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Are net zero energy buildings necessarily also net zero emission buildings? Time-integrated analysis using dynamic grid emission factors

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ABSTRACT

The built environment significantly contributes to greenhouse gas emissions, with a considerable amount released during the building operation. With warming climates, the building industry has been developing net zero energy buildings to improve energy efficiency and achieve carbon neutrality. However, further research is needed to evaluate if net zero energy buildings are also net zero in terms of operational emissions. Moreover, the impact of electricity mix variations in the electricity grid on operational emissions from net zero energy buildings needs further analysis. This study explored the ability of low-carbon electricity sources to meet the energy demand of net zero energy buildings in various study locations across the Group of Seven countries. Annual operational emission intensity analysis using static grid emission factors for each city indicated an underestimation of 111 % in Paris and an overestimation of 120 % in New York, compared to hourly dynamic grid emission factors considering electricity mix variations in the electricity grid. The misestimations in operational emission intensity could lead to flawed design practices like over-insulated building envelopes. The 24/7 carbon-free energy analysis indicated a minimum value of 63.6 % in Tokyo considering energy use met by low-carbon energy sources, highlighting the necessity of integrating energy storage in new and existing buildings for peak shaving and supplementing electricity when the renewable energy sources are intermittent. The study outcomes indicate that net zero energy buildings are not necessarily net zero emission buildings when hourly electricity mix variations in the utility grid are factored in.

1. Introduction

1.1. Study background

With increasing global and national commitments towards combating warming climates, efforts to decarbonize the built environment are rising. According to the findings from the Global Status Report for Buildings and Construction [1], operational energy demand in the building sector increased by 4 % in 2021 compared to 2020, the most significant rise in the past decade, and CO_2 emissions increased by 5 % to 10 $GtCO_2$ in 2021 compared to 2020. This is particularly concerning since the increase in energy use and CO_2 emissions has occurred despite significant investments in energy-efficient strategies for the building sector. Net zero energy buildings (NZEBs) with onsite renewable energy generation to meet annual building energy load is one of the solutions to reduce CO_2 emissions from the buildings [2]. However, the intermittent nature of renewable energy sources and electricity mix variations of the utility grid makes it challenging for NZEBs to achieve carbon neutrality regarding operational emissions. Additionally, these grid-connected buildings use electricity from the utility grid when onsite generation does not meet the energy load. In contrast, when excess energy is generated onsite, it is exported back to the electricity grid [3].

The energy sources used for electricity generation influence the electricity grid's greenhouse gas (GHG) emissions. The share of various energy sources in the annual electricity generation in the Group of Seven countries for 2023 is shown in Fig. 1 using the International Energy Agency (IEA) data [4]. Representative study locations from the G7 countries are used in this study as they are some of the most advanced economies globally. Additionally, these countries could play a significant role in influencing actions towards decarbonizing the built

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environment, such as the G7 Climate Policy, which aims to promote clean energy technologies and reduce emissions through policy changes for a sustainable net zero transition [5]. Canada, with 58 % from hydro, and France, with 64 % from nuclear, rely on low-carbon sources as primary energy sources for electricity generation. Fossil fuels like coal, oil, and natural gas represent 63.9 % of the total electricity generation in Japan, 59.4 % in the United States, and 54.3 % in Italy [4]. Wind, at 27.0 %, and coal, at 26.6 %, form primary energy sources in Germany, while natural gas, at 33.7 %, and wind, at 28.7 %, form a significant share of electricity generation in the United Kingdom. The electricity mix data from Fig. 1 shows a diverse range of electricity generation sources across the G7 countries for 2023, relying on fossil fuels in countries like Germany, Italy, Japan, the United Kingdom, and the United States. The dependence on fossil fuels for electricity production could create challenges to growing efforts to decarbonizing the built environment.

1.2. Literature review

CO_2 emissions from building operations considering dynamic grid emission factors from the German electricity grid are evaluated in [6], with the study indicating a variation of up to 2098 $kgCO_2$ in overall annual emissions while using dynamic and static grid emission factors for scenarios with thermal storage and photovoltaic generation. Similarly, [7] carried out building optimization considering dynamic grid emission values and found that ignoring future variations in electricity mix may overestimate operational emissions by 49.0 to 64.8 %, which could result in over-insulation of the building envelope that could exacerbate the indoor built environment [8]. The study indicates the significance of accounting for electricity mix variations in the electricity grid in building performance analysis focusing on decarbonization efforts. In line with these studies, findings from [9] showed that GHG emission calculation using dynamic grid emission factors provided a more accurate representation than static grid emission factors. This was particularly evident during peak loads.

Similarly, [10] found a 44 % reduction in GHG emissions from building electricity use while using spatially and temporally sensitive dynamic grid emission factors compared to static grid emission factors. These findings are supported by [11], which found emission misestimations while using static grid emission factors instead of dynamic grid emission factors. Moreover, the significance of estimating hourly electricity production mix in the utility grid is underscored in [12] for efficient GHG accounting [13]. Studies from [14] focused on how photovoltaic systems could contribute to the targets set for decarbonization in Switzerland. The study also reported that using static emission factors could overestimate the ability of photovoltaic systems to reduce GHG emissions by a factor of 2. In line with these studies, [15] reported a measured energy approach for existing buildings that account for dynamic emissions from the electricity grid. Although studies from [16] provide a comprehensive analysis of the life cycle assessment of passive houses considering grid decarbonization, yearly CO_2 emission factors considering current and future electricity mix variations were used that could misestimate emission patterns from the operational stage, according to [7]. The global warming potential of the reference building was decreased by 13 % when renewable energy is the primary source in the electricity grid compared to the existing electricity mix in Belgium, according to [17]. The findings from [17] also indicate an increase in environmental impact when both heating and cooling demand is met by electricity, and [18] suggests a decrease in GHG emissions by 30 % and cost by 20 % through heating electrification.

Increasing renewable energy sources in [19] provided insights for decarbonization initiatives for the Brazilian healthcare sector by quantifying electricity use-related GHG emissions from a reference hospital building and found approximately 1750 $kgCO_2eq$ over seven years from 2017 to 2023. However, the study used monthly electricity generation values characterized by energy sources to account for the electricity mix. Monthly electricity mix data has a lower resolution than hourly electricity mix data. Thus, hourly electricity mix data could provide more accurate emission patterns. Similarly, although findings from [20] provided insights into the mismatch between electricity use and GHG emission profiles of NZEBs, the evaluation is limited to annual and monthly assessment balance periods. The significance of life cycle analysis of buildings in carbon emission accounting is addressed in [21] with the study proposing a multi-scale input-output analysis for low-carbon building assessments. This study proposes an accounting procedure for various stages like building construction, material transportation, building fitment, outdoor facilities, building operation, waste treatment, property management, and building demolition, thereby designing a comprehensive framework for the entire service life

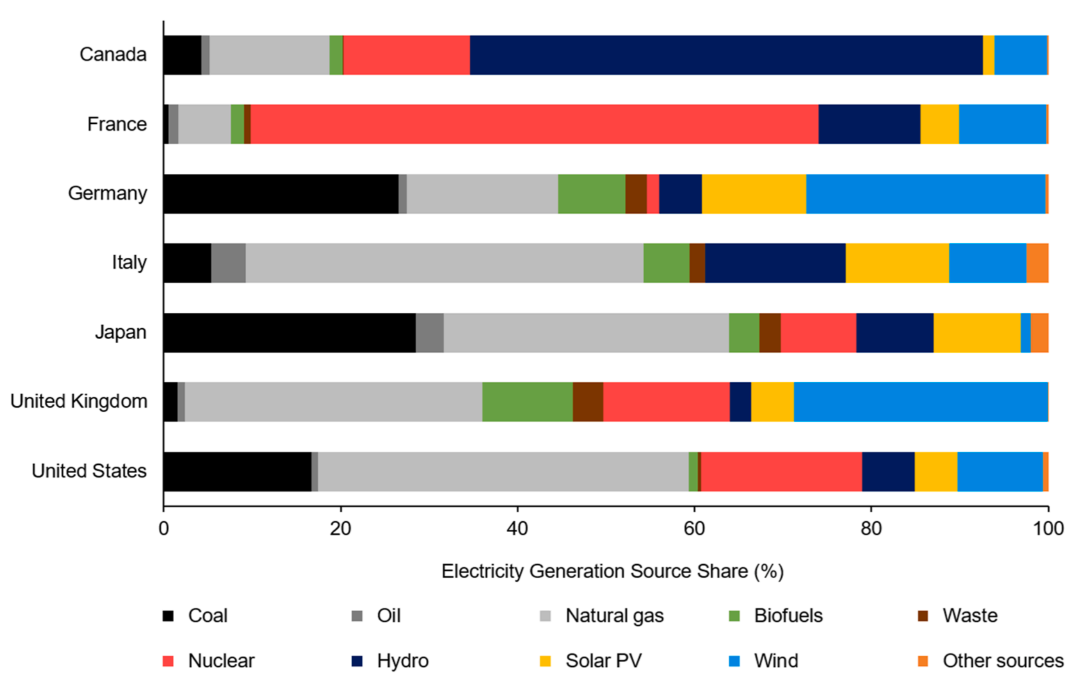

Fig. 1. Percentage share (%) of electricity generation sources from the G7 countries for 2023.

considering indirect resource utilization. Similar to building operational emissions, embodied carbon from building materials also significantly contributes to GHG emissions, with findings from [22] identifying steel and cement sectors as the leading contributors to embodied GHG emissions at approximately 90 % of total embodied GHG emissions among different building materials. These findings further emphasize the need for studies considering timber buildings. The analysis of existing studies identified a scarcity of studies focusing on operational emissions from NZEBs, and this is addressed in this study using dynamic grid emission factors [23].

1.3. Study relevance

Assessing operational emissions from office buildings is significant since office buildings typically have higher operational energy use compared to residential buildings [24]. Similarly, non-residential building energy use also contributed to 32 % of the global CO_2 emissions from the building sector in 2019, according to the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report from Working Group III: Mitigation of Climate Change [25]. The reference NZEB used in this study [26,27] is designed with low embodied carbon materials that are renewable like timber, which can be demounted and reused once its utility is over, thereby decreasing wastage, which adds to its relevance. The building model is also integrated with a rooftop photovoltaic system to meet the annual electricity use. Moreover, the emission misestimation findings from [6,9–11] are highly significant for NZEBs as evaluations using static grid emission factors would report minimal operation emissions since the electricity use is met by onsite electricity generation.

The comparative study approach assessing operational emissions from the reference NZEB using dynamic and static grid emission factors could support the decarbonization efforts and redefinitions of built environments focusing on carbon in developed economies where a large market segment utilizes office spaces. This study is critical in advancing global decarbonization efforts by addressing a significant gap in understanding operational emissions from NZEBs. As countries strive to meet ambitious climate goals under frameworks like the Paris Agreement, accurate emission accounting becomes essential to design buildings that are not only energy-efficient but also truly carbon-neutral. By utilizing dynamic grid emission factors, this research provides a more precise method to evaluate the carbon intensity of NZEBs, enabling policymakers and designers to implement strategies that align with science-based targets and foster a sustainable transition in the built environment.

1.4. Research objectives

The main objective of this study is to assess whether NZEBs equate to net zero in terms of operational emissions when accounting for the electricity mix variability in the electricity grid over time. Although onsite renewable energy generation systems like photovoltaic systems can be sized to meet the annual energy load from the building, it may not always guarantee zero operational emissions when the hourly electricity mix of the utility grid is considered. This study evaluates using dynamic and static grid emission factors to demonstrate discrepancies in operational emissions in NZEBs across various study locations and climate zones across the G7 countries. Operational emission intensity (OEI) analysis considering hourly electricity mix variations in the utility grid and onsite renewable energy generation will provide a better understanding on whether NZEBs are truly net zero in terms of operational emissions.

Dynamic grid emissions enhance the accuracy of OEI measurements by accounting for the real-time variations in the electricity mix in the utility grid. Unlike static grid emission factors, which assume a uniform annual average, dynamic factors reflect hourly fluctuations in grid carbon intensity caused by changes in the share of renewable and fossil fuel energy sources. This higher temporal resolution allows a more realistic assessment of emissions during building operation, particularly in grid-connected NZEBs. By capturing these variations, dynamic grid emissions provide a nuanced understanding of the relationship between energy use patterns and emissions, enabling better-informed design and operational decisions that minimize carbon footprints. Furthermore, the study evaluates 24/7 carbon-free energy (24/7 CFE), a versatile metric that accounts for self-consumption and accurate carbon accounting. 24/7 CFE uses an hourly matching strategy, focusing on energy self-sufficiency and resiliency levels. Self-sufficiency optimization involves maximizing self-produced energy to reduce dependence on the utility grid while ensuring no photovoltaic production is curtailed or wasted. The 24/7 CFE evaluation will identify further steps to improve building operations using low-carbon energy sources.

This study was developed in the framework of IEA Energy in Buildings and Communities (EBC) Technology Collaboration Programme (TCP), through its international research and development project Annex 89: Ways to Implement Net-zero Whole Life Carbon Buildings [28]. Furthermore, the study results can support the building sector to determine existing performance gaps and achieve science-based targets set by the Paris Agreement [29–-31] in built environments, which is an objective of IEA EBC Annex 89 [28].

2. Methodology

The study conceptual framework that illustrates the research methodology is shown in Fig. 2. The whole building energy performance simulation was performed using DesignBuilder v7.0.1 as the graphical user interface and EnergyPlus v9.6.0 as the simulation engine [32].

2.1. Study locations

The study covers eight locations as shown in Fig. 3. These cities are: a. Toronto, Canada, in cool humid climates (5A); b. Paris, France, in mixed humid climates (4A); c. Berlin, Germany, in cool humid climates (5A); d. Rome, Italy, in warm humid climates (3A); e. Tokyo, Japan, in warm humid climates (3A); f. London, United Kingdom, in mixed humid climates (4A); g. Los Angeles, United States, in warm marine climates (3C); and h. New York, United States, in mixed humid climates (4A). The climate zones are determined according to American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) 169 - Climatic Data for Building Design Standards [33]. This classification system uses annual and monthly climatic data from 9237 global locations. It includes parameters like temperature occurrence percentiles, humidity, and wind speed [33,34], making it an appropriate classification system for building performance studies. Typical Meteorological Year (TMY) files from various study locations were obtained from [35] derived from hourly weather data from 2009 to 2023 in EnergyPlus Weather Format (EPW).

2.2. Grid emission factors

Grid emissions factors (gCO_2eq/kWh) measure GHG emissions from each unit of electricity produced. Grid emission factors could be either static or dynamic. Static grid emission factors consider GHG emissions from each unit of electricity produced as a yearly value, while dynamic grid emission factors represent hourly changes in the electricity mix to calculate GHG emissions from each unit of electricity produced. Dynamic grid emission factors provide high-resolution data, which is important for building operational emission analysis since: a. It represents the varying GHG emissions from the electricity grids more accurately [6] and b. It avoids inaccurate characterization of building operational emissions that might lead to inconsistent design [7] and poor technology choices. This study uses a comparative approach to analyze the OEI using static and dynamic factors to decode the variations from each approach. The static grid emission factors for the G7

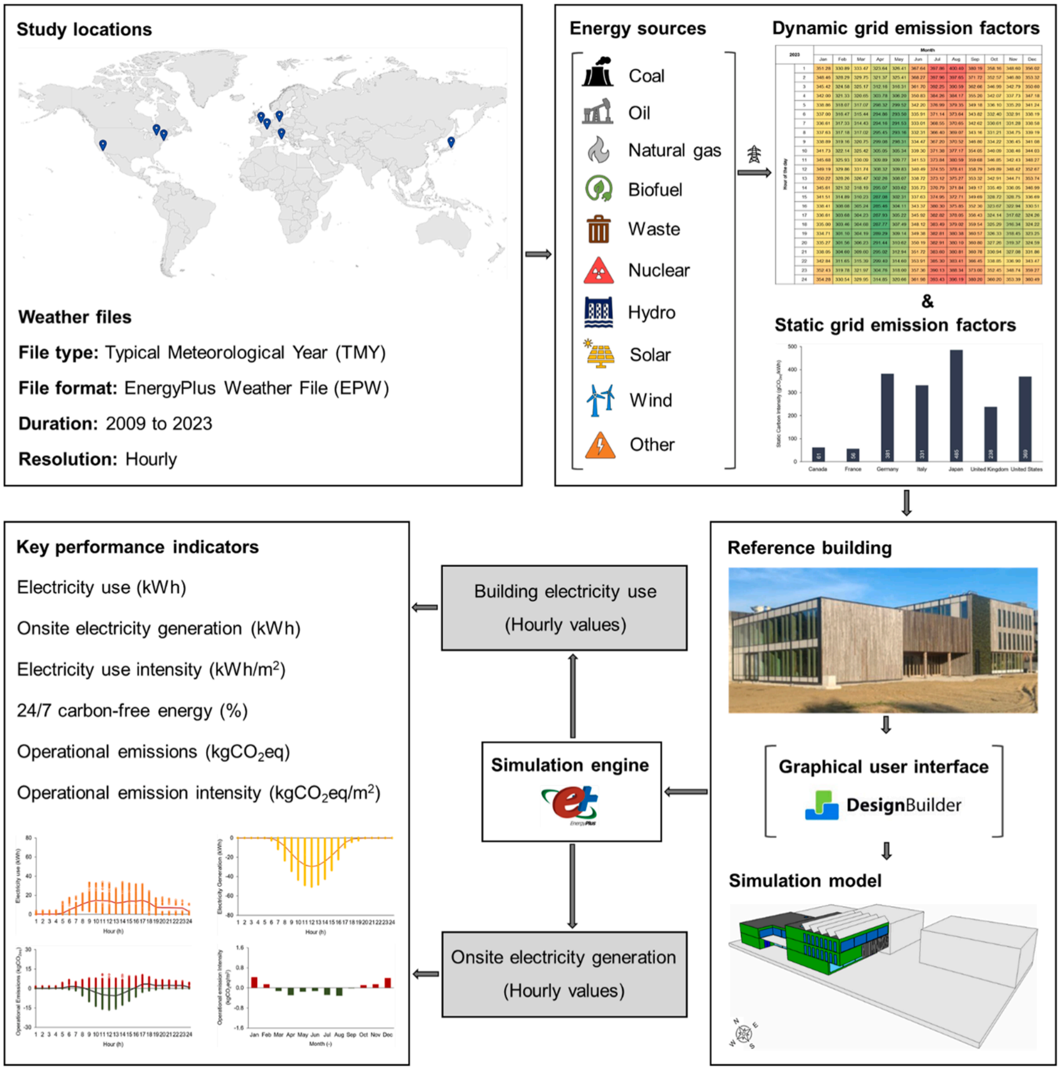

Fig. 2. Study conceptual framework used to assess operational emissions from NZEBs considering dynamic grid emission factors at various study locations across the G7 countries.

countries for 2023 are shown in Fig. 4 [37], which are used to calculate static OEI ($kgCO_2eq/m^2$) from the reference building in various study locations across the G7 countries.

Dynamic grid emission factors use hourly direct emission values from the electricity grids, considering diurnal and seasonal variations in the electricity mix. The dynamic grid emission factors averaged for hours per day and month over the year [6,38] for the G7 countries for 2023 are listed in Appendix A created using data from [37]. The analysis of dynamic grid emissions was adjusted for energy outputs of the building simulations, and the results indicate varying patterns across the G7 countries. These tables indicate how carbon intensities in the utility grid vary diurnally and monthly, whereas, for calculations of key performance indicators, hourly direct carbon intensity values and percentage share of low-carbon electricity sources were matched with hourly building energy use for better accuracy. These variations can be observed monthly, e.g., The electricity generation in Canada (Ontario) and the United States is more carbon-intensive from July to August. In contrast, carbon-intensive periods are from January to March for France, Germany, and Italy. Furthermore, the carbon intensity varies over the day, e.g., most carbon-intensive hours are observed around 09h00 to 17h00 for Japan, while these hours are less carbon-intensive in Italy than the rest of the hours throughout the year.

2.3. *Reference net zero energy building*

The reference NZEB used in this study is a timber office building that incorporated circularity principles with building materials that are renewable, reusable, and recycled or upcycled. The building is modular, with a frame made from cross laminated timber (CLT) components [26]. The modular design of the reference building includes adaptable workspaces, which can be disassembled once its utility is over [27]. The building envelopes, including floors, roofs, and interior partitions, are made of timber. The building exterior view from [39] is illustrated in Fig. 2. The operational schedule factors of the reference building vary from 0, representing 0 %, up to 1, representing 100 % of the total capacity. The occupancy, lighting, heating, and cooling schedules for the reference building are shown in Fig. 5 [40]. The maximum occupancy factor in the building is maintained at 0.9 during weekdays from 09h00 to 17h00, except at 13h00 with a value of 0.5. The lighting factor is maintained at one during weekdays from 07h00 to 24h00. The operational schedules and building characteristics are detailed in [40]. Occupancy profiles for the reference building are as per ASHRAE 90.1 – Energy standard for buildings except low-rise residential buildings [41] implemented in existing studies like [42]. Lighting, heating, and cooling schedules were obtained from the building services. The characteristics of the reference building are listed in Table 1. The building comprises

Fig. 3. Study locations with climate zones [33] evaluated for operational emissions from NZEBs considering dynamic grid emission factors across the G7 countries using base map from [36].

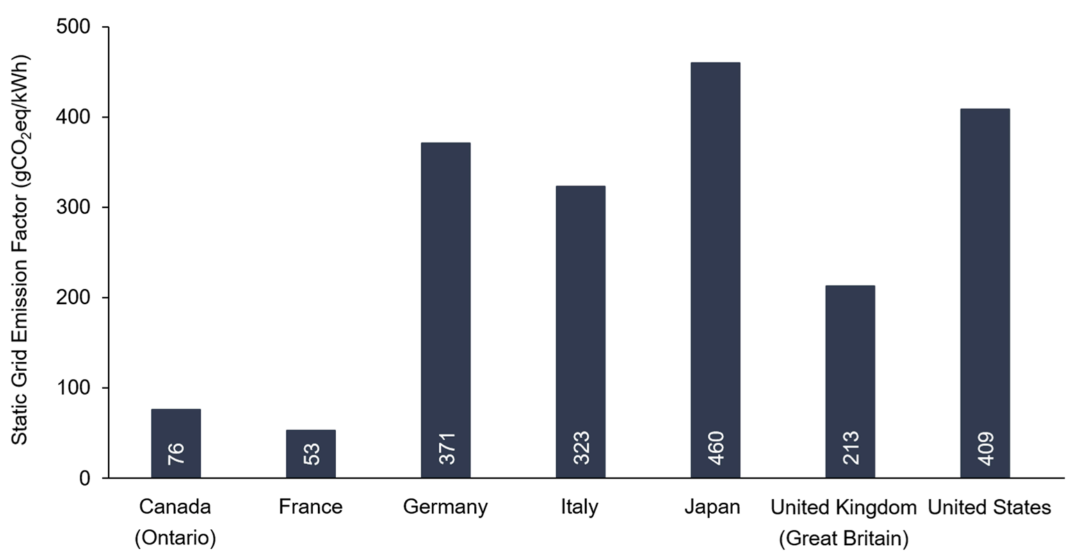

Fig. 4. Static carbon intensity (gCO_2eq/kWh) from the electricity grids in the G7 countries.

three floors with an occupied surface area of 2086 m^2 to accommodate about 116 occupants. Each floor forms a separate thermal zone with a lightweight interior wall that can be moved to change the spatial distribution. The lighting rate is set at 5 W/m^2 at 500 lx according to European Norm (EN) 12,464–1 - Light and lighting [43], while indoor equipment gain is set at 6 W/m^2. The building energy simulation model used in this study is available in [44].

A reversible water-to-water heat pump with heated floors and chilled beams is used for space conditioning in the building. The system also consists of six ground-installed geothermal tubes. Mechanical ventilation with heat recovery is used at a rate of 7.55 L/s/person, according to the building energy performance report [40]. The heating and cooling factors represent the capacity of the space conditioning system with 0 representing 0 % or no operation and 1 representing 100 % or full capacity. The heating factor is set at one throughout the weekdays during winter and the weekdays during summer from 06h00 to 19h00. In contrast, the cooling factor is set at 1 for weekdays during summer from 06h00 to 19h00 and 0.5 during the rest of the hours. Heating systems function at half the capacity during weekends and holidays, while cooling systems are shut down during weekends and holidays. The modeling ensured that minimum nighttime air temperature, mean radiant temperature, and operative temperature values were maintained above 10 °C in the reference building for each study location during the study period to avoid system issues like freezing of pipes during the winter season as shown in Table B1 in Appendix B. This indicates that the indoor air temperature never goes down to 0 °C, thereby avoiding the dangers freezing in main heat supply pipelines in the building [45]. The operational schedules for heating and cooling systems are created by integrating heating and cooling factors into the schedules through scripting option available in DesignBuilder. The heating and cooling setpoints are set at 18 °C and 25 °C, and humidity is set at a minimum of 30 % and a maximum of 70 %. Domestic hot water (DHW) is produced using the same boiler as the heating system at a temperature of 60 °C as recommended by the World Health Organization (WHO) [46] at a rate of

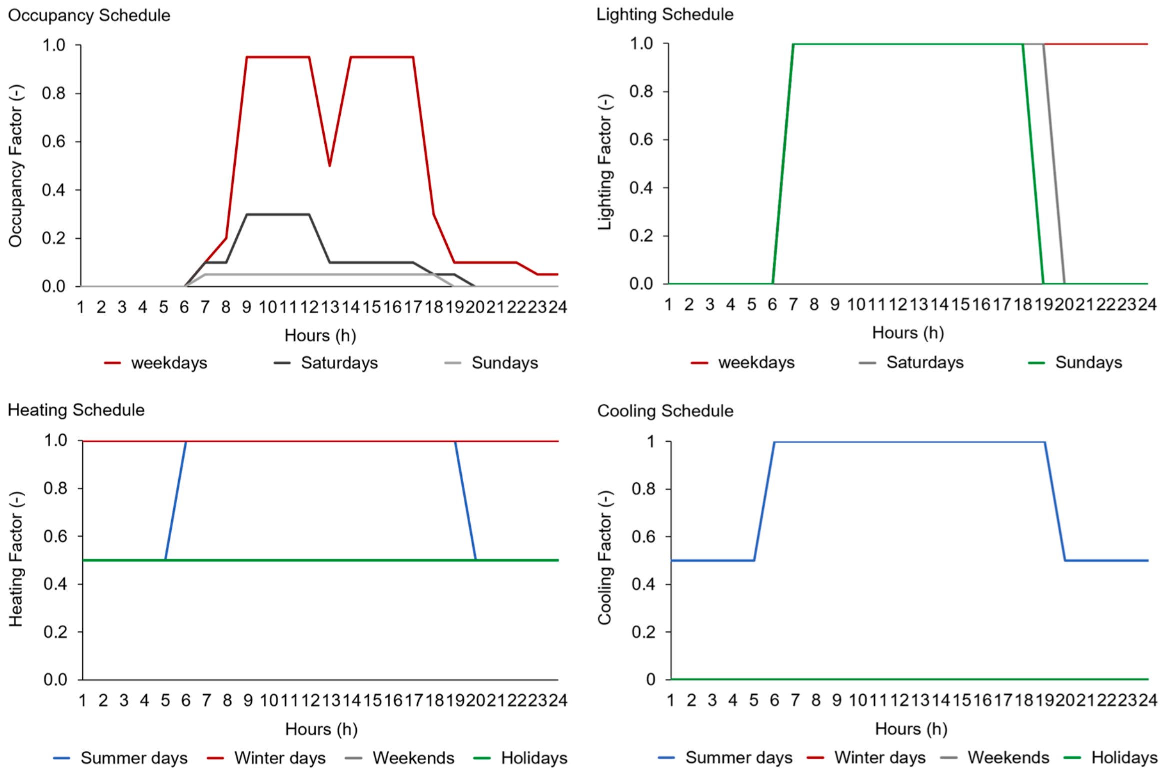

Fig. 5. Reference net zero energy building operational schedules.

Table 1
Characteristics of reference net zero energy building used in the study.

Building characteristics	Value
Number of floors (-)	3
Total area (m^2)	2086
Number of occupants (-)	116
Window-to-wall ratio (%)	30.50
Window G-value (-)	0.691
Window U-value (W/m^{2}K)	1.960
External wall U-value (W/m^{2}K)	0.170
Internal partition U-value (W/m^{2}K)	1.639
External roof U-value (W/m^{2}K)	0.226
Ground floor U-value (W/m^{2}K)	0.138
External floor U-value (W/m^{2}K)	0.219
Internal floor U-value (W/m^{2}K)	0.719

0.65 l/m^2. According to the building energy performance report, the reference building is considered a high-performance building with an infiltration rate of 0.6 ACH at 50 Pa. The building energy performance simulation model was calibrated based on total energy use and building characteristics [40] as it was under construction. The weather scenarios from Brussels in Belgium, where the original building is located, were used for this process. A mean bias error (MBE) value of −0.4 was observed between the building energy performance report and simulation energy loads, less than 5 %, as recommended by ASHRAE Guideline 14 - Measurement of Energy, Demand, and Water Savings [47]. A rooftop photovoltaic system is integrated with the building model, which was sized to meet the annual electricity demand from each study location. The reference building characteristics, including envelope thermal transmittance values, are listed in Table 1. Detailed envelope characteristics of the reference building are available in [26].

2.4. Key performance indicators

The following key performance indicators are used in this study to evaluate if the reference NZEB is also net zero in terms of operational emissions using dynamic grid emission factors for various study locations across the G7 countries.

Electricity use in kWh is the total amount of electricity used by the reference building each hour including room, lighting, heating, cooling, and DHW electricity use.

Onsite electricity generation in kWh is the amount of total electricity generated each hour by the rooftop photovoltaic system on the reference building.

Electricity use intensity (EUI) in kWh/m^2 is calculated monthly using the sum of the difference between hourly electricity use and onsite electricity generation per square meter per month, as in Eq. (1).

$$EUI = \frac{\sum_{i=1}^{n}(E - R_e)}{A} \tag{1}$$

where E is hourly building electricity use, R_e is hourly onsite electricity generation, A is building surface area, and i is hourly values.

24/7 carbon-free energy (24/7 CFE) in % is a measure of the percentage of hours met by carbon-free electricity sources [48] during the reference building operation. 24/7 CFE metric is based on methodologies developed by Google [49]. The hourly CFE score is an hourly matching approach and is a measure of the percentage of the reference building operational load met by carbon-free electricity sources during any given hour. This includes the share of low-carbon energy sources from the electricity grid - a dynamic combination of carbon-free and carbon-based resources, in addition to onsite carbon-free electricity generated from rooftop photovoltaic systems. An annual score metric for 24/7 CFE is a measure of the average of the hourly CFE scores for each of the nominal hours of the year with building energy use as in Eq. (2). The hourly electricity mix data with the percentage of low-carbon electricity sources are available from [37]. The time step (i) varies from 1 to 8760, which is the number of hours in a year.

$$24\Big/7\ CFE = \frac{\sum_{i=1}^{8760}\min\,(energy\ use,\ CFE\ supplied)}{\sum_{i=1}^{n}(energy\ use)} \times 100 \tag{2}$$

Hourly operational emissions (O_e) in $kgCO_2eq$ are the difference between hourly electricity use and onsite electricity generation multiplied by dynamic grid emission factors as in Eq. (3) [50].

$$O_e = (E - R_e) \times D_f \tag{3}$$

where D_f is hourly dynamic grid emission factors considering the variations in electricity mix in the electricity grid.

Operational emission intensity (OEI) in $kgCO_2eq/m^2$ is calculated monthly and annually. Monthly OEI is calculated using the sum of the difference between hourly electricity use and onsite electricity generation multiplied by dynamic grid emission factors per square meter per month as in Eq. (4). Annual OEI is calculated using dynamic and static grid emission factors to quantify the variations in carbon intensity for different approaches as in Eqs. (4) and (5).

$$Dynamic\ OEI = \frac{\sum_{i=1}^{n}\left((E - R_e) \times D_f\right)}{A} \tag{4}$$

$$Static\ OEI = \frac{\sum_{i=1}^{n}(E - R_e)}{A} \times S_f \tag{5}$$

where S_f is annual static grid emission factor.

3. Results

The diurnal profile of hourly and average electricity use in kWh is illustrated on a single 24-hour profile in Fig. 6. Hourly electricity use in the reference building is the total sum of room, lighting, heating, cooling, and DHW electricity use. The annual electricity use in kWh from the reference building in: a. Toronto was 70,577 kWh, with lighting

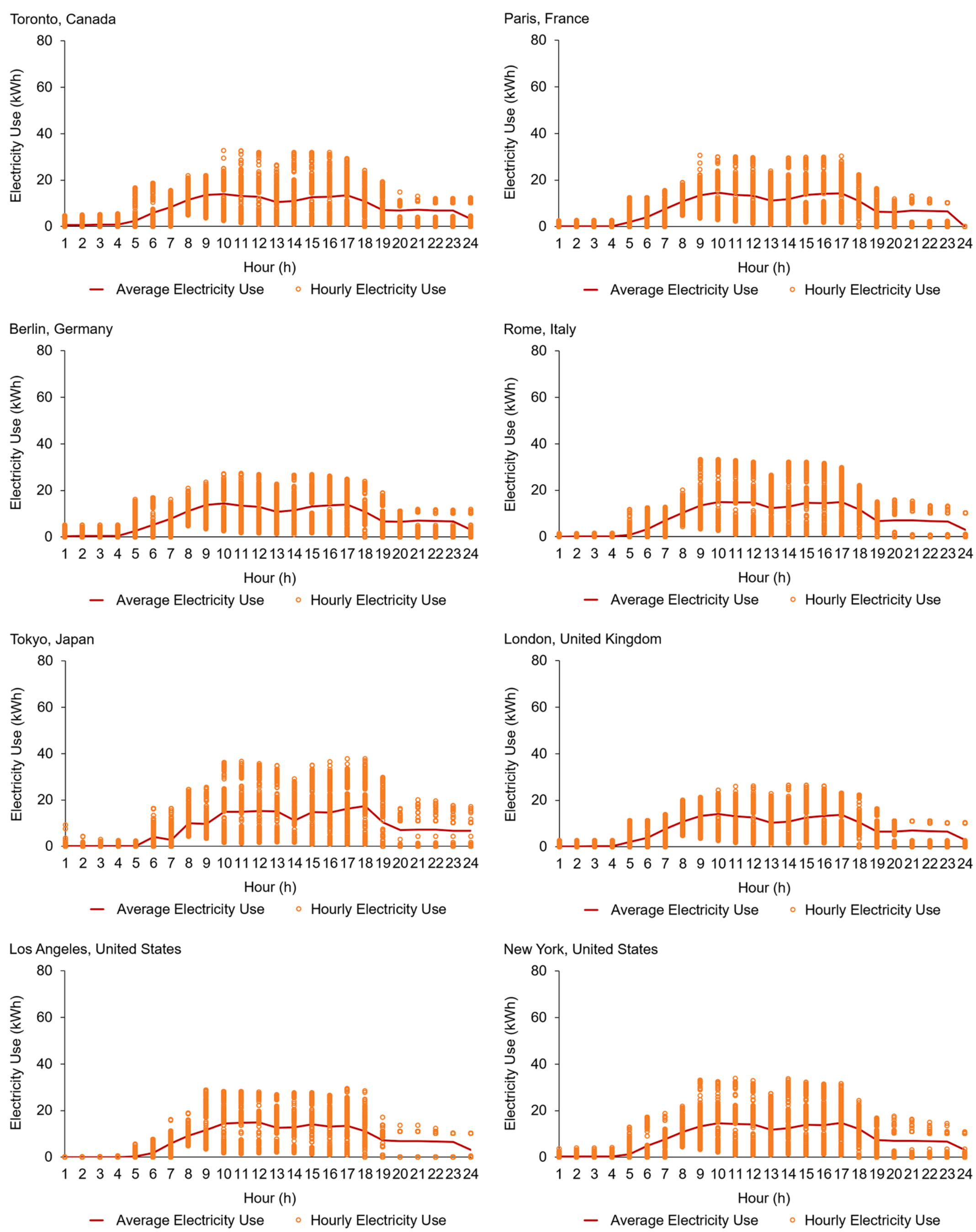

Fig. 6. Average and hourly electricity use (kWh) from the reference net zero energy building at various study locations represented on a daily profile.

contributing around 44.4 % of the total end use; b. Paris was 68,795 kWh, with lighting contributing around 48.2 % of the total end use; c. Berlin was 70,827 kWh, with lighting contributing around 47.6 % of the total end use; d. Rome was 71,985 kWh, with lighting contributing to 42.5 % of the total end use; e. Tokyo was 75,375 kWh, with lighting contributing to 42.3 % of the total end use; f. London was 68,020 kWh, with lighting contributing to 48.6 % of the total end use; g. Los Angeles was 68,354 kWh, with lighting contributing to 44.7 % of the total end use; h. New York was 72,548 kWh, with lighting contributing to 43.4 % of the total end use. In all study locations, lighting was the largest electricity end-user in the reference building, followed by room electricity use.

Onsite electricity generation from the reference building is the measure of electricity generated by the photovoltaic systems located on the rooftop. The annual onsite electricity generation in kWh in presented in Table 2. The diurnal profile of hourly and average onsite electricity generation in kWh is illustrated on a single 24-hour profile in Fig. 7.

Monthly net EUI was calculated as the difference of hourly building electricity use and onsite electricity generation per month by the surface area of the reference building. Maximum and minimum monthly EUI in kWh/m^2 of the reference building across the study locations are listed in Table 3. A positive monthly EUI indicates that the building used more electricity than it generated, and vice versa for negative monthly EUI values. The analysis suggests a comparable pattern of higher EUI during winter and lower EUI during summer in the study locations, which could be a result from higher onsite electricity generation at reference buildings during summer months compared to winter months. The monthly EUI variations of reference building across various study locations are shown in Fig. 8.

The share of 24/7 CFE for the reference building was calculated as a share of operational hours met by low-carbon energy sources from the electricity grid and onsite electricity generated by rooftop photovoltaic system on the reference NZEB. The 24/7 CFE in % for various study locations are shown in Fig. 9, which varied across the study locations from 63.6 % in Tokyo to 97.5 % in Paris. 24/7 CFE in other study locations was observed as 75.3 % in New York, 80.4 % in Los Angeles, 81.7 % in Berlin, 82.1 % in Rome, 84.5 % in London, and 95.8 % in Toronto. These results indicate that although the annual electricity use from the reference building was met by total onsite electricity generation, this does not guarantee continuous building operation using low-carbon energy sources from the electricity grid and onsite electricity generated from the rooftop photovoltaic system.

Hourly operational emissions from the reference building consider hourly electricity used, onsite electricity generated, and dynamic grid emission factors. The hourly operational emissions in kgCO_2eq /m^2 in the reference building varied from: a. −4.12 to 2.54 kgCO_2eq in Toronto, with an around 0.45 kgCO_2eq at 18h00; b. −2.29 to 2.43 kgCO_2eq in Paris, with an average around 0.36 k kgCO_2eq at 18h00; c. −20.72 to 14.63 kgCO_2eq in Berlin, with an average around 3.40 kgCO_2eq at 18h00; d. −9.38 to 8.19 kgCO_2eq in Rome, with an average around 2.83 kgCO_2eq at 18h00; e. −22.06 to 16.22 kgCO_2eq in Tokyo, with an average around 6.91 kgCO_2eq at 18h00; f. −9.53 to 6.23 kgCO_2eq in London, with an average around 1.51 kgCO_2eq at 18h00; g. −11.57 to 9.89 kgCO_2eq in Los Angeles, with an average around 3.33 kgCO_2eq at 18h00; h. −16.47 to 10.64 kgCO_2eq in New York, with an average around 3.52 kgCO_2eq at 18h00. Positive hourly operational emissions indicate that the reference building releases emissions during building operation, and vice versa for negative hourly operational emissions. These values suggest that NZEBs do not necessarily mean that they are also net zero regarding operational emissions. The diurnal profile of hourly and average operational emissions in kgCO_2eq is illustrated on a single 24-hour profile in Fig. 10.

Monthly OEI was calculated as the sum of hourly emissions per month estimated using dynamic grid emission factors by the surface area of the reference building. Maximum and minimum monthly OEI in kgCO_2eq/m^2 of the reference building varied from: a. 0.12 kgCO_2eq/m^2 in December and −0.11 kgCO_2eq/m^2 in July in Toronto; b. 0.13 kgCO_2eq/m^2 in January to −0.04 kgCO_2eq/m^2 in July in Paris; c. 1.21 kgCO_2eq/m^2 in January to −0.49 kgCO_2eq/m^2 in July in Berlin; d. 0.49 kgCO_2eq/m^2 in January to −0.22 kgCO_2eq/m^2 in July in Rome; e. 0.45 kgCO_2eq/m^2 in September to −0.47 kgCO_2eq/m^2 in April in Tokyo; f. 0.32 kgCO_2eq/m^2 in January and November to −0.23 kgCO_2eq/m^2 in May in London; g. 0.25 kgCO_2eq/m^2 in January to −0.31 kgCO_2eq/m^2 in July in Los Angeles; h. 0.43 kgCO_2eq/m^2 in January to −0.32 kgCO_2eq/m^2 in August in New York. The analysis suggests a comparable pattern of higher OEI during winter and lower OEI during summer in the study locations. However, these patterns do not always align with the monthly EUI patterns in Toronto with differing electricity use and carbon-intensive operation months. The monthly OEI variations from the reference building across various study locations are shown in Fig. 11.

The annual OEI values from the reference building was calculated using different approaches: a. hourly values of electricity use, onsite electricity generated, and dynamic grid emission factors, and b. annual values of electricity use, onsite electricity generated, and static grid emission factors. The annual dynamic and static OEI in kgCO_2eq/m^2 from the reference building across the study locations are illustrated in Fig. 12. The annual dynamic OEI in kgCO_2eq/m^2 in the reference building at various study locations varied from −0.43 kgCO_2eq/m^2 in Tokyo to 2.30 kgCO_2eq/m^2 in Berlin. These values for other study locations were observed as −0.11 kgCO_2eq/m^2 in Los Angeles, −0.10 kgCO_2eq/m^2 in New York, 0.02 kgCO_2eq/m^2 in Toronto, 0.27 kgCO_2eq/m^2 in Paris, 0.34 kgCO_2eq/m^2 in London, and 0.78 kgCO_2eq/m^2 in Rome. On the contrary, an approach using static grid emission factor showed minimum variations in static OEI varying from −0.03 kgCO_2eq/m^2 in Paris to 0.02 kgCO_2eq/m^2 in New York. Furthermore, the static approach indicated underestimation in OEI by up to 111 % in Paris, and overestimation by 120 % in New York. This supports the significance of calculating OEI using dynamic grid emission factors.

Table 2
Onsite electricity generation (kWh) across the study locations.

Study location	Total generation (kWh)	Highest average hourly generation (kWh)	Hour of the day
Toronto, Canada	70,577	28.36	12h00
Paris, France	69,831	26.86	12h00
Berlin, Germany	70,818	28.07	12h00
Rome, Italy	72,145	29.47	12h00
Tokyo, Japan	75,330	31.07	12h00
London, UK	68,067	26.56	12h00
Los Angeles, USA	68,439	27.48	12h00
New York, USA	72,447	29.69	12h00

4. Discussions

The main findings, strengths, and limitations, alongside recommendations for future practice and research from the study, are presented in this section.

4.1. Findings and recommendations

The findings from this study align with [20] that found energy and GHG emission profiles do not mirror each other, and energy metrics might not be suitable to reflect operational emissions NZEBs. The reference building is a timber office building with increased electricity use during daytime as shown in Fig. 6. The electricity use pattern from the reference building across the study locations shows a varying monthly pattern with higher EUI during the winter compared to the summer. This is because of higher onsite electricity generation

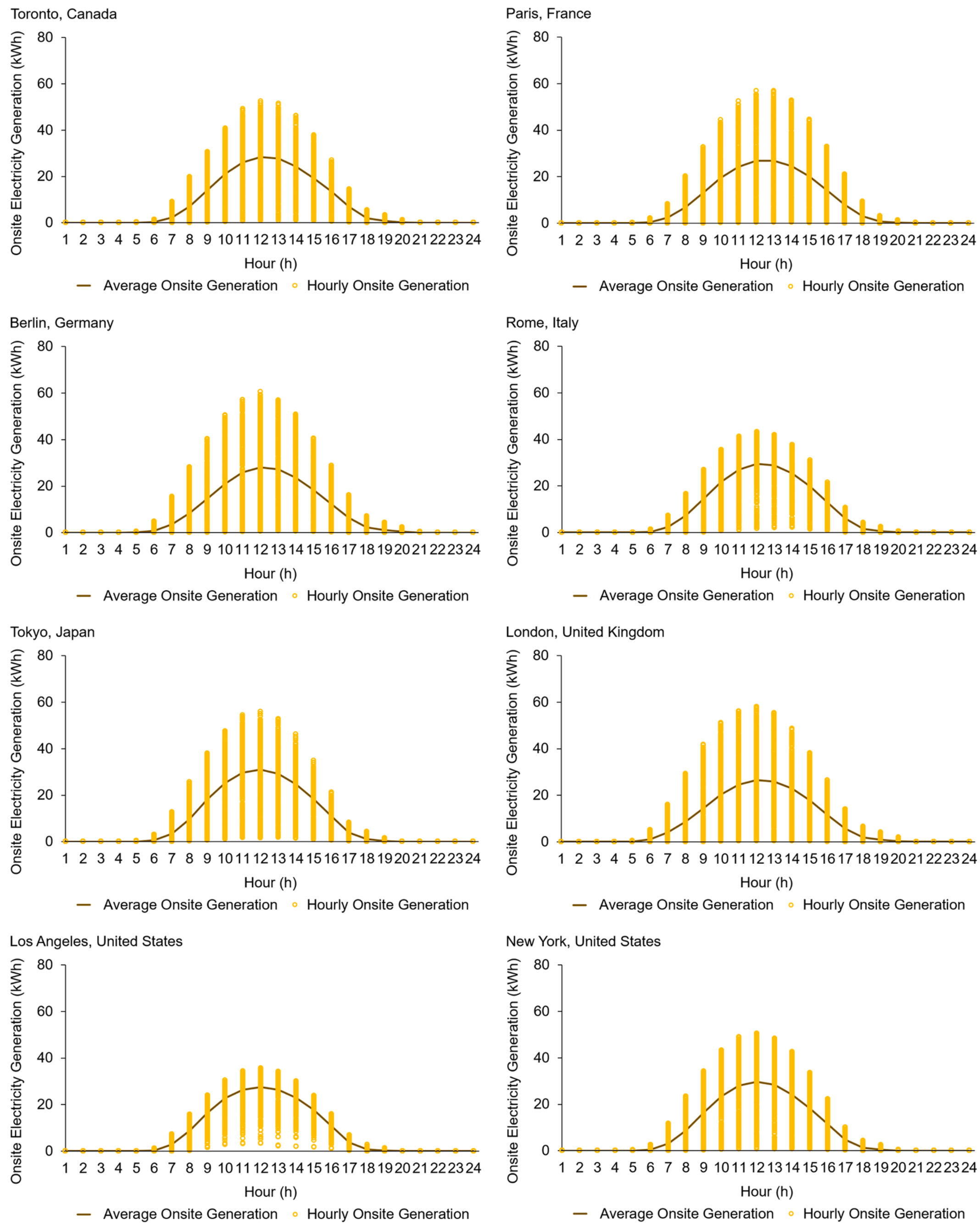

Fig. 7. Average and hourly onsite electricity generation (kWh) from rooftop photovoltaic system on the reference net zero energy building at various study locations represented on a daily profile.

Table 3
Monthly maximum and minimum net energy use intensity (kWh/m^2) across the study locations.

Study location	Monthly net energy use intensity (kWh/m^2)	
	Maximum	Minimum
Toronto, Canada	2.14 (January)	−1.53 (August)
Paris, France	2.54 (January)	−2.01 (July)
Berlin, Germany	3.17 (January)	−2.54 (July)
Rome, Italy	1.50 (January)	−1.18 (July)
Tokyo, Japan	1.12 (September)	−1.01 (May)
London, UK	2.47 (January)	−2.09 (July)
Los Angeles, USA	0.73 (January)	−0.82 (July)
New York, USA	1.28 (January)	−0.92 (April)

compared to electricity use during summer, resulting in a net negative EUI across the study locations, except in Tokyo. The onsite electricity generation from photovoltaic systems is considered negative since we are evaluating the tradeoffs strictly from a building perspective. The electricity imported from the grid adds to operational emissions, while electricity exported to the grid from onsite generation compensates for this carbon-intensive grid electricity, while displacing the emissions. The data from Fig. 1 shows that the electricity grid in both Germany and Japan are dependent on fossil fuels as primary energy source. The static grid emission factor in Japan is 460 gCO_2eq/kWh, whereas in Germany, it is 371 gCO_2eq/kWh from Fig. 4. However, the analysis using these factors shows minimal operational emissions from Tokyo and Berlin, since annual electricity use from the building is met by onsite electricity generation from the rooftop photovoltaic system. In contrast, when

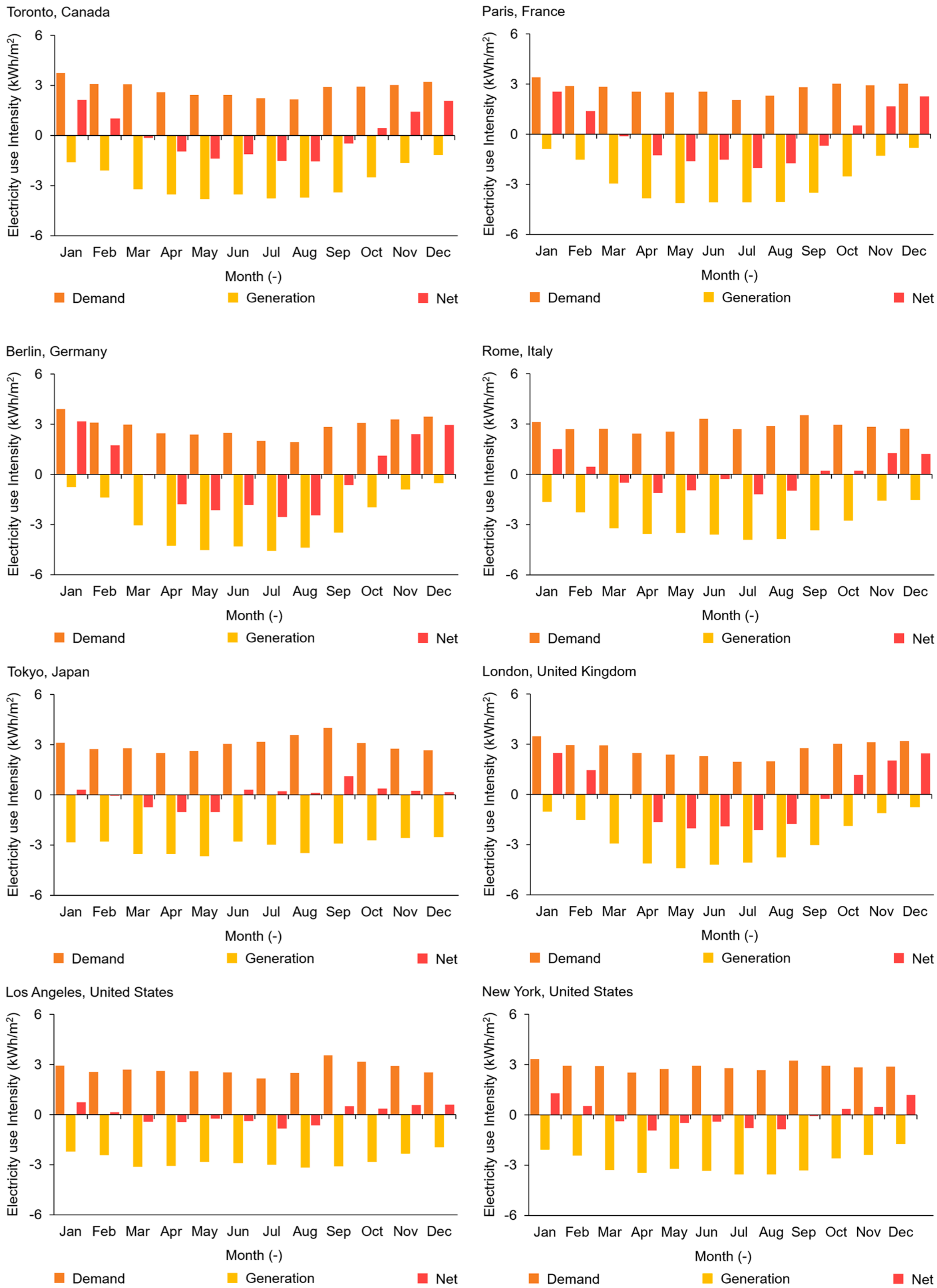

Fig. 8. Monthly electricity use intensity (kWh/m^2) of the reference net zero energy building at various study locations.

hourly dynamic grid emission factors are used, the annual OEI varies from −0.43 kgCO_2eq/m^2 in Tokyo to 2.30 kgCO_2eq/m^2 in Berlin. The unique outcomes in Tokyo and Berlin could be attributed to the varying carbon-intensive hours of the electricity grids. The electricity grid is more carbon-intensive during daytime in Tokyo, as in Table A5, while in Berlin, the electricity grid is more intensive during nighttime, as in Table A3. This indicates that the onsite electricity generated in Tokyo replaces more carbon-intensive grid electricity during building operations in addition to exporting cleaner energy into the electricity grid, resulting in a lower annual OEI. In contrast, onsite electricity generated in Berlin replaces comparatively less carbon-intensive grid electricity during the building operation, reducing its overall impact and resulting in a higher annual OEI. Additionally, a comparison of the annual OEI of the reference building across the study locations using dynamic and static grid emission factors indicates an underestimation of up to 111 % in Paris and an overestimation of up to 120 % in New York when using static dynamic grid emission factors.

Misestimation of operational emissions using static grid emission factors from the reference building could lead to flawed design practices underlining the significance of using high-resolution hourly dynamic

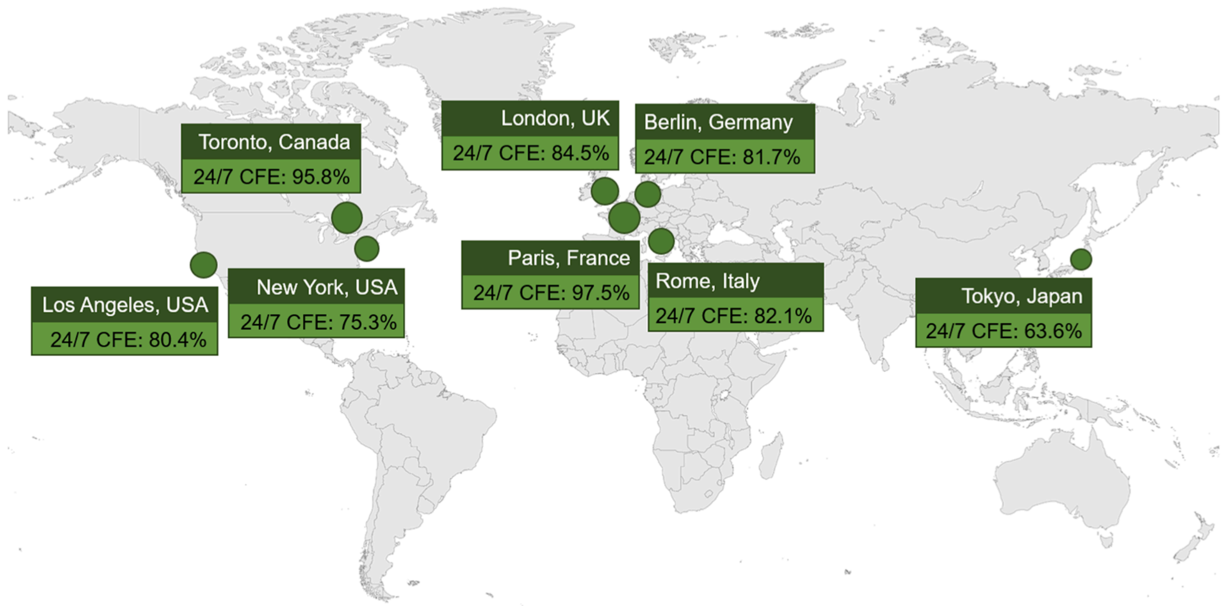

Fig. 9. 24/7 carbon-free energy indicating the share of building energy use met by low-carbon energy sources from the electricity grid and onsite electricity generated by rooftop photovoltaic system on the reference net zero energy building at various study locations.

grid emission factors for operational emission calculations. Additionally, static grid emission factor provides a single annual value for carbon intensity of the grid, which in turn makes comparison of seasonal and diurnal variations in operational emissions impractical. Furthermore, studies from [6] indicate that with more increase in the share of renewable energy in the electricity mix, a general deviation between dynamic and static approaches is foreseen, including an overestimation of operational emissions as in [7]. The 24/7 CFE metric that indicates the share of building energy use met by low-carbon energy sources from the electricity grid and onsite electricity generated by rooftop photovoltaic system on the reference building varied from 63.6 % in Tokyo to 97.5 % in Paris. The excess onsite electricity generated from rooftop photovoltaic system during the daytime is exported back to the electricity grid since the reference building is not equipped with battery energy storage systems. This highlights the necessity of integrating battery energy storage systems [14], including technologies like electric vehicles, to NZEBs for peak shaving and to supplement grid electricity during nighttime operations when photovoltaic systems are intermittent. This would in turn improve the share of carbon-free electricity for the building operations. Moreover, integrating battery energy storage systems will decrease the GHG emissions from the built environment by moving the onsite electricity to utility grid exports to hours with high GHG emission intensities. Integrating retrofit strategies will also effectively reduce operational emissions from the buildings [51]. Future studies should also consider how variations in input parameters like renewable energy shares or grid decarbonization rate would influence the tradeoffs to the robustness and replicability of the conclusion. Although achieving energy efficiency and carbon neutrality is a significant step towards a sustainable built environment, the strategies should also focus on occupant comfort in high-performance buildings. In summary, the study outcomes suggest that NZEBs are not necessarily net zero in terms of operational emissions, when high-resolution dynamic grid emission factors that account for hourly electricity mix variations in the electricity grid are used. The summary of the main findings is listed in Table 4.

4.2. Strengths and limitations

The main strengths of this study are based on multiple aspects. Firstly, the study contributes to the existing knowledge base of operational emission accounting in NZEBs by using novel dynamic grid emission factors that account for variations in electricity mix in the electricity generation. Secondly, the comparative analysis of dynamic and static grid emission factor approaches identifies misestimation in OEI of the reference building with static approach that could lead to flawed design practices. Thirdly, the study uses a calibrated building model based on a timber office building constructed on the principles of circularity, promoting the use of renewable, reusable, and recyclable or upcyclable building materials.

However, the study does have a few limitations. The regional and national differences in building codes should be factored in for reference buildings in future studies that span diverse geographical locations and climate zones. Moreover, the simulation model was only calibrated for the original location of the reference building. It is recommended that future studies perform location-specific calibration to account for climate variabilities, occupancy, and system schedules. Although the study focuses on static and dynamic grid emission factors, alternative operational emission accounting approaches like location-based methods considering regional variations in terms of local utility grid sources could provide information on the feasibility of intermediate solutions for practitioners. Additionally, for a more accurate representation of building performance tradeoffs, TMY data from 2009 to 2023 should be compared with historical emission factors subject to availability of the data.

4.3. Implications for practice and research

With growing concerns about warming climates, achieving carbon neutrality in the built environment is a significant step towards meeting the ambitious goals set by The Paris Agreement. This global agreement aims to limit the rise in global temperature above pre-industrial levels below 2 °C, with further efforts to limit it to 1.5 °C [29,30]. To achieve net zero carbon in the building sector, all new buildings must be 100 % neutral in terms of operational carbon and at least 40 % lower in terms of embodied carbon by 2030, while all new and existing buildings should be carbon neutral across the whole life cycle by 2050 [52,53]. Currently, NZEB definitions focus on energy use [3] and do not reflect operational emissions, considering electricity mix variations in the electricity grid. Although the latest definition from the United States Department of Energy (USDOE) [54] for zero emission buildings integrates energy use

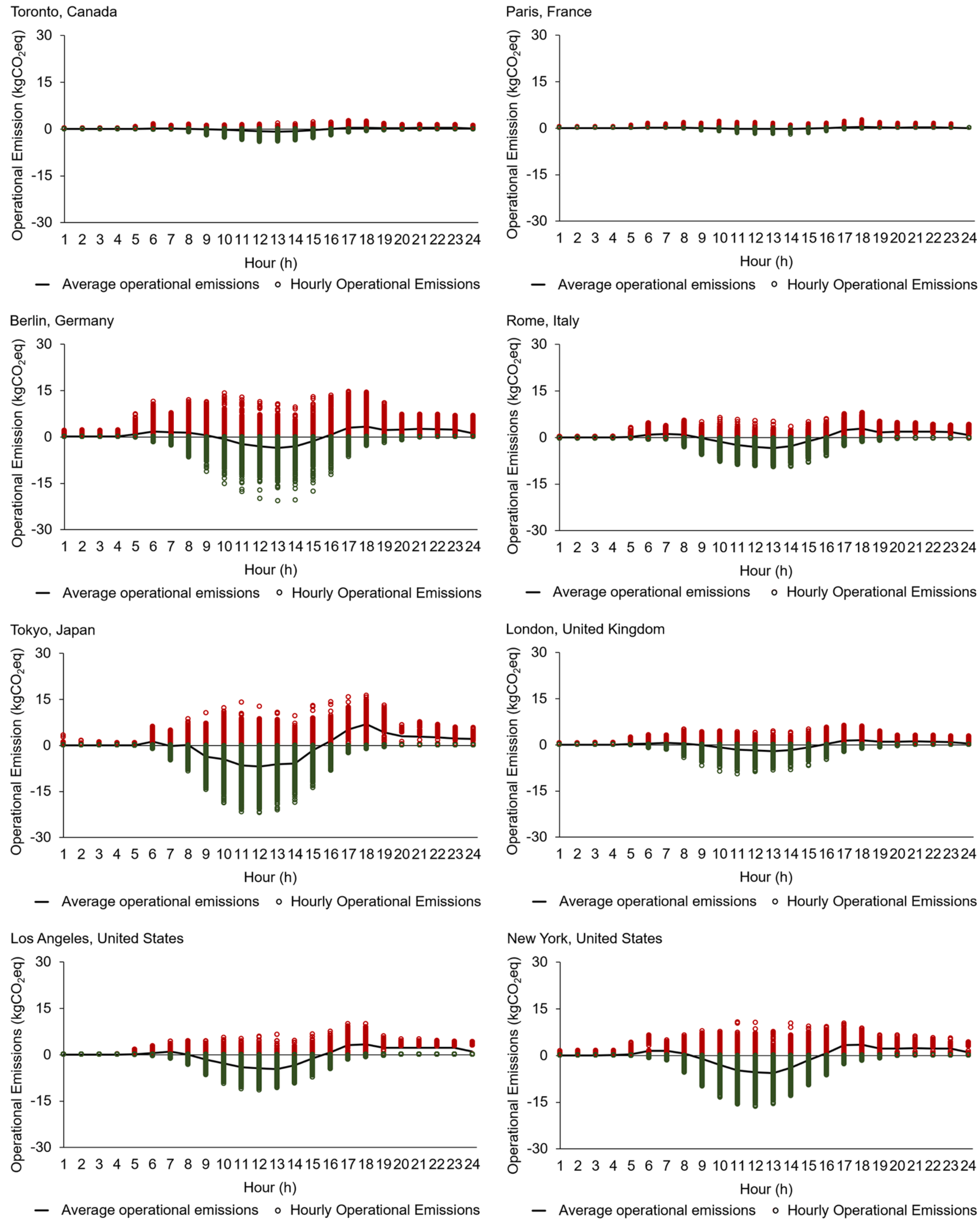

Fig. 10. Average and hourly operational emissions ($kgCO_2eq$) from the reference net zero energy considering dynamic grid emission factors at various study locations represented on a daily profile.

and direct operational emissions, further guidelines on emission accounting methods are of vital importance. This is because operational emission analysis using static grid emission factors will misestimate operational emissions from NZEBs as the annual electricity use is met by annual onsite electricity generation, whereas emission analysis using dynamic grid emission factors will provide more realistic hourly operational emission patterns from NZEBs will support decarbonization effort in the built environment.

Similarly, the study methodology and findings could be used in future revisions of existing standards like ISO 14,064–1 – Greenhouse gases — Part 1: Specification with guidance at the organization level for quantification and reporting of greenhouse gas emissions and removals [55]. Future research should address a wider variety of building types, such as residential and mixed-use buildings to capture operational emissions across diverse contexts [56] since residential buildings typically have a different load profile compared to office buildings, with higher energy use during night. Expanding the scope to include grid scenarios with rapidly transitioning or less stable electricity mixes, including developing countries and regional variations, can provide a more global perspective on the impacts of grid decarbonization. Additionally, robust policy integration involving actionable representation for policymakers will significantly improve the applicability in real-world scenarios like practical urban and regional planning. Furthermore, exploring the integration of advanced energy storage solutions, such as plug-in batteries and grid-interactive technologies, can enhance the ability of buildings to optimize energy use and reduce emissions during periods of high grid carbon intensity. This approach will offer actionable insights for achieving carbon-neutral building

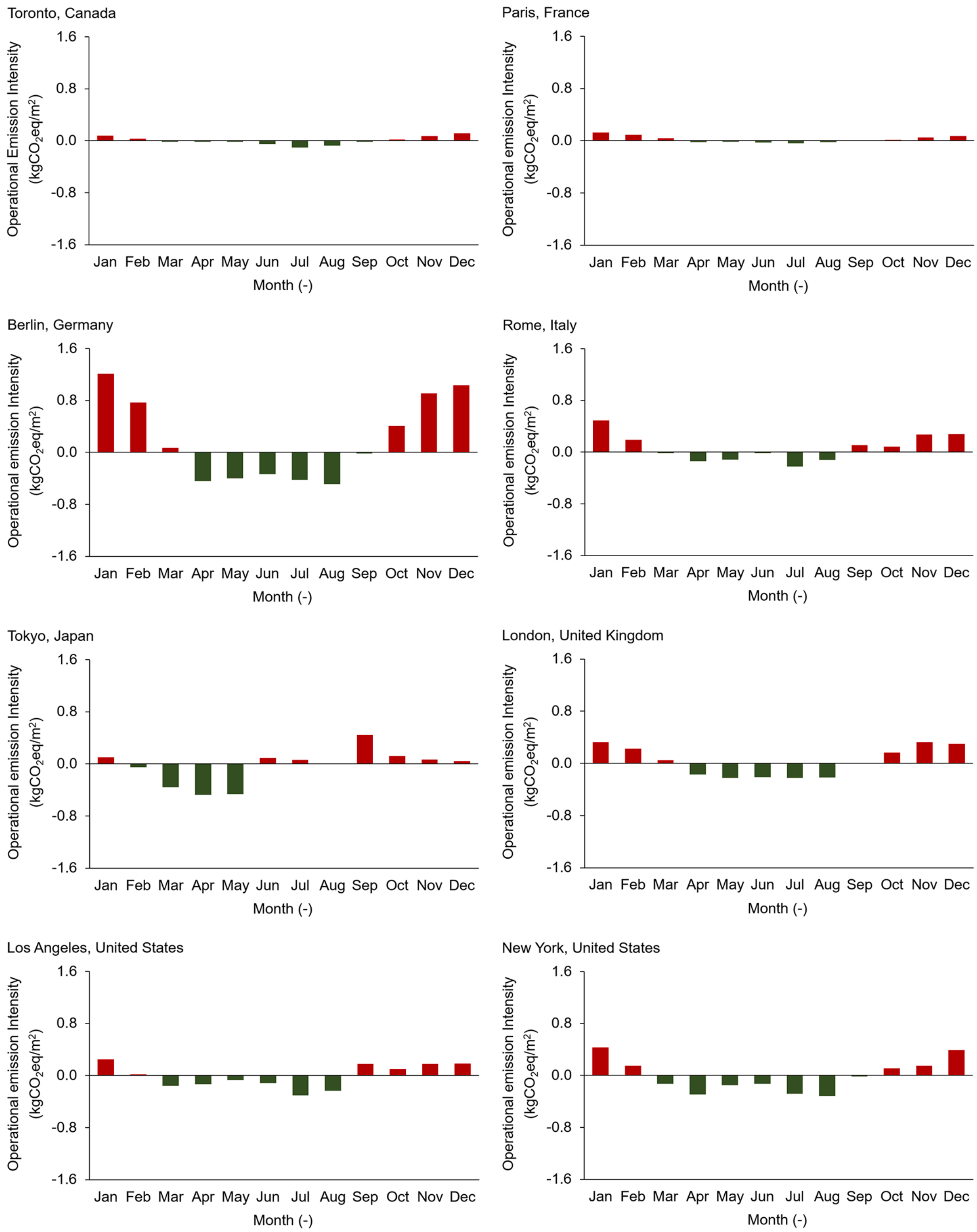

Fig. 11. Monthly operational emission intensity ($kgCO_2eq/m^2$) of reference net zero energy building considering dynamic grid emission factors at various study locations.

operations across different regions and sectors.

5. Conclusions

Decarbonizing the built environment is a crucial step toward combating warming climate, and the research outcomes from this study emphasize including dynamic grid emission factors considering electricity mix variations in the electricity grid in building operational emission calculations. Although energy-efficient NZEBs significantly reduce electricity use in buildings by meeting annual electricity use with annual onsite electricity generation, they are not necessarily net zero in terms of operational emissions. The analysis assessed EUI, 24/7 CFE, and OEI covering eight study locations in various climate zones across the G7 countries. EUI from the reference NZEBs indicated increased electricity use during winter and lower electricity use during summer, except in Tokyo. Similar EUI patterns in the study locations are primarily due to higher onsite electricity generation during summer, with the largest variations from 3.17 kWh/m^2 in January to -2.54 kWh/m^2 in July observed in Berlin. However, the monthly OEI showed a varying pattern from EUI in Toronto with differing electricity use and carbon-intensive months. The study also calculated a 24/7 CFE to evaluate the share of energy use in the reference building met by electricity from low-carbon energy sources from the electricity grid and onsite electricity generated from the rooftop photovoltaic systems. The analysis showed a minimum value of 63.6 % in Tokyo, highlighting the need for battery energy storage systems for peak shaving and supplementing electricity when renewable energy sources are intermittent.

Furthermore, the study results indicate that the reference NZEB

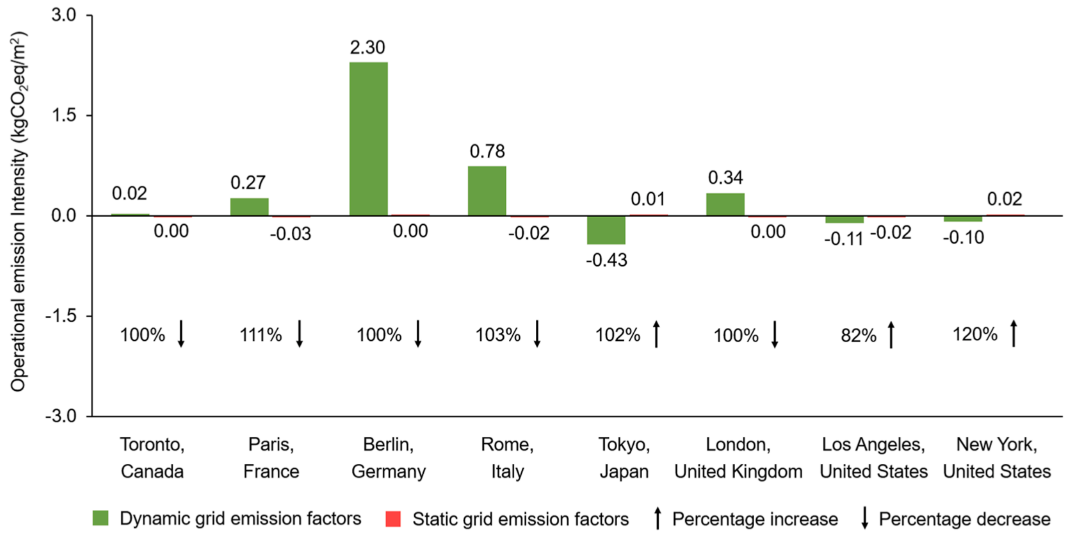

Fig. 12. Comparison of annual operational emission intensity ($kgCO_2eq/m^2$) from reference net zero energy building considering dynamic and static grid emission factors at various study locations.

Table 4
Summary of main findings in comparison to existing literature.

No.	Main findings
1	Net zero energy buildings are not necessarily net zero emission buildings in terms of operational emissions. The operational emissions from the reference net zero energy office building varied from −0.43 $kgCO_2eq/m^2$ in Tokyo to 2.30 $kgCO_2eq/m^2$ in Berlin. To the author's knowledge, this is one of the first studies that addressed net zero energy building performance from this perspective and therefore adds to originality of the study.
2	Static grid emission factors can create misestimations in building operational emissions, which can lead to design flaws. Dynamic grid emission factors provides a more accurate and granular representation of building operational emissions. This aligns with the findings from existing literature that indicate misestimations like [6,9–11]. Study results indicate that static grid emission factors underestimated operational emission by 111 % (0.30 $kgCO_2eq/m^2$) in Paris, while it overestimated operational emissions by 120 % (0.12 $kgCO_2eq/m^2$) in New York in comparison to dynamic grid emission factors.

could release operational emissions of up to 2.30 $kgCO_2eq/m^2$ in Berlin. In comparison, the reference NZEB in Tokyo could have reduced operational emissions by up to −0.43 $kgCO_2eq/m^2$ annually, where OEI is strongly influenced by operational hours and hourly dynamic grid emission factors in the study locations, which underlines the significance of factoring in the electricity mix variations in the electricity grid to operational emission calculations. Moreover, a comparative analysis of the annual OEI of the reference NZEB showed an overestimation in emission intensity from 82 to 120 % and an underestimation from 100 to 111 %. The misestimation of OEI while using static grid emission factors could lead to flawed design practices that could exacerbate the built environment. Therefore, the study suggests a need to redefine NZEBs in terms of carbon, which could further advance the decarbonization of the built environment and open prospects of sustainable building design practices [57], while ensuring building resilience in changing climates [58]. Additionally, these effort can support the United Nations (UN) Sustainable Development Goals (SDG) like Goal 7: affordable and clean energy that ensures affordable, sustainable, and reliable energy, Goal 11: sustainable cities and communities that focuses on resilient and sustainable cities, and Goal 13: climate action to combat deteriorating impacts of warming climates [59,60].

CRediT authorship contribution statement

Deepak Amaripadath: Writing – review & editing, Writing – original draft, Formal analysis, Methodology, Software, Visualization, Conceptualization, Investigation, Data curation. **David J. Sailor:** Methodology, Validation, Conceptualization, Writing – review & editing. **Aurora Bertini:** Software, Writing – review & editing, Methodology. **Mike Barker:** Validation, Conceptualization, Methodology, Writing – review & editing. **Shady Attia:** Software, Conceptualization, Validation, Methodology, Writing – review & editing.

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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Appendix A

The average dynamic grid emission factors in gCO_2eq for electricity grids in the G7 countries including Canada (Ontario), France, Germany, Italy, Japan, the United Kingdom (Great Britain), and the United States are averaged by hours per day of each month for 2023 using data from [61–67] as shown in Table A1–Table A7]. The color scale varies from Red (higher gCO_2eq/kWh) to Green (lower gCO_2eq/kWh) respectively, for each study location. The methodology used to compute the average dynamic grid emission values was obtained from [6,38], as explained in the methodology section. The summary statistics of monthly and annual values of hourly dynamic grid emission factors across the study locations are listed in Table A8.

Table A1
Average dynamic grid emission factors (gCO_2eq/kWh) for hours per day of each month from Canada (Ontario).

2023		Month											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Hour of the day	1	47.13	39.81	35.13	35.43	26.81	32.86	76.86	97.82	81.23	25.64	75.04	50.65
	2	42.76	37.42	35.43	33.49	25.57	32.65	79.11	97.15	82.79	26.81	72.42	46.40
	3	36.32	32.13	33.49	28.79	22.51	28.26	75.08	93.98	78.14	25.57	65.94	38.43
	4	27.63	27.07	28.79	25.39	15.40	18.78	62.86	85.36	66.48	22.51	57.45	30.02
	5	19.54	21.87	25.39	19.66	10.37	11.50	49.05	76.87	52.74	15.40	46.26	24.19
	6	15.70	17.88	19.66	16.90	6.87	6.25	36.46	67.19	39.97	10.37	37.16	18.45
	7	15.09	16.46	16.90	16.24	6.82	5.95	30.84	59.94	34.75	6.87	33.53	16.23
	8	15.41	15.99	16.24	17.71	8.38	7.57	31.43	56.89	32.68	6.82	33.96	18.02
	9	17.51	16.76	17.71	21.19	11.32	9.70	33.43	56.92	33.94	8.38	36.48	22.07
	10	22.24	20.13	21.19	26.92	14.87	12.75	39.04	60.49	37.46	11.32	42.18	28.76
	11	29.51	24.17	26.92	30.74	18.16	16.48	46.98	65.03	44.48	14.87	48.45	35.28
	12	35.72	26.59	30.74	33.98	20.44	18.31	54.52	71.91	50.70	18.16	53.61	43.08
	13	40.37	29.16	33.98	35.21	20.65	20.45	62.99	79.20	59.96	20.44	56.98	44.82
	14	43.99	30.28	35.21	35.04	20.75	21.88	69.30	85.67	68.53	20.65	60.44	46.10
	15	45.43	32.45	35.04	34.63	21.33	22.60	72.71	90.79	74.32	20.75	64.95	48.28
	16	46.52	32.01	34.63	32.34	21.88	23.52	73.79	92.95	77.80	21.33	67.64	46.93
	17	48.60	30.34	32.34	28.73	22.31	24.03	75.35	94.54	79.67	21.88	69.76	45.62
	18	49.11	29.88	28.73	28.83	21.11	26.44	75.48	94.31	78.52	22.31	72.25	46.19
	19	47.91	31.60	28.83	30.00	21.69	29.44	76.95	94.78	76.97	21.11	72.32	46.89
	20	46.60	33.53	30.00	30.81	24.11	31.77	76.53	93.60	76.33	21.69	72.42	48.62
	21	47.74	35.92	30.81	32.50	25.69	33.86	76.23	92.54	77.14	24.11	73.65	51.52
	22	49.97	36.58	32.50	33.45	26.70	34.81	77.38	94.58	77.63	25.69	74.89	53.11
	23	53.43	38.19	33.45	32.55	26.46	35.31	77.46	95.26	79.18	26.70	74.24	53.31
	24	53.21	39.98	32.55	33.84	26.50	35.11	77.00	96.63	78.95	26.46	73.79	52.91

Table A2
Average dynamic grid emission factors (gCO_2eq/kWh) for hours per day of each month from France.

2023		Month											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Hour of the day	1	50.58	65.23	52.08	26.44	15.03	23.79	23.53	23.63	14.28	12.12	24.03	24.40
	2	48.55	61.74	49.93	25.46	14.87	23.18	22.68	23.27	13.95	11.78	23.49	23.97
	3	47.28	59.97	49.11	26.36	15.03	23.25	23.47	23.29	14.89	12.43	23.23	23.59
	4	47.97	61.97	50.12	30.69	16.33	24.06	25.20	24.75	17.75	14.73	24.06	24.40
	5	49.53	65.25	51.56	33.83	18.19	25.43	25.23	25.10	19.99	17.09	26.30	26.78
	6	51.25	66.55	51.96	35.02	18.58	26.21	24.91	24.54	20.11	18.76	29.59	29.55
	7	51.63	66.71	51.88	33.07	17.07	24.23	23.68	22.95	18.24	19.04	30.80	30.48
	8	51.22	66.47	49.06	29.34	15.63	22.17	22.02	21.05	16.10	18.38	29.96	29.96
	9	49.50	64.00	45.86	24.63	14.25	20.02	20.40	18.76	13.28	17.02	28.15	28.90
	10	47.93	60.34	43.31	22.14	13.99	19.27	19.68	18.25	12.82	15.78	26.52	27.76
	11	46.87	56.39	40.75	19.22	13.44	18.45	18.27	17.44	11.75	14.90	26.08	27.12
	12	45.10	54.05	38.91	18.65	12.77	17.86	17.72	17.06	11.20	14.50	25.80	26.50
	13	45.67	54.30	39.67	17.75	12.49	17.37	17.16	16.79	11.26	14.33	26.61	26.51
	14	46.31	54.34	41.41	16.58	12.27	17.58	16.74	16.72	12.43	14.93	28.50	27.63
	15	47.43	55.29	43.53	18.55	12.62	20.15	18.54	19.16	17.32	18.03	30.59	28.74
	16	49.18	59.64	47.41	24.42	15.46	24.80	22.50	24.62	23.28	21.39	32.80	30.30
	17	53.64	66.16	53.56	31.20	18.90	28.37	27.63	29.84	27.09	22.95	34.36	31.84
	18	54.39	70.49	57.37	34.31	20.31	29.84	30.45	31.92	26.32	21.59	34.90	32.36
	19	53.63	70.36	56.30	33.89	20.19	29.48	30.44	31.46	23.27	19.88	33.42	31.11
	20	51.74	69.70	53.22	34.00	19.83	30.11	31.14	30.93	22.34	18.56	30.88	29.11
	21	51.72	69.87	53.04	35.13	19.92	30.11	31.11	30.34	22.42	18.09	29.88	27.99
	22	51.76	71.62	53.30	31.60	17.96	27.40	28.29	27.86	19.72	16.05	29.91	27.52
	23	50.22	68.63	50.90	28.55	16.31	25.11	25.60	24.92	16.56	13.17	27.84	25.04
	24	50.47	65.06	52.27	28.55	15.99	24.78	24.98	24.25	15.20	12.65	24.32	24.38

Table A3
Average dynamic grid emission factors (gCO_2eq/kWh) for hours per day of each month from Germany.

2023		Month											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Hour of the day	1	361.44	427.43	338.15	376.14	300.49	338.67	280.67	340.90	375.69	309.42	323.48	323.11
	2	361.11	428.82	340.48	379.27	301.84	339.76	279.62	343.06	379.04	312.02	319.32	321.73
	3	363.76	431.08	344.42	386.38	309.51	342.52	278.92	347.97	391.33	321.93	320.57	323.14
	4	370.68	437.72	356.24	390.00	309.76	337.01	271.48	349.78	396.61	332.68	332.02	329.63
	5	381.05	446.51	371.47	382.50	297.85	318.99	258.15	335.04	388.77	340.88	349.46	338.18
	6	392.03	452.15	375.35	358.48	275.20	290.82	238.99	307.06	354.34	335.76	367.20	344.42
	7	397.49	441.91	359.88	321.64	243.37	254.42	211.54	273.08	311.69	315.36	365.94	347.05
	8	393.44	419.07	334.00	283.01	213.80	218.73	185.22	238.47	263.77	289.98	353.77	340.77
	9	384.42	391.02	307.92	256.32	194.23	193.20	167.69	214.31	225.47	269.22	341.63	330.64
	10	377.08	369.99	290.78	242.23	187.48	184.05	159.51	201.31	207.11	258.01	334.31	322.96
	11	373.22	358.72	280.21	235.97	185.08	179.70	159.01	196.47	202.60	255.91	332.80	318.81
	12	375.44	359.37	278.47	238.13	185.65	182.82	161.36	200.39	207.63	264.71	338.98	320.53
	13	385.02	375.86	287.59	248.27	193.58	191.27	166.69	212.29	231.05	286.44	352.47	329.73
	14	399.79	407.21	309.33	269.55	207.69	211.80	178.32	236.97	274.76	321.14	371.22	339.33
	15	408.57	444.14	343.66	313.96	234.45	248.91	205.32	275.69	344.79	363.17	382.79	344.01
	16	407.73	466.66	383.27	370.97	273.05	298.16	246.43	324.94	407.57	383.93	384.43	348.09
	17	404.12	466.38	399.46	406.83	314.01	340.21	287.26	362.00	433.54	386.43	386.36	350.33
	18	399.71	461.49	397.22	414.80	336.67	368.55	319.07	382.55	429.17	379.47	381.76	346.83
	19	394.36	458.33	389.23	411.50	335.51	377.00	329.82	388.85	417.29	365.43	374.17	339.09
	20	387.74	454.70	378.24	407.66	330.66	373.10	328.00	387.54	406.78	355.22	364.99	331.55
	21	383.89	452.18	365.46	398.84	319.53	366.65	320.26	379.88	398.06	342.59	361.65	329.48
	22	376.37	448.23	349.15	387.00	306.76	350.98	300.99	366.36	388.66	327.50	354.11	322.20
	23	369.23	441.36	335.21	380.91	297.88	343.13	288.10	355.48	379.76	316.05	344.72	312.17
	24	365.35	439.75	327.58	380.72	296.24	341.29	284.00	349.00	374.98	310.27	338.88	307.69

Table A4
Average dynamic grid emission factors (gCO_2eq/kWh) for hours per day of each month from Italy.

2023		Month											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Hour of the day	1	347.07	356.77	335.92	241.50	210.90	259.29	271.21	256.80	259.31	233.68	202.10	226.08
	2	348.41	356.00	333.38	241.80	213.52	257.78	270.08	255.19	260.33	234.51	202.55	225.25
	3	347.85	354.55	332.31	246.34	220.90	263.65	274.36	258.55	266.32	241.40	203.26	227.11
	4	347.83	354.40	334.31	253.44	224.80	263.88	274.30	261.74	276.24	251.26	207.49	233.81
	5	339.59	350.04	331.03	243.80	215.09	244.29	258.16	247.40	274.96	253.34	219.79	243.66
	6	338.78	336.48	308.13	220.80	195.23	223.12	235.81	223.32	253.74	240.65	222.91	249.07
	7	320.49	313.61	279.66	201.60	185.77	211.77	222.94	201.25	231.82	224.99	211.47	241.11
	8	305.40	297.66	261.41	185.01	177.16	198.46	212.18	185.77	215.09	212.33	199.62	230.75
	9	298.05	290.42	248.19	172.78	165.04	189.65	204.46	175.58	203.93	200.67	190.91	223.27
	10	294.39	282.10	239.22	163.77	154.78	185.69	200.85	172.50	194.55	193.25	186.57	220.38
	11	295.96	280.68	235.06	159.34	155.64	185.91	198.35	169.94	191.29	189.18	184.42	220.79
	12	298.06	278.61	235.21	162.76	162.50	189.84	201.95	170.56	195.65	194.05	186.41	222.43
	13	302.90	284.49	244.68	167.58	167.48	192.00	203.32	175.12	204.32	204.01	197.38	233.95
	14	314.91	298.73	259.50	179.31	180.71	202.18	214.39	188.29	219.99	221.39	213.85	249.85
	15	324.45	318.59	281.89	200.43	197.57	221.52	228.74	210.59	250.23	248.38	227.15	258.77
	16	323.98	331.67	311.53	231.80	215.71	244.88	250.75	237.38	280.40	262.27	231.43	257.88
	17	323.88	330.74	320.86	249.49	233.85	264.39	271.74	261.97	293.23	265.63	233.62	256.66
	18	326.66	331.75	323.07	253.25	243.83	277.88	284.01	271.91	295.61	266.22	234.25	256.64
	19	332.60	340.29	328.68	256.26	244.51	281.10	286.85	273.93	294.19	266.53	233.63	257.77
	20	332.73	345.43	334.09	261.69	245.67	292.64	294.41	278.00	292.03	262.85	227.22	253.78
	21	335.74	350.92	336.57	260.62	239.16	292.66	292.20	276.41	283.23	256.62	217.89	249.50
	22	338.74	356.09	334.83	248.60	221.22	273.41	278.44	264.43	267.95	243.13	213.09	242.70
	23	337.07	355.42	330.18	243.64	215.39	263.80	274.47	259.76	261.25	236.00	204.07	232.92
	24	341.41	355.38	328.96	244.50	213.42	259.29	271.65	258.90	258.49	233.60	202.66	231.99

Table A5
Average dynamic grid emission factors (gCO_2eq/kWh) for hours per day of each month from Japan.

2023		Month											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Hour of the day	1	347.82	339.73	285.85	267.31	258.89	307.68	320.01	322.20	319.37	270.75	300.71	335.03
	2	332.66	325.00	274.95	263.57	256.28	306.59	318.84	320.11	317.86	265.33	290.19	320.28
	3	326.86	314.31	268.32	258.51	254.23	304.66	319.94	321.14	319.96	265.61	287.93	316.70
	4	338.49	323.48	284.69	273.18	270.06	319.34	332.76	333.37	335.75	288.76	309.13	333.93
	5	356.74	337.56	302.73	289.94	288.56	333.93	348.71	348.82	354.93	315.71	338.12	360.84

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Table A5 (*continued*)

2023		Month											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	6	386.21	364.52	334.27	318.23	316.95	353.90	369.17	370.60	380.45	355.49	379.23	395.32
	7	420.99	401.42	377.38	356.93	354.28	379.15	393.88	397.62	409.31	402.85	422.79	432.29
	8	441.42	437.07	419.50	399.67	393.64	404.76	417.66	423.17	436.38	432.42	437.35	444.15
	9	442.66	444.76	438.71	427.14	424.20	429.09	437.56	440.49	445.40	434.66	437.21	444.32
	10	442.00	443.90	438.01	428.53	429.48	436.95	442.90	441.63	444.25	432.91	435.72	443.32
	11	441.15	442.98	436.78	426.54	427.43	435.24	441.40	439.34	442.22	430.74	434.19	442.17
	12	439.70	441.50	434.94	423.99	424.81	432.90	439.10	436.84	440.06	428.42	431.99	440.62
	13	437.33	439.49	432.70	421.32	422.11	430.78	436.85	434.31	438.04	426.42	429.74	438.60
	14	435.83	437.97	431.26	419.91	420.42	429.37	435.00	432.40	436.46	424.98	428.09	437.09
	15	432.89	434.60	427.95	415.77	415.68	425.02	430.26	427.35	432.31	421.01	423.90	433.96
	16	431.55	434.36	426.94	414.22	413.64	422.57	427.13	423.80	429.65	418.42	422.18	432.58
	17	431.80	434.51	428.08	415.70	414.99	422.67	426.05	422.59	428.75	418.98	423.02	433.18
	18	432.07	434.88	429.50	418.11	417.59	424.44	426.53	422.76	429.25	421.49	425.20	434.17
	19	432.32	435.24	430.19	418.32	415.39	421.95	424.55	422.19	429.92	423.23	426.41	434.68
	20	433.51	436.28	428.82	414.12	405.38	410.86	418.61	419.69	427.62	422.30	427.38	435.61
	21	434.32	436.28	422.77	383.29	360.89	376.13	386.81	396.10	411.45	414.21	424.81	435.03
	22	433.95	422.00	382.91	334.92	313.04	344.69	355.07	363.79	373.58	364.28	402.74	431.30
	23	405.99	387.75	340.39	301.37	286.81	327.86	337.65	343.99	346.67	317.10	363.30	397.54
	24	377.29	360.54	308.18	281.26	272.07	318.25	327.09	331.77	330.24	288.20	329.62	362.44

Table A6

Average dynamic grid emission factors (gCO_2eq/kWh) for hours per day of each month from United Kingdom (Great Britain).

2023		Month											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Hour of the day	1	106.41	124.43	126.12	139.51	133.95	163.38	130.02	136.19	130.30	92.72	105.91	94.07
	2	103.82	123.90	124.80	140.61	133.39	165.22	129.80	135.04	127.76	93.14	105.73	91.18
	3	102.30	123.59	124.06	144.09	138.64	167.59	130.82	136.62	131.90	97.35	106.21	90.83
	4	104.58	126.78	127.60	152.84	146.65	170.08	132.50	143.26	141.81	108.07	107.79	92.77
	5	110.44	135.69	137.76	161.80	153.42	166.22	136.22	152.10	154.42	124.90	119.52	101.53
	6	126.16	154.06	151.45	159.29	151.05	158.17	133.01	152.39	157.57	135.00	142.54	117.75
	7	137.25	165.23	153.11	151.75	139.96	144.97	123.23	143.23	145.65	133.43	155.51	124.56
	8	138.63	159.97	148.65	141.01	130.57	133.92	114.78	133.11	134.81	124.87	154.58	122.59
	9	133.32	152.29	141.82	129.41	123.46	125.01	108.84	127.65	125.67	117.53	148.58	120.47
	10	127.58	145.73	136.14	120.50	117.02	118.12	105.87	122.75	119.11	111.42	143.90	118.59
	11	124.27	140.22	132.76	115.67	113.95	112.39	103.86	119.42	115.15	109.49	141.11	116.34
	12	123.79	137.49	130.45	112.20	109.17	109.39	101.17	117.46	113.26	110.20	142.58	117.55
	13	125.20	139.14	131.86	112.65	107.99	111.83	99.76	118.74	117.72	114.84	147.04	117.93
	14	131.23	145.35	136.60	119.08	112.33	118.70	104.04	124.25	129.81	124.88	155.56	122.81
	15	139.24	159.13	144.67	133.94	124.69	131.42	112.37	138.73	147.72	140.42	167.00	126.45
	16	149.90	172.01	159.46	152.85	141.00	150.40	122.74	156.08	167.05	155.06	174.80	132.65
	17	153.80	177.39	169.89	164.91	153.27	164.92	133.67	169.96	177.85	162.41	178.29	133.89
	18	150.06	176.94	174.32	171.96	160.83	173.62	141.11	178.95	180.32	155.75	174.02	129.01
	19	143.99	174.26	168.95	172.27	166.32	179.03	149.09	182.18	172.94	144.61	168.22	123.56
	20	137.30	169.60	161.31	170.09	167.82	181.74	152.41	176.74	166.11	131.13	158.93	114.49
	21	127.60	158.14	147.44	164.11	163.38	178.03	146.89	169.20	153.58	115.17	142.73	104.14
	22	118.63	145.64	132.91	142.93	139.74	165.14	131.85	149.47	135.62	97.10	129.50	95.71
	23	107.73	129.02	121.45	141.00	137.37	162.99	129.66	144.15	130.05	93.32	115.68	87.14
	24	108.71	129.08	122.60	143.20	136.07	162.06	130.10	142.38	129.36	93.13	113.86	89.29

Table A7

Average dynamic grid emission factors (gCO_2eq/kWh) for hours per day of each month from the USA.

2023		Month											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Hour of the day	1	349.98	329.12	333.19	321.67	326.53	366.16	397.75	397.10	372.49	351.80	345.92	355.17
	2	347.07	326.64	329.50	319.81	325.13	367.06	392.30	389.95	363.57	346.99	344.19	352.39
	3	343.83	322.77	324.59	311.20	315.83	360.39	384.47	384.17	356.17	342.11	339.38	349.10
	4	340.38	319.66	320.69	302.11	305.68	349.64	377.45	379.33	350.11	336.10	337.19	341.52
	5	337.21	316.69	317.37	296.22	298.06	341.47	371.67	373.64	344.81	332.40	334.78	338.30
	6	335.47	315.21	315.63	293.61	292.37	335.10	368.45	370.65	341.63	330.61	332.85	339.77
	7	335.14	315.28	315.62	292.95	290.93	331.93	366.45	369.07	342.20	331.21	336.54	340.60
	8	336.26	316.19	317.35	294.25	292.58	331.16	366.82	370.72	346.63	334.22	337.45	342.40
	9	337.49	318.12	321.08	297.81	297.65	333.48	371.35	377.17	354.09	340.09	338.80	345.08
	10	340.36	321.19	325.89	303.81	304.79	338.46	373.52	380.59	359.73	346.85	342.97	350.76
	11	343.73	325.00	330.52	308.87	309.59	341.26	372.90	378.41	358.79	349.89	347.94	355.59

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Table A7 (*continued*)

2023	Month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
12	346.84	328.52	332.01	307.55	310.01	342.10	371.89	375.12	353.30	342.91	345.00	355.67
13	347.65	327.05	326.31	301.69	308.41	340.29	369.21	372.91	348.50	335.49	336.23	350.23
14	343.35	320.29	319.57	294.74	304.25	337.15	373.76	373.38	348.60	328.92	329.36	340.00
15	339.68	314.21	311.67	286.78	302.58	338.96	377.54	376.46	351.58	323.67	323.29	333.92
16	336.88	307.60	305.79	285.06	304.38	342.83	382.81	378.54	355.77	324.14	318.13	325.31
17	334.54	303.35	303.33	286.01	306.47	345.91	383.61	379.72	359.08	325.29	316.92	322.61
18	333.53	300.58	302.47	287.34	308.63	348.39	381.72	380.29	360.56	326.33	319.18	326.41
19	333.26	299.04	302.77	288.89	310.41	349.27	381.91	380.43	360.99	327.26	319.34	326.87
20	333.59	299.23	303.77	291.11	311.73	349.84	382.80	380.81	362.73	330.94	327.64	334.32
21	336.16	302.12	308.07	294.95	313.33	351.02	384.40	383.41	366.87	338.31	338.80	347.53
22	340.98	309.10	314.15	299.50	315.30	353.21	389.95	388.20	372.93	352.45	349.67	362.36
23	351.52	317.99	320.47	304.83	318.71	356.84	393.01	394.95	379.38	361.41	354.54	361.84
24	354.80	326.62	329.34	313.61	322.91	362.18	398.18	399.34	379.37	359.57	348.73	357.83

Table A8
Summary statistics of hourly dynamic grid emission factors across the study locations including monthly and annual values.

Location	Statistics	Monthly												Annual
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Canada (Ontario)	Maximum	83.86	94.81	82.84	79.80	98.07	116.10	138.66	104.86	134.17	108.93	113.38	119.97	138.66
	Minimum	2.48	4.27	2.58	2.67	2.77	3.48	16.08	3.34	0.00	2.99	2.85	3.00	0
	Average	37.39	38.20	28.93	19.45	22.51	62.78	83.10	64.18	59.82	39.83	56.27	58.51	46.93
France	Maximum	107.50	64.16	126.78	76.70	33.87	44.29	57.45	63.96	42.10	41.80	66.43	82.20	126.78
	Minimum	17.26	32.44	12.54	6.46	6.99	5.72	4.52	5.24	3.54	4.93	10.98	10.67	3.54
	Average	49.73	49.89	48.91	27.48	16.14	23.87	23.81	23.72	17.56	16.59	28.47	27.73	30.43
Germany	Maximum	660.81	494.83	590.35	610.53	513.90	524.58	489.86	605.90	564.68	624.23	656.34	684.42	684.42
	Minimum	131.59	210.35	133.12	119.77	114.43	95.23	92.10	99.12	130.59	91.78	110.64	110.93	91.78
	Average	383.88	295.44	343.45	343.38	268.76	291.32	246.10	307.06	341.27	322.65	353.21	331.73	329.26
Italy	Maximum	430.08	374.61	405.98	316.28	303.16	363.61	341.97	342.99	357.48	329.05	343.04	403.77	430.08
	Minimum	220.01	259.22	139.74	101.30	74.91	83.87	108.16	74.44	112.82	100.47	97.17	124.12	74.44
	Average	325.71	319.69	300.36	220.42	204.16	239.13	248.98	230.64	251.01	234.83	210.57	239.42	252.33
Japan	Maximum	451.52	448.82	450.03	435.30	437.87	443.81	450.31	447.43	452.62	442.82	446.25	454.43	454.43
	Minimum	227.53	332.41	200.53	186.28	165.76	219.80	242.23	263.57	209.81	192.75	217.09	235.10	165.76
	Average	409.81	415.73	382.74	365.49	360.70	383.28	392.23	393.17	398.33	378.51	392.96	408.96	389.15
UK (Great Britain)	Maximum	251.62	158.18	275.91	262.01	244.57	258.97	237.92	261.79	260.36	252.20	280.64	281.72	281.72
	Minimum	37.13	49.61	27.02	31.43	45.02	47.68	34.90	38.98	24.52	26.68	39.52	24.45	24.45
	Average	126.33	87.58	141.92	144.07	137.59	150.60	125.16	144.59	141.90	120.25	141.65	111.89	136.01
USA	Maximum	401.08	405.46	371.30	361.97	368.50	389.44	410.77	419.72	400.78	398.10	390.16	392.04	419.72
	Minimum	295.41	345.96	247.79	241.25	253.26	283.57	335.61	326.02	305.83	285.25	279.69	264.04	241.25
	Average	340.82	382.75	317.96	299.35	308.18	346.42	379.75	380.60	357.91	338.29	336.03	343.98	339.00

Appendix B

The minimum nighttime temperatures maintained in the reference building across the study locations for entire study period, including the weekends are listed in Table B1. The indoor temperature values indicate that the building is not subjected to system issues like freezing pipes during the winter season.

Table B1
Minimum hourly nighttime indoor temperature during the entire operational period across the study locations.

Location	Minimum hourly nighttime indoor temperature during the entire operational period		
	Air temperature (°C)	Mean Radiant Temperature (°C)	Operative temperature (°C)
Toronto	12.00	10.47	11.24
Paris	10.47	11.30	11.65
Berlin	12.00	10.56	11.28
Rome	12.00	11.84	11.92
Tokyo	12.00	11.68	11.84
London	12.00	11.20	11.60
Los Angeles	12.63	13.49	13.06
New York	12.00	10.94	11.47

Data availability

Data will be made available on request.

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