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Performance Evaluation of a Nearly Zero-Energy Office Building in Temperate Oceanic Climate Based on Field Measurements

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Abstract: This field study evaluated the building performance of a nearly zero-energy office building near Brussels, Belgium, located in the temperate climatic zone. The building's thermal comfort and energy parameters were monitored from May 2018 to April 2019. The time-integrated thermal discomfort, primary energy use, and greenhouse gas emissions from the building were then analyzed using the monitored data. The case study evaluated the HVAC system performance with an air-cooled chiller with water cooling coils and a water boiler with water heating coils. The findings indicated an indoor overheating degree of 0.05 °C and an indoor overcooling degree of 0 °C for the observed period. The building's primary cooling energy use was found to be 37.54 kWh_{PE}/m^2.a and primary heating energy use was found to be 46.08 kWh_{PE}/m^2.a for the monitored period. The cooling and heating greenhouse gas emissions were 10.14 kg.CO_2e/m^2.a and 8.34 kg.CO_2e/m^2.a, respectively. The observed data also indicated that the HVAC system in the building was operational throughout the monitoring period from May 2018 to April 2019, including a 24/7 schedule. Finally, the paper provided implications for practice and future work based on the study findings.

Keywords: thermal discomfort; time-integration; overheating; overcooling; primary energy; greenhouse gas emissions; HVAC

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1. Introduction

Buildings are one of the key emitters of greenhouse gas (GHG) emissions. In standardized nations, buildings account for nearly 40% of all energy consumption [1]. Buildings require energy to guarantee indoor environmental quality with heating, cooling, ventilation, etc. The total energy used to operate the building can be decreased through effective design techniques and energy-efficient HVAC systems. Field investigations of commissioned and occupied buildings help identify areas for improvement in spatial thermal comfort, energy efficiency, and GHG emissions. Field research into existing buildings can aid in understanding the reason for the energy performance gap or the significant discrepancies between predicted and actual building performance. These discrepancies are caused due to actual occupant behavior, modeling, system control, installation errors, and weather conditions [2].

The performance gap between predicted and measured energy use is a growing interest in the building industry, as energy efficiency and emission goals are becoming more relevant, in addition to the increasing energy costs [3]. This difference between predicted building energy use at the building design stage and measured building energy use during building operation appears to be quite large, in the range of 1.5 to 2 as per scientific studies from [4]. Hence, the energy performance gap describes the discrepancy between predicted and measured energy performance [5]. The building industry cannot expect to advance toward an energy-efficient, carbon-neutral building sector that ensures occupant comfort without closing this performance gap, while addressing a broad range of influencing factors that span from the building's life cycle to its operation [2].

An essential component of the European strategy to meet future energy and climate targets is the reduction in energy consumption in buildings [6]. According to the Energy Performance of Buildings Directive (EPBD), European Union (EU) member countries must create long-term renovation plans that will make it easier to convert the existing structures into nearly zero-energy buildings (nZEBs) at a reasonable cost [7]. In order to strengthen long-term renovation strategies in the national building renovation plans to convert the building stock into zero-emission buildings by 2050, a revision to the Energy Performance of Buildings Directive is being proposed [8]. Particularly in Belgium, energy performance of buildings (EPB) regulations aim to minimize the building's primary energy use and CO_2 emissions, while maintaining occupant comfort [9].

Since July 2008, new constructions and renovations that require a building permit must meet these energy performance requirements in Belgium. The applicable energy performance requirements were established for parameters such a primary energy consumption, overheating, ventilation rate, insulation level, technical installation, etc. [10]. These requirements vary depending on the function of the building or unit, such as residential, office, educational, or other non-residential buildings and are based on whether the building is new or renovated. Over the years, these requirements became more stringent, and in order to implement the Energy Performance of Buildings Directive for offices and schools, the energy performance directive E70 was released in 2011 [10]. The existing studies that address the energy performance gap are listed in Table 1 with their research methodology, building types, and key recommendations.

Table 1. Summary of existing studies that address the energy performance gap in buildings.

Authors	Methodology	Building	Recommendations
Cozza et al. [11]	Qualitative w/review	Residential	Inform the occupants about optimum usage, as well as assess their level of comfort and satisfaction. Give the building designers and other stakeholders involved feedback and support best practices.
Cuerda et al. [12]	Modeling w/simulations Observational w/monitoring	Residential	The use of monitored data reduces the uncertainties due to the pre-bound effect during the design phase and rebound effect during the user phase. The use of the mixed-method approach to define the building models and occupant behavior will create models that will accurately simulate energy use and bring the results closer to reality.
Liang et al. [13]	Observational w/surveys	Commercial	Facility managers listed occupant energy consumption, increased occupancy, and technology failures as the top reasons for the energy performance gap. Engineering, organizational, and behavioral factors all influence the energy performance gap. Therefore, too much emphasis on a single aspect is inappropriate and insufficient.
Allard et al. [14]	Observational w/monitoring	Residential	To find any deviations from the intended design or flaws in the completed building, calibrating the simulation model is essential. A method gap should be introduced to perform the performance gap analysis to identify the procurement gap effectively.

Table 1. *Cont.*

Authors	Methodology	Building	Recommendations
Coleman and Robinson [15]	Observational w/monitoring and surveys	University	The response to the energy performance gap should keep up and create innovations for social wellbeing. Thus, energy performance gap studies will lead to the creation of innovative solutions. Designers, operators, and occupants should communicate both successes and failures.
Khoury et al. [16]	Modeling w/simulations	Green commercial	The simulation process must consider the variation between ideal yet realistic conditions of use and standard values. The optimization potential corresponds to the difference between the actual and ideal conditions of use. Building optimization and responsible behavior can reduce the energy performance gap.
Robinson et al. [17]	Observational w/monitoring and surveys	University	Reliable energy forecasting at design stage is a crucial component of the performance gap. This might be underestimated if realistic building use expectations are not set during the design phase.
Fedoruk et al. [18]	Observational w/monitoring	University	Neither economic nor technical constraints hindered energy performance, but the roadblocks came from how various life-cycle stages were specified and& implemented. The main issues emphasize the significance of having efficient energy monitoring capabilities, bridging life cycle stage gaps, and design and operation feedback processes.
de Wilde [19]	Qualitative w/review	All buildings	This study summarizes the following performance gaps between (i) first-principle predictions and measurements, (ii) machine learning and measurements, and (iii) predictions and display legislation certificates. Only a comprehensive and coordinated strategy that combines model validation and verification, improved data collection, better forecasting, and a shift in industry practices can close the performance gap.

The literature presented in Table 1 addressed the energy performance gap, including mitigation and adaptive approaches, but they do not address indoor thermal comfort in the buildings. Indoor thermal comfort conditions have been one of the core subjects of this study, as thermal comfort has a huge impact on occupant satisfaction, which should be addressed while evaluating energy performance. An effective benchmarking process to achieve the EPBD targets will be incomplete without field studies to identify the potential aspects for improvements in building performance.

The reference building is a passive house-certified building through dynamic simulations. The building is designed with high thermal insulation, airtightness, optimized construction nodes, and dual-flow ventilation with heat recovery to improve energy efficiency. In addition, passive measures against overheating by free cooling and night cooling strategies are also adopted. However, field evaluation of building performance parameters is required to evaluate the energy performance gap between the designed and real buildings. Based on this context, the following research questions are formulated:

1. How do the indoor thermal comfort conditions vary in the reference building?
2. How do space cooling and heating energy use vary in the reference building?
3. How do greenhouse gas emissions vary in the reference building?

The main novelty presented in this paper is the implementation of a time-integrated, multizonal thermal discomfort evaluation using a year-long field measurement of a real office building. The indoor overheating degree ($IOhD$) and indoor overcooling degree ($IOcD$) were measured by averaging the temperature difference between the indoor operative temperature over the total number of zonal occupied hours. The indicator is developed as part of the International Energy Agency Annex 80 activities on resilient cooling in buildings [20]. These indicators calculate and predict the discomfort in the reference building over a period of time rather than at a particular instance, as is the case in other existing thermal comfort indices. The case study building was an nZEB located in a temperate oceanic climate (Cfb). The study evaluates energy performance, while considering thermal comfort in the building. In our review of the existing literature, we did not find similar studies that evaluated the building performance of nZEBs including thermal comfort and energy use in a temperate oceanic climate (Cfb) using time-integrated indicators.

This paper provides insights on the time-integrated thermal discomfort evaluation, primary energy use, and GHG emissions. This study has the potential to improve thermal comfort, while also assisting the construction industry in its efforts to build energy-efficient office buildings with low emissions. The structure of the paper is outlined as follows. Section 2 describes the review methodology, which includes climate data in Section 2.1, the reference building in Section 2.2, and performance evaluation in Section 2.3. Section 3 discusses the study results with thermal discomfort in Section 3.1, primary energy use in Section 3.2, and GHG emissions in Section 3.3. Section 4 discusses the main findings in Section 4.1, strengths and limitations in Section 4.2, and implications for practice and future work in Section 4.3. Section 5 closes the paper with the conclusions.

2. Methodology

In this study, a representative office building near Brussels, Belgium, was assessed using data monitored from May 2018 to April 2019. The environmental parameters and site energy use were observed during this period. Hourly ambient temperature data and monthly site electricity and natural gas energy use data were used here for the analysis. According to the Köppen–Geiger classification, the building was situated in the temperate oceanic (Cfb) zone [21].

In these heating-dominated regions, the building design was primarily aimed at maintaining the heat during the winter. This was achieved by using airtight and highly insulated design principles, which prevent heat dissipation during summer. Hence, relying solely on passive cooling techniques to maintain thermal comfort during hot summers might make it challenging to stop overheating issues.

The study conceptual framework that visualizes the methodology used in this study is shown in Figure 1. The study workflow is as follows:

1. A real office building located in Brussels, Belgium, with a baseline HVAC system of an air-cooled chiller (electric) with water cooling coils and a water boiler (natural gas) with water heating coils was identified.
2. The building performance parameters for thermal comfort and energy use were extracted from the energy management system (EMS) maintained by Equans and from the weather station outside the building from May 2018 to April 2019.
3. The collected data were analyzed using the key performance indicators (KPIs) that quantified the time-integrated thermal discomfort, site cooling and heating energy use, primary cooling and heating energy use, and cooling and heating GHG emissions.

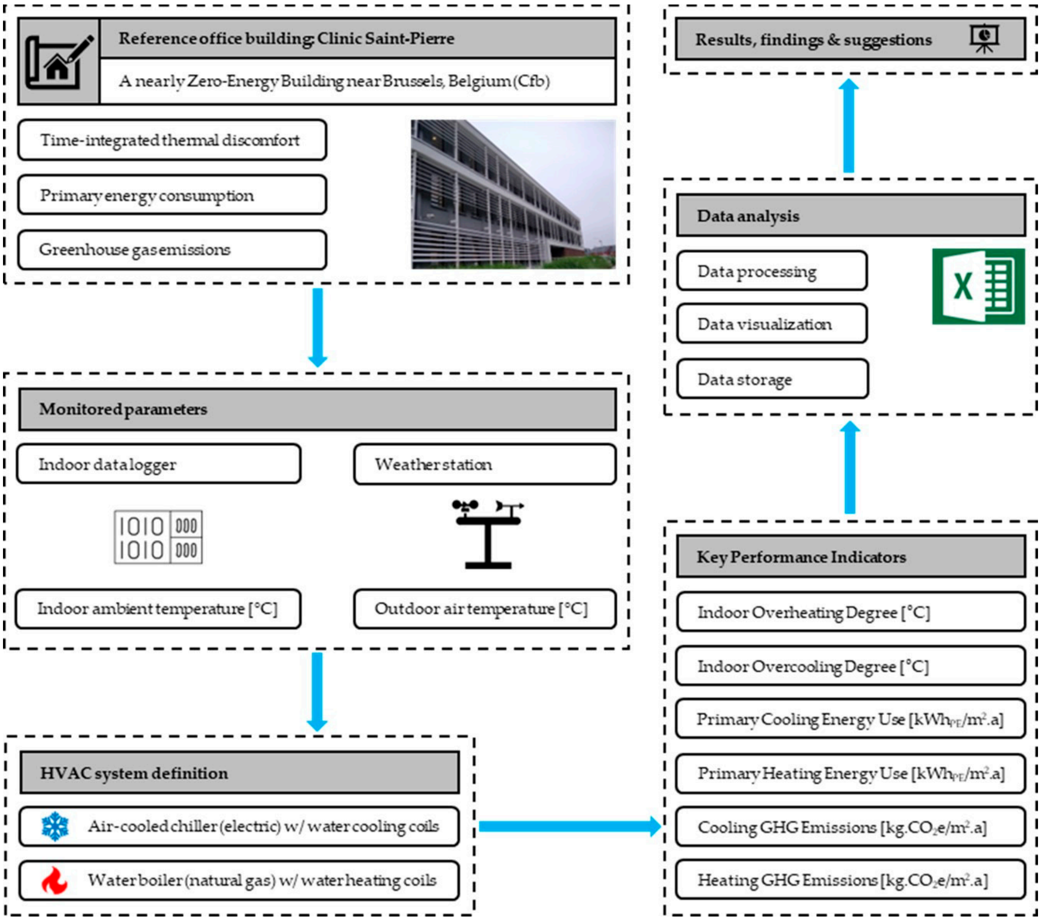


Figure 1. Study conceptual framework.

In this study, the formal analysis of the monitored data was carried out using a state-of-the-art workstation at the Sustainable Building Design (SBD) Lab, Super COmputeR ProcessIng wOrkstatioN (SCORPION), which uses a processor with 6 cores, 128 threads, and a 256 MB cache for the computing power and performance. This is in combination with 128 GB of random access memory (RAM) and a graphics card of 24 GB that masters most scientific applications.

2.1. Climate Data

Any study that deals with building performance must obtain accurate data on the climate, and this determines the reliability of the study [22]. The hourly outdoor air temperature was collected from the outdoor weather station, which was used for mapping the thermal comfort of the measurement locations in the reference building. The data used in this paper were gathered from the weather station installed outside Clinic Saint-Pierre, located in a temperate oceanic climate zone (Cfb).

Temperate oceanic regions in Europe are characterized by mild summers and cool winters, as well as evenly distributed relative humidity and precipitation throughout the year. However, due to the increasing effects of climate change, warmer winters and hotter summers are becoming increasingly common, adding to the thermal discomfort and cooling loads in the building.

Temperate oceanic climates are prevalent in Western European cities, such as London, Paris, Copenhagen, Brussels, Amsterdam, and so on. In addition, other major cities from around the world with similar climates include Auckland, Bogota, Canberra, Nairobi, Vancouver, and Santa Fe. According to the Köppen–Geiger climate classification [21], the climate zone of the reference building is shown in Figure 2.

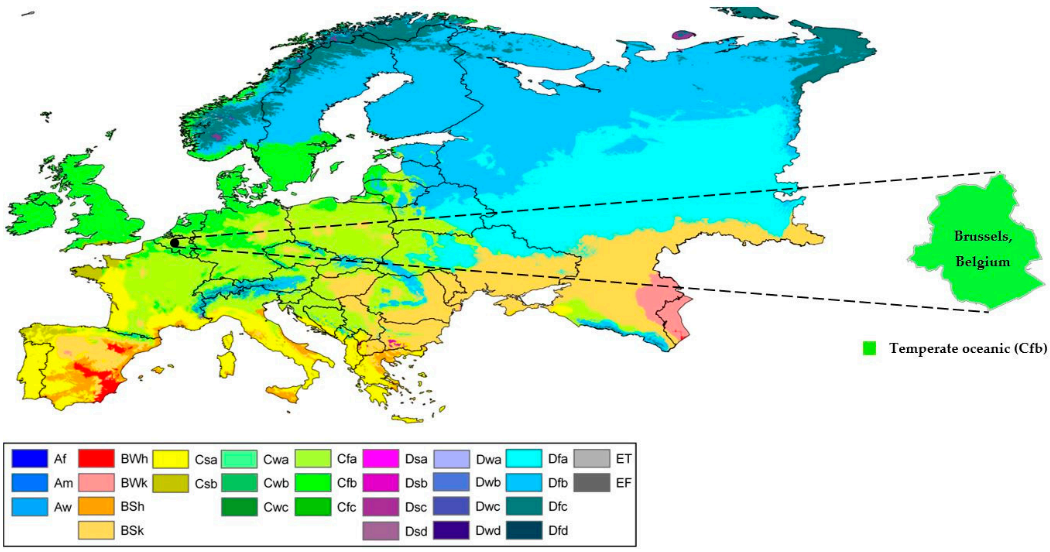


Figure 2. Reference building location and climate zone as per the Köppen–Geiger classification [18].

2.2. Reference Building

The reference building is situated near Brussels, Belgium, at a latitude and longitude of 50°40′04.67′′ N and 04°33′39.68′′ E, and at an elevation of 112 m. The reference office building is an nZEB and has three floors and a parking space in the basement. It has a multi-purpose hall, along with office rooms, conference rooms, and other amenities. The building is equipped with fixed horizontal slats for solar shading. A maximum of 357 people can be accommodated in the building, with 168 in the multi-purpose hall and 189 in other conditioned areas, such as office rooms, meeting rooms, and cafeterias.

The heating, ventilation, and air conditioning (HVAC) strategy used in this study is an air-cooled chiller (electric) with water cooling coils and a water boiler (natural gas) with water heating coils. The outdoor air supplied to the building through the mechanical ventilation unit is preheated/cooled before it is supplied to the building zones, where it is heated/cooled again. The mechanical ventilation units were equipped with heat recovery units. The reference building is built with a heavy concrete structure that creates high thermal inertia. The reference building characteristics are listed in Table 2.

Table 2. Reference nearly zero-energy office building characteristics.

Parameter	Values
Offices, cafeterias, and multi-purpose spaces	3090 m^2
Underground car parking area	1140 m^2
Window-to-wall ratio	38.25%
Window G-value	0.50
Window U-value	0.50 $W/m^2.K$
External wall U-value	0.35 $W/m^2.K$
Roof U-value	0.25 $W/m^2.K$
Ground floor U-value	0.25 $W/m^2.K$
Basement floor U-value	0.25 $W/m^2.K$
Airtightness	0.60
Maximum ventilation rate	21,600 m^3/hr

The monitored data were obtained from the EMS maintained by Equans. The main functionalities of the EMS [23,24] were as follows:

- Monitoring, regulating, and communicating the energy used by the building.
- Planning energy use according to usage patterns and needs, considering the costs.
- Managing the energy demand from various office equipment.

The reference building's exterior view with horizontal slats for solar shading is shown in Figure 3a, and the interior view is shown in Figure 3b.

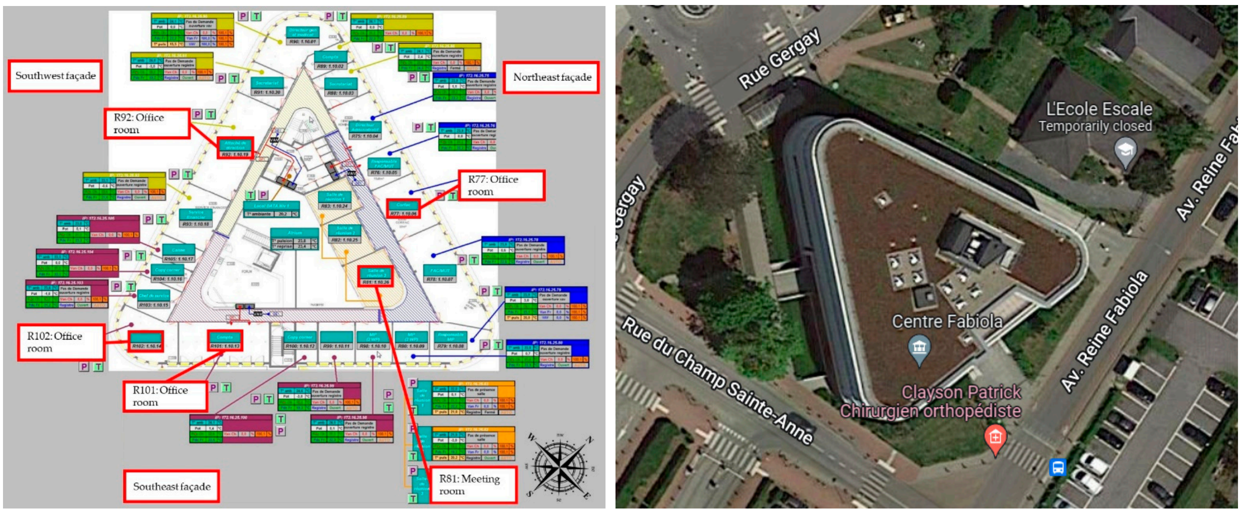
(**a**) (**b**)

Figure 3. Clinic Saint-Pierre, Brussels, Belgium: (**a**) building exterior; (**b**) building interior.

The reference building has high insulation and airtightness values. The composition of the reference building is as follows:

- The external walls consist of three layers. Cast concrete, MW glass wool roll, and plasterboard are used from the outer layer to the inner layer.
- The ground floor consists of four layers. Urea formaldehyde foam, cast concrete, floor screed, and timber flooring are used from the outer layer to the inner layer.
- The internal floors consist of a layer of an aerated concrete slab.
- The external roof consists of four layers. Asphalt, MW glass wool roll, air gap, and plasterboard are used from the outer layer to the inner layer.

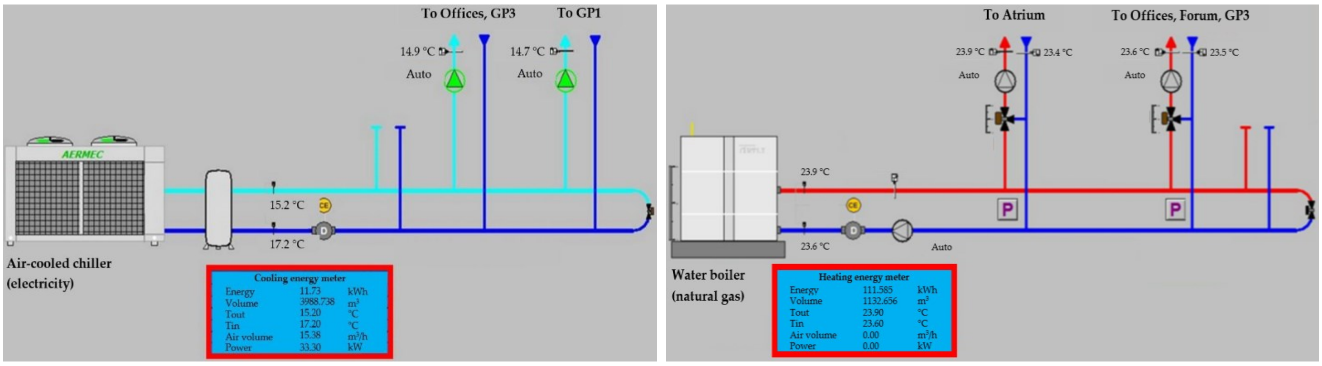
The measurement locations for thermal comfort monitoring are shown in Figure 4a, and a satellite image of the building surroundings is shown in Figure 4b. The measurement locations on Floor +1 of the reference building are highlighted in red borders.



(**a**) (**b**)

Figure 4. Reference building measurement locations used for the thermal comfort evaluation: (**a**) measurement locations on Floor + 1; (**b**) satellite image with landscape from Google maps.

The measurement locations for the monitoring of building energy use (kWh) are shown in Figure 5a for cooling energy use (electricity), and in Figure 5b, for heating energy use (natural gas).



(**a**) (**b**)

Figure 5. Reference building measurement locations used for the energy use evaluation: (**a**) cooling energy (electricity) use (kWh); (**b**) heating energy (natural gas) use (kWh).

2.3. Performance Evaluation

Performance evaluation gives a crucial and quantified analysis of the target parameters within the scope of the case study. The list of parameters is given below.

2.3.1. Time-Integrated Thermal Discomfort

Thermal comfort is defined as "the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation" according to ASHRAE Standard 55 [25]. Thermal comfort is one of the most important factors that affect occupant productivity, health, and well-being [26]. This is significant since, especially in developed nations, people spend up to 90% of their time indoors [27].

In this study, the thermal discomfort indicators used are asymmetric indices that include overheating and overcooling-specific [28]. The overheating and overcooling discomfort was estimated using *IOhD* [29,30] and *IOcD* [30]. The *IOhD* and *IOcD* are multizonal indices that add together the heating and cooling degree hours over the total number of zonal occupied hours. *IOhD* and *IOcD* are given in Equations (1) and (2), respectively.

$$IOhD = \frac{\sum_{z=1}^{Z} \sum_{i=1}^{N_{occ}(z)} \left[\left(T_{in,z,i} - T_{comf,upper,z,i} \right)^{+} \times t_{i,z} \right]}{\sum_{z=1}^{Z} \sum_{i=1}^{N_{occ}(z)} t_{i,z}} \quad (1)$$

$$IOcD = \frac{\sum_{z=1}^{Z} \sum_{i=1}^{N_{occ}(z)} \left[\left(T_{comf,lower,z,i} - T_{in,z,i} \right)^{+} \times t_{i,z} \right]}{\sum_{z=1}^{Z} \sum_{i=1}^{N_{occ}(z)} t_{i,z}} \quad (2)$$

- Z is the total number of conditioned zones in the building.
- i is the occupied hour counter.
- $N_{occ}(z)$ is the total number of zonal occupied hours in zone Z.
- $T_{in,z,i}$ is the indoor operative temperature in zone z at time step i in (°C).
- $T_{comf,upper,z,i}$ is the maximum comfort threshold in zone Z at hour i in (°C). $T_{comf,lower,z,i}$ is the minimum comfort threshold in zone Z at hour i in (°C).

The $T_{comf,upper,z,i}$ and $T_{comf,lower,z,i}$ are derived from the EN 16798-1 [31] PMV/PPD comfort models category II equations recommended for new commercial buildings [32]. The indoor operative temperatures are then mapped, with respect to the EN 16798-1 PMV/PPD comfort model, category II limits, and adaptive comfort model; category II upper and lower limit equations [31] based on outdoor running mean temperature (T_{rm}) are given in Equations (3) and (4), respectively.

$$T_{comf,upper,z,i} = 0.33 \times T_{rm} + 18.8 + 3 \quad (3)$$

$$T_{comf,lower,z,i} = 0.33 \times T_{rm} + 18.8 - 4 \quad (4)$$

2.3.2. Primary Energy Use

Estimating building energy use was a crucial strategy for evaluating emissions in this study. Building energy performance is critical because many factors affect it, including building construction, weather, occupants, sociological factors, and equipment [33]. The majority of the energy used in the buildings was used to maintain a comfortable indoor environment in terms of thermal comfort, including heating and/or cooling, and air quality, including ventilation. Other building energy loads include electric lighting, domestic hot water, and electrical equipment, such as computers, printers, etc. [34]. This paper considers the site energy use and primary energy use from the building cooling and heating systems, in terms of kWh/m^2.a.

Energy performance calculations frequently produce site energy, also known as final energy. Different energy sources should be weighted differently because they have different utilization rates and environmental impacts. According to the concept of primary energy, each energy source was given a score based on how much of an impact it would have on the environment. Primary energy use covers the consumption, and losses incurred during the conversion, such as when switching from oil or gas to electricity, distribution of energy, and the final consumption by end users [34]. Energy demand was multiplied by this factor, which can vary depending on the type of energy source [35].

The primary energy conversion factor, which is between 2.5 and 3.0 for most European countries, reflects the fact that producing electricity consumes more fuel, such as coal or natural gas, than producing heat using natural gas does [35]. The site energy use (E_{Site}) was then converted to primary energy use ($E_{Primary}$) using Belgian coefficients of 2.5 for electricity and 1.0 for natural gas [36,37]. The primary energy conversion formula is given in Equations (5) and (6), respectively.

For electricity,

$$E_{Primary}\left(\mathrm{kWh_{PE}/m^2.a}\right) = 2.5 \times E_{Site}\left(\mathrm{kWh/m^2.a}\right) \quad (5)$$

For natural gas,

$$E_{Primary}\left(\mathrm{kWh_{PE}/m^2.a}\right) = 1.0 \times E_{Site}\left(\mathrm{kWh/m^2.a}\right). \quad (6)$$

2.3.3. Greenhouse Gas Emissions

Since 2005, there has been a decline in the EU building sector's historical GHG emissions, with a 24.79% decrease in emissions in Belgium in 2020 compared to the 1990s. Higher standards for new construction, measures to improve the energy efficiency in existing buildings through the replacement of heating systems, the installation of thermal insulation, and the use of more efficient heating systems, as well as efforts to decarbonize the electricity sector, are the causes of this. In addition, warmer temperatures have also contributed to the decline in GHG emissions [38].

The effect of cooling and heating energy use on the environment was assessed in the paper by calculating GHG emissions separately. The GHG emissions were expressed in terms of kg.CO_2e/m^2.a and represent the emissions from the energy used for space conditioning per square meter from the cooling and heating system. Primary energy use was converted into GHG emissions use by using the Belgian emission coefficients of 0.270 kg.CO_2e/kWh for electricity ($GHG_{Electricity}$) and 0.181 kg.CO_2e/kWh for natural gas

($GHG_{Naturalgas}$) [39]. The GHG emissions are calculated using cooling and heating energy use. The GHG emission conversion formula is given in Equations (7) and (8), respectively.

For electricity,

$$GHG_{Electricity} = 0.270\ \mathrm{Kg.CO_2e/kWh} \times E_{Primary}\left(\mathrm{kWh/m^2.a}\right) \quad (7)$$

For natural gas,

$$GHG_{Naturalgas} = 0.181\ \mathrm{Kg.CO_2e/kWh} \times E_{Primary}\left(\mathrm{kWh/m^2.a}\right) \quad (8)$$

3. Results

This section presents the results, including thermal discomfort, energy use, and GHG emissions. The results from the performance evaluation are listed in Table 3.

Table 3. Performance evaluation of the reference building from May 2018 to April 2019.

Category	Key Performance Indicators	Values
Time-integrated thermal discomfort	Indoor overheating degree	0.05 °C
	Indoor overcooling degree	0 °C
Energy use	Site cooling energy use (electricity)	15.02 $kWh/m^2.a$
	Primary cooling energy use (electricity)	37.54 $kWh_{PE}/m^2.a$
	Site heating energy use (natural gas)	46.08 $kWh/m^2.a$
	Primary heating energy use (natural gas)	46.08 $kWh_{PE}/m^2.a$
GHG emissions	Cooling emissions (electricity)	10.14 $kg.CO_2e/m^2.a$
	Heating emissions (natural gas)	8.34 $kg.CO_2e/m^2.a$

3.1. Time-Integrated Thermal Discomfort

The time-integrated thermal discomfort analysis of the reference building, Clinic Saint-Pierre, was performed from May 2018 to April 2019. The indoor overheating and overcooling values were calculated using *IOhD* and *IOcD* indicators and are shown in Figure 6. The *IOhD* and *IOcD* values of the building were estimated at 0.05 °C and 0 °C.

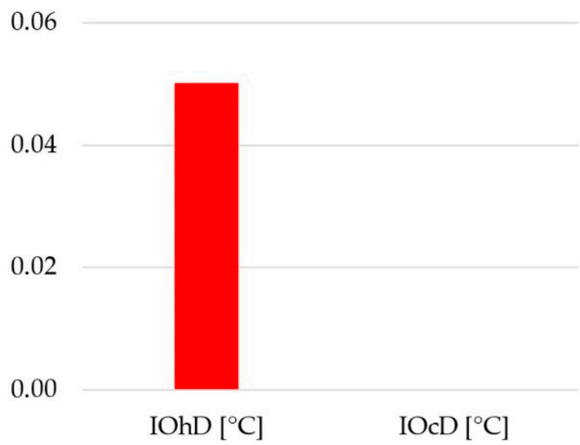


Figure 6. Building overheating value using *IOhD* and overcooling value using *IOcD* from May 2018 to April 2019.

The indoor ambient air temperature values at various measurement points in the building, with respect to the PMV/PPD comfort model and adaptive comfort model category II limits and outdoor air temperature, are shown in Figure 7.

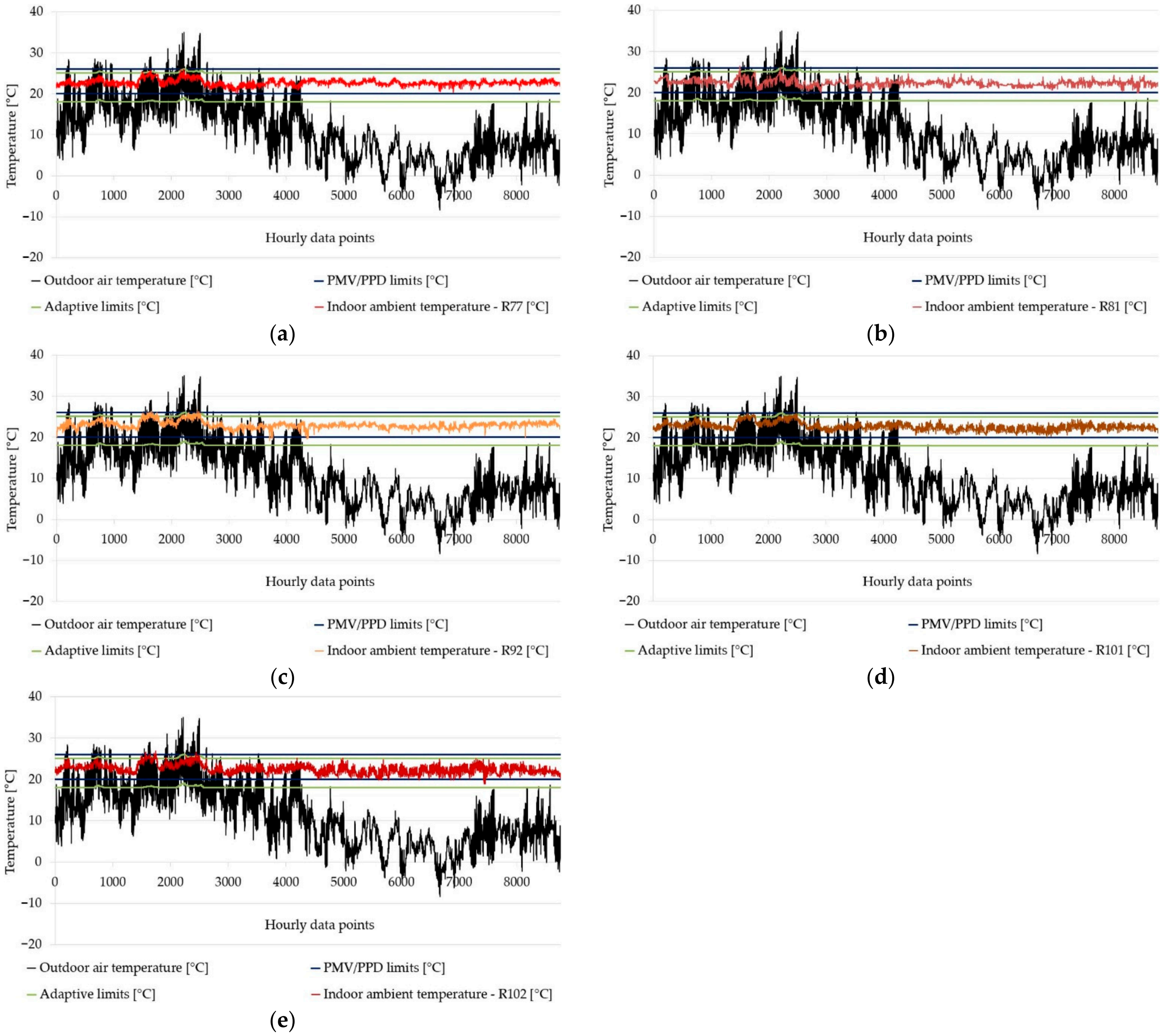
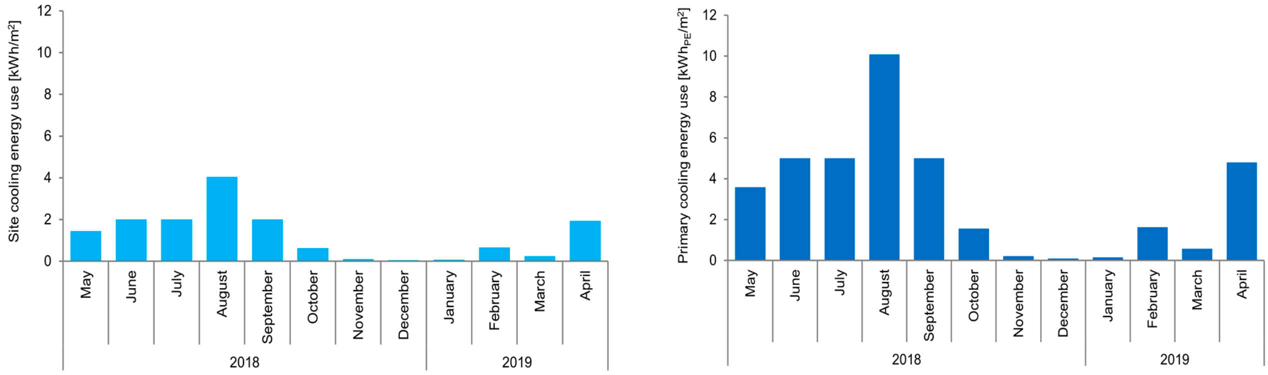


Figure 7. Hourly indoor air temperature (°C) with outdoor air temperature (°C) from May 2018 to April 2019 with PMV/PPD and adaptive category II: (**a**) R77; (**b**) R81; (**c**) R92; (**d**) R101; (**e**) R102.

3.2. Primary Energy Use

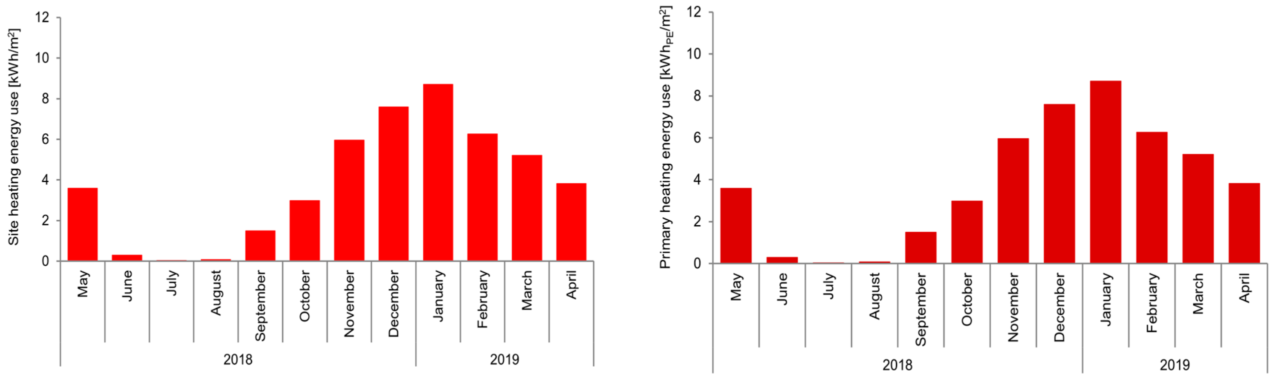
The building site cooling and heating energy use of the reference nearly-zero energy office building was analyzed using the monthly consumption data for electricity (cooling) and natural gas (heating) collected from May 2018 to April 2019. The monthly site cooling energy use per square meter is shown in Figure 8a, and the primary cooling energy use per square meter is shown in Figure 8b. The annual site cooling energy use per square meter was 15.02 kWh/m^2.a and the annual primary cooling energy use per square meter was 37.54 kWh_{PE}/m^2.a for the reference building.

The monthly site heating energy use per square meter is shown in Figure 9a, and the primary heating energy use per square meter is shown in Figure 9b. The annual site heating energy use per square meter was 46.08 kWh/m^2.a and the annual primary heating energy use per square meter was 46.08 kWh_{PE}/m^2.a for the reference building. The site energy use and primary energy use for heating purposes are the same, since the energy source was natural gas.



(**a**) (**b**)

Figure 8. Total monthly electricity use from May 2018 to April 2019 for space cooling: (**a**) site cooling energy use (kWh/m^2); (**b**) primary cooling energy use (kWh$_{PE}$/m^2).



(**a**) (**b**)

Figure 9. Total monthly natural gas use from May 2018 to April 2019 for space heating: (**a**) site heating energy use (kWh/m^2); (**b**) primary heating energy use (kWh$_{PE}$/m^2).

3.3. GHG Emissions

Following the building energy use analysis, the total monthly GHG emissions from the cooling and heating systems were calculated from May 2018 to April 2019 using Belgian conversion factors [39]. In addition, annual CO_2 emissions in kg per square meter of the building for cooling and heating were calculated separately. The total monthly cooling and heating GHG emissions per square meter from May 2018 to April 2019 are shown in Figure 10. The annual cooling GHG emissions per square meter was 10.14 kg.CO_2e/m^2.a and annual heating GHG emissions per square meter were 8.34 kg.CO_2e/m^2.a from the reference building.

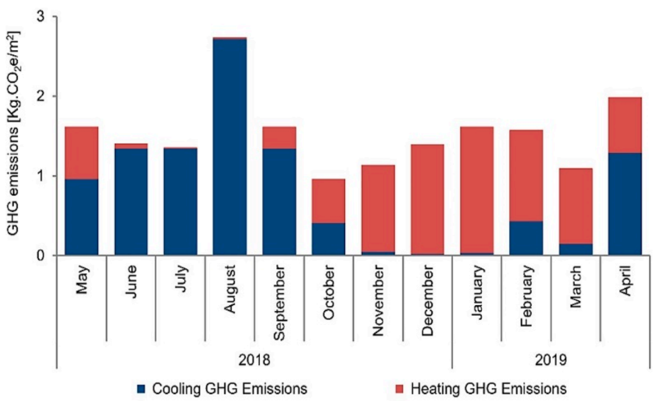


Figure 10. Total monthly GHG emissions (kg.CO_2e/m^2) from May 2018 to April 2019 with cooling and heating GHG emissions.

4. Discussion

This section presents the main findings, strengths and limitations, and implications for practice and future work based on the field measurements on the reference nearly-zero energy office building in Brussels, Belgium.

4.1. Main Findings

1. The time-integrated analysis of spatial thermal comfort indicated only 0.05 °C of overheating and 0 °C of overcooling in the building during the monitored period and is available from the dataset [40]. However, with an increased rate of climate change and the urban heat islands [41], higher rates of summer discomfort can be foreseen.
2. The primary energy use of the building was estimated at 37.54 kWh_{PE}/m^2.a for cooling and 46.08 kWh_{PE}/m^2.a for heating. To decrease the primary energy use and dependency on natural gas for heating purposes, the building should integrate renewable energy sources into the energy mix. These values indicate that building energy use is higher than expected.
3. The GHG emissions from the building were estimated to be 10.14 kg.CO_2e/m^2.a for cooling and 8.34 kg.CO_2e/m^2.a for heating. Integration of renewable energy sources and/or low carbon sources, such as nuclear energy, will decrease the building GHG emissions and accelerate EU decarbonization goals.
4. The HVAC system used in the building was an air-cooled chiller with water cooling coils and a water boiler with water heating coils. The system conditions the outdoor air through the mechanical ventilation unit, and this air heats/cools the building.
5. However, the current system is not recommended for the future to ensure maximum hygienic airflow in the building and occupant health. Technologies such as SAPPceiling [42,43] will be an energy-efficient and sustainable solution for future operations.
6. An occupancy-based HVAC operation schedule will improve the energy performance of the reference building. In addition, integrating the building with renewable energy sources for heating and cooling loads will decrease primary energy use and natural gas dependency.

4.2. Strengths and Limitations

Implementing a time-integrated, multizonal thermal discomfort evaluation for field measurements of a real office building in a temperate climatic zone was the main novelty of the paper. The indoor overheating degree and indoor overcooling degree were determined by averaging the temperature difference between the indoor operating temperature and the total number of zonally occupied hours. This paper helps designers and professionals to evaluate building performance using actual monitored data from a field investigation.

This paper's main concepts and criteria were based on observational research based on field measurements. The study uses multizonal monitoring using different measurement locations with different façades. The paper recommends an occupancy-based HVAC schedule to improve energy performance and emission rates. Based on the paper's findings, future studies can focus on developing nZEBs that are energy-efficient, carbon-neutral, and guarantee occupant thermal comfort.

As far as the limitations were concerned, this paper deals with spatial thermal comfort measurements. Thermal comfort evaluation is a much more complex process and human perception of comfort is a large factor. Hence, future work should also focus on post-occupancy evaluation using qualitative surveys, in addition to the field measurements.

4.3. Implications for Practice and Future Work

1. Post-occupancy surveys and interviews are essential in determining how the users might influence the building's energy use. Researchers can compare the qualitative data collected through these interviews and surveys to understand how the occupants perceive buildings in terms of thermal comfort.

2. In addition to the quantitative data from the field monitoring, qualitative data from occupant surveys will enable a thorough evaluation of the building's performance. This will emphasize that the buildings must be efficient in terms of energy use and emissions, but they must also be efficient and useful in terms of thermal comfort.
3. HVAC systems will always be an integral part of the building systems, even though well-designed building envelopes can significantly reduce cooling and heating loads [8]. Efficient HVAC sizing can save energy use, while providing thermal comfort.
4. In addition, well-designed building envelopes and foundations can significantly reduce humidity infiltration. However, residual humidity transfer, in combination with the humidity produced by the occupants and building operations, will continue to make humidity removal a priority in building systems to ensure occupant health [8].
5. A mixed mode building operation and HVAC operation based on building occupancy will reduce energy use and GHG emissions. The research should also be expanded to determine the effects of mixed-mode building operation [44] on building performance.
6. These developments should consider the design, control, operation, and safety issues associated with the mixed-mode building operation. The need for the removal of latent heat in humid climates might prove a major barrier to mixed-mode building operations.
7. Future studies should also conduct a deeper analysis with multiyear observation to understand the building system patterns. Although there has been remarkable improvement in energy efficiency over the past few decades, there is still a significant amount of untapped potential, regarding theoretical limits and equipment performance.

5. Conclusions

The main concepts of this paper are based on quantitative field research methodology. This study conducted a field investigation of a nearly zero-energy office building for performance evaluation in terms of thermal discomfort, energy use, and GHG emissions. The results show that there was significant energy use for space heating and space cooling in the building. The building's overheating and overcooling discomfort were negligible. The study results could, in turn, help the EU achieve its goal of reducing emissions by 55% by the 2030s by identifying potential recommendations to reduce energy use.

The paper recommends that frameworks for evaluating building performance should evolve in research and practice, while advancing knowledge in occupant health and hygrothermal discomfort. nZEBs are one of the key ideas that can lead to energy-saving potentials and low carbon emissions. They are crucial not just for standardized nations, but also for developing nations. However, to keep up with the nZEB concept and operate in a manner that can minimize the operational environmental impact of buildings, the construction industry should be able to adapt [45] quickly.

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