61). This builds on previous work that used building management systems databases to create measured energy profiles to calibrate a dynamic model to be used for continuous online modeling and evaluation of the performance gap (12). The calibrated model was found to reduce the performance gap by improving fault detection and allowing for data-driven diagnostics (12). Therefore, these studies illustrate the potential in automating some aspects of building commissioning and monitoring to empower the operator with efficient data-driven trends.

In meta-analyses of commissioning projects, different benefits of new building commissioning were highlighted to include energy savings and improved building operation performance (15,62). Building operator motivation of pursuing such projects ranges from extending equipment life, complying with building codes or rating systems such as LEED and increasing occupant productivity (15). In analyzing 105 office existing commissioning projects a median of 6% energy savings was found in North America (15). Although new building commissioning is also common, there is limited data quantifying the energy savings (15). Another study evaluated the impact of existing building commissioning of 592 buildings in the Texas A&M International University (62). Of these 592 buildings, 32 were offices and they had electricity savings ranging from 1% to 43% with a median of 13% (62). These studies illustrate the motivation and potential size of energy savings from investing time, effort, and financial capital in building commissioning.

Commissioning can play a role in decreasing peak demand energy consumption which has cost benefit savings for building operations. In an existing building commissioning project, an estimated 37% energy reduction in annual peak demand was found using a calibrated modeling approach on a campus building (63). In another study, average savings were measured to be 33% using demand response strategies such as thermostat setpoint adjustment with a reduction in minimum airflow if a variable air volume system is available (64). This can decrease energy consumption while maintaining occupant comfort (64). Therefore, monitoring peak demand consumption and finetuning operating procedures can lead to reduced energy consumption and operating costs.

2.5 COVID-19

Residential buildings were more investigated in the literature, likely due to the increased occupancy during the pandemic; however, the decreased occupancy in office buildings also created an opportunity to investigate base building energy consumption. The literature described in this section looked at a variety of housing options and housing investigating both energy impacts and indoor air quality of the COVID-19 pandemic. This study aims to add a missing perspective. Empirical data from a northern climate office building energy consumption can add to the COVID-19 literature by providing insight of unoccupied building operation and the transition to an increased remote working environment.

Several studies looked at residential housing to investigate the impact of increased home occupancy on energy consumption. In a study of Canadian social housing, energy consumption was found to slightly increase overall during the first few months of the lockdown (65). More interesting changes took place in the hours of energy consumption as occupancy schedules changed with some working from home (65). Similar findings with the peak demand times shifting were found in another residential Canadian case study looking at 500 homes (66). They also found that the average household energy consumption increased by 12% in 2020 relative to 2019, however, some of this increase has been attributed to weather variation between the two years (66). Further investigation showed that there were mixed consumption patterns, with some households showing significant increases while others had minor changes (66). This variation might suggest the impact of different energy consumption behaviours and attitudes towards energy conservation at the household level.

In office studies, simulation approaches were used to investigate the impact of continued operation under COVID-19 guidelines regrading increased ventilation and fresh air intake (31,67). It was estimated that offices may consume up to 28% more energy depending on their climatic zone with the gap between pre and post-COVID-19 consumption patterns increasing for areas of colder climates (31). Another study predicted an increase of average delivered demand increasing up to 19% under different lockdown scenarios (67). Interestingly, it was reported that the mean demands would decrease by up to 12%, which may contribute to a similar total energy consumption demand (67). Moreover, a higher electricity demand was predicted for residential buildings when confinement levels increase, whereas office and school energy consumption were expected to decrease (67).

One data-driven approach applied statistical correlation analysis on national energy consumption under COVID-19 conditions (30). It was reported that in the case of offices, monthly electricity consumption remained within 5%, except for March; however, gas energy consumption decreased by 8% in some regions (30). In contrast, another study found that the first lockdown led to a 64% decrease in monthly energy consumption in a case study building used as an exhibition hall and office (68). The large difference between the two studies findings could be attributed to functional difference in outdoor temperature and the availability of data to draw the conclusions (i.e., Kang et al. (2021) (30) used big data to compare many buildings, whereas Su et al. (2022) (68) had one case study building and compared a few months of energy consumption). Therefore, empirical COVID-19 studies showed different energy consumption patterns depending on the region and data availability.

Other studies looked at changes in energy consumption in university campuses (69,70). The transition to online courses left campuses less occupied during the pandemic, depending on the academic period (e.g., exams, study days, regular semester days) (70). As campuses have many different types of buildings ranging from offices to laboratories, there was a wide range of impact observed on energy consumption. One study showed that campus building's weather-corrected energy consumption was reduced by approximately 20% during the post-pandemic year (69). The highest energy reductions comparing the energy consumption before and during strict lockdown were found in library buildings, with a 74% decrease (69). In another campus, it was reported through statistical analysis that research, academic and non-habitable spaces which are not occupied by people, such as building service areas had the greatest impact on energy use (70). Energy savings of 16% were found during the COVID-19 period although most research buildings were still operational at this time (70). Lastly, one campus found little change in energy consumption of office buildings, whereas laboratories showed different trends (71). These findings demonstrate the impact of reduced occupancy from COVID-19 on different building types in a higher education setting.

In terms of prevention of COVID-19 spread, many studies focused on analyzing the indoor air quality (72–75). Different filter types (e.g., advanced carbon, ionization, high efficiency particulate air (HEPA)) were used as a common improvement technology to remove contaminants from the surroundings (72). While ventilation can dilute contaminants, using 100% fresh can have huge energy implications, thus there is a need to improve HVAC systems to integrate air purifying techniques while keeping energy efficiency in mind (72). Another group recommended applying MERV 7 as a primary filtration and minimum efficiency reporting value (MERV) 14 as secondary filters to remove the majority of airborne particles and reduce the spread of COVID-19 (73). In a study looking at places of worship, keeping the windows open and reducing occupancy to reduce the spread of COVID-19 was found to produce average particulate matter concentration 2.5 and 10 levels lower than pandemic guideline values (74). It was not analyzed how these concentrations changed due to the pandemic (i.e., increased or decreased). Furthermore, in a study minimizing energy consumption and virus transmission, different scenarios were evaluated and offices were reported to have the lowest per capita consumption given that occupants would wear their masks indoors (75).

The limited COVID-19 empirical office studies published at the time of writing (November 2022) suggest that more literature in this space is needed to provide insights on how commercial buildings consumed energy during the pandemic. Additionally, the energy consumption pattern observed in offices post

COVID-19 resulting from the increased remote working remains unclear. The absence of occupants also presents a unique opportunity to understand how a building behaves without occupants. This can help improve base building design by pointing out areas of phantom loads.

2.6 Lighting and Plug Loads

Lighting and plug loads can be responsible for up to 30% of Canadian commercial building energy consumption with plug load consumption seeing over a 50% increase in the last 18 years (16). Occupant behaviour including presence compared with absence, can impact both these loads' energy consumption. Literature aims to understand the ways that lighting controls can be improved and interventions that can be made to nudge energy conservation occupant behaviour. This study aims to add empirical data to this body of literature which mainly looked at short term-controlled studies and simulations of control approaches.

Lighting controls are typically studied using simulation approaches or controlled intervention studies to understand energy savings potential while maintaining occupant comfort (18,76). In a study investigating occupant preference to different dimming approaches in an open floor office plan, it was found that occupants can find some lighting distributions unfavourable (76). This highlights the importance of considering occupant preference as well as energy consumption (76). In a double-blind occupancy study using automatic occupant centric controls, 38% energy savings were achieved in offices compared with standard controls (18). In a daylighting smart control design study, luminaire-based occupancy and light sensors were used with different control options (e.g., centralized, distributed) (19). Although this study provided a great starting point for smart controllers, further research is needed to assess the energy consumption of similar designs. In wireless lighting control study, impairments were found to contribute to illumination performance degradation, leading to a higher settling time of luminaires (20). Further investigation on energy consumption and improved performance of wireless lighting control options are needed to propel these control strategies forward.

Plug loads can be more impacted by occupants in comparison to other loads like HVAC that might be set on a specific operational schedule. If tenants do not unplug their laptops and other electronics, this occupant behaviour factor can directly impact energy consumption. Impacts of occupant behaviour, studies with energy consciousness nudging gaming interventions (21,22), found that plug load energy consumption can be decreased by up to 7% on workdays (22). Baseline data illustrated occupant schedules from 8:00 AM to 5:00 PM with minimal weekend and evening overtime (21). This illustrates the difference between work culture and the demand for specific services these firms provide (e.g., in tax accounting, there might be increased work demand during tax periods to meet client requests). It was found that depending on the occupants' engagement in energy saving behaviour, there might be limited opportunities to achieve additional savings using behavioural changes alone (21). Although these studies investigated the impact of occupant behaviour, prior to COVID-19 there were limited opportunities to study the minimum energy consumption these loads can consume without occupant intervention.

Occupant centric controls can be applied to HVAC, lighting and plug loads to decrease idle energy consumption. In a high-resolution sensor control study of 72 installed LED luminaires, it was found combining occupancy and daylighting harvesting led to a 79% energy savings in an open-plan office (77). Different control scenarios such as different power configurations were tested under various lighting conditions (e.g., blackout blinds closed, blinds retracted, partially closed) (77). Power consumption profiles during the day were analyzed, showing a maximum of 13W/m^2 as a baseline consumption level (77). Another study used a WiFi occupancy based smart control system that allowed for brightness adjustment in each luminaire in an office building (78). The study used a smart lighting control App to allow occupants to adjust the brightness of surrounding lights using their mobile device (78). The App could also detect where occupants are located to improve lighting schedule accuracy and avoid idle energy consumption when spaces are unoccupied (78). The experiment found 82% energy savings compared to using a static schedule and 51% reductions relative to a PIR sensor based lighting control scheme (78). This shows the potential of smart controls and how they can be applied to reduce energy consumption without invading occupant privacy. Lastly, another study formulated an adaptive lighting and blinds control algorithm to learn occupant behaviour (79). The office was equipped with dimmable fluorescent lamps and the blinds' positions were monitored through a camera (79). The data was analyzed to develop a regression model to predict when the lights would go on and when the blinds would be closed (79). Estimated energy savings due to using these adaptive control methods were approximately 25% (79). These studies highlight the variety of different control options available to reduce lighting energy consumption while keeping occupant comfort in mind.

2.7 Key Themes and Research Implications

The literature reviewed in this section is from the past ten years, highlighting the relevance of this topic in the last decade. With the abundance of simulation studies investigating ways to quantify and close the performance gap, there is a need for more empirical studies on energy consumption in buildings. Specifically, net-positive energy buildings in a cold climate region, can allow for better understanding of the implications of design decisions on operations. To ensure that new buildings are on track to meeting their design goals, commissioning decisions play a large role in monitoring and verifying building performance and empowering it to realize energy conservation. Granular data used to quantify the impact of commissioning decisions can help future building operators select targeted energy savings projects.

Occupant behaviour has been a challenge to understand, especially without a way to quantify the minimum energy consumption of a building without occupants. COVID-19 created the opportunity to collect and analyze such data, empowering researchers, and operators with a better understanding of the impact of occupancy on energy consumption. Findings from this study can add to the body of literature on lighting and plug load energy consumption, providing the novel contribution of post-COVID-19 analysis to help navigate building design in a remote working world. Data provided in this study can be used to simulate energy consumption of office buildings in a northern climate with similar design controls (e.g., daylighting).

Chapter 3 Methodology

3.1 Research Approach

This research is part of a five-year research project which investigates the Culture of Sustainability and its development in green office buildings (80). In this phase of the research, the energy consumption and generation of the case study building were analyzed. In particular, this study focused on HVAC commissioning decisions made by building operators and the impact of occupancy on lighting and plug load energy consumption during COVID-19. The purpose of this two-part investigation is to uncover ways that commissioning and occupancy impact energy consumption from three and a half years of operational data in a Canadian multi-tenant office building.

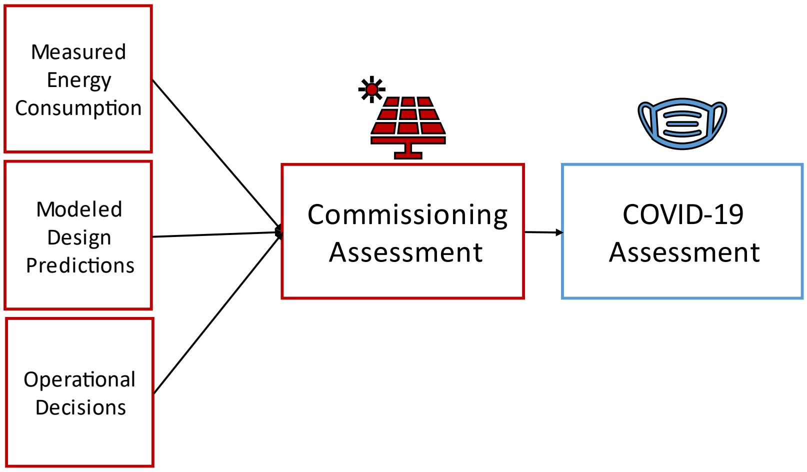


Figure 5: Summary of the broader data analysis process

To gain a holistic understanding of the impact of operator decisions on building energy consumption, a mixed methods approach was applied as demonstrated in Figure 5. There were two main analysis phases, one focused on commissioning activities and the other investigated the impact of COVID-19 on energy consumption. Specifically, an explanatory sequential design was followed where quantitative energy meter data was collected and analyzed before conducting key informant interviews with building operator and energy advisor to follow up on the results and to add qualitative data analysis to further understand the contributing factors to the observed trends. Explanatory sequential designs described by Creswell and Creswell (2017) (81), typically has two distinct data collection phases, focusing on the quantitative and qualitative data, followed by a data analysis and integration phase where the two types of data are analyzed separately and the quantitative data informs the qualitative data collection portion. To establish validity, the researcher can consider different options of following up on quantitative results in more depth in the qualitative data collection setting (81). The data collection process was iterative and took many rounds of quantitative results analysis, followed by key informant interviews to improve understanding of the observed energy consumption and generation phenomena.

A case study research technique was applied in this project to understand the energy consumption phenomena in this multi-tenant office building. As discussed by Yin (1981) (82), an explanatory case study attempts to provide a rendition of the facts that took place and provide explanations and considerations of these facts to lead to a conclusion based on the explanation that seems most aligned with the facts observed. In the case of evolv1, the project observed energy consumption and generation levels and tried to uncover the contributing factors that may be correlated with these observations. The tenants were aware that data on their energy consumption was collected through communication with the building operator; however, the individual occupants were indirectly impacted by this method of data collection. The purpose of this investigation is to share how future buildings may be operated to reduce their energy consumption levels. Additionally, the investigation during COVID-19 highlights the minimum energy consumption observed with minimal occupants in a northern office building. This disruption provided an opportunity to study a new phenomenon, the unoccupied but operational building, which was challenging to explore during pre-COVID times. Table 3 provides a summary of the major key events that took place in evol1 from January 2019 to June 2022, the three and a half years of operation during the time of the study.

Table 3: Summary of key events to provide context for data analysis

Year	Key Events
2019	Commissioning on-going (January – September) Adjusted thermostats to rely on return air temperature to improve occupant comfort (January) Fine tuned pumps and other HVAC controls to reduce consumption (July) Occupancy: baseline occupancy established (January – December)
2020	Set-back mode, temperature of 18 °C for heating and 26 °C for cooling during all hours of the day (April – October) One floor on occupied settings, operating at 22°C during weekday office hours (8 am – 5 pm) with unoccupied settings during off hours and weekends (November – December) Occupancy: typical (January – March), minimal* (April – October), and increases to approx. 20% occupied when one tenant returned (November – December)
2021	Set-back mode, temperature of 18 °C for heating and 26 °C for cooling during all hours of the day (January – October) One floor operates at 22°C during weekday office hours (8 am – 5 pm) with unoccupied settings during off hours and weekends (November – December) Occupancy: minimal (January – October), approx. 25% occupied (November – December)
2022	Variable air volume (VAV) controls were reset (March) Entire building operating on occupied settings (January – Present) Occupancy: Occupants return to work periodically using a hybrid work-from-home model

*Minimal occupancy = <10%

3.2 Electricity Meters and Sensors

In the quantitative data collection, first the process started with extracting annual energy consumption data from a virtual database. The raw data was measured every 15 minutes for each of the 43 energy consumption meters, the metering points and their equipment type are displayed in Table 4. This data was then added up to produce a daily energy consumption load for each of the meters. Then the data was further processed to combine different energy meters if they were in the same end-use category. Depending on the end-use category, external data such as outdoor air temperature was collected and analyzed with the empirical data collected. Depending on the granularity of the data required for the level of analysis (e.g., daily, monthly or annually), the data was further aggregated to generate daily, monthly and annual energy consumption profiles. More details on the steps of this process can be seen in Appendix B.

Similarly, quantitative data was collected from two solar electricity generation meters to understand the load profiles in a northern climate. This data was analyzed with the energy consumption data collected to assess the net-positive status of the building. For annual comparisons, estimates of 2022 total generation and consumption were provided. The average solar electricity generation was used to estimate 2022 generation and the consumption was approximated by doubling January to June measurements.

Another source of data used was temperature sensors used to assess occupant experience of the indoor temperature. There were seven passive infrared (PIR) sensors on the first floor that were collecting measurements hourly to record the occupant experience in 2019. Those measurements were compared with 2022 data to assess the impact of commissioning activities on average surface temperatures.

Table 4: Summary of equipment name and type at different metering points and their end-use category

Equipment Name (meter points)	**Equipment Type (Current)**	**End-use category**
TX-6X1D (Base lighting, interior/exterior)	Transformers	Lighting
ATS Life Safety (Lighting, FA panel)	Sub-Feed	
LP-1LA (Tenant Lighting)	Sub-Feed	
LP-2A (Tenant Lighting)	Sub-Feed	
LP-2XTL (3rd floor tenant lighting)	Sub-Feed	
LP-A (Tenant lighting)	Sub-Feed	
LP-C (Tenant lighting)	Sub-Feed	
B-1 (Main boiler VRF loop)	Boiler	
AHU-1 (Atrium air handler)	HVAC Package	
DP-6X2B (2nd floor FCU's, BB power)	Sub-Feed	
DP-6X3B (3rd floor FCU's BB Power)	Sub-Feed	
HP-1 (Heat pumps)	Heat Pump	
HP-2 (Heat pump)	Heat Pump	
HUM-1 (MUA-1 humidifier)	Humidifier	
HW-1 (Heat wheel part of MAU-1)	HVAC Package	
MAU-1A (Supply fan)	HVAC Package	
MAU-1B (Return fan)	HVAC Package	
MPD-6X (1st floor Main Mechanical panel)	Sub-Feed	
TX-2XPH (Penthouse panel - mech)	Transformers	
TX-MPD-2X (1st floor Main Mechanical panel)	Transformers	
GEO WELL PUMP (Geothermal loop pump)	Pumps	Pumps
P-1 (VRF loop pump)	Pumps	
P-2 (VRF loop pump)	Pumps	
P-3 (Heating loop pump)	Pumps	
P-4 (Heating loop pump)	Pumps	
P-5 (Cooling loop pump)	Pumps	
P-6 (Cooling loop pump)	Pumps	
P-7 (MUA-1 glycol loop pump)	Pumps	
P-8 (MUA-1 glycol loop pump)	Pumps	
P-9 (Main boiler injection pump)	Pumps	
ATS-A NON-LIFE SAFETY (Generator, security)	Sub-Feed	Plug Loads
DHWH-C1 (Base building hot water heater)	Boiler	
DP-6X1B (Plug loads, Hand dryers, Elevator)	Base Building	
MCR (Tenant server panel)	Sub-Feed	
PP-2XTA (Tenant plug loads)	Sub-Feed	
PP-2XTB (Tenant plug loads)	Sub-Feed	
PV-LINE (Rooftop PV)	Solar Panel	Base Building
PV-LOAD (Parking lot PV)	Solar Panel	
RP-B (Tenant plug loads)	Sub-Feed	
RP-D (Tenant plug loads)	Sub-Feed	
DP-AA (Tenant Plugs)	Sub-Feed	
RP-1A (Tenant Plugs)	Sub-Feed	
EV Charger	Car Charging	Not part of BEC

3.3 Key Informant Interviews

In the qualitative data collection phase, key informant interviews explored different types of questions pertaining to the case study building operation. The key informants were the building operator who works as a project manager to oversee building operation and maintenance, and the building energy advisor who has building energy consulting experience. In the beginning the questions were more related to the design and how the building generally operates with the different equipment (e.g., how the fan coil units operate and how the building regulates temperature) and then they became more specific regarding energy consumption trends. For example, questions to understand commissioning activities included, what were the major changes that took place in this month that might lead to the observed energy consumption. This led to uncovering key operating decisions such as reducing the humidification level to rely more on the humidity recovered by the enthalpy wheel system and the natural humidification provided by the living wall. These decisions are discussed in more detail in Chapter 4. More specific details on the types of questions asked can be seen in Appendix C.

3.4 Commissioning Activities

3.4.1 Sample

This part of the analysis focused on comparing 2019 consumption levels with 2022 to investigate the impact of commissioning activities. Times of minimal occupancy due to COVID-19, during 2020 and 2021 were excluded from the analysis as they did not represent typical operation and occupancy loads. As the commissioning activities mainly focused on HVAC and pump energy consumption, these end-uses were analyzed in more detail to investigate the observed impacts of specific decisions. Furthermore, the measured energy consumption was compared with modeled predictions to approximate the performance gap prior to commissioning and how it was impacted after commissioning.

3.4.2 Data Collection

A cloud hosted database of the equipment provider with measured electricity meter data was used to collect the electricity consumption data throughout the analysis period. The data from HVAC and pumps were measured by 22 energy meters and the remaining 21 were used for lighting, plug loads and base building energy consumption. One meter was for electric vehicle charging but it was excluded from the building energy consumption calculations. During the data extraction procedure, three and a half years of operational data were saved in the online platform and became available to the researcher. External average outdoor air temperature data was collected from Environment and Climate Change Canada databases for the Region of Waterloo (83).

A similar database had the energy generation data and that was extracted in a similar procedure from an online platform. Both the consumption and generation were aggregated monthly and annually to investigate the net-positive energy status of evolv1.

3.4.3 Data Analysis

Energy use intensity (EUI) is the ratio of building energy consumption to total floor area (84). This was obtained to allow evolv1 to be compared easily with other office buildings as it normalizes to the area. The median energy consumption of Canadian offices in 2018 was found to be 275 kWh/m^2 (85). To calculate the EUI of the building, the floor area was obtained from the design model and used along with the measured energy consumption to estimate the ratio as the following:

$$EUI\ (kWh/m^2) = measured\ electricity\ in\ kWh\ /\ total\ floor\ area\ in\ m^2$$

After normalizing the area, several assessments were completed. Firstly, the generation and consumption data were analyzed monthly to uncover the electricity generation profile of the building. Then, the commissioning activities qualitative data was collected through key informant interviews and that pointed towards investigating specific energy meters to quantify the energy savings. Moreover, the peak demand consumption was analyzed using three HVAC meters to uncover the impact of commissioning decisions on these loads. One external variable that was considered was outdoor air temperature relative to HVAC energy consumption, in the first 6 months of 2019 relative to 2022, after commissioning activities took place. Lastly, a performance gap assessment was completed by comparing measured and modeled energy consumption data. The modeled predictions were obtained from a collaboration with the building designers and the original energy model was obtained to assess the annual, end-use and monthly performance gaps.

3.5 Occupancy and COVID-19

3.5.1 Sample

To further investigate the performance gap, the impact of occupancy on lighting and plug loads was analyzed. This part of the study focused on the energy consumption during the COVID-19 period during 2021. The data was extracted from the online data base in a similar procedure to the commissioning activities analysis. Baseline energy consumption was established using 2019 data and 2022 data was used to estimate energy consumption levels post-COVID-19. The lighting and plug loads were the main focus of this investigation as they are occupant impacted loads in this case study building. These loads were used to better understand when occupants were in the building during 2019 and how the mainly unoccupied building in 2021 consumed energy. Depending on the temporal granularity of the analysis, hourly, daily, monthly or annual aggregated data was used.

3.5.2 Data Collection

The data was collected in a similar manner to the commissioning activities section, however there was no use of the solar electricity meters as this was not needed in this analysis. This part of the analysis focused on 22 lighting and plug load electricity meters and the remaining 21 were used only for calculating the total building energy consumption. Data from 2020 was collected but it was not the focus of the analysis since it was a mixed occupancy period, with the transition from baseline occupancy in March to minimal occupancy due to COVID-19 lockdown. External data for irradiance was collected from the National

Aeronautics and Space Administration (NASA) databases (86). This was used to investigate the relationship between outdoor daylighting conditions and lighting energy consumption.

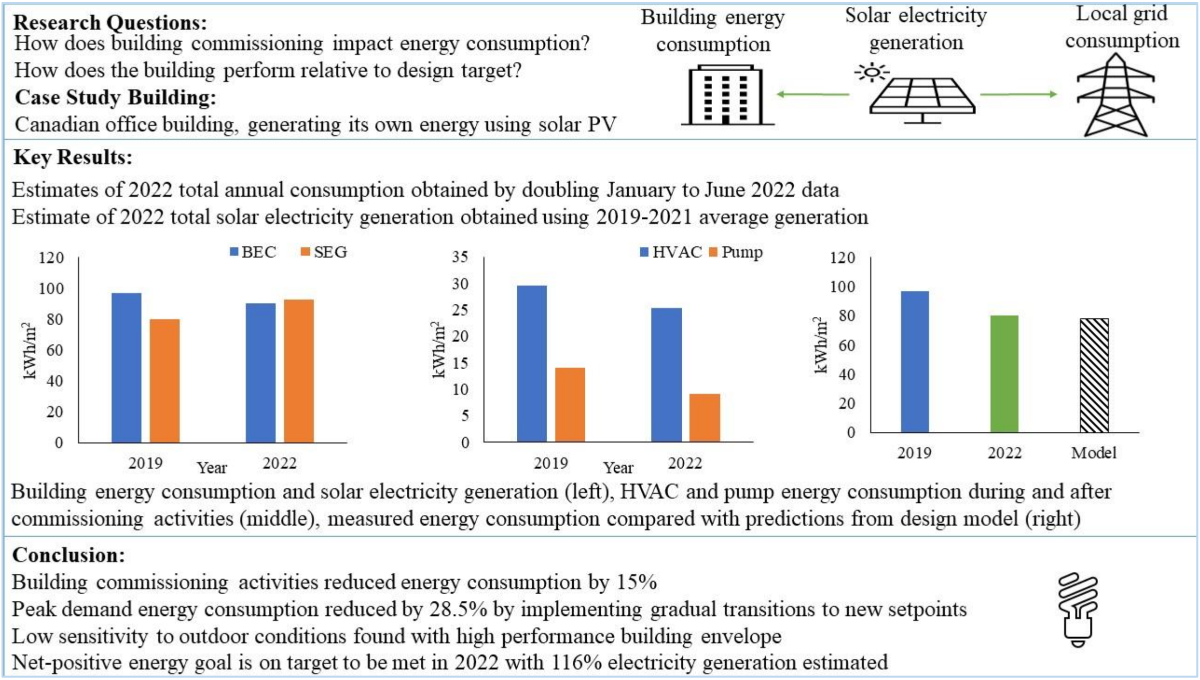
3.5.3 Data Analysis

Three main levels of analysis were conducted to investigate the impact of occupancy and COVID-19 on building energy consumption. Firstly, irradiance data was used to investigate the correlation between outdoor conditions and lighting energy consumption. Then, the 2019 baseline data and 2021 minimal occupancy data were compared for seasonal variation across the years. To further investigate the significance of the difference from reduced occupancy during COVID-19, a daily statistical analysis using a monthly unpaired t-test was completed to compare lighting, plug load and total consumption levels in 2019 with 2021 and 2021 with 2022. Lastly, hourly profiles were created for lighting, plug load and base building energy consumption to investigate occupant schedules and the changes due to reduced occupancy during COVID-19.

Chapter 4 Net-positive office commissioning and performance gap assessment: empirical insights

4.1 Abstract

During commissioning activities, many decisions can be made to reduce building energy consumption and help building operation to meet design goals. Decisions made in this period include reducing the temperature in unoccupied spaces such as mechanical equipment rooms, reducing the setpoints on specific equipment (e.g., amount of fresh air entering the building) and resizing equipment, such as pumps, to better meet operational and user needs. Energy meter data from January to December 2019 was compared with the first six months of 2022 to quantify the impact of commissioning decisions on building energy consumption. Interviews with key informants such as the building operator and energy advisor, were conducted to gain a holistic understanding of operational decisions. It was approximated that building commissioning activities primarily on HVAC reduced building energy consumption (BEC) by 15% per year. Lastly, it was found that building operator expertise and the tools (e.g., live data from energy meters) available to them improved the efficiency and effectiveness of commissioning activities and ongoing operational decisions.



Research Questions:
How does building commissioning impact energy consumption?
How does the building perform relative to design target?
Case Study Building:
Canadian office building, generating its own energy using solar PV

Key Results:
Estimates of 2022 total annual consumption obtained by doubling January to June 2022 data
Estimate of 2022 total solar electricity generation obtained using 2019-2021 average generation

Building energy consumption and solar electricity generation (left), HVAC and pump energy consumption during and after commissioning activities (middle), measured energy consumption compared with predictions from design model (right)

Conclusion:
Building commissioning activities reduced energy consumption by 15%
Peak demand energy consumption reduced by 28.5% by implementing gradual transitions to new setpoints
Low sensitivity to outdoor conditions found with high performance building envelope
Net-positive energy goal is on target to be met in 2022 with 116% electricity generation estimated

Figure 6: Graphical abstract summarizing key findings and conclusion

4.2 Introduction

4.2.1 Background

In an effort to decarbonize the built sector, responsible for 30% of global energy consumption and 27% of total energy sector emissions (1), net-zero energy buildings have been generating their own electricity using renewable energy technologies such as solar photovoltaic (PV) systems (47). Net-zero energy buildings, zero energy buildings and zero net energy buildings are terms used synonymously (34). They have the same design goals, that is to generate as much electricity on-site as they consume annually (8). This means that the overall or net energy demand from the grid is less than or equal to the energy generation by the building (34). To reach net-zero energy status, there is balance of energy import and export to and from the local grid to be maintained in a period of year (8). This balance is completed on a source energy basis between the energy delivered and exported (6). If a building produces 30% or more of its net energy through renewable on-site generation, then this can be considered a nearly zero energy building (32). There are two main ways to account for energy generation, first is net-zero site energy which is accounted for on-site energy generation, and the other is net-zero source energy (primary energy) which accounts for the energy balance between imported and exported energy from and to the grid, including the energy needed for delivery and generation (32).

Other types of net-zero buildings, include net-zero carbon, life cycle zero energy buildings and off-grid zero energy buildings (34). Canada green building council defines a zero-carbon building as one that is “highly energy-efficient and minimizes greenhouse gas emissions from building materials and operations” (35). Carbon offsets can be used to counterbalance emissions until the building operation can support the zero-carbon performance goal (35). Going one step beyond zero-carbon are the life cycle zero energy buildings which include embodied energy of the building and its components. The on-site energy generation aims to be as much as the lifetime embodied energy within the materials and systems (32,36). Lastly, off-grid zero energy buildings are not connected to an off-site energy generation facility and produce all of their energy through renewable sources without relying on any external grid support (34). Birkeland (2008) (33) describes positive developments as physical developments that have net-positive impacts during their life cycle by improving economic, social and ecological conditions. He asserts that positive developments would not only generate clean energy, water or air but also leave the ecology or physical environment better than before the development activity took place (33). From this paradigm stems the net-positive energy buildings (NPEB) which is a development whose energy generation exceeds its energy consumption on an annual basis (7). This paper provides a post-occupancy, empirical energy analysis from a NPEB case study in Southwestern Ontario, Canada, displayed in Figure 7.

Figure 7: Case study building exterior showing parking lot and roof solar PV systems, image from (87)

Minimizing building energy consumption (BEC) during operation is integral to meeting annual demand using the on-site electricity generated. After construction, commissioning prepares the building for occupancy and ongoing operation. The building operator can be the project manager or other personnel in charge of leading the maintenance teams and managing the relationship with the occupants. During commissioning, the building operator and maintenance team learn how the equipment operates and finetune it to maintain occupant comfort and attempt to meet design goals (14,15). A measurement of net-zero energy buildings failing to meet their design goals is the performance gap, which is when design predictions are different from measured consumption (13). This case study aims to investigate the role of building commissioning activities on total, HVAC and pump energy consumption in a NPEB case study. The performance gap was assessed by comparing operational data with energy model predictions from the design phase.

Building commissioning seeks to assess the quality of equipment operation and work towards achieving performance targets from the design phase (56). There are two main types of commissioning: new building commissioning and existing building commissioning. New building commissioning is focused on preparing buildings for occupancy after construction, whereas existing building commissioning aims to improve ongoing building operation after the building has been built for a while. New building commissioning is an established process with guidelines from ASHRAE (57) and Natural Resources Canada (88); however, the building commissioning activities in this study include informal energy fine-tuning efforts beyond the official commissioning for occupancy process.

Commissioning is a holistic and systematic process where operator decisions can lead to energy savings (15) which can reduce the performance gap (9–11). The performance gap can be due to several factors including optimistic design targets, ineffective building operation and limited building commissioning (12). Insights from building operators in this case study uncover lessons to improve future building operation.

4.2.2 Related Studies

Although commissioning is often in the transition period between construction and occupancy, continuous commissioning can ensure ongoing energy savings as the operator learns more about the building behaviour over time. To improve the efficacy of this continuous process, automatic commissioning building management systems and advanced controls were found to improve building start-up and energy efficiency by up to 35% in newly built and existing buildings (61). A case study of continuous commissioning in a campus building reports the importance of data visualization tools to facilitate data-driven energy diagnostics (89). Lastly, in a meta analysis of 446 North American existing building commissioning projects, energy savings were found to typically range from 3.4% to 12.4% (15).

Building commissioning effectiveness is impacted by operator experience and proactiveness (58,54). If commissioning is not completed or is done poorly, a building may never realize its design potential and fall into a permanent performance gap. A previous literature review found that poor communication and collaboration among stakeholders can lead to a performance gap (60). Collaborations among stakeholders are one way to work towards meeting design goals (60). Building monitoring and maintaining building systems, are an important factor in ensuring the continued benefits of building commissioning (59).

There are several factors impacting annual BEC variation, with weather being a key confounding variable (55,90). Differences between weather data used in building modeling and that experienced can contribute to the performance gap observed during operation (90). Improving the building envelope performance, including insulation, airtightness and window glazing, are energy conservation measures to reduce the impact of outdoor conditions on building BEC (91). Another aspect of reducing energy consumption is through the use of energy efficiency measures (HVAC, electric lighting and plug loads) system operation, which can be improved during commissioning activities. One way this has been done is through automated simulated HVAC building commissioning analysis which can reduce consumption for similar outdoor conditions by using fault detection (92). An implementation of this method led to estimated savings of 5% after 5 months of operation in a U.S. office building (92).

Part of office building commissioning can include investigating the transition between weekend unoccupied mode and weekday occupied mode to reduce the peak demand that can be generated by the transition. On a Monday start-up procedure, the building reaches new setpoints which can lead to a spike in electricity consumption. Peak demand electricity consumption can be permanently reduced by fine-tuning HVAC operating procedures (93). Higher peak demand can result in increased operational cost and pressure on the local grid. This peak demand on the grid may be exaggerated in a NPEB as there is no pre-dawn solar generation to reduce the net peak experienced. In a peak demand commissioning project, it was estimated that using calibrated simulations led to an average of 34% electricity savings (93). Similarly, another study found that using calibrated simulations to improve HVAC lighting and plug load controls achieved 30% peak demand reduction (64).

Design strategies also contribute to building energy performance during operation. The significant relationship between building envelope and energy consumption of office buildings provides energy savings opportunities (91). A simulation study of offices in different climatic regions demonstrates the impact of glazing and building envelope insulation on energy-savings (94). Solar air pre-heaters can be used to reduce BEC by increasing fresh air temperature (95). Heating and cooling using water-cooled VRF heat pumps can reduce BEC while improving thermal comfort (96). Studies of enthalpy wheel performance show that it can operate efficiently under high temperature difference conditions (97), which is inline with the operating conditions in a Southwestern Ontario climate with very cold temperatures in winter.

4.2.3 Motivation and Objectives

The performance gap and building commissioning have been researched using a variety of methods, mainly simulations as illustrated above. There are a few empirical studies on NPEBs, specifically offices in a northern climate. However, there is limited empirical data on how these types of high-performance buildings operate post-occupancy. Three main questions were investigated using a mixed methods approach of combining quantitative energy metering and design model data with qualitative key informant interview data: i) Is the case study building meeting the design goals of net-positive energy operation; ii) What were the decisions made during commissioning activities and how did they impact BEC; and iii) How does the NPEB case study perform in comparison to the disaggregated end-use energy design targets? Empirical data from a recently constructed NPEB is analyzed to demonstrate how the performance gap can be reduced while maintaining occupant comfort through commissioning activities.

4.3 Methodology

This section describes in detail the methodology applied to assess the performance gap between modeled and measured building energy consumption (BEC). Energy savings achieved through commissioning activities were quantified through the methodology summarized in Figure 8. The experimental findings and discussion are presented in the subsequent section.

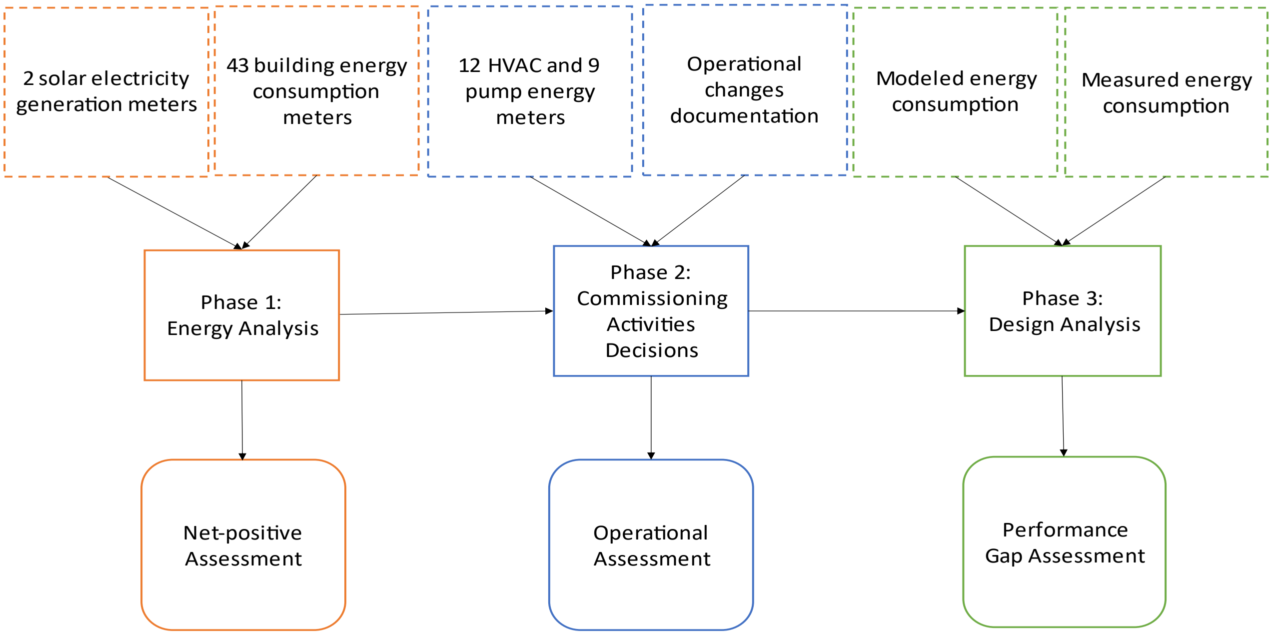


Figure 8: Summary of the methodology used for investigation

4.3.1 Research Approach

The emerging theme from the literature suggests a need to use mixed methods approaches to get a deeper understanding of operational decisions (31,32). As such, a combination of quantitative and qualitative methods can be applied to gain a holistic understanding of the building operation and commissioning decisions. Quantitative data is collected from digital building management systems (BMS) databases to calculate the measured energy consumption and then compared with the predictions from the design phase. Qualitative insight can be provided from key informant interviews to explain the ‘how’ and ‘why’ certain operational setpoint modifications and equipment adjustments were made.

4.3.2 Research Site

The case study building is a multi-tenant office NPEB shared by four tenants, including a university classroom and a business incubator partnership.

Table *5* provides the design specifications of the building.

Table 5: Summary of building design specifications

Architectural	
Site	Southwestern Ontario, Canada
ASHRAE climate zone	6A
Net floor area, m^2	9, 406
Orientation	East-west long axis
Window type, S	Triple-glazed
Window-to-wall ratio	37
Visible light transmittance	0.53
Solar heat gain coefficient	0.32
U value, center of glass window $W \cdot m^{-2} \cdot {}^oC^{-1}$	1.14
Rated RSI-value wall, $m^2 \cdot {}^oC/W$	5.3
Rated RSI-value roof, $m^2 \cdot {}^oC/W$	7.0
Mechanical	
Main system, type and features	Centralized dedicated outdoor air system (DOAS). Open loop geothermal exchange system.
Damper control	Modulated based on CO_2 levels (demand control ventilation)
Heat recovery	81% efficient enthalpy wheel which recovers sensible and latent heat from building exhaust
Domestic water	Low-flow fixtures and rainwater harvesting system
Space heating and cooling	Water-cooled variable refrigerant flow (VRF) system
VRF coefficient of performance	3.1
Other ventilation system	Solar air pre-heater
Electrical	
Pump controls	Variable frequency drives (VFD)
On-site roof PV nominal capacity, kWp	264
On-site parking lot PV nominal capacity, kWp	504
Inverter capacity, kW (kW/unit) (No. units)	619 (33) (19)
Lighting power density, W/m^2	4.75
Other features	3 storey and 5.7 m wide living wall

4.3.2.1 Climate and Weather Conditions

The case study building is located in a 6A ASHRAE climate zone. In 2019 the recorded mean temperatures ranged between 27 ºC and -21 ºC in 2019 as outlined in Figure 9 (right), obtained with data from Environment and Climate Change Canada (83). In Figure 9, there is the measured average monthly temperature compared with the climate average dry bulb temperatures from the ASHRAE handbook fundamentals (98). Similarly, the monthly HDD were obtained and summarized in Table 7. To compare the modeled weather data with the measured, HDD and CDD from 2019 were summarized in Table 7.

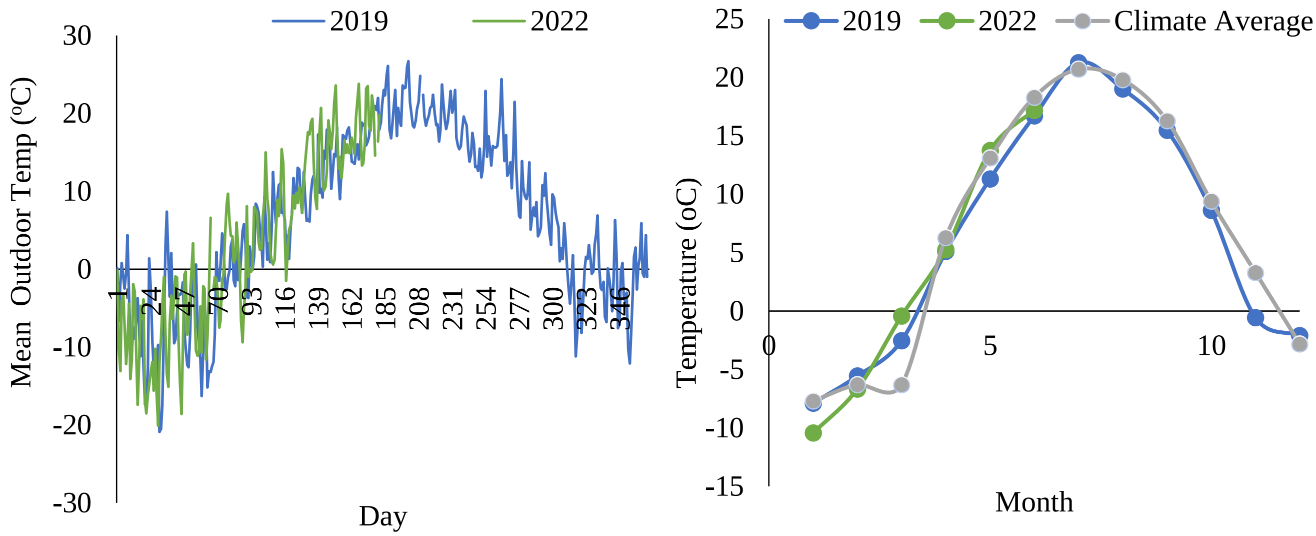


Figure 9: Daily mean outdoor temperature (left) and average of daily monthly temperatures and the monthly design dry bulb temperature from ASHRAE (right)

Table 6: Monthly 18 ºC HDD for 2019-2022

Month	2019	2022	Month	2019
Jan	802.1	881.7	**Jul**	2.2
Feb	659.8	691	**Aug**	16.9
Mar	636.5	567.5	**Sep**	89.6
Apr	386.8	382.3	**Oct**	294.1
May	207.5	146.7	**Nov**	556.9
Jun	53.6	57.5	**Dec**	623.1

Table 7: Annual 18 ºC HDD and 18 ºC CDD for operational years 2019 and model

Year	HDD	CDD
2019	4,329	181
Model	4, 062	1, 170

4.3.3 Data Analysis

An 18-month performance assessment was conducted. Commissioning activities and weather were monitored and analyzed for their impact on energy use. Measured performance was compared to the design model to assess the performance gap. Due to COVID-19, there were changes in the building operation to adjust to periods of minimal occupancy, as such 2020 and 2021 operational data was excluded from this analysis and assessed separately. Although the building operation is on occupied mode (i.e., heating to 22ºC, cooling to 24ºC) for 2022, the occupancy remains low (approximately 30% of the maximum occupant intensity) since most occupants did not return to work everyday, but instead come in once or twice a week and otherwise work from home. This represents the general increase in remote work observed as a result of COVID-19 (31). This change may impact the BEC in 2022 in terms of internal heat gains and tenant plug loads that might be reduced; however, this new hybrid operation mode provides important insight to be considered for future building design. As such, it was analyzed as a “normal” mode of operation compared with 2019 as the commissioning year.

4.3.3.1 Net-positive Energy Assessment

Monthly data from two solar electricity generation (SEG) meters were combined to calculate the SEG and this was compared with the BEC calculated from the 43 energy meters to assess the net-positive status. Firstly, the SEG to BEC ratio is defined as the total solar electricity produced to total building energy consumed. When the ratio is greater than 100%, the NPEB is contributing the surplus energy to the local grid, achieving net-positive energy status. Then the monthly consumption and generation were added up to assess 2022 progress in comparison to 2019. The average SEG from the past 3 years was used to estimate the expected SEG for 2022. Doubling the 2022 January to June BEC was used to approximate the total BEC for 2022.

4.3.3.2 Commissioning Activities

Several interviews were conducted with the building operator and energy advisor to understand the operational decisions made and occupant requests. This perspective is integrated in the analysis to provide potential explanations for observed changes in EUI.

The building was equipped with passive infrared (PIR) sensors in various places of the first floor as seen in Figure 10. They measured temperature to a resolution of 0.1°C with an accuracy of ±0.2°C (99). The measurements do not impact building operation and are used for investigation purposes. To assess the impact of commissioning activities on the indoor temperature, hourly measurements of seven PIR sensors on the first floor were collected for 2019 and 2022 (January to June). Then the hourly averages were calculated for each month to determine the average mean radiant temperature that would have been felt by the occupants. Variation between hourly measurements was found to be minimal (e.g., a standard deviation of 0.4°C for January 2019 northwest corner meeting room) and a monthly average was used to demonstrate variation between seasons and years under different operating conditions. The data was split into weekday and weekends, nights (7 PM to 8 AM) and days (8 AM to 6 PM) to distinguish between the different operating modes (i.e., the building operates on different settings while occupants are present during weekdays 8 AM to 6 PM).

Using the weekday hourly averages, two analyses were completed. First, the average first floor temperature was calculated and compared 2019 with 2022 to determine the impact on the average floor. Then, they were analyzed individually to compare 2022 with 2019, demonstrating variation from room-to-room.

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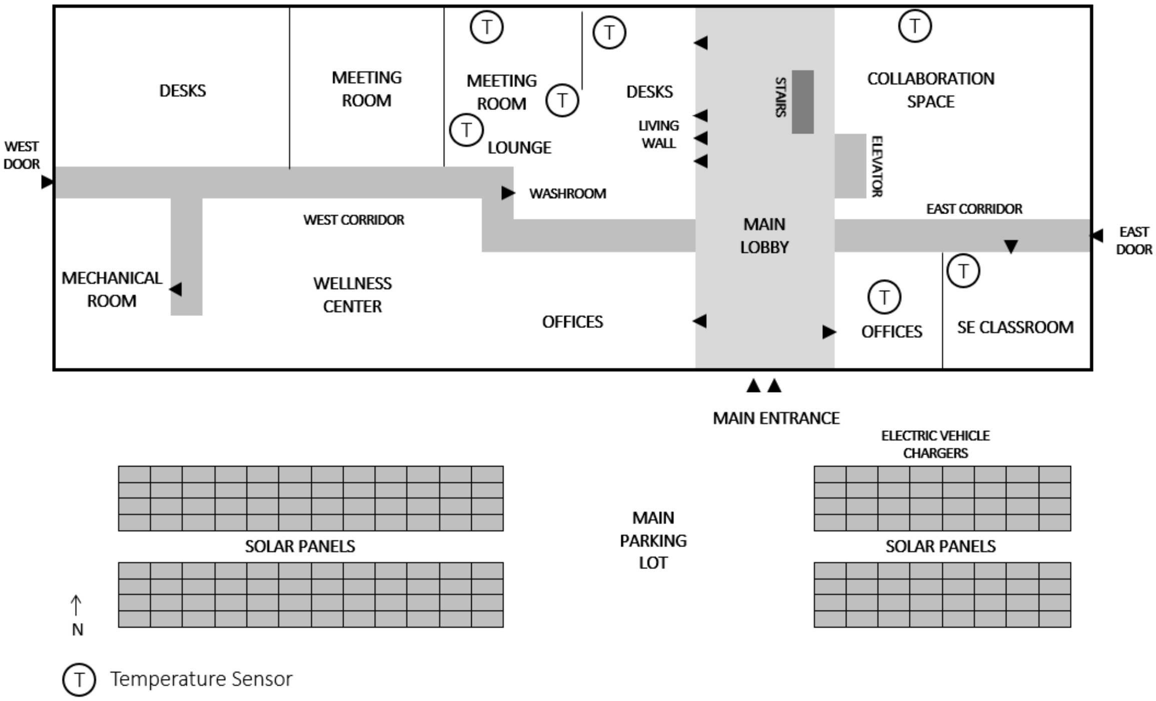


Figure 10: First floor plan of the case study building providing an orientation of where temperature sensors are located

4.3.3.3 Commissioning Energy Analysis

To assess the impact of commissioning decisions on energy consumption, HVAC and pump energy analysis was completed for 18 months. Data was collected from 12 HVAC energy meters and 9 pump energy meters, measuring at 15-minute intervals. HVAC meters were analyzed individually to assess the impact of commissioning decisions to improve HVAC controls. The most relevant HVAC energy meters were analyzed individually to demonstrate the impact of commissioning activities.

4.3.3.4 Peak Demand Analysis

The peak demand consumption of three fan-coil energy meters was averaged for four Mondays in February and June 2019 and compared with four Mondays in February and June 2022. The meters were separated to show the start up times in February and June 2022 that led to the decrease in the overall peaks. February and June were selected as they are typically the coldest month and warmest months in Southwestern, Ontario climate and can best demonstrate the peak demand needed to bring the building to a comfortable temperature. In February 2019 all floors changed to the occupied setpoints at 7AM whereas this was changed to a 4 AM – 5 AM – 6 AM start-up in 2022. In June 2019 the staggered start up continued but it was changed again and by June 2022, the building followed a 2 AM – 4 AM – 6 AM start-up. The new procedures starting in March 2019 changed the setpoint to the third floor, then to the second floor and ending at the first floor. Peak demand is measured in 15-minute rolling average intervals and have demand charges based on the type peaks formed (93). The 15-minute rolling averages of the three fan coil meters were added up to show the peak before and after commissioning activities.

4.3.3.5 Weather Impact Assessment

Weather contributes to variation in BEC (100). Daily HVAC energy consumption was analyzed with mean outdoor temperature information obtained from Environment and Climate Change Canada's measured data (83). Weekdays and weekends were separated as they operate on different setpoint schedules with weekends following more unoccupied settings (18°C in winter and 26°C in summer) and weekdays following occupied settings (22°C in winter and 24°C in summer).

4.3.3.6 Performance Gap Analysis

The energy model from design phase was acquired for comparison purposes through collaboration with the building designers. There were no simulations conducted for this investigation. The design model was completed on EnergyPlus during the preconstruction phase. There were 99 thermal zones simulated using a hourly run period for 8760 hours. The modeled net conditioned building area was 9406 m^2 which was used in the calculations of energy use intensity (EUI) for the measured energy consumption. The BEC was compared with the energy model to identify areas where differences emerged. The measured EUI aggregated from 43 energy meters and modeled EUI were compared to show annual and monthly performance gaps.

To assess the performance gap on an end-use basis, the 43 energy meters were divided into 5 main categories outlined in Table *8*. Although some meters measure more than one end-use, to simplify the analysis, the meters were assigned to the category which consumed the majority of the load.

Table 8: End-use category and the associated energy meters

End-use category	**Operational energy use**	**Modeled energy use**
Base building	Security panel, back up generator, one fan coil unit, shared area plugs loads, hand dryers, base building hot water heater and solar panel inverters	Equipment
Tenant Plug Load	Server panel, tenant computer and other small equipment plug loads	
HVAC	Heat pumps, mechanical panels, base building, fan coil units	Heating, cooling, fans and pumps
Pumps	Geothermal pump, VRF loop pumps, makeup air unit glycol loop pumps, heating and cooling loop pumps	
Lighting	Tenant, interior and exterior lighting	Lighting

4.4 Results and Discussion

4.4.1 Net-positive Energy Assessment

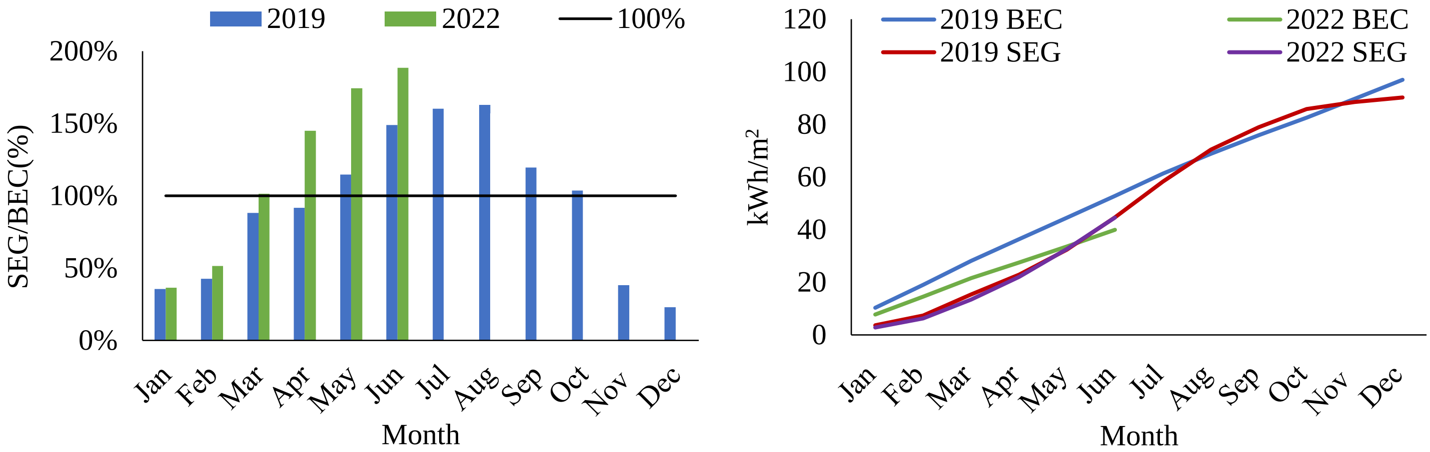


Figure 11: Solar electricity generation (SEG) to building energy consumption (BEC) ratio (left) and cumulative BEC and SEG 2019 and 2022 (right)

The building relies on the local grid for supplemental energy from October to April, but from May to September the NPEB produces more energy than it consumes, and excess energy goes to the local grid. This energy generation pattern demonstrated in Figure 11 (left) is to be expected for a colder northern location with higher winter BEC and lower SEG. The SEG/BEC ratio increased in 2022 after the commissioning activities took place and reduced the BEC. No commissioning activities took place on the solar PV system; however, SEG is also impacted by irradiance which can reduce the amount of solar electricity generated. In January 2019, the case study building generated 25% more solar electricity than it did in January 2022 suggesting that January 2019 was sunnier and/or less snow covered than 2022.

The lowest SEG/BEC ratio found was in January and December 2019 at 35% and 23% respectively. Although the BEC was reduced in January 2022 relative to January 2019, due to the low irradiance nature of those months, the difference in the ratios is small. The ratio is highest during summer months as seen in June 2022 where the building exceeded its energy consumption by an additional 88%. This demonstrates the seasonal differences in PV system output in Southwestern Ontario.

Borrowing an additional 7% of its 2019 energy supply from the grid, the NPEB did not achieve net-positive status during the commissioning year (2019) due to initial differences between the design model and actual operation, which will be further described in the Performance Gap section. In the SEG curves of Figure 11 (right) the 2022 SEG curve is tracking along the 2019 curve with minimal deviation, whereas the 2019 BEC is much higher than the 2022. This demonstrates the BEC improvements from commissioning activities (keeping in mind weather and decreased occupancy as confounding variables). Using the average SEG generation from 2019, 2020 and 2021, it can be expected that 2022 will generate 871,700 kWh or 92.7 kWh/m^2 of floor area. Doubling 2022 energy consumption from January to June to approximate the 2022 BEC, gives an estimate of 79.9 kWh/m^2. This means that the case study building is expected to be at 116% SEG/BEC or 16% net-positive energy by the end of 2022.

4.4.2 Commissioning Activities

4.4.2.1 Building Operation Expertise, Data and Tools

Building operators collaborated with the maintenance group and designers to manage reaching the design performance and to reduce the time required for commissioning activities. The expertise on the commissioning activities team included a project manager dedicated to overseeing the fine-tuning activities (referred to as the building operator). The building operator has an engineering background with over 15 years experience in consulting and facilities management. As the building is near a university, it also benefited from access to researcher expertise. The energy advisor whose input influenced the energy performance of the building also had an engineering background and over 15 years of building energy consulting experience. Operator collaboration with the energy advisor, design and maintenance teams improved the HVAC and pump controls and implemented distinct building operating schedules (i.e., weekends and off hours operating on unoccupied mode).

Access to tools and data such as a building automation system (BAS) and live energy meter data allowed for continuous monitoring of finetuning decisions' impact on energy consumption. Examples of the information available in the BAS can be seen in Figure 23 - Figure 25 in Appendix A. The availability and access to these tools enhanced the efficacy of the commissioning activities (completed in 9 months rather than the usual 16-18 months) and effectiveness of the energy saving decisions since they were more targeted.

4.4.2.2 Commissioning Decisions

Beyond design decisions to select high efficiency equipment (e.g., VRF heat pumps, enthalpy wheel), operating setpoints were modified to reduce energy consumption without compromising on occupant comfort. These decisions helped achieve the energy performance goals from the design phase. Continuous monitoring post construction is used to identify energy savings opportunities that might go unnoticed (14). The building operator continues to monitor the energy performance to meet annual targets.

During the first occupancy year, 2019, the building had ongoing commissioning activities from January to September. These activities were beyond the formal commissioning process and were completed to further reduce BEC as it was higher than predicted by the design and pointed towards a performance gap. The decisions included equipment resizing, decommissioning of some equipment and setpoint fine tuning. These decisions and their impact on energy consumption will be further described in the following sections.

During 2019, the building main condenser water loop pumps were driven by 10 hp motors and this was observed to not be a sufficient capacity for effective operation, as such the pumps and their motors were upsized to 15 hp in March 2021 to ensure sufficient power. Currently, the pumps operate in a lead-lag sequence, where the leading pump operates below 65% and the lag pump starts once the leading one exceeds 66% for more than 20 minutes and then the two pumps share the load equally. Although this option can use more energy than the original design, it was the more reliable option to ensure smooth operation.

Additionally, to reduce peak demand, the building operator changed the Monday start up procedure for returning out of unoccupied mode in March 2019. As the building operates on an unoccupied mode during weekends, the building equipment such as condensers and heat pumps need time to adjust to the new setpoints. Staggering building floors to allow for more time between setpoint changes was used to reduce peak energy consumption. Originally, the start up procedure had the third floor starting its change from

18ºC to 22ºC at 4 AM and the second floor at 5 AM. This was changed to start earlier, with the third floor at 3 AM and the second floor at 5 AM and lastly, ending with the first floor at 6 AM (in both sequences).

In January 2019, the HVAC set-back schedules were modified to have an occupied and an unoccupied schedule with the temperature set back during non-office hours (i.e., maintaining 18ºC in winter and 26ºC in summer from 6 PM to 3 AM). Additional meetings with the design team after 6 months of operation highlighted other energy-saving opportunities that were implemented. The condensing water supply and return temperatures were fine-tuned, decreasing the lower bound by 3ºC in winter months and by 5ºC in summer. Additionally, the condenser loop temperature setpoint decreased by 11ºC and the operating pressure increased by 13.8 kPa to improve efficiency. Furthermore, the chilled water temperature, and HVAC temperature setpoint were decreased by 3ºC (15ºC for winter months and 29ºC for summer months) in unoccupied spaces such as mechanical rooms. Programing logic for equipment (e.g., make-up air unit, heat pumps, geo-well pumps) start up was modified to ensure smooth operation. On weekends and weekdays, the heat pumps were programed to shut down if the outdoor air temperature was greater than 15ºC. These changes contributed to the overall reductions observed in the annual BEC. In addition, significant action items such as halving the airflow rate to the make-up air unit, reducing boiler setpoints and decommissioning the humidification system to rely on natural humidification can be demonstrated more clearly in individual HVAC energy meters and will be further discussed in the upcoming section.

When occupants moved into the building in January 2019, it was observed that the thermostats had not been moved during fit-out from the perimeter of the room. This led to measurements that did not reflect occupant experience. To improve occupant comfort, the fan coil return air temperature sensor was used for feedback measurement instead of the perimeter thermostats.

The building operator’s continuous monitoring of energy consumption led to an investigation in March 2022 that uncovered that the VAV controls were drawing more fresh air to a less occupied floor. As a result, the demand control ventilation strategy was re-examined and reset to ensure proper function. This demonstrates a continuous commissioning process that has been argued to ensure building systems stay optimized as the building is operated (59).

4.4.2.3 Commissioning Activities Impact on Indoor Temperature

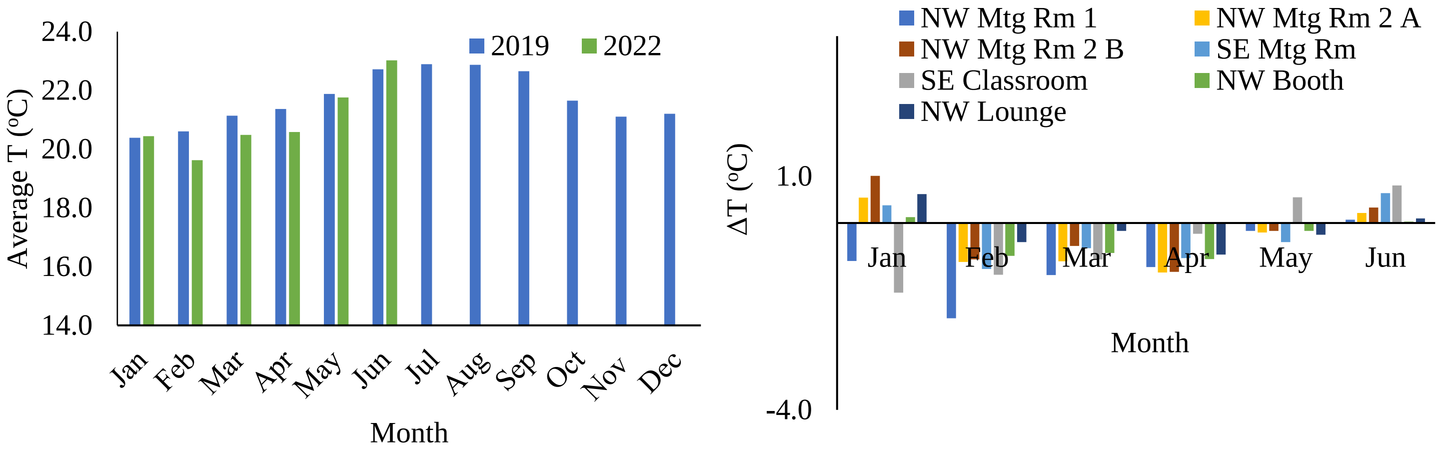


Figure 12: Average temperature (left) and temperature difference (right) on weekdays from 8AM to 6 PM using 7 first floor PIR sensors, comparing 2019 to 2022

To assess the indoor temperature during commissioning activities and post commissioning activities, the average temperature comparison in Figure 12 (left) suggests that the temperature on the first floor remains within 0.1^{o}C to 1^{o}C, with the largest difference observed in February. This suggests that commissioning activities had minimal impact on indoor temperature and occupant comfort. The temperature setpoints returned to occupied mode in January 2022, operating at 22^{o}C in the winter and 24^{o}C in the summer.

In Figure 12 (right), the ΔT measurements generally show consistency with the differences observed in the averages. The biggest temperature difference at the individual sensor level was in February when a meeting room in the northwest corner was 2.0^{o}C cooler. The second largest difference was the classroom in January with 2022 temperatures 1.5^{o}C lower than in 2019. All other monthly workday sensors values were within a degree, which shows consistent temperature control post-commissioning. This suggests that a uniform comfort level was maintained in the building as setpoints are reached by the HVAC system. The second half of the year appears to have a smaller temperature difference possibly due to internal heat gains having a greater impact in winter months; however, a more detailed analysis is needed to confirm this hypothesis.

4.4.2.4 Impact of Commissioning Activities on Energy Consumption

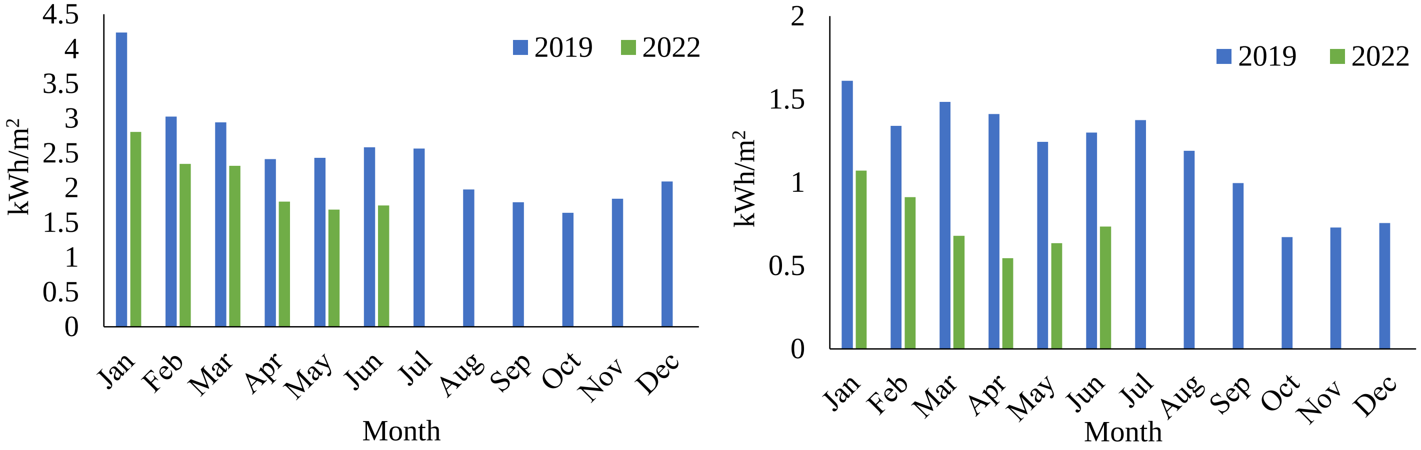


Figure 13: Monthly HVAC energy consumption (right) and pumps (left) 2019 and 2022

Reductions in HVAC and pump energy consumption summarized in Figure 13 were a total of 9.9 kWh/m^2 and 5.3 kWh/m^2 per year respectively. This indicates that the commissioning decisions reduce annual BEC by approximately 15 kWh/m^2 or 15% of 2019 BEC. Previous meta-analysis of 105 commissioning projects in North American offices found a median energy savings of 6% (15) and this case study results suggest that higher energy savings are achievable, which is in line with another meta-analysis of 32 U.S. office projects that found a median of 14% electricity savings (62).

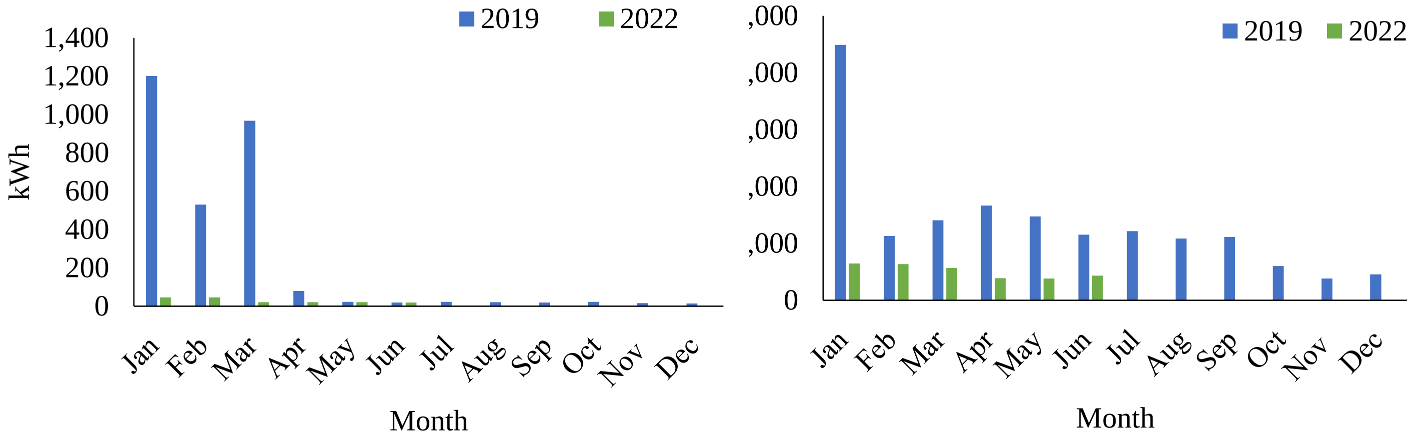


Figure 14: Monthly boiler energy consumption (right) and make-up air unit (left) 2019 and 2022

The biggest difference in energy savings can be observed in January as the building was still starting up and operational schedules were being implemented. For example, energy consumption for winter was reduced when comparing January with March 2019. Part of the increased consumption observed in January and February of 2019 were due to ongoing temperature setpoint finetuning due to the initial thermostat location. Most commissioning activities had concluded by September 2019 and energy reductions were observed. The pump upsizing upgrade in March 2021 led to decreases in overall HVAC energy consumption relative to 2019 consumption as displayed in Figure 13 (left).

The boiler system was designed to provide additional heat, but initially operated with an improper setpoint causing high energy consumption during the first three months as seen in

Figure 14 (right). The boiler normally operated during very cold weather conditions, as a back up system to the open loop geothermal heat exchanger. In January to March of 2019, the setpoint was 18°C for heating which led to increased and unnecessary operation. When the temperature decreased to 15°C for heating the temperature and the Monday start-up procedure was modified to stagger the setpoint changes as discussed in the Peak Demand analysis section, operation became inline with the expectations. Consumption decreased from 1, 200 kWh in January 2019 to 47 kWh in January 2022.

Changing the MAU supply air setpoint to from 28°C to 24°C in cooling, from 22°C to 18°C in September 2019 and halving the minimum fresh air settings (lowering from approximately 4, 200 L/s to 2, 200 L/s) contributed to saving 16, 537 kWh, representing 1.8% of 2019 BEC. Although the temperature decreased for cooling and increased for heating which would typically use more energy, due to the enthalpy wheel heat recovery system, these operational setpoints are more efficient.

Figure 14 (left) demonstrates the monthly trends captured by the energy meter. The difference between March 2019 and November 2019 (months of similar temperature as demonstrated by the similar number of 18ºC HDD as demonstrated in Figure *9* is 1, 023 kWh or 0.1087 kWh/m^2 provides a monthly estimate of the savings. Although the fresh air supply rate decreased, the building is equipped with CO_2 sensors that use demand control ventilation to ensure the building operates comfortably for the occupants. This decrease in fresh air settings did not negatively impact the indoor CO_2 levels but merely prevented over ventilation. The results in this study suggest that the fresh air intake in the make-up air unit were reduced while maintaining adequate CO_2 levels (set point is at 800ppm, meeting the 300-500 ppm differential range as outlined by ASHRAE standard 62.1 (101)).

The energy advisor recommended that comfortable building humidity levels can be achieved with the living wall alone. This led to the humidification system being decommissioned as of July 2019 and full elimination of the associated electric load going forward. It can be approximated that this change saved 13, 600 kWh annually (average 1, 700 kWh/m, operating for 8 months) or 1.5% of the total 2019 BEC.

4.4.3 Peak Demand Analysis

In

Figure 15, 2019 start-up took place at 7 AM for all three fan coil units and this was changed to the staggering procedure which reduced the peak by 14.15 kW (9.9% savings). By June 2019 as seen in

Figure 15 (top right) the staggering starts up procedure was already implemented and the peak had been reduced, however the building operator implemented a further set-back to test whether the peak demand can be further reduced and as demonstrates, the peak was reduced by an additional 16.14 kW (28.5% savings). Shifting the demand time from a gradual start at 4 AM to a gradual start at 2 AM was found to have a larger impact compared to the shift from 7 AM to the gradual start at 4 AM. This suggests that giving the equipment more time to adjust to the new setpoints is an effective strategy for reducing peak demand. Comparing

Figure 15 top left and right shows that winter start ups can use 2.3 times more energy than a summer start up.

Studies by Morsy et al. (93) and Yin et al. (64) found electricity demand savings of 34% and 30% respectively, confirming that the findings from this case study building are within reason although there are different ways to achieving energy savings.

The peak demand savings from this case study benefits the local grid and utilities by reducing the demand during peak periods (7 AM). Additionally, it reduced reliance on the building's boiler system by giving the system condenser loop more time to adjust to the change in setpoint and enough time for the ground heat loop to draw water and warm up.

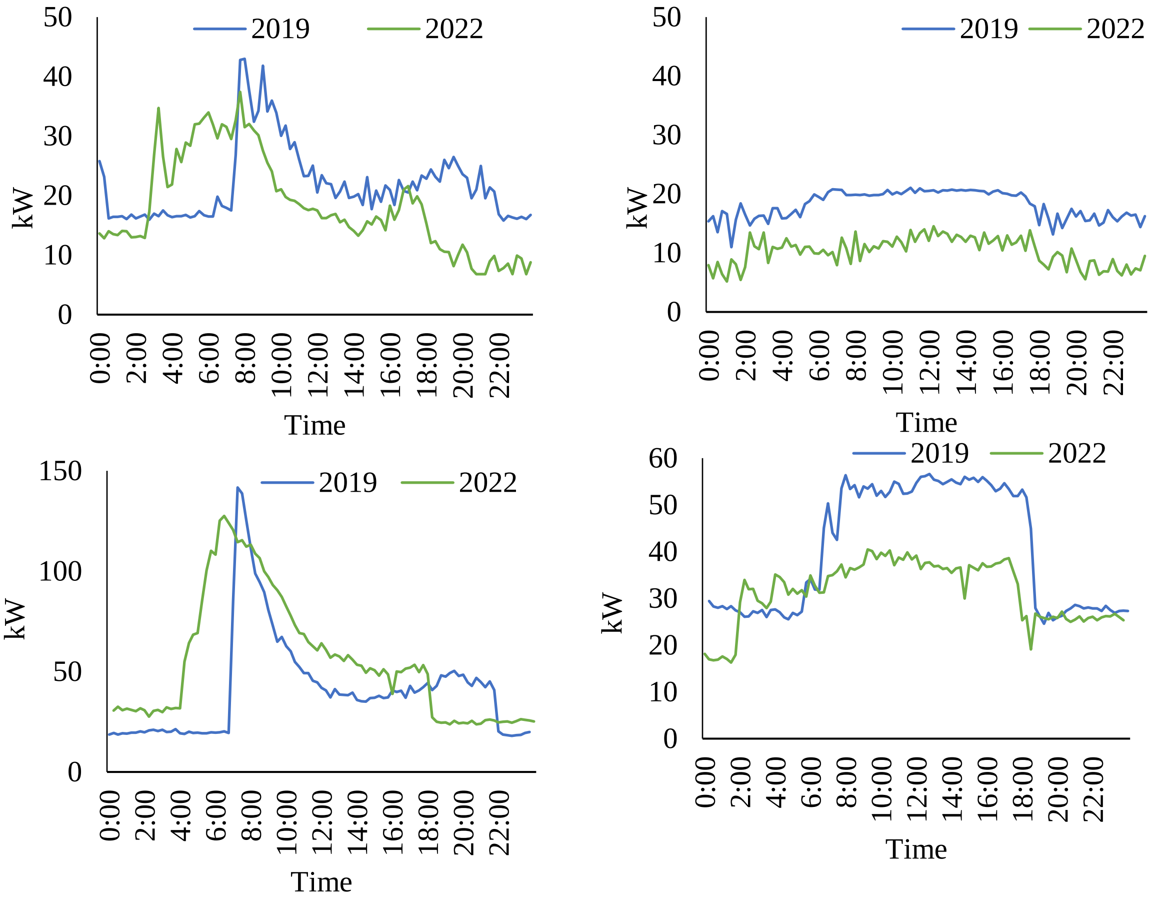


Figure 15: Fan coil units energy consumption February (top left) and June (top right) and pumps energy consumption February (bottom left) and June (bottom right)

Pump operations were also impacted by the decision to stager the start up time.

Figure 15 bottom demonstrates the changes observed in the energy consumption levels. The trend observed for the initial change from starting at 7 AM to staggering at 4 AM – 5 AM – 6 AM demonstrates a similar reduction in peak demand as previously observed with the fan coil units. Interestingly, the change from the 4 AM – 5 AM – 6 AM to 2 AM – 4 AM – 6 AM reduced the overall consumption, with the smaller peaks observed at similar times. The pump consumption is much flatter, suggesting that the new operating procedure had a larger impact on the pumps than the fan coil units which are still seeing some spikes.

4.4.4 Weather Impact

In Figure 16 2019 consumed more energy (average of 0.0292 kWh/m^2, COV = 0.839 and 0.0224 kWh/m^2, COV = 0.868 for weekdays and weekends respectively) than 2022 for a similar temperature range. This further illustrates the building commissioning impact on HVAC energy consumption. Lastly, the relatively flat curves suggest a decoupling between outdoor temperature and energy consumption, likely due to a combination of the advanced HVAC system and high-performance building envelope reducing heat loss.

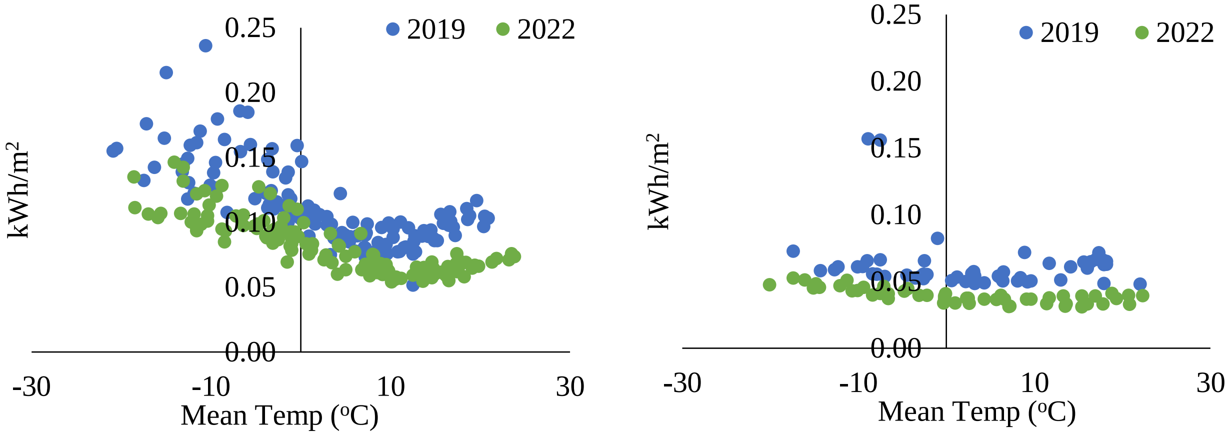


Figure 16: Average daily temperature versus HVAC total energy consumption for weekdays (left) and weekends (right), 2019 and 2022

Note: The two points on the left graph at (-8.9, 0.16) and (-7.9, 0.15) are two weekend days in January 2019, prior to implementing an unoccupied schedule during weekends.

4.4.5 Performance Gap

4.4.5.1 Annual Operation and Model Comparison

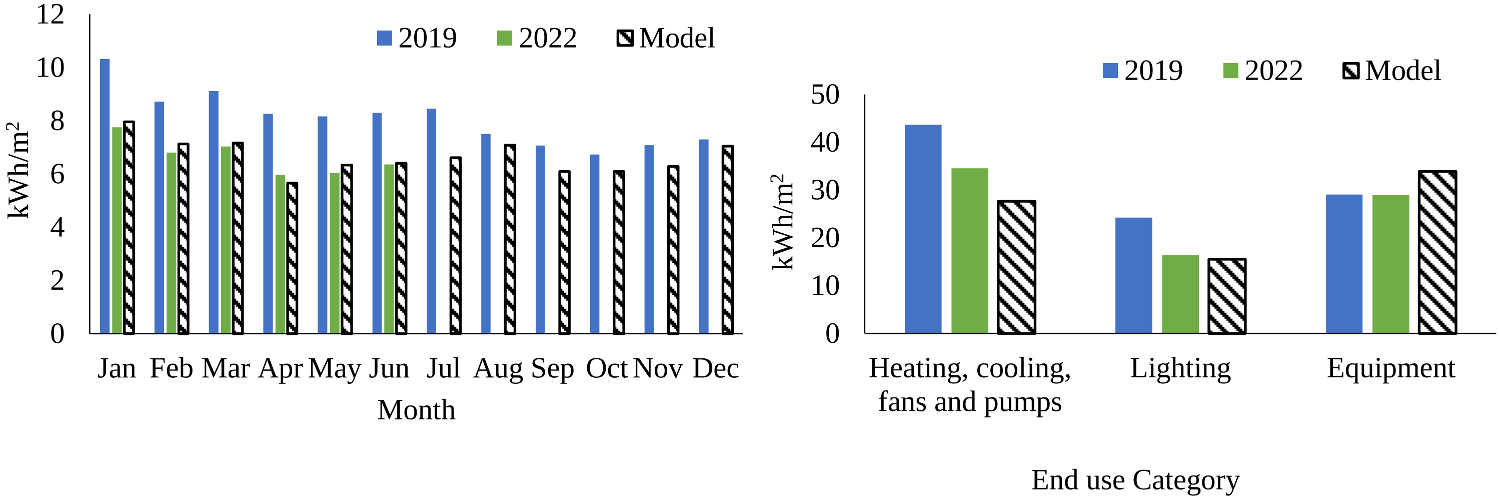


Figure 17: Monthly operation vs modeled energy consumption (left) and end-use comparison using 2022 approximations (right)

To assess the performance gap, the energy model from the design phase was compared on an EUI basis with the 2019 and approximate 2022 overall BEC. It was found that in 2019, the building consumed 96.9 kWh/m^2, 21.5% more energy than the model had predicted. Post-commissioning, it can be approximated that 2022 total BEC would be in line with model prediction, consuming 78.8 kWh/m^2 and on target to meet its net-positive energy goal. The accuracy of the BEC approximation for this model was particularly important as one of the design goals was to produce a net-positive energy building, producing 5% more than its consumption (105%). It can be seen how commissioning activities contributed to closing the overall performance gap and reducing BEC to meet the model predictions of 79.8 kWh/m^2.

Jradi et al. report lack of continuous commissioning, inappropriate building management and control strategies as some of the causes of the energy performance gap in buildings (12). The results of this case study building demonstrate that closing the performance gap using building operator expertise and data-driven recommendations is also possible.

4.4.5.2 Monthly Operation and Model Comparison

Figure 17 (left) displays the monthly performance gap assessment. 2022 energy consumption is more inline with model predictions than the first seven months of 2019. From August 2019 to December 2019, it can be seen how the performance gap decreased likely. From Figure 17 (left), the building uses more energy in the coldest months (January and February) and in the hottest months (generally July and August) which is to be expected. Comparing January 2022 with June 2022, typical winter and summer months, it can be seen how the case study building consumes 22% more energy for heating than cooling, which is inline with design model estimations.

4.4.5.3 End-use Comparison

In Figure 17 (right), the interior equipment category was the highest energy end-use as it contained miscellaneous tenant plug loads. Following this end-use category is the heating, cooling, fans, and pumps loads which total 27.6 kWh/m^2 or 20% less than the equipment load approximation. Moreover, the model had estimated minimal exterior lighting, with most of the focus on interior lighting. Daylight harvesting, coupled with occupancy sensors were a design control strategy used to reduce office lighting when spaces were unoccupied. The implementation of these controls during building fit-up might have been less extensive than the model assumed. These strategies are applied during operation; however, occupant training may improve energy consumption as the lighting fixtures can be more advanced in design. Lastly, there was a small amount of energy associated with the water systems as the water needed to be heated up for the heating loop used for the fan coil unit operation, and for occupant showers and washrooms which was included as part of the base building energy meters.

Commissioning activities focused on the HVAC and reduced the performance gap from 58% in 2019 to an expected 25% in 2022. Weather is a confounding variable in these results and the model had a different number of HDD and CDD than was measured during 2019 as summarized in Figure *9*. Additionally, the estimated 2022 value suggests that the lighting energy use will within 6% of model predictions, more so than during the commissioning year when the lighting energy use measured was more than double that modeled. This may be due to decreased occupancy associated with occupants working from home during some weekdays. Lastly, the interior equipment (i.e., the base building including the tenant plug loads) seems to have been overestimated by the energy model, with the measured being 15% less than modeled in 2019 and expected to be less in 2022.

4.4.6 Limitations and Future Research

There are three main limitations identified for this case study. Firstly, although this case study provides empirical data to improve understanding of high-performance buildings relative to design goals, it remains difficult to generalize the results as the operational strategies may be context dependent. Secondly, the results were also impacted by COVID-19 as occupancy was lower in 2022. There were 12 months of typical occupancy data available and those were used to understand typical energy consumption; however due to ongoing commissioning, there was overlap between reductions due to decreased occupancy and those from permanent commissioning challenges. Lastly, there was missing data (<2%) in the energy meter databases and they were filled with averages from the previous month.

Future research can consider investigating the economic feasibility of similar commissioning decisions, permanent COVID-19 impacts and the other confounding variables impacting energy consumption. The economic assessment and feasibility of these commissioning activities were outside the scope of this study. Building energy performance can be investigated to see the permanent impacts of COVID-19 on how occupants use office buildings (e.g., the rise of remote working).

4.5 Conclusion

This case study investigated a NPEB performance in southwestern Ontario, Canada, looking at consumption during and after HVAC focused commissioning activities. This study demonstrated how operator expertise and building energy management tools can be used to implement data-driven commissioning activities. First, it was found that the case study building did not achieve net-positive status while undergoing commissioning; however, it is on track to achieving its target in 2022, after commissioning took place and occupants are returning to work from the pandemic. Secondly, several commissioning decisions took place including finetuning temperature and humidity operational setpoints, implementing gradual start-up procedures to transition from unoccupied to occupied mode and lastly, upgrading specific equipment to improve efficiency and reliability. Peak demand was reduced by 28% when the building operator implemented a fan coil start up procedure that had different start up times for each floor, rather than all floors at once. It was approximated that the combination of these activities reduced BEC by 15% annually. Investigating the impact of outdoor air temperature on the HVAC energy consumption showed the reductions in energy consumption under similar weather conditions. Although the overall performance gap was closed and the building is expected to meet its target EUI in 2022, 77.8 kWh/m^2, there remains a performance gap in specific end-uses, such as lighting and plug loads. This case study showed how it is possible to reach net-positive energy performance (116% estimated for 2022) by working to reduce BEC through HVAC continuous commissioning. Lastly, this study recognises the potentially permanent changes observed from COVID-19 as demonstrated in decreased building occupancy despite the return from lockdown.

Future building design can consider dynamic building operations that reduce the baseload necessary for operating a building at minimal occupancy. Suggestions to improve building energy performance based on the lessons learned from this case study include:

- Design buildings with variable occupancy in mind; implementing strategies to cope with reduced occupancy such as demand control ventilation

- Apply on-site energy generation strategies (solar PV, geothermal, etc..) to reduce BEC reliance on the grid
- Monitor building energy consumption and investigate if it is possible to reduce operational setpoints for unoccupied spaces, implement a distinction between occupied and unoccupied office hours
- Modify weekday start-up procedure to reduce peak demand consumption by giving the equipment more time to adjust to new setpoints

Chapter 5 Lighting and plug load energy consumption: A COVID-19 occupancy investigation

5.1 Abstract

The pandemic created an opportunity to assess and quantify the impact that building occupancy has on the energy consumption of high-performance office buildings. Previously, building science research found it challenging to accurately quantify the occupant impact on building energy consumption. Occupancy related consumption is especially important in high performance buildings because heating and cooling loads are reduced. The COVID-19 natural experiment provided researchers, designers, and operators with an opportunity to acquire valuable building energy consumption (BEC) data that can be used to determine the impact of occupancy level. 2019 BEC data was used as a baseline of typical occupancy, and it was compared with 2021 as a year of minimal occupancy. The results show that there is a significant difference between 2019 and 2021 lighting and plug load energy consumption. When occupancy levels decreased by 90%, a 10% reduction of the total BEC was observed. Lighting and plug load energy consumption in 2021 were 31% and 26% less than 2019 baseline levels. Lastly, 2022 BEC data shows a new energy consumption pattern in offices due to the hybrid mix office/remote work and the associated reduced occupancy post-pandemic.

Research Questions:

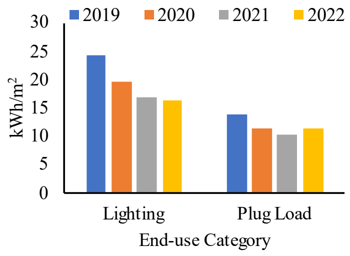
What is the difference in energy under minimal occupancy?
How different were the end use-categories in different operational periods (i.e., how were they impacted by reduced occupancy)?

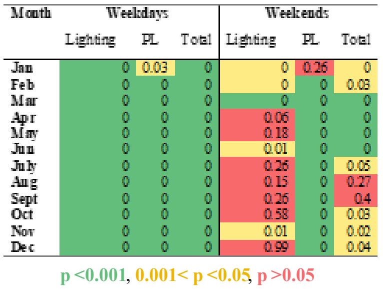
Case Study Building:

Net-positive energy Canadian office building, generating its own electricity using solar PV and exportin g excess energy to the local grid

Key Results:

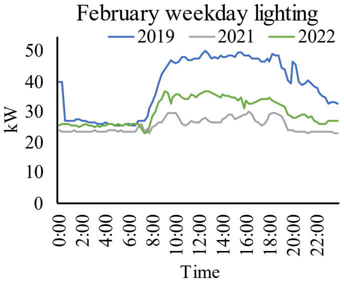
Impact of telework on lighting, plug and base building loads observed during and post -pandemic





Month	Weekdays			Weekends		
	Lighting	PL	Total	Lighting	PL	Total
Jan	0	0.03	0	0	0.26	0
Feb	0	0	0	0	0	0.03
Mar	0	0	0	0	0	0
Apr	0	0	0	0.06	0	0
May	0	0	0	0.18	0	0
Jun	0	0	0	0.01	0	0
July	0	0	0	0.26	0	0.05
Aug	0	0	0	0.15	0	0.27
Sept	0	0	0	0.26	0	0.4
Oct	0	0	0	0.58	0	0.03
Nov	0	0	0	0.01	0	0.02
Dec	0	0	0	0.99	0	0.04

$p < 0.001$, $0.001 < p < 0.05$, $p > 0.05$



t-test results for lighting, plug load (PL) and total energy consumption comparing 2019 with 2021

Conclusion:

Minimal occupancy consumption decreased total building energy by 10%
Lighting and plug load energy consumption decreased by 31% and 26% respectively due to decreased occupancy in 2021
Significantly different consumption patterns observed in 2021 relative to 2019 and in 2022 relative to 2021 levels

Figure 18: Graphical abstract summarizing the research questions, key results and conclusion

5.2 Introduction

5.2.1 Background

COVID-19 is a contagious, airborne disease caused by SARS-CoV-2 coronavirus which was declared a global pandemic in March 2020 and continues to impact consumer, employee and organizational wellbeing (1), public health and the global economy (103). Several mitigation strategies were put in place to reduce the spread of the virus, and these included social distancing, avoiding social gatherings, increased remote working (104) increasing indoor ventilation (73) for essential businesses and closing nonessential businesses (105). These measures were believed to contribute to ongoing global economic recession (106,107). Needless to say, COVID-19 also impacted energy consumption whether through decreased transportation or increased in residential energy consumption (108). Global weekly energy demand decreased by 25% on average in mid-April 2020 in countries that had full lockdowns (109). More specifically, electricity demand decreased in some parts of the world, for example, weather adjusted electricity demand in China decreased by 11% in February 2020 under lockdown compared with February 2019 (108); however, these decreases varied depending on the lockdown measures and how stringent they were. In the first quarter of 2020, global energy demand saw a 4% decrease, with global coal demand decreasing by 8% compared with the first quarter of 2019 (109).

In Canada, the province of Ontario declared a state of emergency on March 17, 2020, and remained in various stages of COVID-19 lockdown and reopening under restrictions (105) until lockdown was fully lifted on February, 17, 2022 (110). During this time, many people worked from home as a COVID-19 mitigation strategy (104). While this was happening, office buildings often continued operating on business-as-usual HVAC control schedules, if not increasing their fresh air flowrate to meet COVID-19 guidelines (31). Several mitigation strategies focused on improving indoor air quality to reduce the spread of the virus by improving filtration and ventilation. The American society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) and the World Health Organization (WHO) provided several guidelines to help building operators manage the pandemic (111–114).

COVID-19 transformed the way office buildings are used. Remote working led to the creation of work-from-home offices and a decreased use of conventional offices. To mitigate the spread of COVID-19, many employers allowed their employees to work remotely if it was possible and this led to about 37% of the Canadian workforce working remotely from May 2020 to Dec 2021 (115). Depending on the industry, the ability to work from home was higher for those that had professional services such as education, technical, financial, information and administrative activities (115). The highest percentage of employees remote working was found in educational services at 80% of employees working from home in May 2020 and that decreased to 17% by Dec 2021, indicating that occupants began returning to their offices towards the end of 2021 (115). Furthermore, 17% of businesses reported likely or very likely continuing to offer employees the possibility to work remotely after the pandemic (116). The Canadian Center for Occupational Health and Safety outlined advantages for individuals working remotely including improved work-life balance, increased flexibility with time management and saving time and cost in commuting (117). Benefits identified for organizations included savings in energy, office space requirements, maintenance and house keeping (117).

Investigating the energy implications of this transformation are key to designing buildings that are better suited to meet occupant needs. Occupant interactions with building systems – from turning the lights on or off, to leaving laptops / monitors / printers on, standby or off, or using the elevators – impact building energy use. Describing the impacts of occupant behaviour on energy consumption remains a challenge due to its complex and dynamic nature (1, 2). This understanding is especially important for net-zero and net-positive buildings with high performance standards where the relative importance of occupant energy decisions may be greater (118).

This study investigates the impact of occupancy on occupant sensitive loads, focusing on lighting and plug load in a net-positive energy office building. Net-positive energy buildings are high-performance buildings that generate more energy on-site than they consume in a period of an average year (7). The additional energy is exported to the utility grid or used to locally charge electric vehicles (EVs) connected to the building.

5.2.2 Motivation and Objectives

Prior to COVID-19, measured energy consumption of buildings was often found to differ significantly from predictions made during the design phase. Measured energy consumption can be up to 2.5 times higher than predicted (9). This difference is sometimes referred to as the "performance gap” and it presents a roadblock to the realization of energy conservation (9). Reducing energy consumption is especially important for high performance buildings as they aim to generate some or all of their energy supply through on-site renewable energy generation (46,119). If a building consumes more energy than predicted, this can contribute to increased operating costs and emissions (2, 4, 5). Occupant behaviour is found to be a contributing factor to the performance gap (41,51,118). Control over building interfaces such as lights, blinds and thermostats was investigated in a literature review and it was reported that energy use and comfort can be opposed; however, with well-understood human-building interfaces, both comfort and energy savings can be achieved (41). Open ended survey questions were used to understand the impact of occupant training on satisfaction with office questions and the results report that occupants who received effective training were more satisfied with their environment than those who did not receive training (51). In an investigation seeking to develop occupancy profiles based on building monitoring data, different occupant behaviours and attitudes towards energy conservation were found to impact their energy consumption (118). The relationship between occupant behaviour and building energy consumption is a complex one that could benefit from understanding how a building consumes energy in the absence of occupants. The presented study under minimal occupancy conditions can provide a way to estimate how much energy consumption may be attributed to occupants and provide initial insights on the impact of remote working on high performance office buildings.

Empirical lighting, plug load energy use data will be provided from this case study to provide insight on measured energy consumption. This data can be used by building energy modelers to create occupancy profiles when modeling different equipment operating schedules to better predict energy consumption in a post COVID-19 world.

There have been residential energy COVID-19 studies (25–27, 31); however, there are few empirical studies looking at the impact of reduced occupancy on office energy consumption. More data on high performance green building operations under typical, COVID-19 and post-COVID-19 conditions are needed. This paper aims to answer two main questions: i) what is the difference in total energy consumption levels with minimal occupancy and ii) how different were the lighting, plug load and total consumption levels and patterns in different operational periods (i.e., how were they impacted by reduced occupancy)?

The structure of the paper is as follows: first there is a brief review of the literature followed by a detailed description of methodology. A variety of methods were used to analyze measured data from three and a half years of operation. Then, the monthly and annual energy consumption were compared for differences between baseline occupancy consumption (2019), minimal occupancy consumption (2021) and post-COVID-19 occupancy consumption (2022). Statistical analysis (t-test) was applied to compare the energy consumption levels and hourly load profiles were created to infer occupant schedules. The analysis continued with a detailed analysis and discussion of the results and their contribution to the emerging COVID-19 impact literature. The paper concludes with a reflection on key lessons learned and how they may be applied to future building operation.

5.3 Literature Review

5.3.1 COVID-19 Studies

This literature review was completed to determine how other COVID-19 studies were conducted (methods) and their findings (results). Investigations that examined lighting and plug load energy consumption were also analyzed to understand different control options and their impact on energy consumption. It was found that some studies focused on the impact of COVID-19 on residential electricity consumption (65,66), while others considered university buildings (69,70). A third group of studies focused on indoor air quality to reduce the spread of COVID-19 (14 –16). Finally, a few studies were found to analyze the energy implications of COVID-19 in offices (30,31).

In an analysis of 500 Canadian homes, the average household energy consumption increased by 12% in 2020 relative to 2019, however, some of this increase has been attributed to weather variation between the two years (66). Zhang et al. (2020) investigated the impact of occupancy due to the COVID-19 lockdowns using a simulation approach, relying on existing building regulations and they report that homes and shopping centers consumed the most energy, accounting for 37% and 31% of total energy consumption of a typical urban city (67), respectively. Lastly, Rouleau and Gosselin report significant increase in electricity consumption in Canadian social housing during the first month of the pandemic, however this increase only lasted for one month and the demand times shifted from peak consumption after office hours (typically after 5 PM) to during typical working hours(8 AM to 5 PM) for the remaining months (65).

In office studies, simulations were used to investigate the impact of continued operation under COVID-19 guidelines regarding increased ventilation and fresh air intake (31,67). It was estimated that offices may consume up to 28% more energy depending on their climate zone with the gap between pre and post-COVID-19 consumption patterns increasing for areas of colder climates (31). In contrast, another study predicted an increase of average demand for electricity increasing up to 19% under different lockdown scenarios (67). Interestingly, it was reported that the mean systems demands (total heating, cooling and domestic hot water) would decrease by up to 12%; however, there would be a higher average delivered electricity demand of the entire district which may contribute to a similar total energy consumption demand since the increases and decreases were similar and nearly canceled each other out (67). Moreover, a higher electricity demand was predicted for residential buildings when confinement levels increase, whereas office and school energy consumption were expected to decrease (67). Cortiços and Duarte (2021) simulated US high rise offices to understand the permanent impacts of continuing operation post-COVID-19 while following the ventilation guideline changes made to reduce the risk of spreading the disease (31). They conclude that continuing with the COVID-19 guidelines may exacerbate energy consumption at higher levels than pre-COVID-19 (31). Kang et al. (2021), studied South Korean offices, and found that electricity consumption decreased by 5% in most months when comparing 2019 with 2020 (30). Lastly, Park et al. (2019) highlight the importance of operating schedules and occupant centric controls to reduce building energy consumption when the building is minimally occupied (120,121).

5.3.2 Occupant Centric Loads

There are typically three main occupant centric loads considered; HVAC, lighting and plug loads. These end-uses tend to be more impacted by occupancy than other loads such as base building ones. Typically, lighting would operate on a prespecified schedules that try to approximate when occupants would arrive and depart from a space so that it can be maintained as a comfortable indoor environment. An earlier report of this case study building investigated HVAC system performance (29), while this study focused on understanding the impact of occupancy on lighting, plug loads and total consumption.

Lighting and plug loads are estimated to use 14% and 16%, respectively, of Canadian commercial building energy as of 2018 (16). Plug loads have seen a 54% increase in Canadian commercial building energy consumption when comparing 2018 with 2000 (16). This suggests that they are becoming increasingly important in high performance building design and operation. They also represent a larger share of high-performance buildings' energy consumption where space conditioning requires less energy. In this case study building, lighting and plug loads are approximately 25% and 15% of the total energy consumption, respectively. The advanced HVAC system in the case study building, uses approximately 45% of the total BEC, which is much less than the reported average of 59% for commercial buildings (16).

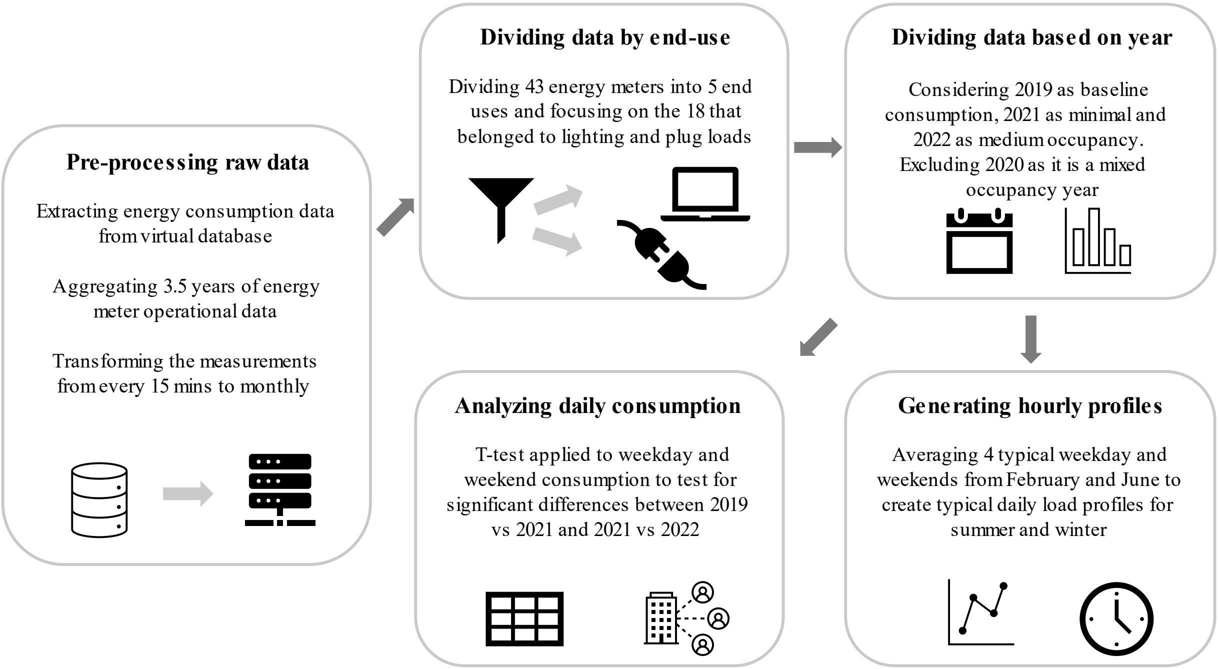
There are varying end-uses that can be included by building energy designers in the plug load energy consumption category. A survey of energy designers found that the term "plug load" refers to miscellaneous loads plugged into a wall socket, controlled by the occupants (122). Another study considered them as small power equipment that experience minimal sensitivity to weather conditions (123). For this paper, plug loads are tenant loads, such as laptops, monitors, device charging, personal heaters, and office kitchen equipment such as refrigerators, microwaves, and dishwashers.

Different approaches have been used to examine plug load energy consumption . Clement et al. (2021) generated electric load curves for small power equipment and office buildings to provide more data to support the shift towards data-driven models (123). They aggregated the load profiles and compared them to identify a stabilization threshold limit. Gandhi and Bragger (2016) and Orland et al. (2014) focused more on the occupant behavior aspect of plug load energy consumption, using gamification to educate building occupants and encourage behavioral change (21,22). Lastly, Fuertes and Schiavon (2014) analyzed plug load energy modeling by surveying designers and they found that the majority of modelers (60% of the survey) considered the average plug load to be below 10.8 W/m^2 (122). Assuming that these simulations would be based on a 2,080-hour work year, this is approximately, 22.5 kWh/m^2.

5.4 Methodology

5.4.1 Research Approach

This research implemented an experimental research approach as summarized in Figure 19, where energy data was collected from a case study building that operated through COVID-19, minimally occupied. Key informant interviews were conducted to understand the operational plan and decisions made to navigate the COVID-19 period. This collected information was integrated in the explanations of the observed phenomena. As the building was operational for 15 months pre-pandemic, the 12 months of 2019 are used as a control period, representing energy consumption under typical occupancy. In early 2019, the HVAC system was consuming more energy than expected and the implementation of various commissioning activities reduced the building energy consumption as described in (29).



Pre-processing raw data

Extracting energy consumption data from virtual database

Aggregating 3.5 years of energy meter operational data

Transforming the measurements from every 15 mins to monthly

Dividing data by end-use

Dividing 43 energy meters into 5 end uses and focusing on the 18 that belonged to lighting and plug loads

Dividing data based on year

Considering 2019 as baseline consumption, 2021 as minimal and 2022 as medium occupancy. Excluding 2020 as it is a mixed occupancy year

Analyzing daily consumption

T-test applied to weekday and weekend consumption to test for significant differences between 2019 vs 2021 and 2021 vs 2022

Generating hourly profiles

Averaging 4 typical weekday and weekends from February and June to create typical daily load profiles for summer and winter

Figure 19: Summary of methodology steps applied to analyze the data and generate study results

5.4.2 Research Site

During the minimal occupancy period (from April 2020 to December 2021), a small team of employees entered the case study building one day per week to ship products and one tenant had some employees return for seasonal work (starting in November 2020 and November 2021). A summary of the major events impacting this case study commercial office building's operation can be seen in Figure 20.

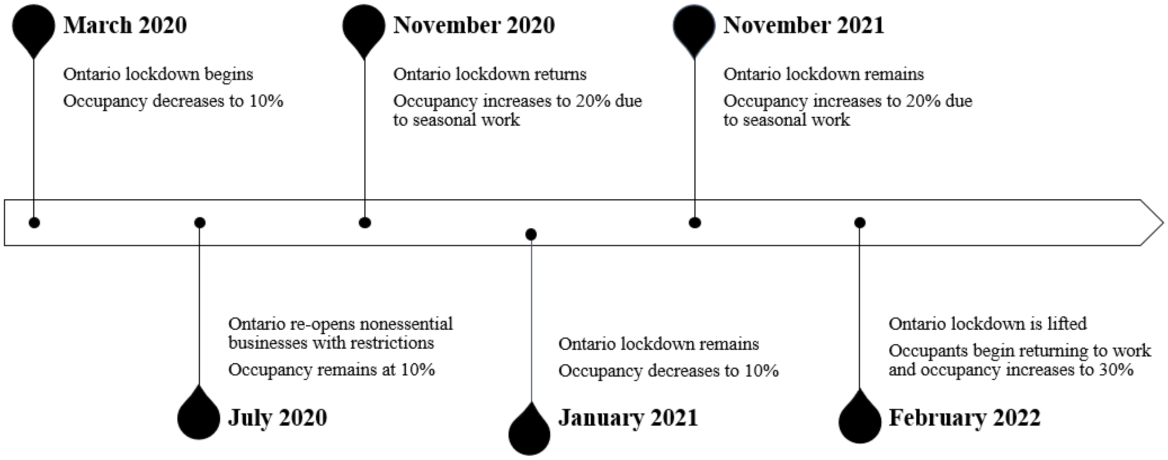


Figure 20: Summary of major COVID-19 events and the changes in building occupancy

The case study net-positive energy building is in southwestern Ontario, Canada. It is designed for peak occupancy of approximately 300 persons, although typical occupancy (pre-COVID-19) was around 200 occupants per day. The building features include a high-performance envelope, a transpired solar air heating collector for preheated fresh air, an enthalpy wheel, geothermal and variable refrigerant flow heat pumps, and on-site solar electricity generation capability of 768 kWp, resulting in its net-positive energy performance. Table 9 summarizes the case study building specifications.

Table 9: Summary of case study building features and specifications

Building Feature	Description
Building envelope	Window-to-wall ratio designed to 37% with continuous glazing Rated R-30 for walls and R-40 for the roof
HVAC	Variable frequency drives used for precise ground source heat pump and motor control Enthalpy wheel for 81% heat recovery Dedicated outdoor air system 3 storey and 5.7m wide living green wall to provide natural humidification
Lighting	LED lights with occupancy sensor controls Windows and shades positioned for daylight harvesting Atrium lighting for the living wall Lighting power density designed to 4.75 W/m^2
Energy generation	825 MWh photovoltaic electricity generated from rooftop and parking Transpired solar air collector used to pre-heat outdoor air
Water management	Rainwater harvesting for closets, washrooms, and living wall irrigation Open loop geo-exchange system providing water at 10 °C

5.4.3 Data Analysis

5.4.3.1 Monthly and Annual Analysis

To analyze the annual and monthly consumption from 2019 to June 2022, energy meter data was collected from 43 energy meters at 15-minute intervals. All energy meters were aggregated and normalized to building area to provide energy use intensity (EUI). Interviews with key informants were conducted to gain a holistic perspective of the key operating decisions during the 3.5 years of building operation.

The 43 energy meters were split into five end-use categories. Lighting and plug load categories were compared on an annual basis to investigate the impact of COVID-19. Those loads were selected as they are most impacted by occupancy. The analysis was performed on a monthly basis for interior and exterior lighting (8 energy meters) and plug loads (12 energy meters), respectively. Similarly, for base building, HVAC and pumps, there were 6, 8 and 9 energy meters, respectively.

Table *10* provides a summary of the end-uses included in each category.

Table 10: End-use category and the energy meters included in operation

End-use category	Operational energy use
Base building	Security generator, hand dryers, base building hot water heater and solar panel inverters
HVAC	Heat pumps, make-up air unit, mechanical panels
Lighting	Tenant interior lighting and exterior lighting
Pumps	Geothermal pump, glycol loop pumps, heating and cooling loop pumps
Plug Load	Server panel, tenant computer and other small equipment plug loads such as fridges

5.4.3.2 Daily Statistical Significance Analysis

To determine the statistical significance of COVID-19 impacts, weekday and weekend energy consumption were analyzed. The weekday (excluding statutory holidays) and weekend consumptions from 2019 were compared to 2021 and 2021 was compared to the first 6 months of 2022 using an unpaired, one tailed T-test to measure statistical significance in the difference between the two means. The null hypothesis being analyzed was whether 2019 daily consumption for lighting, plug load and total is similar to 2021 consumption.

5.4.3.3 Hourly Consumption Profiles

To investigate the hourly energy consumption load profiles of lighting and plug loads, three different occupancy conditions were compared. Data was collected from 15-minute intervals from the 12 and 8 lighting and plug load energy meters, respectively.

A four-day average was calculated for Mondays and Saturdays in February (winter) and June (summer) 2019, 2021, and 2022 to investigate weekday and weekend seasonal consumption patterns. February and June were selected as the typically coldest and sunniest months in a northwestern Ontario climate and as such they represent performance during the two extreme seasons. Mondays were selected to represent workdays as the office building had different load profiles during weekends. These years were selected to represent three levels of occupancy. In 2019 the occupancy was typical, with most tenants working regularly at the office, whereas in 2021 the occupancy was minimal due to the ongoing COVID-19 lockdown in

Ontario and lastly in 2022 the occupancy represents the hybrid remote/office working arrangements that many office buildings experience post COVID-19. The operational year 2020 was excluded from this analysis as it was a mixed occupancy period with the first three months being pre-COVID-19 lockdown and the later months being during the pandemic lockdown. The profile loads were analyzed for consumption patterns on an hourly basis to infer occupant schedules during typical occupancy in 2019. In 2021, the loads were analyzed for baseline building energy consumption under minimal occupancy.

5.5 Results and Analysis

5.5.1 Monthly and Annual Analysis

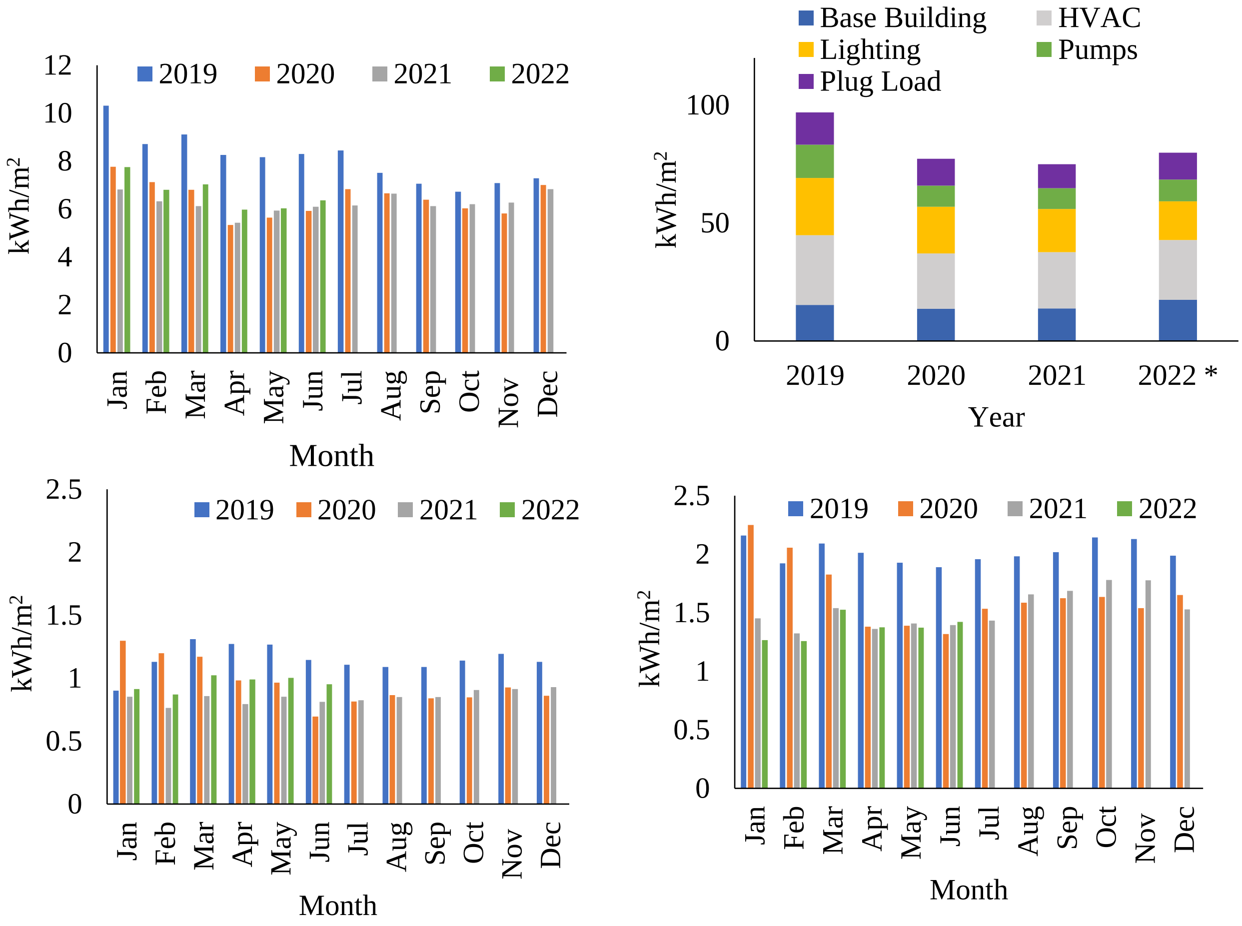


Figure 21: Total monthly energy consumption (top left), annual end-use (top right) lighting (bottom right), plug loads (bottom left)

* 2022 estimate is calculated by doubling January to June consumption levels

In

Figure 21 (top left), 2019 had above expected energy consumption due to initial operating settings and these were gradually adjusted through ongoing HVAC commissioning activities until September 2019. Comparing January to March of 2020 with 2021, a 13% energy reduction is observed, suggesting the impact of occupancy to be 10-15% of total energy consumption. This means that the building consumed 87% of the energy even though less than 10% of the occupants were present. In contrast, the energy consumption in October and November was back to the baseline level, suggesting that although the building was only partially occupied, the overall energy consumption was nearly equal to that at full capacity. This suggests limited sensitivity to the number of occupants. This may in part be due to the floor plans; the case study building has many collaborative and open spaces that, although great for encouraging cooperation among colleagues, can often have a sensor control approach where even one occupant results in all zone lights being on.

Continuing in

Figure 21 (top left) and looking at 2022, the return to the office is leading to energy levels climbing back to post-commissioning levels as observed in early 2020. This suggests minimal lasting impacts of COVID-19 on overall energy consumption despite the decrease in occupancy levels due to hybrid working from home arrangements. Although there are fewer occupants than normal in the building, the HVAC and pumps are operating as if the building is fully occupied to keep the space conditioned for the occupants who do return to the office. These end-uses are the highest energy consumers and since the control strategy is on a floor basis, it is difficult to reduce the operating temperatures and fresh air flowrates for specific offices that are unoccupied.

In

Figure 21 (top right) the energy consumption by end-uses is presented. Firstly, the HVAC energy consumption in 2019 was higher than the subsequent years since commissioning activities were not complete until September 2019. The building was using more energy in the beginning of 2019 as the operations were being finetuned as described in (29). In 2020 and 2021 with the commissioning activities complete, HVAC energy consumption was reduced and more in line with operational targets. To estimate 2022 consumption, the January to June energy total was doubled and it is expected to be on track to achieving 80 kWh/m^2. It can be seen how lighting and plug loads are about 25% and 20% of total energy consumption, respectively. These loads remained relatively constant throughout the different occupancy levels as demonstrated by the clustered column chart and this will be further investigated in the remainder of the study.

Due to ongoing commissioning activities in 2019 described in (29), it is difficult to estimate the baseline HVAC consumption at typical occupancy levels. During 2020 and 2021 while the building was minimally occupied, the operators used an unoccupied mode to reduce the operating temperature by 2 ^{o}C which further reduced energy consumption of the HVAC and the building. Starting in 2022, the operating temperatures returned to occupied settings and energy consumption is expected to reflect the baseline after commissioning activities.

Similar trends are observed in

Figure 21 (bottom right), as expected, energy reduction was observed from lighting baseline consumption in 2019. Lastly, looking at

Figure 21 (bottom left) and comparing 2019 with 2020 plug loads, the impact of decreased occupancy can be observed as an 18% decrease. Comparing 2020 consumption with 2021 during minimally occupied months consumption is similar, including October and November months. Then comparing, 2022 with 2021, consumption is similar in January and February, with the plug loads increasing back to almost the 2019 level of full occupancy by June 2022. This suggests that although not all tenants are working from the office all weekdays, the plug loads such as electronics, fridges and servers remain operational.

Table 11: Lighting (L) and plug load (PL) in kWh/m^2, with a percentage difference comparison

Year	**L**	**PL**	**% Diff L**	**% Diff PL**
2019	24.22	13.77	0%	0%
2020	19.74	11.42	-18%	-17%
2021	16.79	10.20	-31%	-26%
2022	16.44	11.48	-32%	-17%

Table 11 summarizes the EUI for lighting and plug loads categories for the 3.5 years studied. The 2021 minimal occupancy results show that at minimum, the building uses 69% and 74% of the typical occupancy lighting and plug loads levels respectively. The estimates for 2022 show that lighting consumption levels are near the COVID-19 levels, while plug loads are returning faster to the baseline consumption level. The difference between these two loads might be attributed to the nature of plug loads (such as printers or refrigerators) which can be more inconvenient to turn off than lights which often have a single switch. Further investigation into occupant arrival and departure times can be inferred from the hourly load profiles in the following sections.

5.5.2 Daily Statistical Analysis

The visual differences noted above were tested statistically. The null hypothesis being tested by this unpaired, one-sided t-test in Table 12 is that 2019 energy consumption is similar to 2021. The green boxes indicate when the p-value < 0.001 and the null hypothesis can be rejected, meaning that there is a statistical difference, for the yellow boxes, the p-value is between 0.001 and 0.05, meaning that there is still a high probability of a statistical difference; however, the hypothesis cannot be rejected as confidently as the boxes in green. Lastly, the red boxes indicate p-values > 0.05 meaning that there is not enough evidence to reject the null hypothesis.

For weekdays in Table 12 since the p-value was < 0.001, the null hypothesis can be rejected for all end-uses and total energy consumption during weekdays, except the plug loads in January, which is still statistically different with a p-value < 0.005. This suggests that weekdays consumed significantly less energy in 2021 relative to 2019 levels, which is to be expected since the building was minimally occupied.

The previous section found that the difference is approximately 30% for lighting and plug loads. The cause of this significant difference in lighting and plug load consumption levels is the increase in remote work and low level of occupancy during 2021. In the case of total energy consumption, the difference between 2019 and 2021 levels is also partially due to the commissioning activities that took place to reduce HVAC energy consumption.

On weekends in Table 12, the plug load energy p-values were < 0.001, throughout the year except in January, hence there is strong evidence to show that 2019 and 2021 are statistically different. This suggests that tenants worked more on weekends in 2019. Lighting had a mixed consumption pattern with most p-values > 0.05 and a few between 0.001 and 0.05 suggesting that lighting levels on weekends in 2019 were similar to those in 2021, which is interesting because it contrasts with the plug load findings. This may be explained by the open concept layout of the workspace so that lighting comes on when the first person enters the area and is thus less sensitive to the total number of occupants which would be better reflected by the plug load that includes the incremental use of laptops and other devices. The total weekend consumption had mixed results. Evidence supporting a strong statistical difference was found in March – June when one tenant reported increased seasonal work in 2019 but may have managed these tasks with home-based access during 2021. During August and September occupancy levels appear similar (at low levels) across the two years.

Table 13 shows that as expected, weekday energy consumption is generally statistically different in 2022 than 2021. This suggests that although not all occupants are back, the energy consumption levels are different from the minimal occupancy levels of 2021. Interestingly, although some occupants are working remotely, those that do return to the office are using more energy than when the building was unoccupied.

On weekends, the consumption levels in 2021 and 2022 are not statistically different for lighting and total consumption. This suggests that tenants had a similar low level of weekend work in both years. Total consumption is similar likely due to the same HVAC operating schedules on weekends for both 2021 and 2022. This is in contrast to 2019 when HVAC unoccupied schedules were still being implemented for weekends and there were some differences between 2019 and 2021 consumption. Plug loads are statistically different suggesting that a few tenants returned to weekend work in the office during 2022, or they may be leaving electronic devices turned on over the weekend. The difference between lighting and plug loads can be due to the nature of turning off multiple devices compared with a single switch. Occupants might find it more convenient to leave their monitors and printers plugged in over the weekend during 2022. However when they left for prolonged periods of remote work in 2021, they likely took their laptops, monitors and other equipment with them to be used in their new home offices. Lastly, devices such as fridges by nature cannot be used only during weekdays and remain operational through the weekends thus contributing to the differences observed.

Table 12: t-test results for lighting, plug load (PL) and total energy consumption comparing 2019 with 2021

Month	**Weekdays**			**Weekends**		
	Lighting	PL	Total	Lighting	PL	Total
Jan	0	0.03	0	0	0.26	0
Feb	0	0	0	0	0	0.03
Mar	0	0	0	0	0	0
Apr	0	0	0	0.06	0	0
May	0	0	0	0.18	0	0
Jun	0	0	0	0.01	0	0
July	0	0	0	0.26	0	0.05
Aug	0	0	0	0.15	0	0.27
Sept	0	0	0	0.26	0	0.4
Oct	0	0	0	0.58	0	0.03
Nov	0	0	0	0.01	0	0.02
Dec	0	0	0	0.99	0	0.04

Table 13: t-test results for lighting, plug load (PL) and total energy consumption comparing 2021 with 2022

Month	**Weekdays**			**Weekends**		
	Lighting	TPL	Total	Lighting	TPL	Total
Jan	0	0	0	0.09	0	0.93
Feb	0.9	0	0	0.05	0	0.74
Mar	0	0	0	0.1	0	0.99
Apr	0	0	0	0.2	0	0.86
May	0.03	0	0.01	0.06	0	0.92
Jun	0	0	0	0.04	0	0.91

Legend Tables 7 and 8: **$p < 0.001$**, **$0.001 < p < 0.05$**, **$p > 0.05$**

5.5.3 Hourly Consumption Profiles

Figure 22 lighting shows three modes of operation observed on Mondays (weekday profile) and Saturdays (weekend profile) in February and June. Firstly, during weekdays, across the three years lighting and plug loads demand starts rising at approximately 7:30 AM, suggesting when some tenants start arriving, and the demand reaches a peak by 8:30 AM, where it remains for approximately 9 hours, until around 6:30 PM when it starts falling. This pattern remains the same across the three years of operation, although the peaks decreased when occupancy levels decreased. This suggests that although the building was mainly unoccupied in 2021, there were still small increases in the demand at the time when tenants would normally arrive. This might suggest that some lights are running on a schedule and are not manually turned on by the occupants as they arrive. In 2022, it appears as though the occupants who return to the office are following a similar schedule as they in 2019. This suggests a minimal lasting impact on occupant schedules due to the remote work during COVID-19. The lasting impact seen is more so with the occupants that continue to work remotely and only return to the office 2 or 3 days of the week. Decreased occupancy in 2021 contributed to a 39% decreased lighting peak consumption and the increased occupancy in 2022 contributed to a 21% increase relative to minimal occupancy.

When examining the weekday plug loads, similar consumption patterns are seen in Figure 22, although the maximum energy consumption is less in comparison to lighting consumption. Similarly, this pattern with the increase as occupants arrive at 8:30 AM suggests that occupants bring in some of their personal electronics to work and take them home. During 2021, at minimal occupancy levels, the load was almost constant at around 20kW per day suggesting that this is the energy consumption used by fridges and other devices that remain plugged in. The personal electronics that occupants begin using at work add an additional 10 to 20 kW per day. In both 2019 and 2022, the demand returns back to baselevels (i.e., energy consumed at 12 AM) after 6:30 PM suggesting that tenants might be taking home some of their personal electronics or unplugging them which leads to a reduction in demand.

During weekends as displayed on Figure 22, the demand for lighting in February 2019 had increased consumption during the daytime; however, this demand decreased in 2021 and 2022. The increased demand in 2019 could be explained by extra demand during the tax season and office-based work on the weekend. Plug loads were relatively constant during all hours likely due occupants removing their personal electronics; however, some appliance motors remain cycling on and off (e.g., refrigerator). The constant plug load consumption decreased by 50% comparing 2019 with 2021 consumption levels, with a smaller increase (20%) observed in 2022. This suggests that fewer people returned to work on the weekend in 2022 and the increase (10 kW) may also include phantom loads of electronics, monitors, etc. that were left on during the weekend.

Lastly, there is a minimal difference observed between February and June consumption levels. This suggests that seasonal variation does not significantly impact the end-uses. These profiles can be used by energy modelers to simulate potential energy consumption patterns post-COVID-19. The consumption hours can be used to infer occupant schedules which was found to exceed the traditionally assumed 9 AM to 5 PM and span the broader time range from 7:30 AM to 6:30 PM.

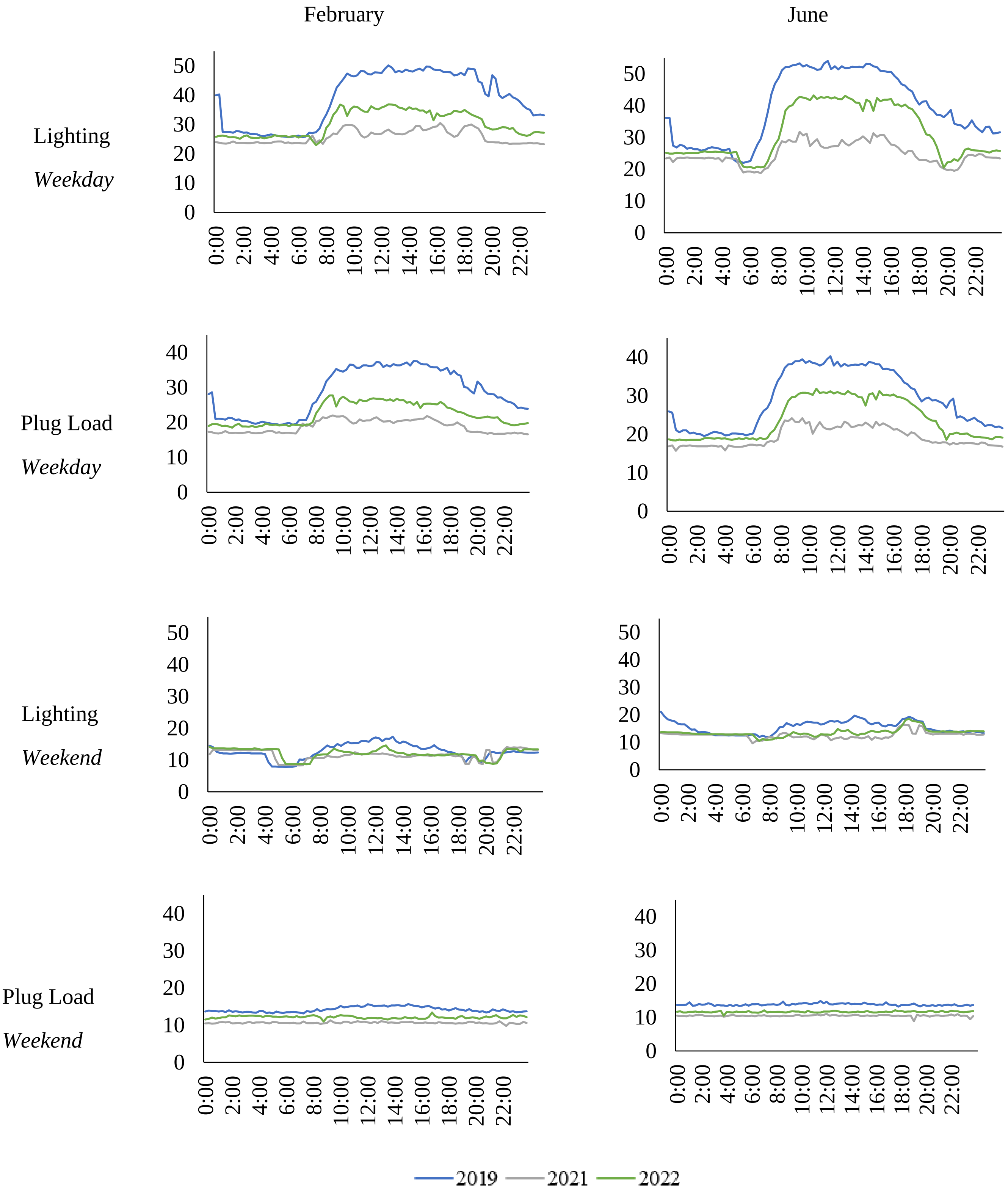


Figure 22: Building energy consumption in kW, hourly by end-use 2019, 2021 and 202

5.6 Discussion

Building energy consumption of a case study net-positive energy office building was analyzed annually, monthly, daily and hourly comparing 2019 with 2021 and 2022 on a lighting, plug load and total basis. EUI in 2021 was found to be 74 kWh/m^2 indicating energy consumption under minimal occupancy., COVID-19 created a disruption to regular building operations to enable measurements to be made during a period of low occupancy. The literature discusses the importance of understanding occupant needs and providing them with adequate training to ensure they understand how to use various building interfaces to ensure both comfort and energy savings (41,51). In this study, it was observed that a small amount of energy (10%) was saved under minimal occupancy conditions. This highlights how occupancy can play a small role in the energy consumption of a high-performance building. Similarly, the consumption profiles provided in this study under minimal (2021), medium (2022) and full occupancy (2019) add to the literature that seeks to develop occupancy profiles based on monitoring data (118).

Comparing three months of occupied and unoccupied operation show that a fully empty building consumed 90% of its typical energy load. This provides insight on the impact of occupant behaviour on the performance gap. In this investigation it was found that under minimal occupancy conditions, the occupants had a small impact on building energy consumption in this type of high performing building. Furthermore, this 10% reduction is higher than findings from a meta-analysis study that found a 5% annual difference in offices (30). Simulation studies predicted a 22% energy consumption increase post COVID-19 in offices of similar climate to the case study building (31). The findings from the first six months of 2022 suggest that lighting remains within 2021 levels and 32% less than the baseline, whereas plug load energy consumption increased by 9% from 2021 levels but remained 17% below the baseline due to increased remote working. Lighting, and plug loads energy consumption were further analyzed for significant differences between the three occupancy levels and hourly consumption profiles were analyzed for seasonal, weekend and weekday comparison.

Lighting and plug load energy consumption decreased by 31% and 26% respectively under minimal occupancy conditions, which suggests that the unoccupied building uses approximately 70% of baseline energy consumption even in these direct tenant related categories. Plug load consumption was found to be 11.7 kWh/m^2 on average which is almost half the findings of a modeler survey study (122). This difference could be due to several factors including overestimates from the survey and reduced energy consumption due to more efficient office equipment such as laptops.

Statistical analysis revealed 2019 and 2021 weekday and weekend consumption were different for almost all months across the end-uses and total consumption. The weekday plug load hourly profile trends are inline with previous study findings, although the case study building is using more energy on weekends than previously found (21). This reflects the work profile of one tenant with some weekend work during tax accounting season and also suggests that efforts could be made to train occupants to reduce phantom loads while the building is unoccupied as found in behavioural intervention studies (21,22). Comparing 2021 consumption with 2022 found a statistical difference, with 2022 energy consumption higher than 2021 which is to be expected. This confirms that although not all occupants are back to the office, most lighting and plug loads have returned. These findings are a contrast to a residential study which found no significant increases in energy consumption beyond the first month of the pandemic (65).

Designers and researchers may use the empirical data provided in this study to assess the impact of occupancy on high performing office building energy consumption. Occupancy has been difficult to measure and this led to a gap in scientific understanding of its impact on energy consumption (9,41,118). This improved understanding can help reduce the performance gap and help realize energy conservation, especially when coupled with energy efficient design strategies.

This provides operators, researchers, and designers with valuable energy consumption data to inspire designs for future buildings. For example, future office buildings may consider different floor design layouts that account for variable occupancy (e.g., more individual office space). Additionally, making use of occupant centric controls such as demand control ventilation or occupancy sensor lighting controls can reduce energy consumption while the building is unoccupied (120). Additionally, occupant centric HVAC controls can reduce overventilation and decrease energy consumption in areas that are unoccupied (124). Lastly, different operating models can be applied by implementing different schedules (e.g., if all tenants will be working remotely on Mondays, then Mondays can be on an unoccupied operating schedule with reduced HVAC setpoints).

5.6.1 Limitations and Future Research

There are three main limitations identified for this study. Firstly, although this study analyzed occupant centric loads, occupant behaviour was not considered. To better understand the observed energy consumption profiles, future studies can include analyzing occupant behaviour using surveys, interviews and other observational methods. Secondly, lighting controls were not validated for this study. The design strategy aimed to use daylight harvesting; however, sensor verification has not been performed, therefore it was assumed that the daylight sensors function as intended (i.e., the lights turned off the lights in the absence of occupants and in the presence of sufficient daylight even when occupants were present) in the design for the operational analysis. Lastly, as this is a single building case study with a few months of data post-COVID-19, the broader conclusions reached based on the results should be considered carefully.

Future research can consider investigating Canadian offices, the relation between occupancy and energy consumption and ways to reduce idle (unoccupied) BEC. Net-zero energy building studies are needed to compare findings and create more meaningful recommendations. Examining occupancy sensor data to determine if there exist any correlations between measured occupancy and energy consumption can provide insights into ways to reduce unoccupied BEC.

5.7 Conclusion

Occupant relationships with office buildings has changed with the focus on remote work during the pandemic followed by a hybrid model of office and remote work post-pandemic. This case study shows that at minimum, the case study building consumes 74 kWh/m^2, with lighting and plug loads at 16.79 kWh/m^2 and 10.20 kWh/m^2 respectively. Comparing three months of operation in 2020 and 2021 indicates a 10% decrease that can be attributed to occupancy. This helps quantify in terms of energy consumption, how occupant behaviour may impact a potential performance gap in a higher performing building operating in northern climate. A weak correlation was found between irradiance and lighting energy consumption and limited seasonal variation was found when comparing monthly lighting and plug load consumption of 2019 (baseline occupancy) with 2021 (minimal occupancy). A decrease of 32% and 26% was found when comparing 2019 and 2021 lighting and plug load consumption respectively. This indicates that these loads are impacted by a pre-specified schedule and are less sensitive to occupancy. A statistical difference was found in weekday energy consumption comparing 2019 as a baseline year with 2021 as a minimal occupancy year, demonstrating that although the overall energy reduction in 2021 lighting and plug loads was about 30%, there is still a statistical daily difference in the consumption profiles. Similarly, comparing 2021 with 2022 found significant differences but at an intermediate level. This indicates that new consumption patterns are emerging post-COVID-19.

Considerations for future buildings:

- Training occupants to use lighting controls can help ensure design goals are met (34)
- Occupant centric controls such as daylighting, occupancy sensing, and demand control ventilation can be used to reduce unoccupied BEC (120)

- Designing a hybrid occupancy mode to accommodate occupants working from the office some days and remote work other days can help adapt building operation to a post COVID-19 world

To reduce phantom plug loads operational strategies such as centralized switches that can turn off office printers, monitors and computers can be considered.

Chapter 6 Discussion and Conclusion

6.1 Overview

This investigation of NPEB examined operations from January 2019 to June 2022, where several key events took place. Firstly, the building operators were finetuning setpoints during the commissioning period from January to September 2019. Then, COVID-19 changed occupancy levels from March 2020 to February 2022, with lasting impacts due to increased remote work still observed from February to June. Access to building operation and design data through various energy meters, sensors and the building operator and designer allowed for a holistic understanding of the performance achieved by the NPEB. During these three and a half years of operation, the NPEB demonstrated that effective design, commissioning and operation of a new office building can achieve the generation of more onsite renewable electricity than it consumes. This was due to a combination of operational decisions made during commissioning. Reduced occupancy from COVID-19 created an opportunity to learn about the minimum building energy consumption under current best operational practices. This study aims to inspire future building designs that realize energy conservation when they are fully, medium and minimally occupied.

6.2 Net-positive Energy Building

An important design goal for the NPEB operation was to generate at least 5% more energy than it consumed. The performance gap can be a barrier to realizing new operational goals (9,10,47,54). As such, the building operators used the design model as an energy target and a metric for achieving success. In the first year of operation, with ongoing commissioning, the NPEB imported 7% of its energy from the local grid; however, in 2020 and 2021, with decreased occupancy as a factor, 123% and 126% solar electricity were generated. The NPEB contributed 23% and 26% energy to the local grid, or about 205, 000 – 226, 000 MWh. This provides valuable empirical data for the performance possible to be achieved in northern climate conditions (Canada). Reducing building energy consumption was essential to ensuring enough surplus energy generation and as such commissioning activities played a large role in reducing the performance gap and ensuring this net-positive energy is possible.

6.3 Commissioning Activities

New building commissioning can be a key part in ensuring that building operation is set up to meet design goals. Commissioning activities focused on HVAC operations in the NPEB ranged from decreasing operational setpoints (e.g., temperature, relative humidity) to reduce excessive operation and upsizing equipment (e.g., pumps) to ensure reliable and efficient operation. Other actions included reducing peak demand consumption by changing the transition from unoccupied to occupied setpoints over the weekends. The savings from the implemented start up procedure contribute to reducing the pressure on the Ontario grid to meet consumer demand during peak times, since the procedure began at 4AM rather than 7 AM. It also allowed building equipment (e.g., geothermal heat pump) to generate the necessary energy to operate the fan coil units and reduce reliance on the local electricity grid. Energy savings observed were 28.5% which was in line with previous peak demand commissioning projects (64,93).

Overall, these decisions were found to reduce total building energy consumption by 15% annually. These savings were higher than the medians of commissioning projects reported by earlier studies (14,15), however this difference can be due to the number of commissioning projects considered in this combination of activities that took place at the NPEB. The medians reported in meta-analysis are for individual energy savings projects (14,15). Generally, the complexity of building equipment can impact the initial building energy consumption and the associated finetuning needed to get operations on target.

6.4 Sensitivity to Outdoor Conditions

Typically, building energy consumption, especially HVAC can be dependent on outdoor conditions (e.g., mean outdoor temperature) (55,100), however, in the NPEB, a weak relationship between mean outdoor temperature and HVAC energy consumption. Additionally, commissioning activities were found to reduce energy consumption at similar outdoor conditions when comparing pre and post commissioning as seen in Figure 16.

6.5 COVID-19 and Occupancy

Occupant behaviour including occupancy and occupant schedules has often been cited as a main contributing factor to the performance gap and realizing energy conservation (50,51,118). COVID-19 created an opportunity for researchers to investigate how a building consumes energy under minimal occupancy conditions and evaluate the impact of occupancy. While many studies focused on indoor air quality (72–74), others considered potential energy consumption increases in residential buildings (65,66,71), higher education buildings (69,70), and a few considered office building (30,31). This study aimed to shed a light on Canadian office building operational trends and lessons learned from operating during the COVID-19 pandemic.

End-uses such as lighting and plug loads are often most impacted by occupancy in offices, depending on the controls available to be modified by occupants (e.g., thermostat modification) (38,48,49). Additionally, with the rise of personal electronics, plug load energy consumption is continuing to increase in offices and residential buildings. Total building energy consumption under minimal occupancy levels was investigated and a 10% decrease which is inline with other COVID-19 office studies (30). The hourly load profiles in Figure 22 show that plug load and lighting energy consumption are similar on weekends, however, plug load consumption is lower during weekdays. Although plug loads are reduced on weekends, they are still consuming some power, suggesting that some equipment (e.g., laptops, monitors) remain plugged in even when occupants have left for the weekend. This is contrary to what was reported by Gandhi et al. (21), which found plug loads to be almost at 0 kW for non-work days. Both end-uses reported in the NPEB showed minimal seasonal variation, further contributing to the hypothesis about low sensitivity to outdoor conditions. Lastly, base building consumption remains relatively similar on weekends and weekdays, with more pronounced peak periods in 2019 under baseline occupancy levels. This trend is as expected since base building energy is mainly impacted by occupants through smaller loads (e.g., elevators, hand driers).

6.6 Conclusion

The objectives of this investigation were to uncover how net-positive buildings perform and share the lessons learned from this case study with industry and research partners. Through a stakeholder collaboration with building operation and design partners, this case study had real empirical data from a live experiment of sorts. The first part of the investigation focused on uncovering the impact of commissioning activities and decisions made by the building operator to ensure meeting design targets. The net-positive status of the building was also assessed using three and a half years of operational data. Then, in the second part of the investigation, the impact of occupancy on building energy consumption and especially occupant centric loads such as lighting and plug loads were investigated. COVID-19 led to a minimal occupancy period in 2021 which was used to contrast typical consumption levels from 2019. As occupants return to work in a hybrid mode, 2022 energy data was used to understand the implications of this new relationship between occupants and offices space.

From this study, it was found that building commissioning activities focused on HVAC and pump operation reduced energy consumption by 15% annually. This significantly closed the overall performance gap and led to the net-positive building generating more energy than it consumed during 2020 and 2021, with 2022 on track to achieving design goals. Lighting energy consumption in 2019, considered the baseline, is almost twice the design model predictions. This suggests that improving lighting controls to reduce excessive operation can be an area of energy consumption improvement. Different strategies to accomplish this can include investigating occupant training on how to use the light switches, using dimmers and modifying the sensitivity on occupancy sensors to reduce accidental triggers (e.g., occupants going up the stairs and turning on the lobby lights even though that space is unoccupied).

COVID-19 data comparing January to March 2020 with 2021 showed a 10% overall energy reduction decrease mainly from lighting and plug loads. Further investigating these loads and comparing with 2022 data, revealed three modes of energy consumption. Even though occupancy decreased to 10% of baseline in 2021, lighting and plug load energy consumption were still at 70% and 75% of baseline respectively. This suggests room for improvement to reduce these idle loads. Some strategies to accomplish these energy reductions include training occupants to turn off the lights and unplug computers, monitors and other electronics if away for a long weekend. Additionally, since not all occupants return to the office every day of the week, with the rise of remote working, one option that may be explored is considering having a corner of the office where there is a shared space for those working from the office, and the remainder of the space can be unoccupied, with the lights and plug loads off to reduce phantom energy consumption.

6.7 Recommendations for Practice

The following are a few points for consideration for potential energy savings

- Occupant training on how to properly use the lighting controls to reduce excess and unintended energy consumption
- Separating lighting controls to allow occupants flexibility in turning on the lights for one section of the shared office rather than the entire space
- Reducing temperature in unoccupied zones for example if the classroom is not to be occupied in August then the temperature for this zone can go to unoccupied settings
- Continuing to monitor building energy consumption to ensure operational targets are met

6.8 Recommendations for Future Research

The following points can be considered for further investigation

- The correlation between lighting and outdoor conditions such as hours of sun or irradiance
- Verification of the installation and programming of the daylighting sensors
- Calibration of lighting sensors if they are not working as intended
- Determining the time constant of the building (time it takes to lose 1 °C) and using that to apply predictive heating or cooling
- Economic assessment of the commissioning activities to determine feasibility
- Impact of occupant interventions through educational games to engage in energy conservation behaviour

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Appendix

Appendix A – Commissioning activities Tools and Data

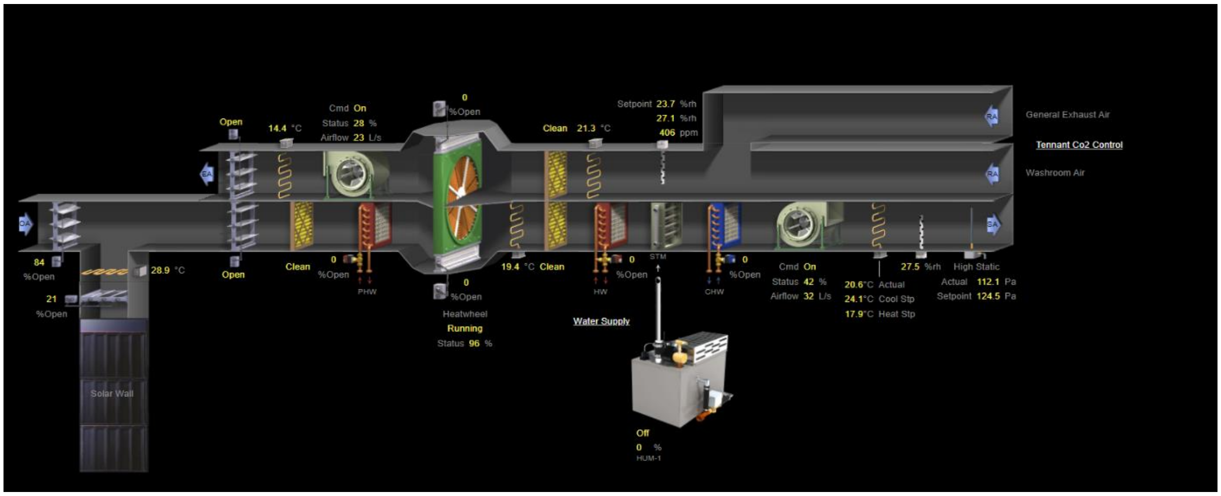


Figure 23: Example of the BAS system demonstrating the make-up air unit during operation

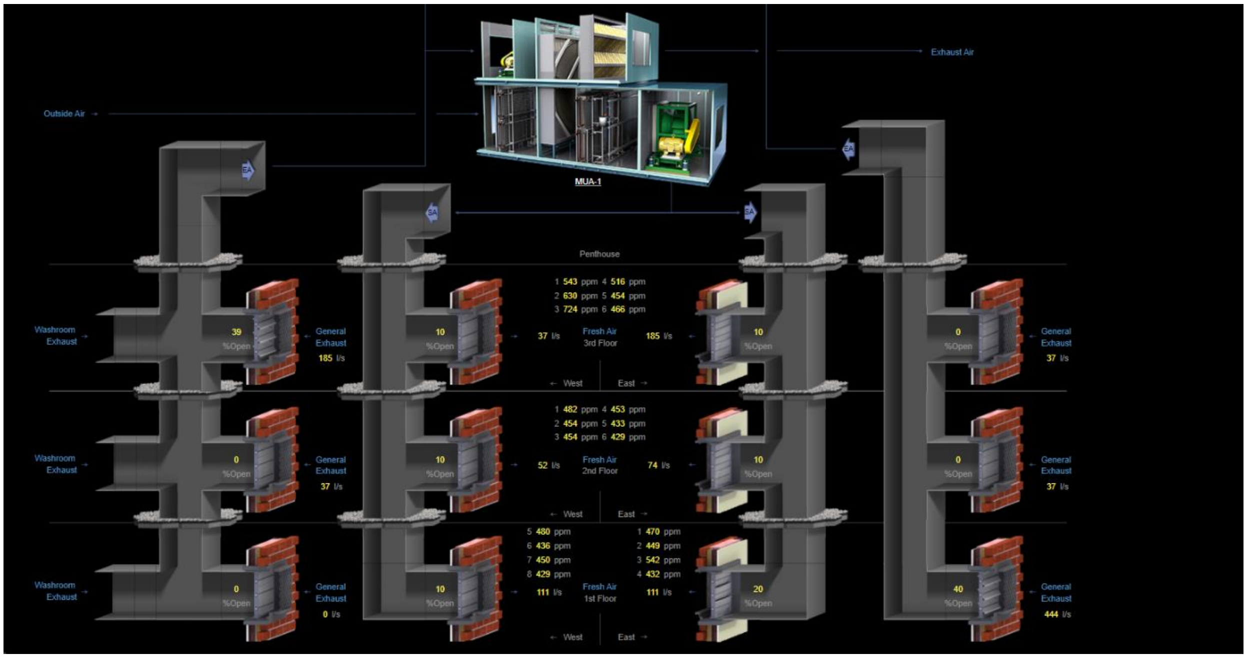


Figure 24: Example of tenant space CO_2 ventilation demand control available in operator BAS to ensure continuous monitoring

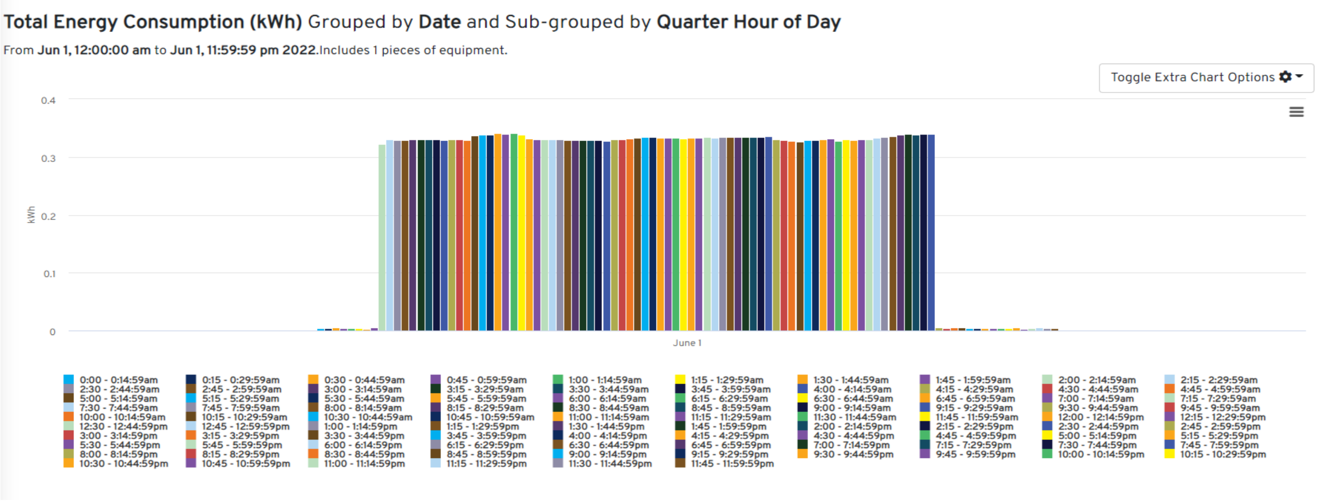


Figure 25: Sample of energy meter live data available for building operators (figure showing air handling unit meter for June 1st, 2022

Appendix B – Data Cleaning Scripts

STEP1

bringing all meters into one file and sum all the days

```
import pandas as pd
import os

df = pd.DataFrame()
name="2022 July and Aug Data"

#change the name of the directory
for file in os.listdir(name):
    dt = pd.read_csv(name + "/" + file, skiprows=6, header=None)

    #remove first column
    dt = dt.drop(dt.columns[0], axis=1)

    #print(dt.head(2))

    dt_sum = dt.sum(axis=0)

    filename = file.split(".")[0]

    df[filename] = dt_sum


df.to_csv(name + " step1.csv")

print("done step 1")
```

STEP2

make new column with date (recall the year so change format to short date and add 2022-01-01 for example) change to month - year category by adding in excel

`=MONTH(cell)&"-"&YEAR(cell)`

copy new column and paste as numbers in the date column

```
import pandas as pd
import os

df = pd.DataFrame()
name="2022 July and Aug Data step1.csv"

dt = pd.read_csv(name, header=None)

#get unique values values in first column except for the first row
dt_unique = dt.iloc[1:, 0].unique()

print(dt_unique)

#for all unique values in row 1 create a new column with the same name and sum all values in that column
for value in dt_unique:
    #print all rows that have first column value
    dt_sum = dt[dt[0] == value]
    #print(dt_sum)
    #change all the values in the columns except for the first one to floats and sum them
    dt_sum = dt_sum.iloc[:, 1:].astype(float).sum(axis=0)
    #print(dt_sum)
    df[value] = dt_sum

df = df.transpose()

df.to_csv(name.split(".")[0] + " step2.csv")
```

```
print("done step 2")
```

STEP 3

change column names to the different end-uses (open the measurement and verification heading table file)

```
import pandas as pd
import os

df = pd.DataFrame()

name="2022 July and Aug Data step1 step2.csv"
dt = pd.read_csv(name, header=None)

#get all unique values in first column
dt_unique = dt.iloc[1:, 0].unique()

#print(dt_unique)

#get header except for first row
dt_header = dt.iloc[0, 1:]

#print(dt_header)

for month in dt_unique:
    #print all rows that have month in the first column
    dt_sum = dt[dt[0] == month]

    print(dt_sum)
```

```
    #change all the values in the columns except for the first one to floats and sum them
    dt_sum = dt_sum.iloc[:, 1:].astype(float).sum(axis=0)

    df[month] = dt_sum



df = df.transpose()

#put column headers except for first column from dt to df
df.columns = dt_header.str.split(".").str[0]

#sum all columns that have the same name
df = df.groupby(df.columns, axis=1).sum()

df.to_csv(name.split(".")[0] + " step3.csv")

print("done step 3")
```

STEP 4

splitting weekend and weekdays

go back to step 1 output and replace the first column with the short date (2022-01-01 etc)

```
import pandas as pd
from datetime import datetime
from datetime import date



weekends = pd.DataFrame()
weekdays = pd.DataFrame()
```

```
name = "2022 Datastep1.csv"



df = pd.read_csv(name, header=0)

#print(df.head())

def is_weekend(datee):
   # print(date)
    year, month, day = datee.split('-')
    #print(year, month, day)
    dates = date(int(year), int(month), int(day))
    return dates.weekday() > 4

#check every row in first column for weekends and add to weekends dataframe

for index, row in df.iterrows():
    if is_weekend(row[0]):
        weekends = weekends.append(row)
    else:
        weekdays = weekdays.append(row)



weekends.to_csv('weekends_' + name, index=False)
weekdays.to_csv('weekdays_' + name, index=False)
```

STEP 5

weather weekday and weekends

```
import pandas as pd
from datetime import datetime
from datetime import date
```

```
weekends = pd.DataFrame()
weekdays = pd.DataFrame()


name = "en_climate_daily_ON_6144239_2022_P1D.csv"


df = pd.read_csv(name, header=0)

#print(df.head())

def is_weekend(datee):
   # print(date)
    year, month, day = datee.split('-')
    #print(year, month, day)
    dates = date(int(year), int(month), int(day))
    return dates.weekday() > 4

#check every row in first column for weekends and add to weekends dataframe

for index, row in df.iterrows():
    if is_weekend(row[4]):
        weekends = weekends.append(row)
    else:
        weekdays = weekdays.append(row)


weekends.to_csv('weekends_' + name, index=False)
weekdays.to_csv('weekdays_' + name, index=False)
```

Appendix C – Key informant interview research questions

Below is a sample of the questions asked regarding during the semi-structured key informant interviews:

- Have there been occupant requests about increasing or decreasing HVAC operating points?
- Is there a log for these changes?
- How do the CO_2 sensors in the dampers work? Do we have other sensors? Were there recent changes to the setpoints?
- What happened during commissioning? Were there supporting documents tracking the changes?
- What were some of the cleaning protocols and how were they changed due to COVID?
- What are the airflow rates, relative humidity and temperature settings?
- Are the nitrous oxide or volatile organic compounds levels monitored?
- What happened after construction? What did tenants have control over during the fit-out process?
- How much of the thermostat setpoints can the occupants change?
- How is the temperature controlled? Is it by zone?
- Were there any alarms or control logic that needed to be changed during commissioning?
- Which energy meters belong in the different end uses?
- Why were changes made to the humidity set points?
- When did occupants return to work from the office more frequently during the pandemic?
- What could have contributed to the energy decrease observed in this month?
- Why were the pumps upsized? How does this improve energy efficiency or operation?

Appendix D – Net-positive energy buildings: towards achieving the SDGs and carbon neutrality

Monika Mikhail, Master's Candidate, University of Waterloo (corresponding author)
monika.mikhail@uwaterloo.ca
(519) 888 – 4567
200 University Ave West
Waterloo, Ontario, Canada N2L 3G1

David Mather, Lecturer, University of Waterloo
Paul Parker, Professor, University of Waterloo

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.

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 (125). 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 (24). 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 (126). EUI is typically measured in kWh/m^2 as the ratio of building energy consumption to building floor area (84).

The United Nations identified major challenges for high income countries' progress toward achieving the SDGs (2). 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 (2). Statistics Canada identifies several data gaps in measuring the progress toward the SDG indicators (25–27). 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.

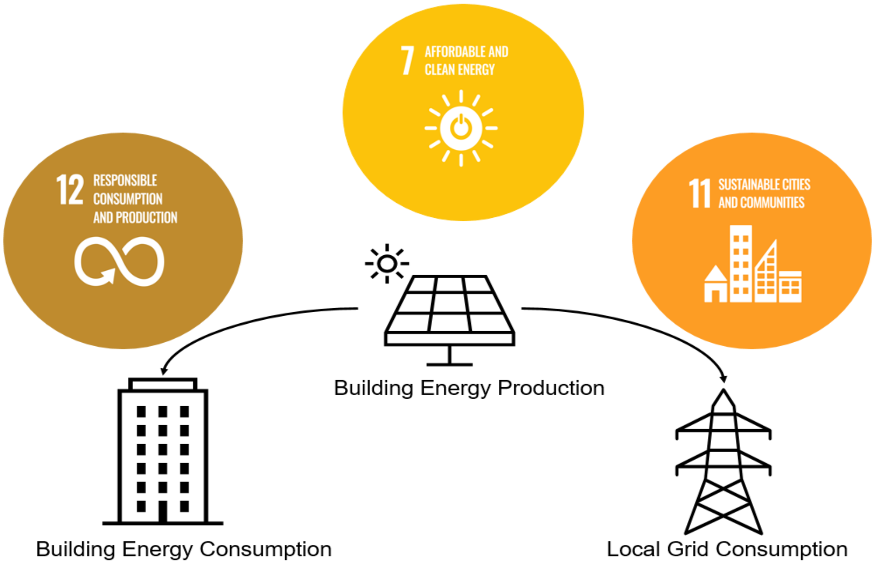


Figure 26: Net-positive energy building operation and impacted SDGs

Research Questions

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

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.

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 (23). A solar wall is also used to increase outdoor air temperature prior to its delivery into the HVAC system with increases of over 20oC being measured on sunny winter days (127). 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 (96). The three-storey building features a 5.7m wide living green wall to improve air quality by using natural humidification (23). These design features earned the building a platinum leadership in energy and environmental design (LEED) rating and zero-carbon building certification (23).

Data Collection and Analysis

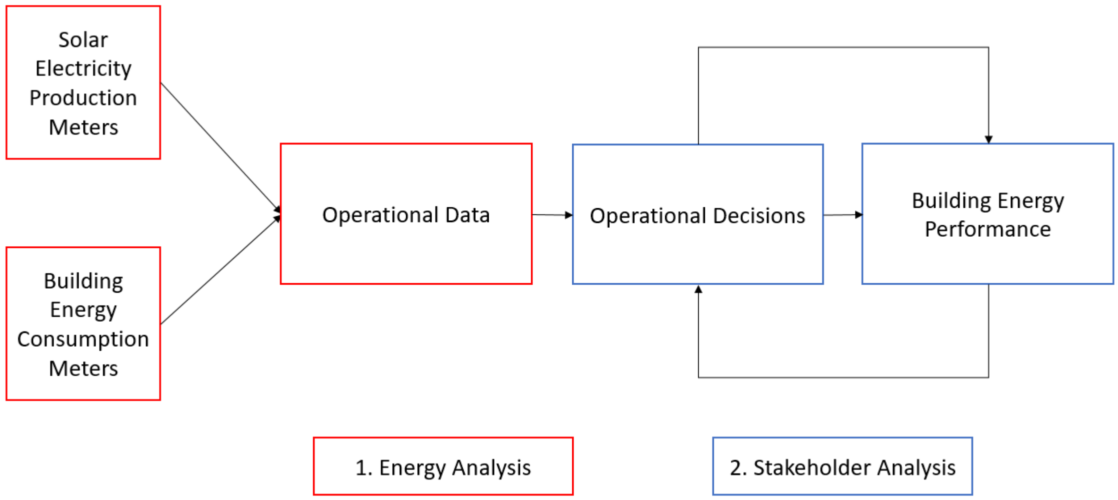


Figure 27: Data collection and analysis process

Figure 27 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.

Results and Discussion

Building Energy Consumption

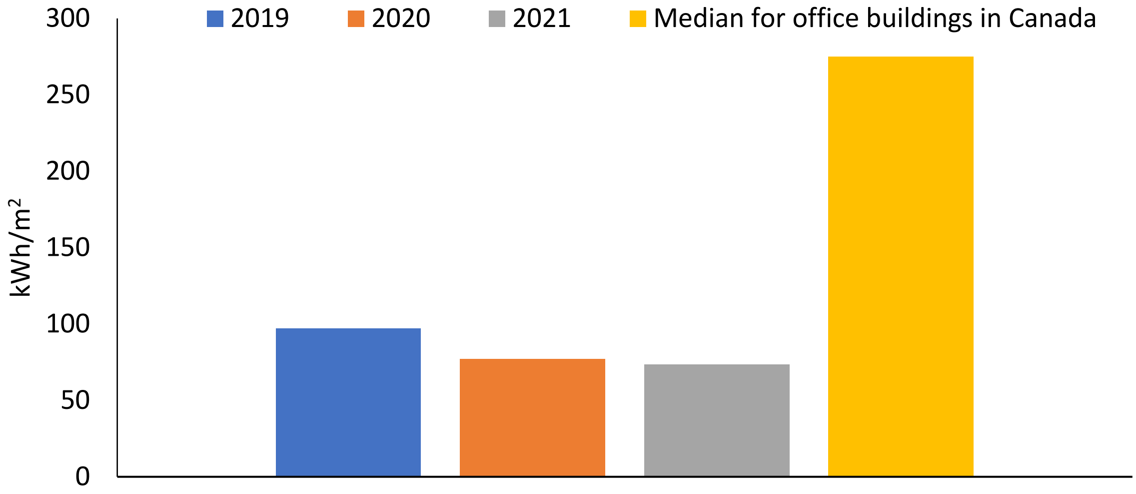


Figure 28: Building energy consumption in EUI from 2019-2021 relative to the 2018 median Canadian office EUI

Figure 3 summarizes the BEC in 2019, 2020 and 2021 as 97 kWh/m2, 77 kWh/m2 and 74 kWh/m2 respectively, averaging 83 kWh/m2 over the three years. A survey of Canadian national median values of EUI in office buildings revealed a median operational EUI of 275 kWh/m2 (85). 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.

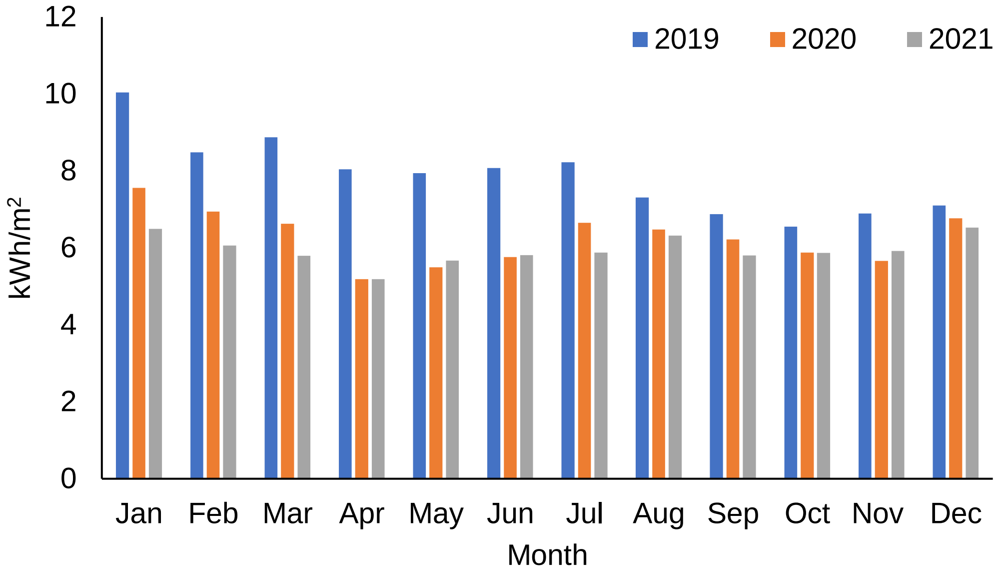


Figure 29: Monthly building energy consumption in EUI, 2019-2021

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 29 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 (94). This includes interior and exterior walls, windows, and the roof which all contribute to the energy performance and comfort of the building (94). 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 (128). Part of this transformation is to become more aware of our consumption patterns and work to reduce excessive energy consumption (128). Therefore, efforts to reduce BEC and EUI are needed to achieve SDGs 7 and 12 by 2030.

Solar Electricity Production

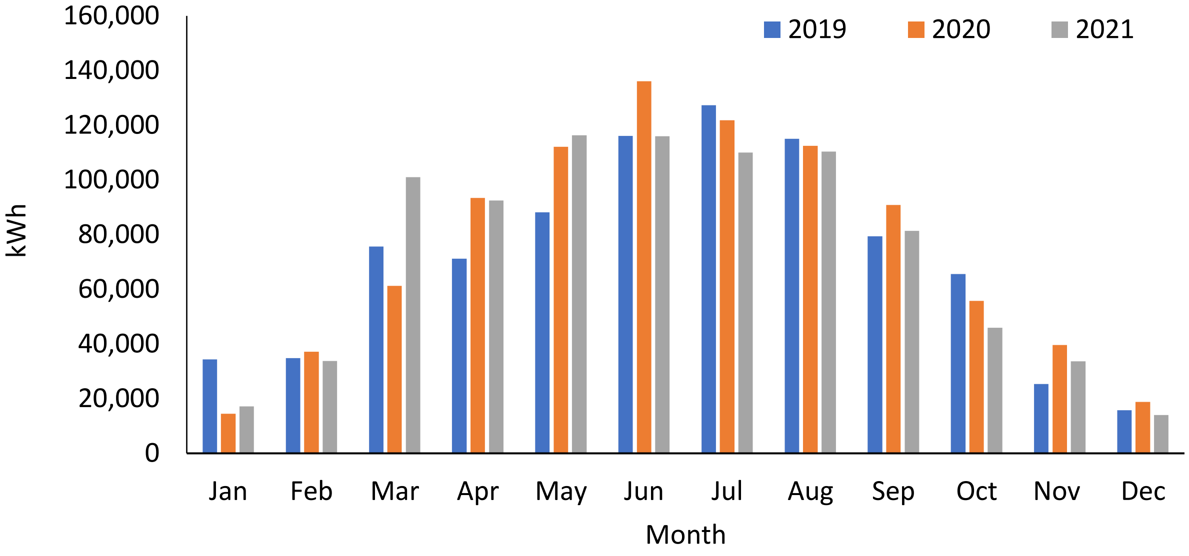


Figure 30: Monthly SEP in kWh 2019-2021

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 30. 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 (24), 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.

Solar Electricity Grid Contribution

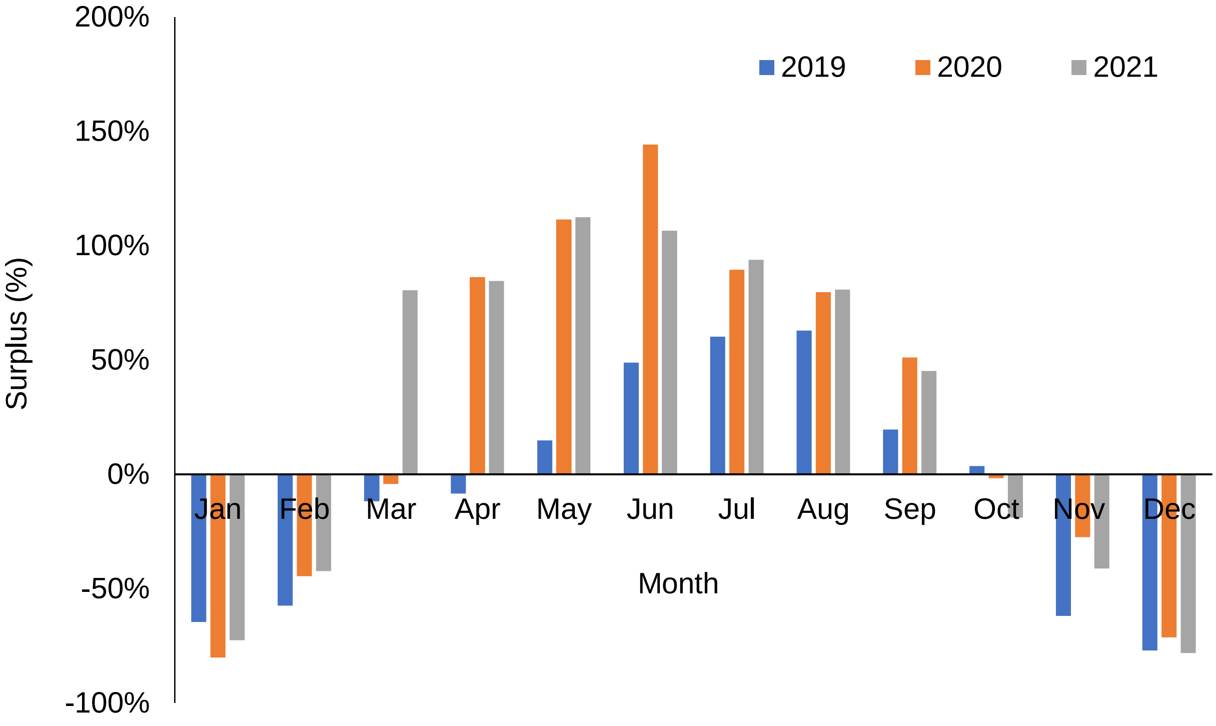


Figure 31: Monthly surplus generation for operation, 2019-2021

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 31 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 (83) and as suggested by Figure 30 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.

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/m2 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.

Appendix E – Towards achieving the SDGs: insights from four years of net-positive energy building operation

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 (1). 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. 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 (129). 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 harmful impacts of the built environment on human health, 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 operation (35). 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 (8). 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 (34). 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 (125). 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 (33). These developments aim to leave the ecology or physical environment better than before they were built (33). This can include improving air, 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

(24). 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 (126). EUI is typically measured in kWh/m^2 as the ratio of building energy consumption to building floor area (84).

In the 2000s, the Millennium Development Goals (MDGs) focused global efforts to tackle poverty (130). They succeeded in enabling the decline of the number of people in extreme poverty, increasing people in working middle class and reducing the number of undernourished people in developing nations (130). Following this success, at the United Nations Conference on Sustainable Development in Rio de Janeiro in 2012, the SDGs were 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 (131). 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 (2). 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 (132), they still serve as a framework to direct attention to global challenges that need urgent action.

The World's Green Building Council (133) highlights 11 SDGs that green buildings contribute to and are summarized below in Table 14**.** 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) (134–136). Whitney et al. (134) 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 towards achieving operational goals (134). Dreyer et al. (135) 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 (135). Lastly, Zitars et al. (2021) analyzed the impact of the case study building on promoting employee health, wellbeing 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 the purposes of 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.

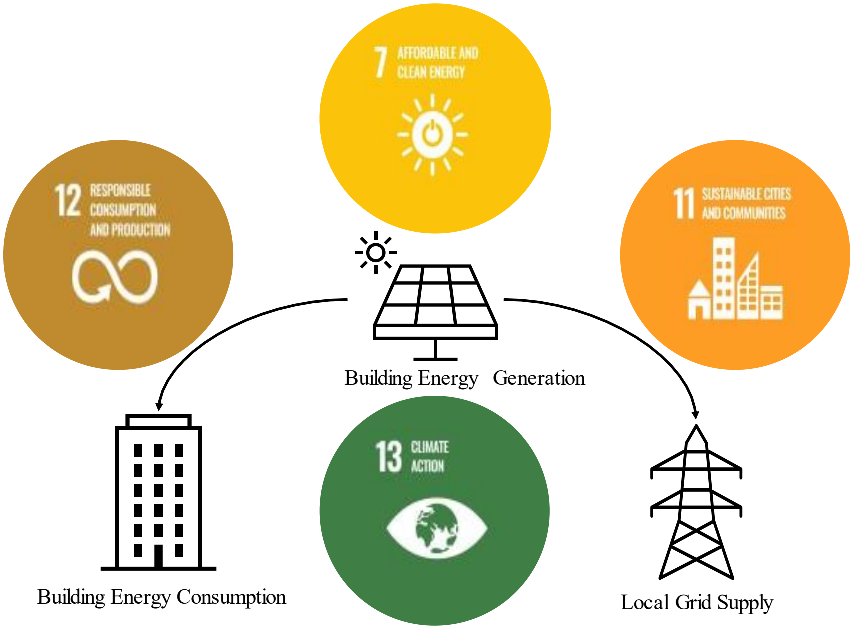
TABLE 14
SUMMARY OF THE WORLD'S GREEN BUILDING COUNCIL'S CONTRIBUTION TO THE SDGS

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 ^{o}C 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 (2). 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 (2). 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 32
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 (137–146). 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 operation. 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 (139,140). 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 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 (139,140).

Other studies looked at the use of sustainable and smart materials in building construction to reduce energy consumption and contribute to the SDGs (137,141,143). Green building materials were reported to help achieve the SDGs mentioned by (133), but specifically, they were found to significantly impact infrastructure resilience (SDG 9) and climate change disaster mitigation (SDG 13) (137). Selecting building façade materials was optimized to select material that decreased energy consumption and was resistant to earthquakes thus improving resilience and safety (143). Additionally, integrating photovoltaics and thermochromic material was found to improve energy use intensity (143). 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 (141). 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 lack of incentives, bias from the developers and limitations of the rating system's design (141).

One case study looked at integrating sustainability development goal targets in a net-positive energy building design in Canada (147). This study was focused on the design aspects that can be integrated in different levels by creating sustainable design visions that incorporate human needs (147). 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 wellbeing of different building occupants (147). 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 ensuring that design goals are met during operation. Heating, ventilating, air conditioning HVAC is 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 (121,148,149). 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 (120,149). Another common energy performance improvement strategy is building commissioning.

Building commissioning generally has two main types: existing building commissioning and new building commissioning (56). Existing building commissioning looks at improving existing building's performance, usually focusing on solving a specific operational challenge after the building has been built for a while (56). It is far less standardized and established relative to new building commissioning which has established standards and guidelines by ASHRAE (57). 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 (14). In meta-analyses of commissioning projects, different benefits of new building commissioning were highlighted to include energy savings and improved building operation performance (15,62). 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 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 (150). 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 (151). 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 (152). This study highlights the economic feasibility of solar PV systems in developing countries (152) to ensure 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 (23). 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 (127). 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 (96). The three-storey building features a 5.7m living green wall to improve air quality by using natural humidification (23). These design features earned the building a platinum leadership in energy and environmental design (LEED) rating and zero-carbon building certification (23). The details of the specifications and the building features contribution to the SDGs are summarized in Table 15.

TABLE 15
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 roof top and parking lot PV Solar wall used to pre-heat outdoor air Open loop geo-exchange system	Increasing renewable energy share in the mix

	providing water to regulate indoor air temperature	

Data Collection and Analysis

FIGURE 33
DATA COLLECTION AND ANALYSIS PROCESS

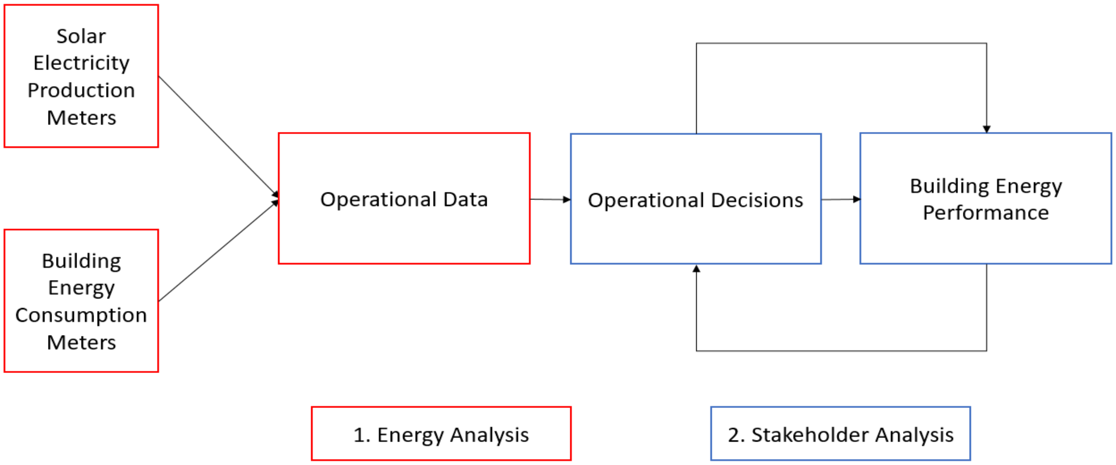


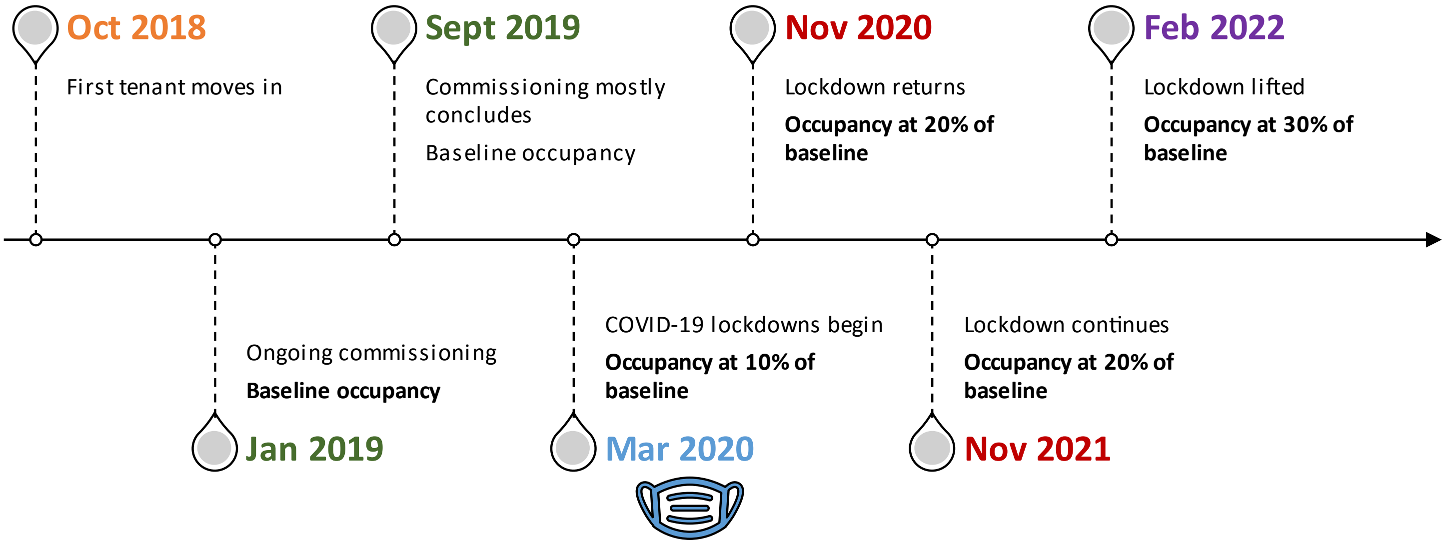
Figure 27 demonstrates the mixed methods used to provide a holistic analysis of this NPEB operation. A combination of quantitative operational energy data analysis and qualitative data collected from key informant interviews with a building operator and energy advisor were used in this study. Digital 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 own 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

There were three main events that 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 34
SUMMARY OF KEY EVENTS AND TIMELINE TAKING PLACE DURING CASE STUDY BUILDING OPERATION



Results

Building Energy Consumption

FIGURE 35
BUILDING ENERGY CONSUMPTION IN EUI FROM 2019-2022 RELATIVE TO THE 2018 MEDIAN CANADIAN OFFICE EUI

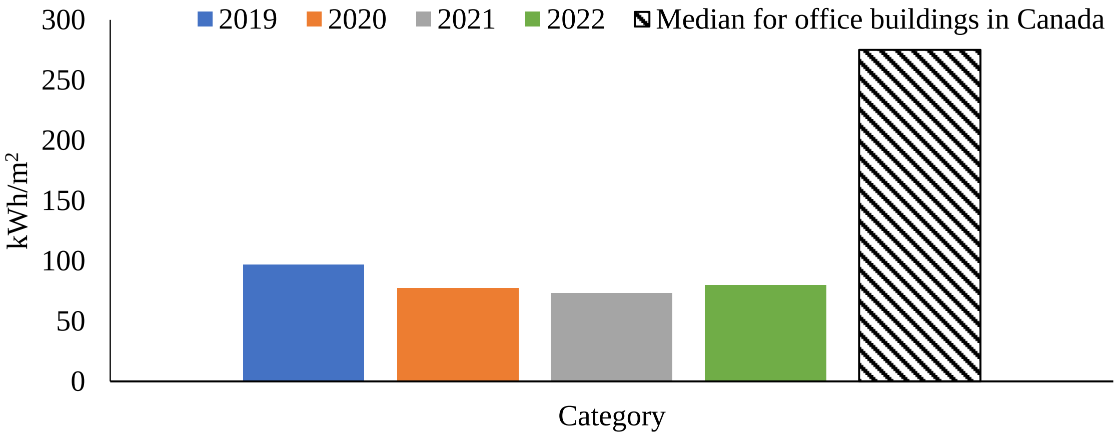
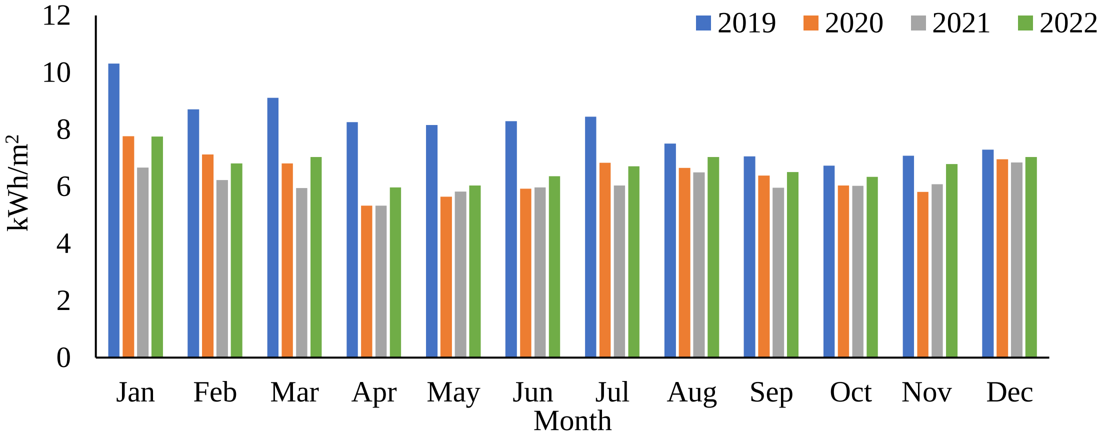


Figure 3 summarizes the BEC in 2019, 2020 and 2021 as 97 kWh/m^2, 77 kWh/m^2 and 74 kWh/m^2 respectively, averaging 83 kWh/m^2 over the three years. A survey of Canadian national median values of EUI in office buildings revealed a median operational EUI of 275 kWh/m^2 (85). Comparing the case study building 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 during 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 36
MONTHLY BUILDING ENERGY CONSUMPTION IN EUI, 2019-2021

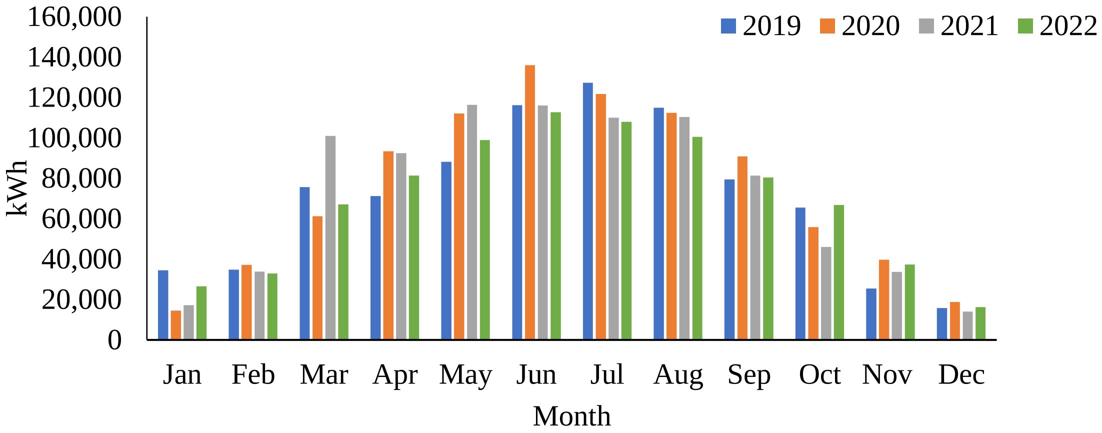


Commissioning typically takes 12-18 months to understand the building operation and make modifications to finetune energy consumption and occupant comfort. Initially, there were occupant requests to adjust the temperature due to the positioning of thermostats. After construction, the room thermometers 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 29 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

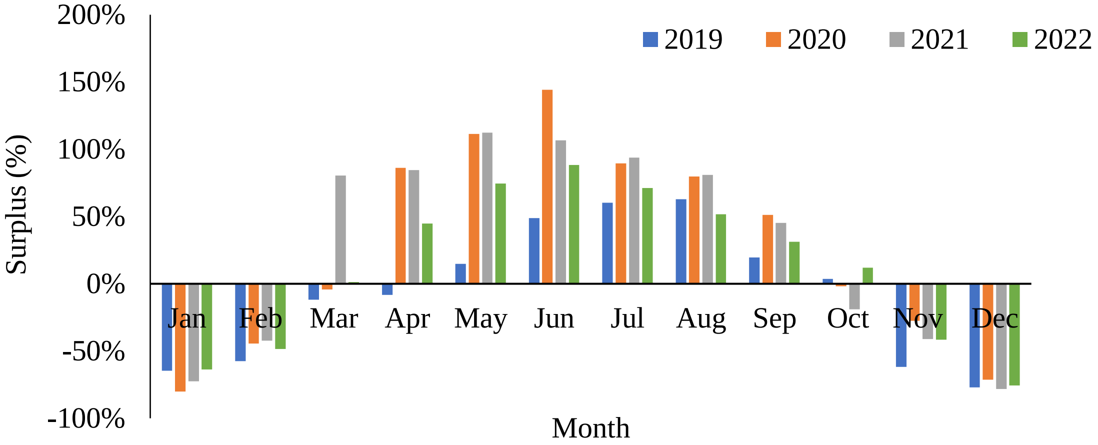
FIGURE 37
MONTHLY SOLAR ENERGY GENERATION, KWH, 2019-2022



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 30. The results show peak production months 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 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 38
MONTHLY SURPLUS GENERATION RELATIVE TO CONSUMPTION, 2019-2022



From Figure 31 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 (83) and as suggested by Figure 30 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 (153).

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 (29).

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 (134,154). 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 15. 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 1.

Building Energy Performance and the SDGs

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 (94). This includes interior and exterior walls, windows, and the roof which all contribute to the energy performance and comfort of the building (94). 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, 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 35.

In this study, the energy consumption and impact of commissioning of a 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) (142). 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 the variable frequency drives, dedicated outdoor air system, living wall, solar PV and solar air preheater mainly focused on reducing energy use intensity, managing indoor air quality and emissions using technology. Although there have been interventions to engage with the NPEB occupants (136) 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 behaviour around how energy is consumed (128). Part of this transformation is to become more aware of our consumption patterns and work to reduce excessive energy consumption (128). 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 (24), one option is to have buildings generate their own 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 (150–152). 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 (151). Additionally, this empirical data supports earlier design assessments of the reliability and stability of onsite solar PV as a method of energy generation (150).

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 16
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 (154), thus forming partnerships to adapt the City’s infrastructure