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Net-positive office commissioning and performance gap assessment: Empirical insights

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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 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.

1. Introduction

1.1. Net-Zero energy buildings and beyond

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 [2]. Net-zero energy buildings have the a design goal to generate as much electricity on-site as they consume annually [3]. This means that the overall or net energy demand from the grid is less than or equal to the energy generation by the building in the period of an average year [4]. This balance is completed on a source energy basis between the energy delivered and exported [5]. If a building produces 30 % or more of its net energy demand through renewable on-site generation, then this can be considered a nearly zero energy building [6]. There are two main ways to account for energy generation, first is net-zero site energy which is accounted for on-site energy generation at the utility meter, 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 [6].

Other definitions of net-zero buildings, include net-zero carbon, life cycle zero energy buildings and off-grid zero energy buildings [4]. Canada Green Building Council (CaGBC) defines a zero-carbon building as one that is “highly energy-efficient and minimizes greenhouse gas emissions from building materials and operations” [7]. Carbon offsets can be used to counterbalance emissions until the building operation can support the zero-carbon performance goal [7]. 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 [6,8]. 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 [4].

Birkeland (2008) [9] 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 [9]. From this paradigm stems the net-positive energy

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Nomenclature

Acronym

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BEC	Building energy consumption
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
SEG	Solar electricity generation
VFD	Variable frequency drive
VRF	Variable refrigerant flow

buildings (NPEB) which is a development whose energy generation exceeds its energy consumption on an annual basis [10]. This paper provides a post-occupancy, empirical energy analysis from a NPEB case study in Southwestern Ontario, Canada, displayed in Fig. 1.

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 [12,13]. 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 [14]. 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 [15]. 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 [16] and Natural Resources Canada [17]; however, the building commissioning activities in this study include informal energy finetuning efforts beyond the official commissioning for occupancy process.

Commissioning is a holistic and systematic process where operator decisions can lead to energy savings [12] which can reduce the

Fig. 1. Case study building exterior showing parking lot and roof solar PV systems, image from (11).

performance gap [18–20]. The performance gap can be due to several factors including optimistic design targets, ineffective building operation and limited building commissioning [21]. Insights from building operators in this case study uncover lessons to improve future building operation.

1.2. 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 [22]. A case study of continuous commissioning in a campus building reports the importance of data visualization tools to facilitate data-driven energy diagnostics [23]. 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% [12].

Building commissioning effectiveness is impacted by operator experience and proactiveness [24,25]. 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 [26]. Collaborations among stakeholders are one way to work towards meeting design goals [26]. Building monitoring and maintaining building systems, are an important factor in ensuring the continued benefits of building commissioning [27].

There are several factors impacting annual BEC variation, with weather being a key confounding variable [28,29]. Differences between weather data used in building modeling and that experienced can contribute to the performance gap observed during operation [29]. 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 [30]. 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 [31]. An implementation of this method led to estimated savings of 5% after 5 months of operation in a U.S. office building [31].

Part of office building commissioning can include investigating the transition between weekend unoccupied mode and weekday occupied mode to the reduce 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 [32]. 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 [32]. Similarly, another study found that using calibrated simulations to improve HVAC lighting and plug load controls achieved 30% peak demand reduction [33].

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 [30]. A simulation study of offices in different climatic regions demonstrates the impact of glazing and building envelope insulation on energy-savings [34]. Solar air pre-heaters can be used to reduce building energy consumption (BEC) by increasing fresh air intake temperature [35]. Heating and cooling using water-cooled VRF heat pumps can reduce BEC while improving thermal comfort [36]. Studies of enthalpy wheel performance show that it can operate efficiently under high temperature difference conditions [37], which is inline with the operating conditions in a Southwestern Ontario climate with very cold temperatures in winter.

1.3. Motivation and objectives

The performance gap and building commissioning have been extensively 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 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.

2. Methodology

This section describes in detail the methodology applied to assess the performance gap between modeled and measured building energy consumption. Energy savings achieved through commissioning activities were quantified through the methodology summarized in Fig. 2. The experimental findings and discussion are presented in the subsequent section.

2.1. Research approach

The emerging theme from the literature suggests a need to use mixed methods 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.

2.2. Research site

The case study is a multi-tenant NPEB office building shared by four tenants, including a university classroom and a business incubator partnership. The office building is fully electric with no electric storage. Table 1 provides the design specifications of the building.

2.2.1. 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 °C

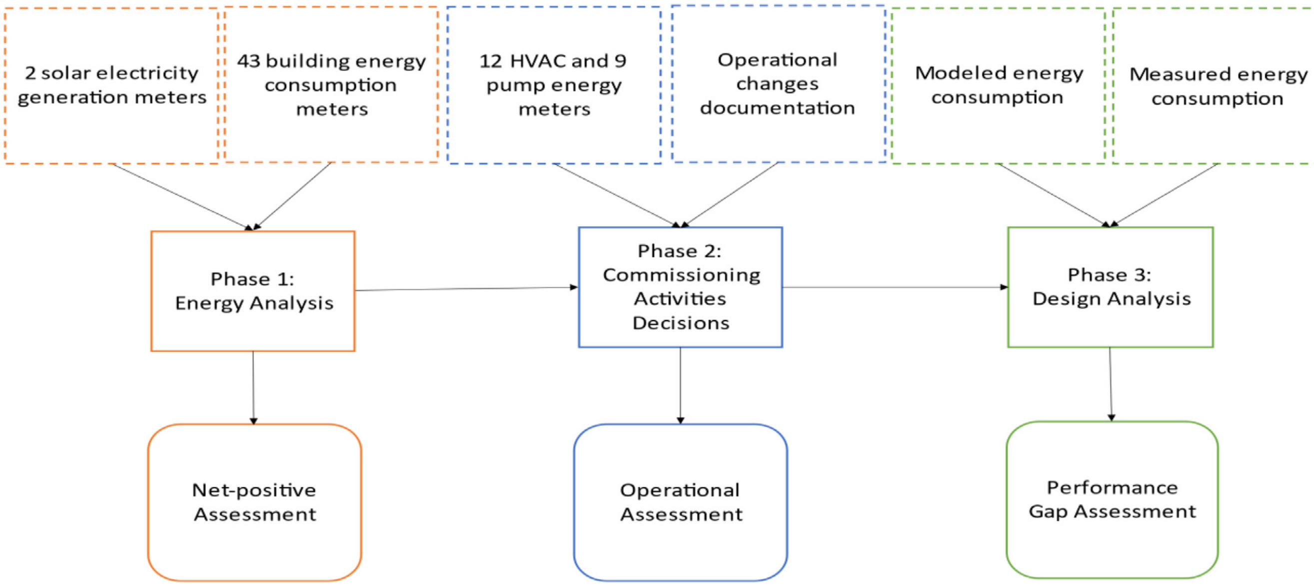

Fig. 2. Summary of the methodology used for investigation.

Table 1
Summary of building design specifications.

Architectural	
Site	Southwestern Ontario, Canada
ASHRAE climate zone (Köppen climate classif.)	6A (Dfb)
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, $W{\cdot}m^{-2}{\cdot}^{o}C^{-1}$	1.14
Rated RSI-value wall, $m^2{\cdot}^{o}C/W$	5.3
Rated RSI-value roof, $m^2{\cdot}^{o}C/W$	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

and −21 °C as outlined in Fig. 3 (right), obtained with data from Environment and Climate Change Canada [39]. In Fig. 3, the measured average monthly temperature is compared with the climate average dry bulb temperatures [40]. Similarly, the monthly HDD were obtained and summarized in Table 2. To compare the modeled weather data with the measured, HDD and CDD from 2019 were summarized in Table 3.

2.2.2. 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 22 °C, cooling to 24 °C) for 2022, the occupancy remains low (less than 50 % of the 2019 occupant level) 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 telework observed as a result of COVID-19 pandemic [41]. 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 insights to be considered for future building design. As such, it was analyzed as a "normal" mode of operation for comparison with 2019 as the commissioning year.

2.2.2.1. 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

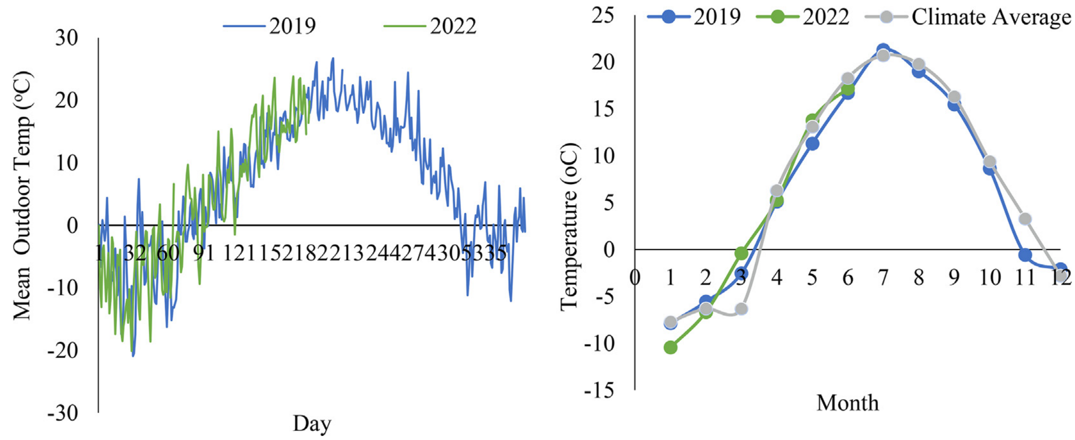

Fig. 3. Daily mean outdoor temperature (left) and average of daily monthly temperatures and the monthly design dry bulb temperature from ASHRAE (right).

Table 2
Monthly 18 °C 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 3
Annual 18 °C HDD and 18 °C CDD for operational years 2019 and model.

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

comparison to 2019. The average SEG from the past three 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.

2.2.2.2. 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 measuring temperature in different corners of the first floor as illustrated by Fig. 4. The measurements were to a resolution of 0.1 °C with an accuracy of ± 0.2 °C [42]. This data collection did not impact building operation and was 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 were 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 for 2019 and compared with 2022 values to determine the impact on the average temperature. Then, they were analyzed individually to compare 2022 with 2019, demonstrating variation from room-to-room.

2.2.2.3. 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, measured 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.

2.2.2.4. 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 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 [32]. The 15-minute rolling averages of the three fan coil meters were added up to show the peak before and after commissioning activities.

2.2.2.5. Weather impact assessment. Weather contributes to variation in BEC [43]. Daily HVAC energy consumption was analyzed with mean outdoor temperature information obtained from Environment and Climate Change Canada's measured data [39]. Weekdays and weekends were separated as they operate on different setpoint schedules with weekends following more unoccupied set-

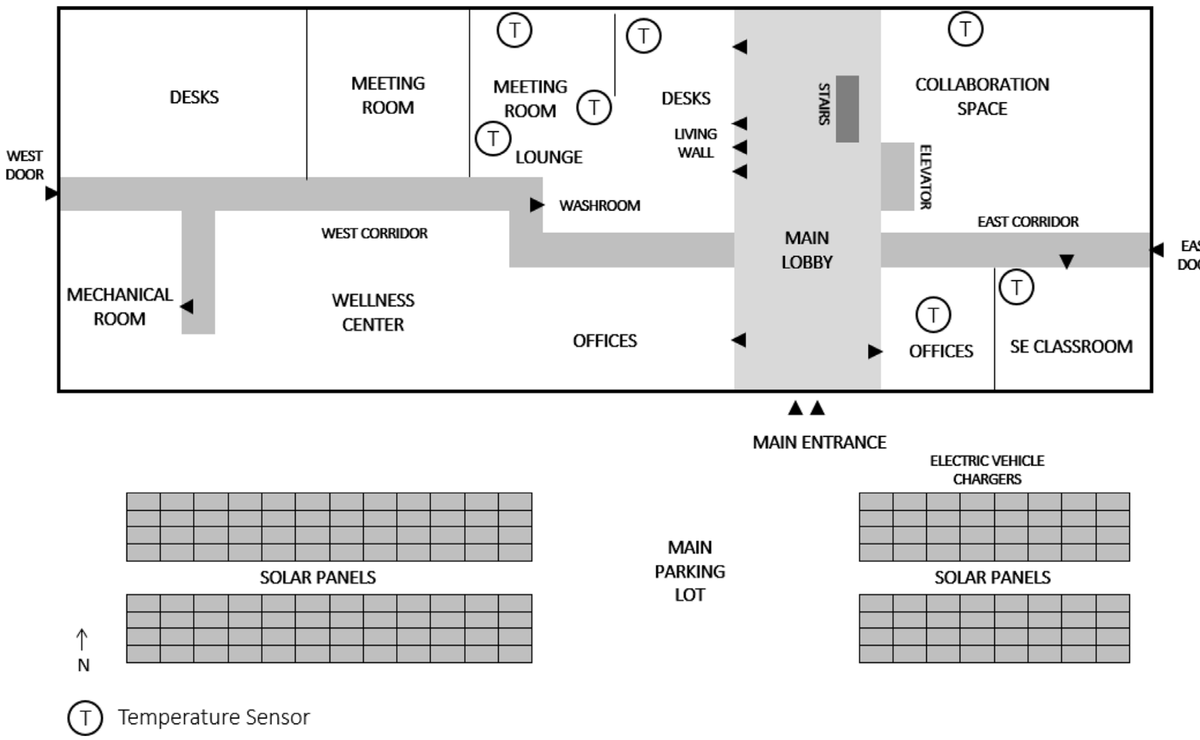

Fig. 4. First floor plan of the case study building providing an orientation of where temperature sensors are located.

tings (18 °C in winter and 26 °C in summer) and weekdays following occupied settings (22 °C in winter and 24 °C in summer).

2.3. Performance gap analysis

2.3.1. Annual and monthly

The energy model from design phase was acquired for comparison purposes through collaboration with the building designers. No additional simulations were conducted for this investigation. The preliminary design model was completed using EnergyPlus. The model inputs and assumptions are reflected in Table 1. There were 99 thermal zones simulated for a typical meteorological year, using hourly time step. The modeled net conditioned building area was 9, 406 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.

2.3.2. End-use comparison

To assess the performance gap on an end-use basis, the 43 energy meters were divided into 5 main categories outlined in Table 4. 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 4
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

3. Results and discussion

3.1. Net-positive energy assessment

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 Fig. 5 (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 Fig. 5 (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.

3.2. Commissioning activities

3.2.1. 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. 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.

3.2.2. 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, summarized in Table 5, 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 [13]. 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 increase the condenser loop flow rate. 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 min 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 and it may increase the efficiency of the equipment on the condenser loop due to higher flow rates.

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 18 °C to 22 °C 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 18 °C in winter and 26 °C 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 3 °C in winter months and by 5 °C in summer. Additionally, the condenser loop temperature setpoint decreased by 11 °C and the operating pressure increased by 13.8 kPa to improve efficiency. Furthermore, the chilled water

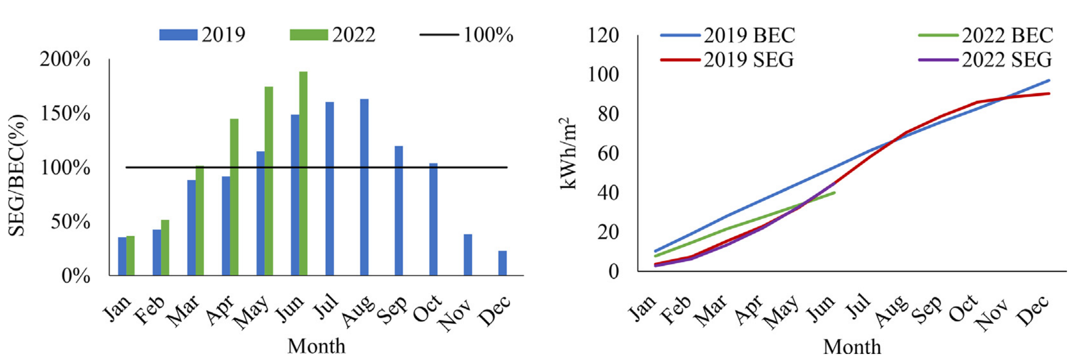

Fig. 5. Solar electricity generation (SEG) to building energy consumption (BEC) ratio (left) and cumulative BEC and SEG 2019 and 2022 (right).

Table 5
Summary of major commissioning decisions and the rationale behind them.

Type of change	Equipment	Description	Rationale
Temperature set-points	Condensing water loop, boiler, make-up air unit	Finetuned set-points, modified occupancy schedules	Reducing excessive operation
Humidity set-point	Humidifier	Reduced set-point	Providing sufficient humidification using the living wall and heat recovery from the enthalpy wheel
Monday start-up procedure	Fan coil units and pumps	Implemented gradual start up	Reducing peak demand
Pump upgrade	Condenser water loop pump	Upsized pumps to increase flowrate on the loop	Improving reliability, efficiency and capacity

temperature, and HVAC temperature setpoint were decreased by 3 °C (15 °C for winter months and 29 °C 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 15 °C. 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 [27].

3.2.2.1. Commissioning activities impact on indoor temperature. To assess the indoor temperature during commissioning activities and post commissioning activities, the average temperature comparison in Fig. 6 (left) suggests that the average temperature on the first floor remains within 1 °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 °C in the winter and 24 °C in the summer.

In Fig. 6 (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 °C cooler. The second largest difference was the classroom in January with 2022 temperatures 1.5 °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 were reached by the HVAC system.

3.2.3. Impact of commissioning activities on energy consumption

Reductions in HVAC and pump energy consumption summarized in Fig. 7 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 % [12] 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 [44].

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 Fig. 7 (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 Fig. 8 (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. Fig. 8 (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 18 °C HDD as demonstrated in Table 2), 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 800 ppm, meeting the 300–500 ppm differential range as outlined by ASHRAE standard 62.1 [45]).

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

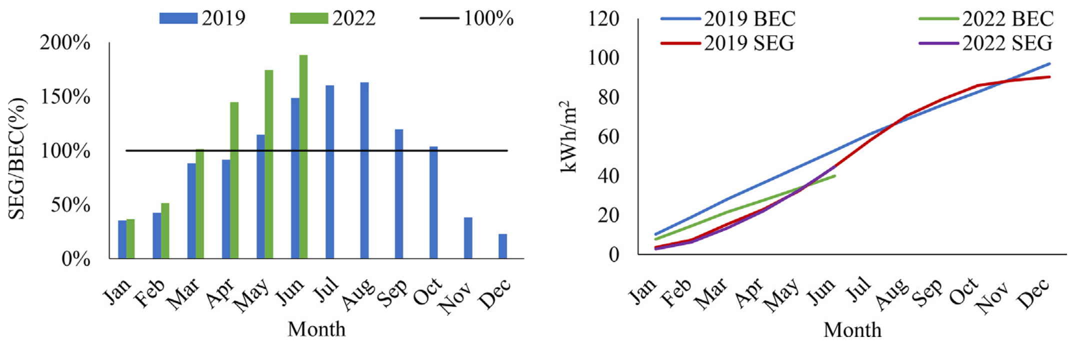

Fig. 6. Average temperature (left) and temperature difference (right) weekdays from 8AM to 6 PM, 7 first floor PIR sensors, comparing 2019 to 2022.

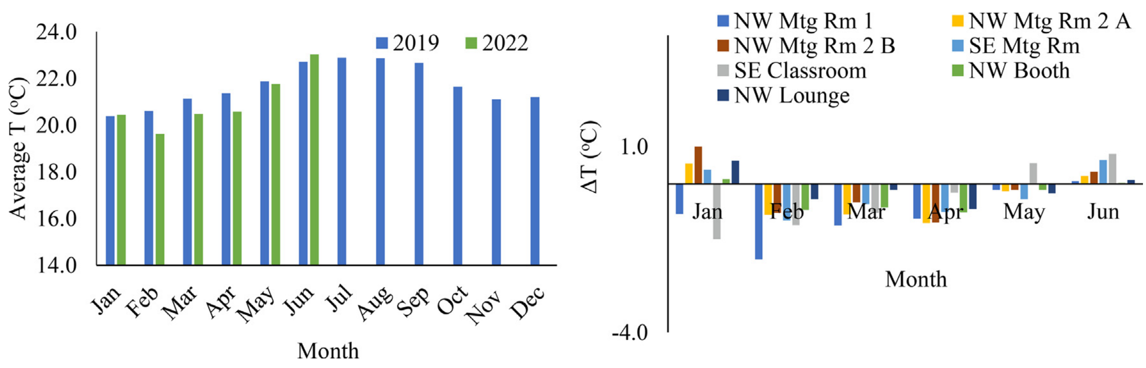

Fig. 7. Monthly HVAC energy consumption (right) and pumps (left) 2019 and 2022.

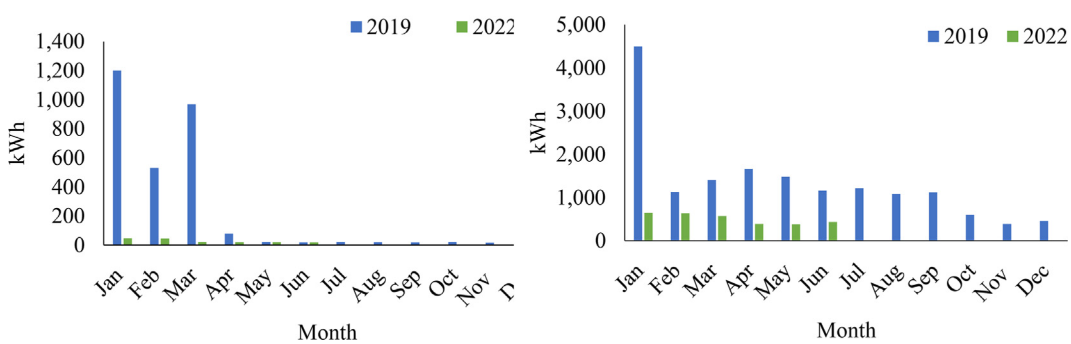

Fig. 8. Monthly boiler energy consumption (right) and make-up air unit (left) 2019 and 2022.

annually (average 1, 700 kWh/m, operating for 8 months) or 1.5 % of the total 2019 BEC.

3.2.4. Peak demand analysis

In Fig. 9, 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 Fig. 9 (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 Fig. 9 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. [32] and Yin et al. [33] 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.

Pump operations were also impacted by the decision to stager the start up time. Fig. 9 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

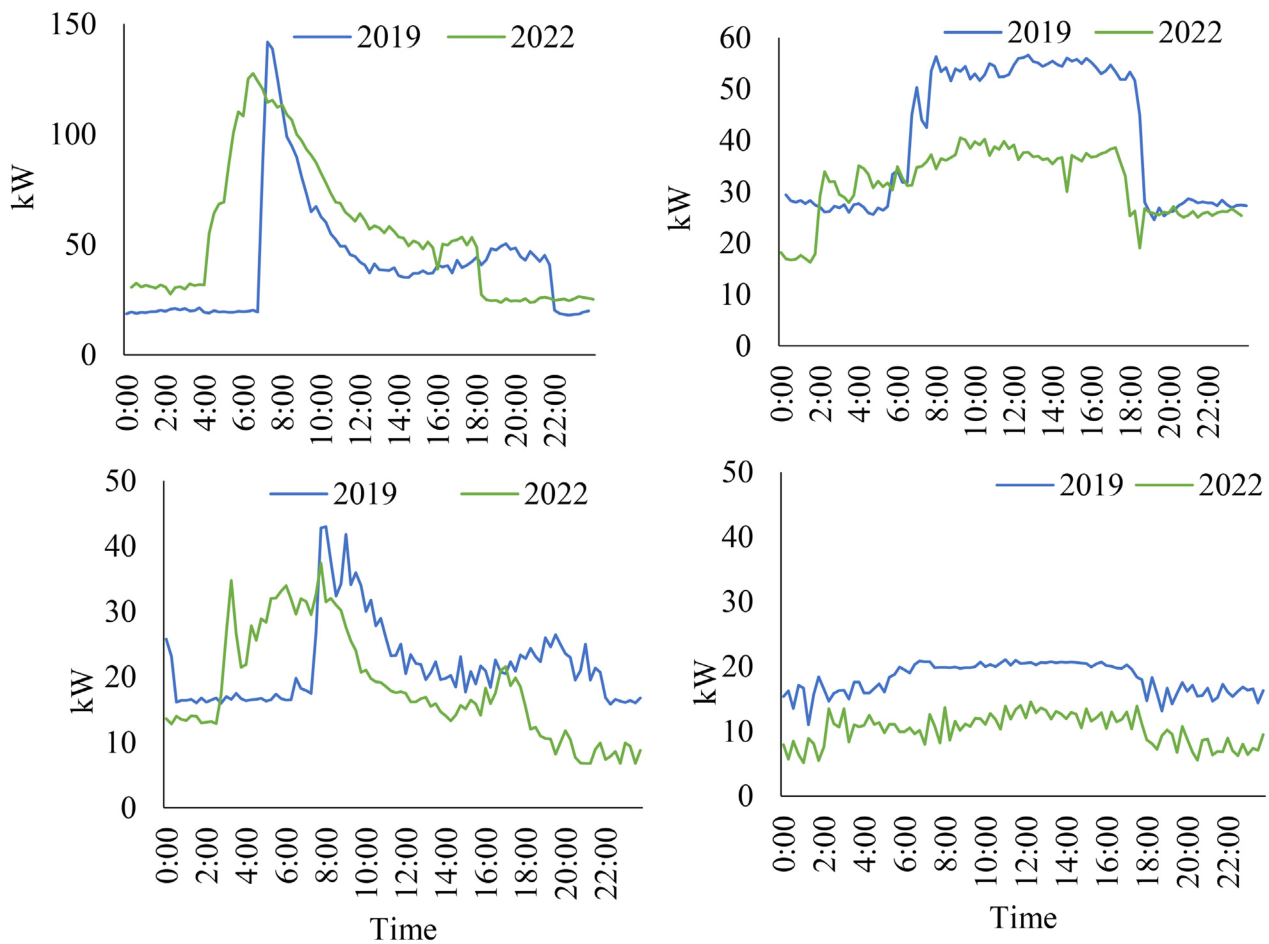

Fig. 9. Fan coil units energy consumption February (top left) and June (top right) and pumps energy consumption February (bottom left) and June (bottom right).

operating procedure had a larger impact on the pumps than the fan coil units which are still seeing some spikes.

3.3. Weather impact

In Fig. 10 2019 consumed more energy (average of 0.0292 kWh/m^2, COV = 0.839 and 0.0224 kWh/m^2, COV = 0.868 for weekends and weekdays 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.

3.4. Performance gap

3.4.1. Annual operation and model comparison

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 [21]. The results of this case study building demonstrate that closing the performance gap using building operator expertise and data-driven recommendations is also possible.

3.4.1.1. Monthly operation and model comparison. Fig. 11 (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 Fig. 11 (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.

3.4.1.2. End-use comparison. In Fig. 11 (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

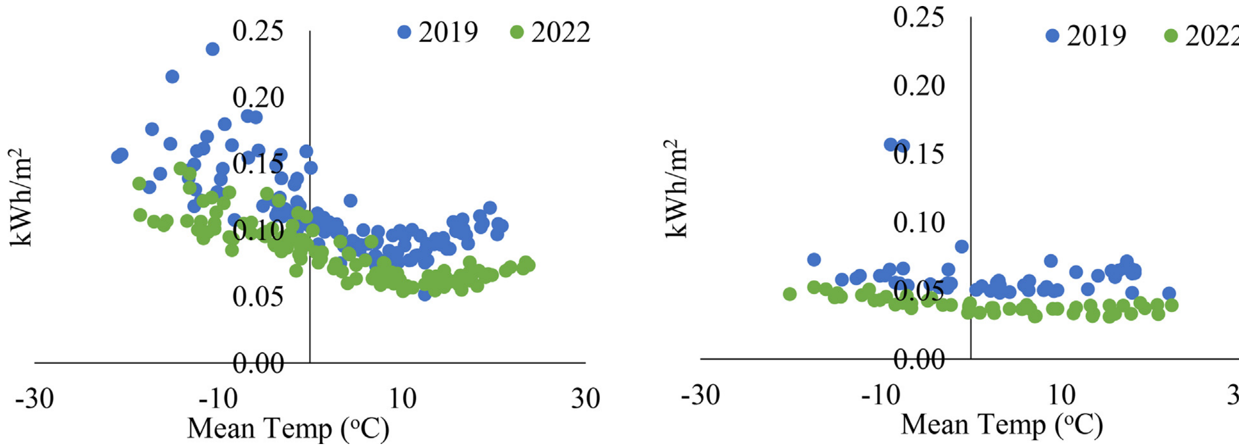

Fig. 10. Average daily temperature versus HVAC total energy consumption for weekdays (left) and weekends (right), 2019 and 2022 Note: The two points on the left graph at (−8.9, 0.16) and (−7.9, 0.15) are two weekend days in January 2019, prior to implementing an unoccupied schedule during weekends.

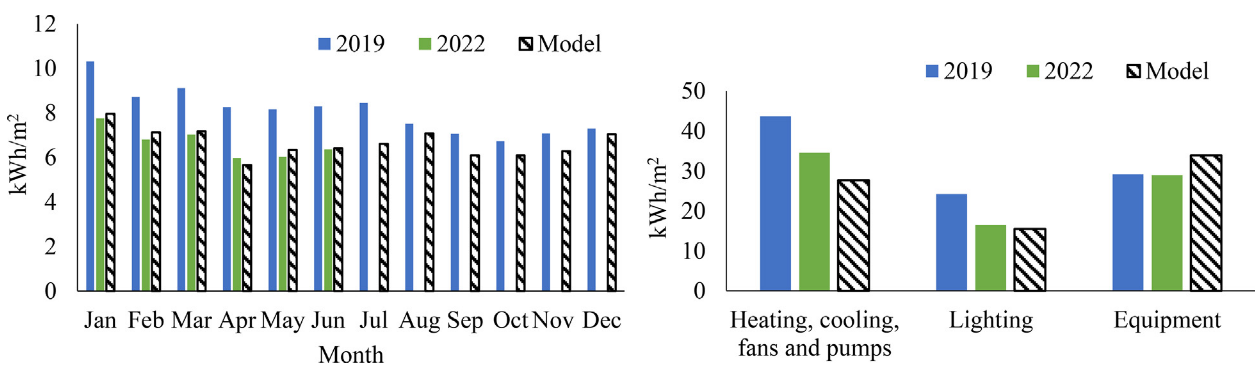

Fig. 11. Monthly operation vs modeled energy consumption (left) and end-use comparison using 2022 approximations (right).

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 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 Tables 2 and 3. Additionally, the estimated 2022 value suggests that the lighting energy use will be within 6% of model predictions, much closer during the commissioning year when the lighting energy use measured was more than double that modeled. This may be due in part 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.

3.5. 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 pandemic 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 teleworking).

4. 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. Firstly, 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 fine-tuning temperature and humidity operational setpoints, implementing gradual start-up procedures to transition from unoccupied to occupied mode. 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 achieve 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

Data availability

Data will be made available on request.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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