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Research Papers

Achieving low-carbon electricity operations in net zero energy residential buildings through plug-in battery energy storage systems

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ABSTRACT

Greenhouse gas emissions from building operations contribute significantly to global emissions. Although net zero energy buildings have been developed to reduce operational energy use, net zero emission operations are not always achieved. Plug-in battery energy storage systems enable building operations using renewable energy sources at night, when photovoltaic systems are intermittent. The application of 24/7 carbon-free energy metrics in the context of plug-in battery energy storage systems in timber residential buildings in the study advances the existing knowledge base. The building performance was assessed using high-resolution dynamic grid emission factors from utility grids across the Group of Seven Countries. Study results indicate that plug-in battery energy storage systems increase electricity use intensity due to energy losses during charging and discharging cycles. However, operational emission intensity is highly dependent on the dynamic grid emission factors. Locations with higher daytime carbon intensity, such as Tokyo, showed an increase, whereas locations with higher nighttime carbon intensity, such as Berlin, showed a decrease. Diurnal analysis revealed increases in daytime electricity use intensity and operational emission intensity during charging cycles, while discharging cycles led to decreases in these metrics during nighttime. Furthermore, the 24/7 carbon-free energy analysis demonstrated improvements ranging from 1.8% in Paris to 32.3% in Tokyo with plug-in battery energy storage systems, highlighting the strong influence of low-carbon electricity sources in the utility grid. The research findings emphasized the importance of integrating plug-in battery energy storage systems into net zero energy residential buildings to enhance low-carbon electricity operations and self-consumption.

1. Introduction

1.1. Study background

According to the World Green Building Council, 39% of carbon emissions from global energy use are emitted from buildings, with operational emissions forming 28% and embodied carbon forming 11% [1]. Decarbonizing the built environment is crucial for limiting global temperature rise below 2 °C compared to pre-industrial levels and achieving the science-based targets of the Paris Agreement [2–4]. To support the transition into carbon-neutral built environments, the World Green Building Council recommends that all new buildings be net zero operational carbon by 2030 and all buildings be net zero operational carbon by 2050 [1]. This is a significant challenge since the increasing magnitude and frequency of extreme heat events is expected to rise in upcoming years [5]. This could further increase operational emissions from buildings unless effective interventions are implemented.

Although developments in high-performance and net zero energy buildings (NZEB) will improve energy efficiency and reduce operational emissions [6], net zero operational emissions are not necessarily guaranteed [7]. Therefore, studies from [6] emphasized the necessity of integrating battery energy storage systems (BESS) in net zero energy residential buildings for more efficient usage of onsite renewable energy systems. Additionally, BESS can optimize the performance of renewable energy systems by providing electricity during intermittent hours when electricity production is curtailed [8,9]. Integrating BESS in buildings also offers added economic benefits to the consumer through peak shaving during high tariff periods. Moreover, the significance of BESS in

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buildings is explained in resilience rating guidelines like Reli 2.0 Certification [10], which recommends onsite photovoltaic systems with BESS as a measure to ensure emergency electricity supply for building operations during power outages.

1.2. Existing literature

Studies spanning eight study locations in the Group of Seven (G7) countries from [7] found that static grid emission factor significantly misestimates operational emissions by up to 122% in net zero energy office buildings and emphasized the significance of using dynamic grid emission factors in building operational emission calculations. Similar results were observed in [11] with a variation of up to 2098 $kgCO_2$ in annual emissions between dynamic and static grid emission factors from the German electricity grid for scenarios with photovoltaic systems and thermal energy storage. In line with these studies, findings from [12,13] recommended dynamic grid emission factors for a more accurate greenhouse gas (GHG) estimation. Additionally, the significance of using high-resolution dynamic grid emission factors was outlined in [14], indicating misestimations in emission values when static grid emission factors were applied. The misestimations in operational emissions from buildings could lead to flawed design practices [15] that could exacerbate the indoor built environment.

Moreover, the impacts of local energy generation coupled with hydrogen storage in decarbonizing single-family residential building stock were evaluated in studies like [16], with the findings indicating a reduction in utility grid dependency and overloads. Coupling photovoltaic systems with hydrogen storage systems also reduced GHG emissions and energy efficiency. Similarly, studies from [17] assessed the role of distributed energy source-based microgrids and BESS in improving resiliency in commercial buildings, with the findings showing improved resiliency, adaptability, and reliability during blackouts. The significance of coordinating low-carbon energy sources in residential decarbonization efforts using a whole system perspective is addressed in [18]. Integrating distributed energy sources and decentralizing utility grids was recommended for enhanced energy efficiency in Japanese residential building stock. In addition to these building level strategies, energy flexibility in buildings can be improved through accurate demand forecasting with advanced demand side controllers that uses machine learning approaches like surrogate models with cross-entropy functions [19]. Moreover, hybrid energy systems that integrate energy conversion, energy storage, and control strategies like renewable-to-demand control and battery-to-demand control will effectively promote energy flexibility in buildings by improving resilience to energy demand fluctuations [20].

The analysis of existing literature indicates a lack of studies evaluating the feasibility of plug-in BESS in achieving low-carbon electricity operations in net zero energy residential buildings across varying climates. Additionally, there is a lack of studies directly linking energy efficiency and carbon neutrality in net zero energy residential buildings equipped with plug-in BESS.

1.3. Study relevance

This study could contribute to the shift towards built environments with net zero operational emissions by providing effective strategies for building operations using low-carbon electricity sources. Moreover, residential buildings contribute 12.5% of all global emissions through electricity use and activities like cooking using natural gas, forming the largest share of emissions from the energy sector [21]. Decarbonizing operational energy use in buildings could significantly mitigate GHG emissions from the built environment [22], which is particularly relevant in the case of the G7 countries. Therefore, it is significant to design strategies to address building decarbonization [23]. The total GHG emissions per capita from energy use in buildings [24,25] across the G7 countries from 2001 to 2021 varies from 21,320 $kgCO_2eq$/capita in Japan to 45,130 $kgCO_2eq$/capita in Canada, compared to a global average of around 7461 $kgCO_2eq$/capita as shown in Fig. 1. The total GHG emissions per capita in Canada are 6.1 times higher and in Japan are 2.9 times higher than the global average.

Similarly, the total GHG emission share from energy use in buildings [24,25] across the G7 countries from 2001 to 2021 formed 38.4% of the global emissions, with the United States accounting for 18.4%, as shown in Fig. 2. In addition to improving environmental sustainability by facilitating building operations using low-carbon electricity sources and reducing GHG emissions [26], plug-in BESS can support building operation when renewable energy sources are intermittent [27], by providing continuous and reliable electricity supply [28], and reducing energy use during peak hours [29]. Although many studies have addressed the strategies, challenges, and pathways for carbon-neutral built environments like [30–32], studies that evaluate the feasibility of plug-in BESS for improving the 24/7 carbon-free energy (24/7 CFE) share in residential building operations are rare, which further adds to the study relevance.

1.4. Research objectives

The primary objective of this work is to evaluate the feasibility of integrating plug-in BESS to achieve low-carbon electricity operations in net zero energy residential buildings across various study locations in the G7 countries under multiple test scenarios. While previous studies [7] have shown that although onsite photovoltaic systems can meet the annual electricity demand of buildings, they do not necessarily ensure net zero operational emissions. This underscores the need for integrating plug-in BESS as a critical strategy for enhancing low-carbon building operations. A key advancement of this study lays in its use of hourly dynamic grid emission factors, which capture real-time variations in the electricity mix with higher temporal resolution. This approach enables a more precise assessment of operational emission intensity (OEI), providing realistic GHG accounting that reflects diurnal fluctuations in emissions from net zero energy residential buildings.

Existing studies from [33] reviewed the current literature on smart home energy management systems, focusing on proper planning and strategies to improve demand requirements from residential buildings and addressing future challenges. While case studies from [34] addressed electricity scheduling strategies with integrated renewable energy and BESS, this study focused on minimizing electricity costs and reducing energy waste. Similarly, [35] also proposed a mixed-integer linear programming (MILP)-based model predictive control for an improved home energy management system. However, this study address how building-level interventions can contribute to increased self-sufficiency and reduced grid dependency to accelerate transitions to net zero emission buildings.

The 24/7 CFE metric, which measures the percentage of building operations met by carbon-free electricity sources to assess the effective utilization of onsite electricity generation under different test scenarios, was applied. By integrating plug-in BESS, this work ensures that surplus electricity generated during peak production hours is neither wasted nor curtailed, thereby reducing dependence on the utility grid. The application of the 24/7 CFE metric in residential building decarbonization offers new insights into optimizing energy storage for continuous low-carbon operations. To the best of the author's knowledge, this is among the first studies to address residential building decarbonization by improving resource efficiency across multiple study locations, considering both operational emissions and real-time grid interactions.

The application of 24/7 carbon-free energy metric in the context of plug-in battery energy storage systems in net zero energy timber residential building, adds to the novelty of the study. This metric and its application is in line with Sustainable Development Goal 7 that focus on ensuring access to affordable and clean energy for all. This study was developed as part of the international research and development project Annex 89: Ways to Implement Net-zero Whole Life Carbon Buildings

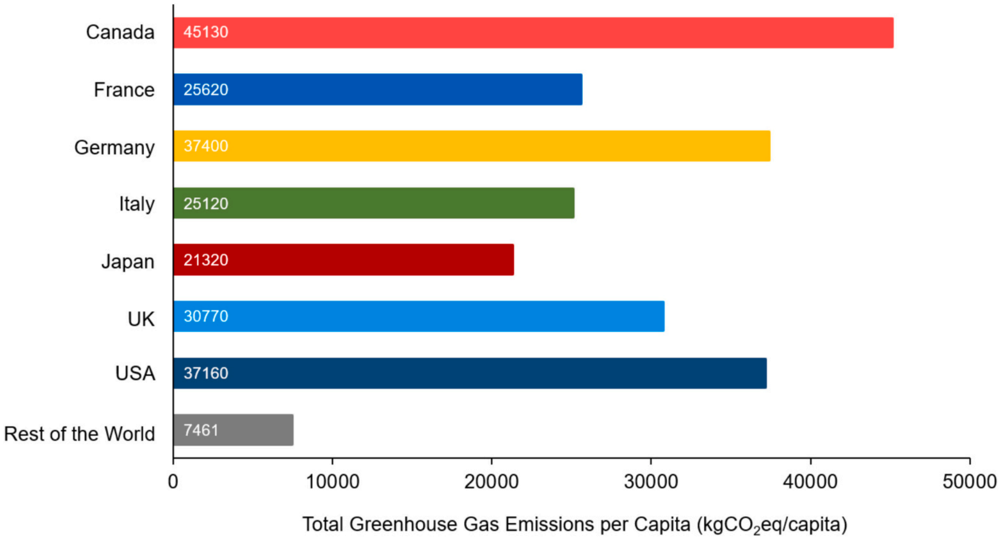

Fig. 1. Total per capita greenhouse gas emissions (kgCO₂eq) from building energy use in the Group of Seven countries and the rest of the world from 2001 to 2021 [24,25].

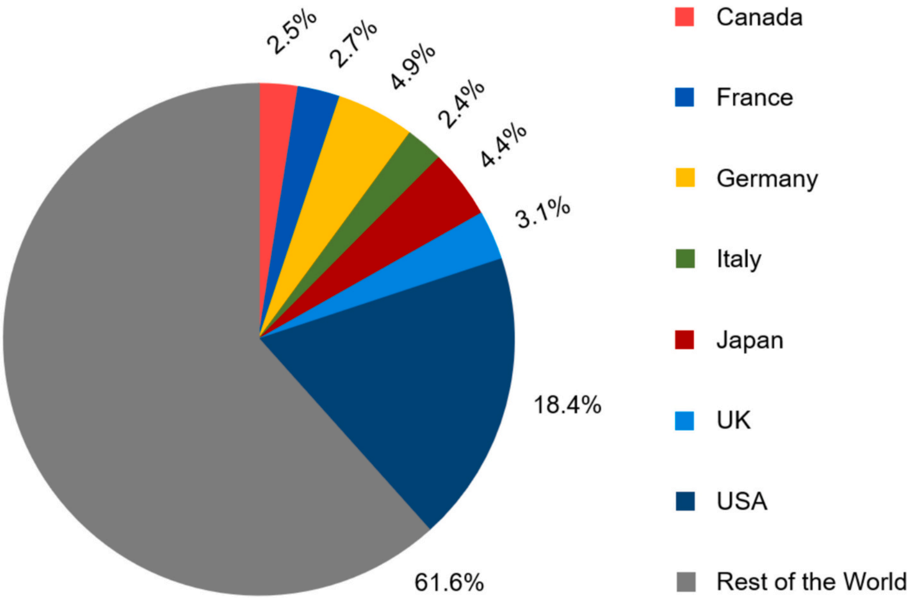

Fig. 2. Total share of greenhouse gas emissions (%) from building energy use in the Group of Seven countries and the rest of the world from 2001 to 2021 [24,25].

[36] under the International Energy Agency (IEA) Energy in Buildings and Communities (EBC) Technology Collaboration Programme (TCP) and directly contributes to the objectives of IEA EBC Annex 89 [36]. By identifying solutions to existing performance gaps in the residential building sector, the findings provide a robust foundation for advancing sustainable and resilient energy strategies in the built environment.

2. Methodology

The research methodology is illustrated using a study conceptual framework as shown in Fig. 3. Various study locations from different climate zones [37], dynamic grid emission factors, characteristics of timber residential building used as the reference NZEB, and key performance indicators that characterize electricity use, share of carbon-free energy, and operational emissions are described in this section. The whole building energy performance simulations for different test scenarios were performed using DesignBuilder v7.0.1 was used as the graphical user interface and EnergyPlus v9.6.0 [38] was used as the simulation engine.

2.1. Study locations

Eight study locations from the G7 countries are covered as shown in Fig. 3. These locations include Toronto in Canada, Paris in France, Berlin in Germany, Rome in Italy, Tokyo in Japan, London in United Kingdom, and Los Angeles and New York in the United States. These study locations cover climate zones, such as warm humid climates (Rome and Tokyo), warm marine climates (Los Angeles), mixed humid climates (Paris, London, and New York), and cool humid climates (Toronto and Berlin). American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) 169 - Climatic Data for Building Design Standards [37] is used for climate classification, which define the climate zones based on annual and monthly climate data including parameters like temperature, humidity, and wind speed from over 9237 global locations [37,39]. Typical Meteorological Year (TMY) files in EnergyPlus Weather (EPW) format for various study locations across the

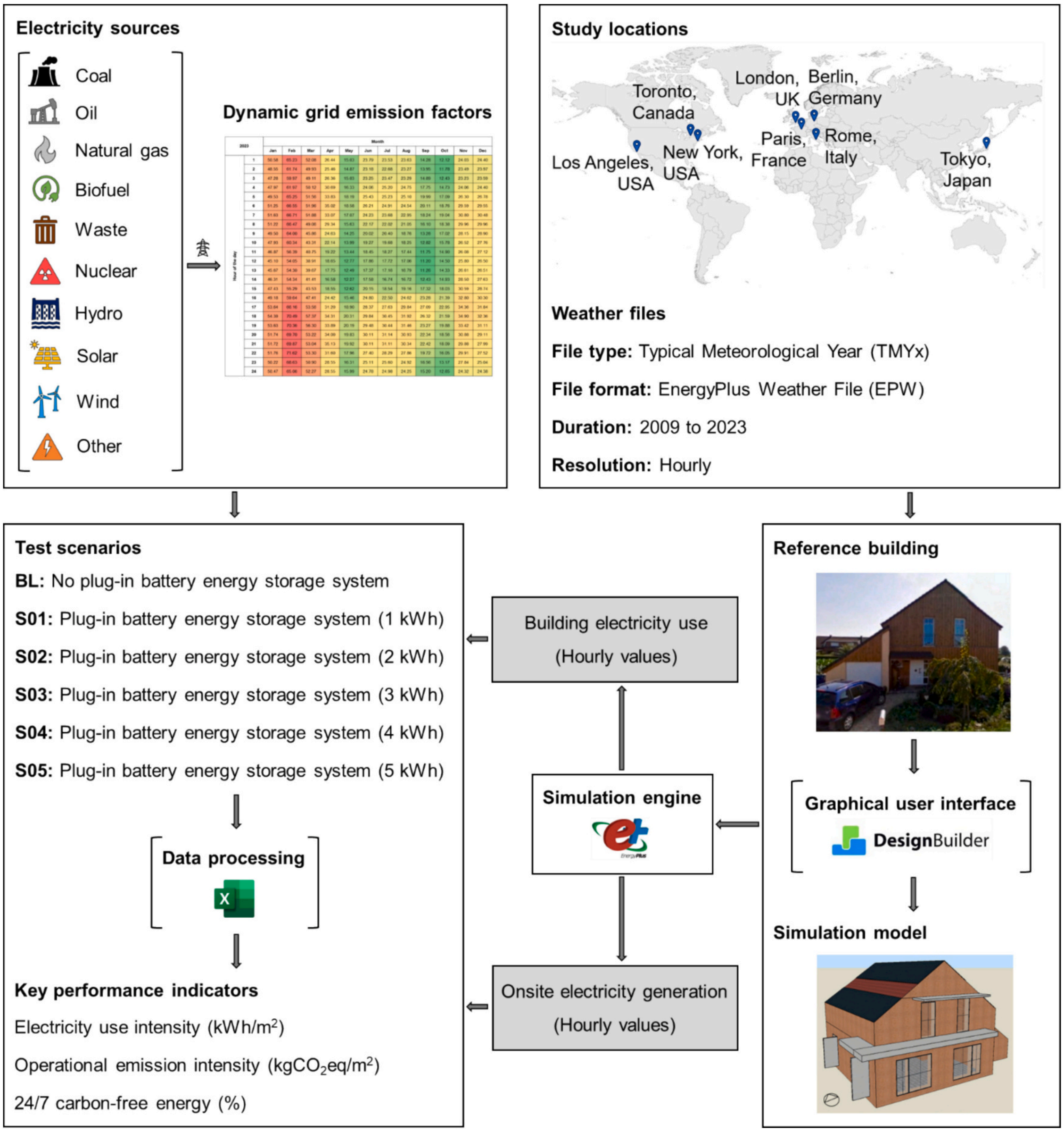

Fig. 3. Study conceptual framework for assessing the feasibility of plug-in battery energy storage systems in enabling low-carbon energy operations in net zero energy residential buildings.

G7 countries are available at [40] and used in studies like [41].

2.2. Dynamic grid emission factors

Dynamic grid emission factor can be defined as the sum of product of hourly electricity generated and emission factors divided by total electricity generated. Hourly values of direct GHG emissions from the location-specific utility grids are used as dynamic grid emission factors to scale operational emissions from the reference building electricity use. Hourly dynamic grid emission factors can be calculated using eq. (1).

$$D_f = \frac{\sum_{i=0}^{n} E \times ef}{\sum_{i=0}^{n} E} \tag{1}$$

Where D_f is the hourly dynamic grid emission factor in kgCO$_2$eq/kWh, E is the electricity generated in kWh, and ef is the emission factor for the individual generation sources in kgCO$_2$eq/kWh, i is time step in hours.

The direct GHG emission data for 2023 is obtained from [42] with emissions data from Ontario and Great Britain is used as representative data for Canada and United Kingdom. Furthermore, the hourly direct carbon intensity and low-carbon percentage of the utility grid varies across the G7 countries as shown in Fig. 4 and Fig. 5. The largest hourly variation in direct carbon intensity was observed for Germany varying from 0.09 to 0.68 kgCO$_2$eq/kWh, whereas the largest hourly variation in share of low-carbon percentage was observed for Italy from 20.4 to 100%. Dynamic grid emission factors have been used for evaluating building operation [11] and photovoltaic system performance [43]. Dynamic grid emission factors provide more accurate diurnal and seasonal patterns by considering real-time fluctuations in electricity generation in these locations, which would in turn improve carbon accounting [7]. A detailed dynamic grid emission dataset for utility grids was calculated using hourly data from [44–50] as shown in [7]. Furthermore, novel approaches for estimating the carbon intensity of electricity generation like machine learning is explained in [51].

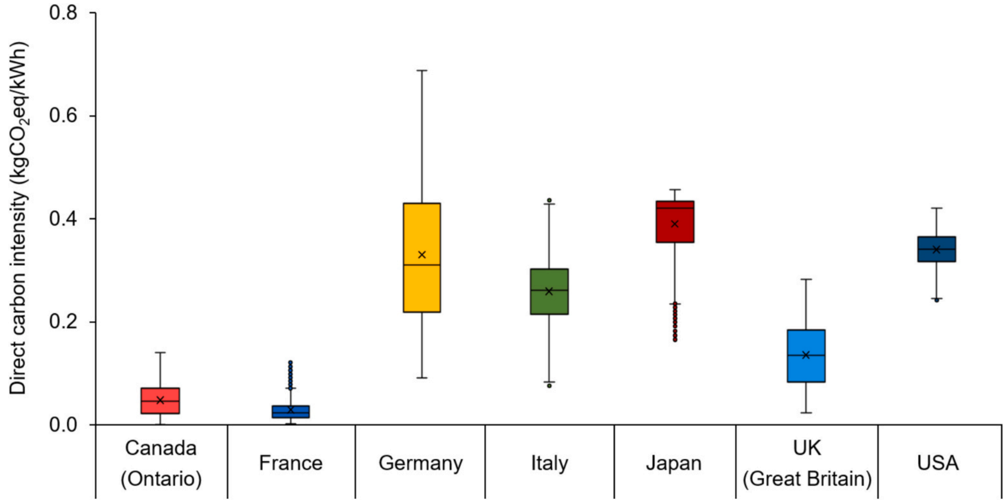

Fig. 4. Hourly variations in direct carbon intensity (kgCO₂eq/kWh) of electricity generation across the Group of Seven countries in 2023 [44–50].

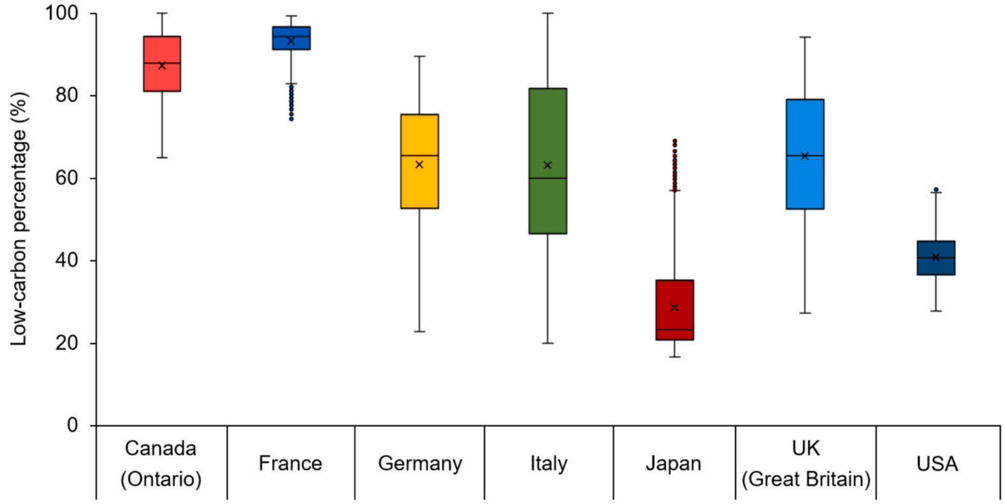

Fig. 5. Hourly variations in the low-carbon percentage (%) in total electricity generation across the Group of Seven countries in 2023 [44–50].

2.3. Reference net zero energy building

The reference building was constructed in the framework of Project Construire avec Energie from the Walloon regional government in Belgium in 2008 [52,53]. It is a timber residential building constructed as a nearly zero energy building, according to the Belgian Passive House criteria [54], with a timber truss work. The base simulation was calibrated for model accuracy according to ASHRAE 140 – Standard method of test for the evaluation of building energy analysis computer programs [55] using hourly simulated indoor air temperature values against measured values from 2015 to 2018 as described in [53,56] for Brussels in Belgium, where the real building is located. A photovoltaic system is implemented on the rooftop to meet the annual electricity use of the reference building through onsite electricity generation, thereby converting the residential building from a nearly zero energy building (nZEB) to NZEB, characterized according to each study location. It houses four people and has a total area of 198.5 m^2, with two floors, an attic, and an unconditioned garage. The layout comprises of a kitchen, living room, dining room, and a bathroom housed on the ground floor, alongside three bedrooms and a bathroom on the first floor. The reference building is classified as an International Organization for Standardization (ISO) 17772-1 Energy performance of buildings – Category II building [57] and is equipped with a Variable Refrigerant Flow (VRF) unit for space conditioning, with the cooling setpoint is set at 26 °C and heating setpoint is set at 20 °C according to ISO 17772-1 [57].

Additionally, it has a mec-hanical ventilation unit with a flow rate of 10 L/s/person and a heat recovery rate of 70%. The reference building has an infiltration rate of 0.5 ACH, and a window-to-wall ratio of 30%, with overhangs and sidefins for solar shading. Domestic hot water is produced using an electric boiler at 0.72 L/m^2/day. The key building features, including geometry, occupancy, envelope, heating system, cooling system, ventilation, and equipment characteristics, are listed in Table 1. The base simulation model and more information on occupancy and operational schedules are available in open access from [58]. BESS plays a significant role NZEBs in addressing the intermittency challenge of photovoltaic systems by supplying renewable energy during nighttime. Plug-in BESS in particular important since it can provide an affordable, compact, and flexible installation with existing standard power outlets in residential buildings [59].

The input values used to model the plug-in BESS include ratings from 1 to 5 kWh [60], with a charging and discharging efficiency at around 0.95 [61]. The study evaluates six test scenarios in the reference building:

a. Baseline (BL) with no plug-in BESS;

Table 1
Characteristics of reference net zero energy building.

Building geometry	
Total floor area [m^2]	198.5
Occupation density [m^2/person]	49.6
Window-to-Wall ratio [%]	30
Building orientation [°]	0
Occupancy characteristics	
Number of occupants [−]	4
Clothing factor [Clo]	0.5 during summer and 1.0 during winter
Metabolic rate [Met]	0.9
Envelope characteristics	
Infiltration rate [ACH]	0.500
Ground floor thermal transmittance [W/m^{2}K]	0.177
Internal floor thermal transmittance [W/m^{2}K]	0.328
External floor thermal transmittance [W/m^{2}K]	0.257
External Roof thermal transmittance [W/m^{2}K]	0.346
External wall thermal transmittance [W/m^{2}K]	0.148
External door thermal transmittance [W/m^{2}K]	2.823
Internal door thermal transmittance [W/m^{2}K]	2.823
Window thermal transmittance [W/m^{2}K]	0.500
Window solar heat gain coefficient [−]	0.687
Solar shading [−]	Overhangs and sidefins
Heating system characteristics	
Heating setpoint [°C]	20
Heating system COP [−]	2.5
Maximum supply air temperature [°C]	35
Cooling system characteristics	
Cooling setpoint [°C]	26
Cooling system EER [−]	3
Minimum supply air temperature [°C]	12
Ventilation characteristics	
Mechanical ventilation flow rate [L/s/person]	10
Heat recovery [%]	70
Domestic hot water system characteristics	
Domestic hot water system COP [−]	0.85
Delivery temperature [°C]	65
Domestic hot water rate	0.72 L/m^2/day
Equipment characteristics	
Lighting power density [W/m^2]	5
Equipment power density [W/m^2]	10

b. Scenario 01 (S01) with a plug-in BESS with a storage capacity of 1 kWh;
c. Scenario 02 (S02) with a plug-in BESS with a storage capacity of 2 kWh;
d. Scenario 03 (S03) with a plug-in BESS with a storage capacity of 3 kWh;
e. Scenario 04 (S04) with a plug-in BESS with a storage capacity of 4 kWh;
f. Scenario 05 (S05) with a plug-in BESS with a storage capacity of 5 kWh.

BESS models for charging and discharging processes are available in existing studies like [62–64]. In the presented BESS model from eq. (2) to eq. (9), charging occurs only during periods of onsite renewable energy surplus, while grid electricity is not considered as a charging source, and this is a significant boundary condition of the model. The plug-in BESS scenarios are modeled based on building electricity use and onsite electricity generation to estimate electricity imported from and exported to the utility grid. Net electricity (E_{net}) values is defined as the difference between onsite electricity generation (R_e) and building electricity use (E_b) as in eq. (2).

$$E_{net} = R_e - E_b \tag{2}$$

where E_b is the building electricity use in kWh, R_e is the onsite electricity generation in kWh. The building electricity is considered as surplus when $R_e > E_b$, and as deficit when $R_e < E_b$. The state of charge (SoC) values is updated based on net electricity (E_{net}) values on an hourly scale. The plug-in BESS is considered in charging mode when $E_{net} > 0$, and the plug-in BESS is considered in discharging mode when $E_{net} < 0$. Additionally, an initial SoC of 30% [65], a maximum SoC of 80%, and a minimum SoC of 20% [66,67] are used as model input values. The SoC values are calculated as in eq. (3) based on conservation of energy principles [68], while accounting for initial SoC, electricity in during charging, and electricity out during discharging.

$$SoC_{n+1} = SoC_n + (E_c \times \eta_c) - \left(\frac{E_d}{\eta_d}\right) \tag{3}$$

where E_c is charging electricity, η_c is charging efficiency, E_d is discharging electricity, and η_d is discharging efficiency, and n is the hourly step. Charging electricity (E_c) for each hour step is calculated as a minimum of electricity rating (E_{rated}), surplus electricity ($E_{net,surplus}$), and maximum electricity stored ($E_{store,\max}$) as in eq. (4), while discharging electricity (E_d) for each hour step is calculated as a minimum of electricity rating (E_{rated}), deficit electricity ($E_{net,deficit}$), and minimum electricity stored ($E_{stored,\min}$) as in eq. (6).

$$E_c = \min\left(E_{rated}, E_{net,surplus}, E_{stored,\max}\right) \tag{4}$$

$$E_{store,\max} = \left(\frac{SoC_{maximum} - SoC_{current}}{\eta_c}\right) \tag{5}$$

$$E_d = \min\left(E_{rated}, E_{net,deficit}, E_{stored,\min}\right) \tag{6}$$

$$E_{store,\min} = (SoC_{current} - SoC_{minimum}) \times \eta_d \tag{7}$$

Electricity is imported from the utility grid ($E_{grid,\text{import}}$) when there is a net deficit electricity after the plug-in BESS is discharged and is calculated as in eq. (8), whereas electricity is exported to the utility grid ($E_{grid,\text{export}}$) when there is a net surplus electricity after the plug-in BESS is charged and is calculated as in eq. (9).

$$E_{grid,\text{import}} = max\left(0, \left(E_{net,deficit} - E_d\right)\right) \tag{8}$$

$$E_{grid,\text{export}} = max\left(0, \left(E_{net,surplus} - E_c\right)\right) \tag{9}$$

2.4. Key performance indicators

Reference building performance in terms of electricity use, operational emissions, and share of electricity generated from carbon-free and low-carbon electricity sources are evaluated using various key performance indicators [7] as given below

Electricity use patterns from the reference building for diurnal and total variations were evaluated using electricity use intensity (EUI) metric in kWh/m^2.y. EUI was calculated as shown in eq. (10).

$$EUI = \frac{\sum_{i=1}^{8760}(E_b - R_e)}{A} \tag{10}$$

where A is the surface area in m^2 and i is the hourly values varying from 1 to 8760, which is total number of hours in an year. EUI for BESS scenarios is calculated using the difference between hourly electricity exported to and imported from the utility grid and normalized by total area.

Dynamic operational GHG emission patterns from the reference building for diurnal and total variations were evaluated using operational emission intensity (OEI) metric in kgCO$_2$eq/m^2.y. OEI was calculated as shown in eq. (11).

$$OEI = \frac{\sum_{i=1}^{8760}\left((E_b - R_e) \times D_f\right)}{A} \tag{11}$$

where D_f is dynamic grid emission factors. OEI for BESS scenarios were calculated using the difference between hourly electricity exported to and imported from the utility grid as in eqs. (8) and (9), which is then multiplied by dynamic grid emission factors and normalized by total surface area.

The share of building operation met by low-carbon electricity sources was evaluated using 24/7 carbon-free energy (24/7 CFE) metric in % [69]. An hourly matching approach recommended by [70] was used to calculate the annual 24/7 CFE as shown in eq. (12).

$$24\Big/7\ CFE = \frac{\sum_{i=1}^{8760} \min(E_b,\ E_{CF})}{\sum_{i=1}^{8760} (E_b)} \times 100 \tag{12}$$

where E_{CF} is the sum of hourly onsite electricity generation (R_e) and low-carbon electricity from the utility grid ($E_b \times LCE_{\%}$) as in eq. (13).

$$E_{CF} = R_e + (E_b \times LCE_{\%}) \tag{13}$$

The hourly electricity mix data that estimates the percentage of low-carbon electricity sources in the utility grids were obtained from [42]. The annual 24/7 CFE analysis for BESS scenarios also accounts for battery charging and discharging electricity. In these scenarios, E_{CF} is

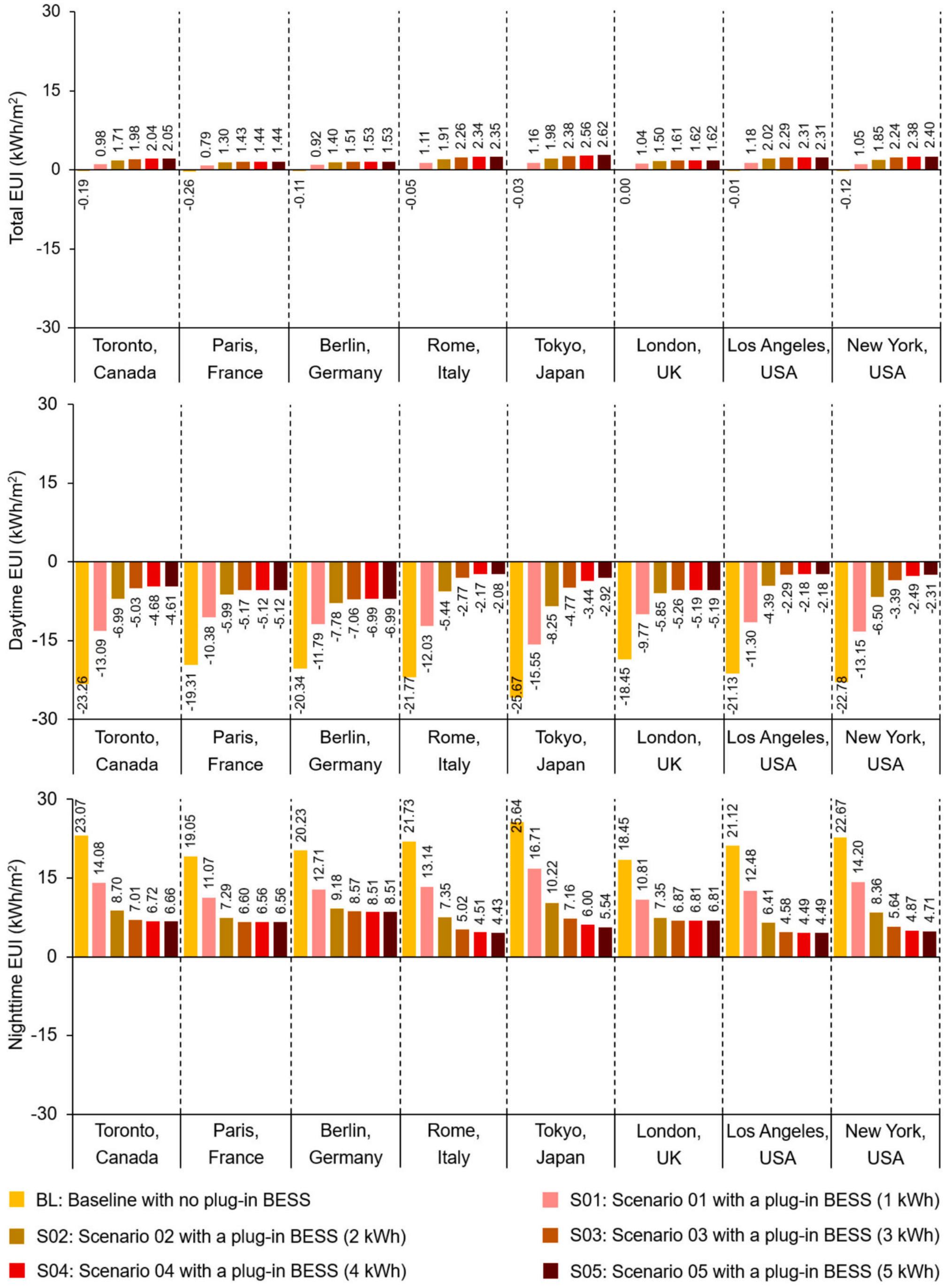

Fig. 6. Variations in electricity use intensity (kWh/m^2) of the reference net zero energy residential building across the locations under different test scenarios.

calculated as the sum of onsite electricity generation, discharging electricity from the BESS, and grid electricity from low-carbon electricity sources, while subtracting charging electricity into the BESS as in eq. (14).

$$E_{CF} = R_e + (E_b \times LCE_{\%}) + E_d - E_c \tag{14}$$

3. Results

The total and diurnal variations of EUI in kWh/m^2.y are shown in Fig. 6. The total EUI for the Baseline without plug-in BESS varied from −0.26 kWh/m^2.y in Paris to 0 kWh/m^2.y in London since the reference building was a net zero energy residential building where annual electricity use was met by annual onsite electricity generation. However, integrating plug-in BESS systems in reference building increased total EUI across all study locations. This can be attributed to the energy losses from plug-in BESS during charging and discharging cycles during plug-in BESS operation. The total EUI increase for test scenarios with plug-in BESS varied from 0.79 kWh/m^2.y in Paris to 2.62 kWh/m^2.y in Tokyo. Considering the diurnal variations, the plug-in BESS was modeled as charging when onsite electricity generation was higher than building electricity use and discharging when building electricity use was higher than onsite electricity generation. This ensured plug-in battery round-trip operation, charging during daytime, and discharging during nighttime.

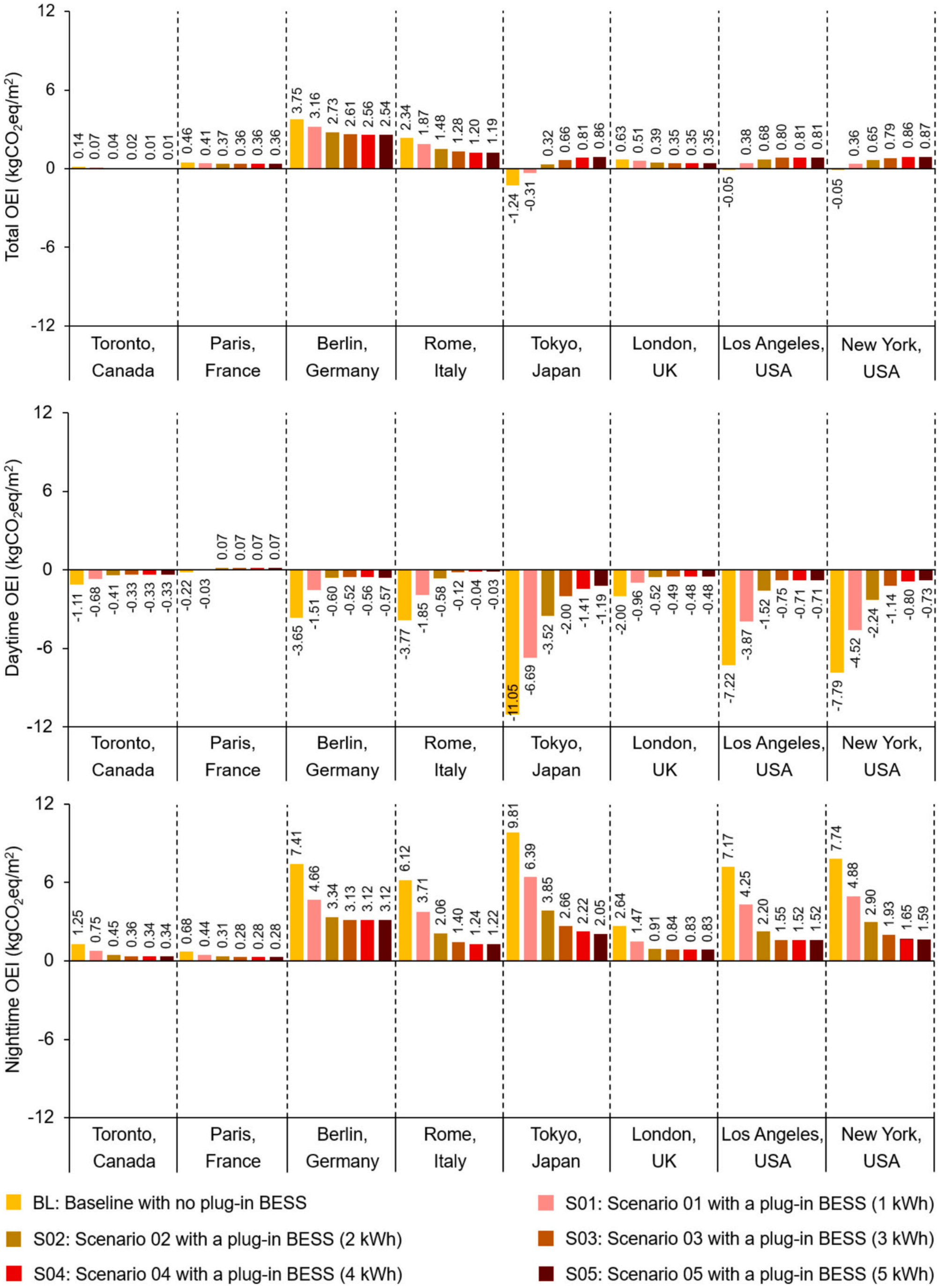

Fig. 7. Variations in operational emission intensity (kgCO₂eq/m^2.y) of the reference net zero energy residential building across the locations under different test scenarios.

This increased EUI during daytime as the excess onsite electricity generated was used for charging plug-in BESS in contrast to the Baseline where the excess electricity was exported to the utility grid. The plug-in BESS is a load equipment during the charging cycle and adds to daytime building electricity use. The implementation of plug-in BESS curbs this electricity export, thereby increasing the daytime EUI to −2.92 kWh/m^2.y compared to a Baseline value of −25.67 kWh/m^2.y in Tokyo and to −4.61 kWh/m^2.y compared to a Baseline value of −23.26 kWh/m^2.y in Toronto. In contrast, the plug-in BESS is a source equipment during the discharging cycle. Therefore, a decrease in nighttime EUI is observed for test scenarios with plug-in BESS compared to Baseline with no plug-in BESS, since plug-in BESS reduces the electricity imported from the utility grid. The implementation of plug-in BESS decreased the nighttime EUI to 5.54 kWh/m^2.y compared to a Baseline value of 25.64 kWh/m^2.y in Tokyo and to 6.66 kWh/m^2.y compared to a Baseline value of 23.07 kWh/m^2.y in Toronto.

Dynamic grid emission factors from the utility grid strongly influence the operational emissions from the reference building. The diurnal variations in dynamic grid emission factors significantly impact the OEI from the reference building integrated with plug-in BESS as shown in Fig. 7. At the same time, total OEI variations between Baseline with no plug-in BESS and test scenarios with plug-in BESS are less significant in study locations like Toronto and Paris. This is because the utility grid heavily relies on low-carbon electricity sources like hydro energy in Toronto and nuclear energy in Paris [7]. Additionally, the highest total OEI increase was observed in Tokyo from −1.24 to 0.86 $kgCO_2eq/m^2$.y with the integration of plug-in BESS while the highest total OEI decrease was observed in Berlin from 3.75 to 2.54 $kgCO_2eq/m^2$.y with the integration of plug-in BESS. This can be attributed to comparatively higher daytime dynamic grid emission factors in Tokyo and higher nighttime dynamic grid emission factors in Berlin. The diurnal variations in OEI values followed a similar pattern to EUI, with increasing OEI during daytime and decreasing OEI during nighttime.

Moreover, similar to variations in total OEI, the variations in diurnal OEI between the Baseline with no plug-in BESS and test scenarios with plug-in BESS are less significant in Toronto and Paris, which relies on

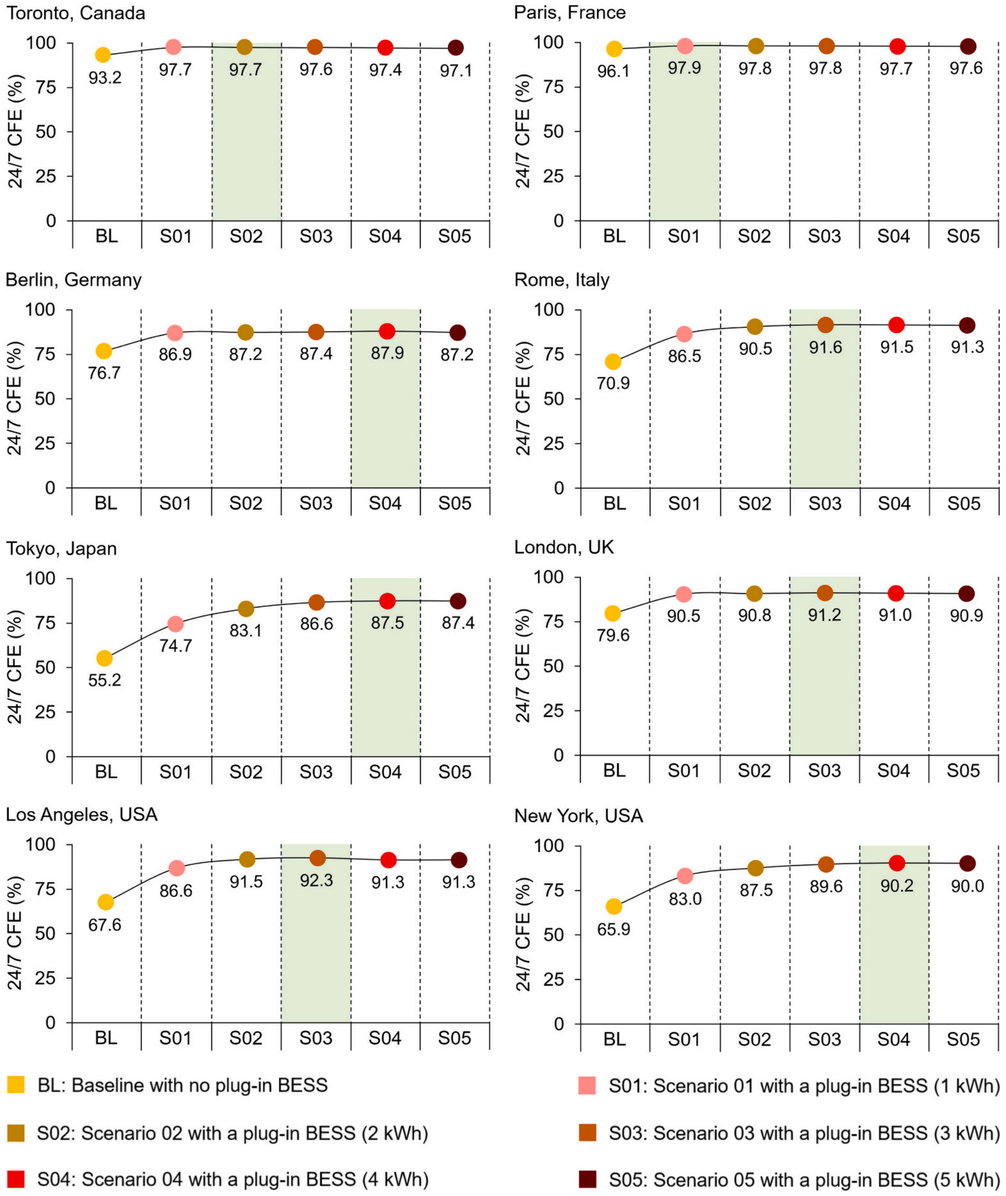

Fig. 8. 24/7 carbon-free energy share (%) of the reference net zero energy residential building across the locations under different test scenarios. The most optimal test scenario for each location is shaded green. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

low-carbon electricity sources, while more significant in Tokyo, New York, and Los Angeles, which relies on carbon-intensive fossil fuels [7] as shown in Figs. 4 and 5. The implementation of plug-in BESS curbed the electricity export to the utility grid. This limited the displacement of grid emissions compared to Baseline, thereby increasing the daytime OEI to −1.19 $kgCO_2eq/m^2$.y compared to a Baseline value of −11.05 $kgCO_2eq/m^2$.y in Tokyo and to −0.73 $kgCO_2eq/m^2$.y compared to a Baseline value of −7.79 $kgCO_2eq/m^2$.y in New York. In contrast, the implementation of plug-in BESS reduced electricity import from the utility grid due to plug-in battery discharging cycle during nighttime operations compared to the Baseline, thereby decreasing the nighttime OEI to 2.05 $kgCO_2eq/m^2$.y compared to a Baseline value of 9.81 $kgCO_2eq/m^2$.y in Tokyo and to 1.59 $kgCO_2eq/m^2$.y compared to a Baseline value of 7.74 $kgCO_2eq/m^2$.y in New York.

Unlike the EUI and OEI calculations, 24/7 CFE calculations do not account for the excess onsite energy exported to the utility grid. The 24/7 CFE metric calculates the share of building operation met by low-carbon energy sources using onsite electricity generated, grid electricity from low-carbon electricity sources - a dynamic combination of carbon-free and carbon-based resources, discharging electricity from plug-in BESS, charging electricity from plug-in BESS. The analysis indicated that integrating plug-in BESS systems in the reference net zero energy residential building improved the low-carbon electricity building operation across all the locations compared to the Baseline with no plug-in BESS as shown in Fig. 8. However, the increase in 24/7 CFE was strongly influenced by the share of low-carbon electricity sources in the utility grids across the locations [7]. This is evident in study locations like Toronto and Paris, where the utility grids relied on low-carbon hydro and nuclear energy, respectively.

The maximum increase in 24/7 CFE in Toronto was 4.5% and in Paris it was 1.8% with the integration of plug-in BESS compared to Baseline with no BESS. In contrast, integrating plug-in BESS in the reference building increased 24/7 CFE in Tokyo by 32.3%, Los Angeles by 24.7%, New York by 24.3%, and Rome by 20.7%. The utility grids from these study locations include a larger share of carbon-intensive fossil fuels in electricity generation [7] as shown in Figs. 4 and 5. In locations like London and Berlin, with a mix of carbon-intensive fossil fuels and low-carbon renewable electricity sources, the 24/7 CFE increase was 11.6% and 11.2% with the integration of plug-in BESS in the reference building. The results also suggested that increasing the energy rating of plug-in BESS beyond an optimum value does not yield any added enhancement to 24/7 CFE. However, these values varied across the locations, indicating the significance of optimizing the plug-in BESS sizing for better building operation considering the location and climate. The green background indicates the most suitable scenario for 24/7 CFE in each study location.

4. Discussions

The study findings and recommendations, alongside strengths and limitations, and implications for research and practice are presented in this section.

4.1. Findings and recommendations

The modeled plug-in BESS has a round-trip efficiency of 0.95, resulting in energy losses during charging and discharging cycles, increasing total EUI in test scenarios with plug-in BESS. The total EUI increase in reference building was observed throughout the locations, varying by 0.79 kWh/m^2.y in Paris to 2.62 kWh/m^2.y in Tokyo. The daytime EUI in the reference building increased across all study locations since excess onsite electricity generated was used to charge the plug-in BESS instead of exporting it to the utility grid. Thus, plug-in BESS is a load equipment during the daytime, increasing EUI by 13.26 kWh/m^2.y in London to 22.75 kWh/m^2.y in Tokyo. In contrast, during nighttime, the plug-in BESS operates as source equipment on the discharging cycle, reducing EUI across all study locations. This reduction in EUI in reference buildings during nighttime varied from 11.64 kWh/m^2.y in London to 20.10 kWh/m^2.y in Tokyo.

The highest total OEI increase in reference buildings was observed in Tokyo at 2.10 $kgCO_2eq/m^2$.y, where the grid is more carbon-intensive during the daytime [7]. The highest decrease in total OEI was observed in Berlin at 1.21 $kgCO_2eq/m^2$.y, where the grid is more carbon-intensive during the nighttime [7]. This is because the excess electricity generated onsite is exported back to the utility grid in the Baseline with no plug-in BESS. In contrast, it is primarily used for charging the plug-in BESS during Scenario 01 to Scenario 04. The amount of utility grid emissions displaced through grid export of electricity generated onsite during the daytime is reduced in scenarios with plug-in BESS comparison to Baseline. Moreover, plug-in BESS increased daytime OEI by 0.29 $kgCO_2eq/m^2$.y in Paris to 9.86 $kgCO_2eq/m^2$.y in Tokyo and decreased nighttime OEI by 0.40 $kgCO_2eq/m^2$.y in Paris to 7.76 $kgCO_2eq/m^2$.y in Tokyo. This increase and decrease in OEI during daytime and nighttime was observed across all the locations. Therefore, analyzing OEI patterns indicate that integrating plug-in BESS in locations with higher daytime dynamic grid emission factors like Tokyo will increase OEI, while OEI will be reduced in locations like Berlin with higher nighttime dynamic grid emission factors.

In addition to providing simulation-based results on EUI and OEI, the role of plug-in BESS in achieving low-carbon building operation through 24/7 CFE evaluation was also highlighted here. Plug-in BESS systems enable hourly matching of self-consumption during peak demand nighttime hours in the reference building, ensuring better building operation reliability during onsite photovoltaic systems are intermittent. The increase in CFE varied from 1.8% in Paris, where the utility grid primarily depends on nuclear energy [7], to 32.3% in Tokyo, where the utility grid primarily depends on fossil fuels like coal and natural gas [7]. This indicates that plug-in BESS improves low-carbon building operation in study locations with carbon-intensive utility grids. The analysis also indicated that increasing the plug-in BESS energy rating beyond an optimal value does not benefit 24/7 CFE. The results found that plug-in BESS is effective in load shifting, reducing the reliance on the utility grid by supplying the reference building with low-carbon electricity generated from onsite photovoltaic systems during nighttime operation. However, future studies should integrate degradation assumptions and capacity sizing degradation for an accurate long-term projection of performance and cost of BESS. Although existing literature focused on demand flexibility considering load equipment, such as lighting, space conditioning, and domestic appliances, according to [71], studies that characterize the role of plug-in BESS in improving low-carbon operation in residential buildings are rare, which adds to the unique perspective of the work. Timber residential buildings play a pivotal role in sustainable architecture and decarbonization of built environment by reducing carbon footprints [72]. Nevertheless, for broader representation of urban building stock, analysis of multiple archetype buildings, including residential and commercial buildings, are recommended.

The lifecycle emissions from BESS depends on various factors like the material, where they are sourced from, manufacturing process, etc. However, recent estimates from [73], indicates greenhouse gas emissions between 61 and 106 $kgCO_2eq$ per kWh of BESS. This means on average a 3kWh BESS system will have an emission between 0.09 and 0.16 $kgCO_2eq/m^2$.y for current reference building considering a 10 year lifespan [74]. In comparison, the reduction of operational emission from integrating a 3 kWh plug-in BESS in the reference building would decrease operational emissions by 0.10 $kgCO_2eq/m^2$.y in Paris, 0.12 $kgCO_2eq/m^2$.y in Toronto, 0.28 $kgCO_2eq/m^2$.y in London, 1.06 $kgCO_2eq/m^2$.y in Rome, and 1.14 $kgCO_2eq/m^2$.y in Berlin, whereas operational emissions are increased by 0.84 $kgCO_2eq/m^2$.y in New York, 0.85 $kgCO_2eq/m^2$.y in Los Angeles, and 1.9 $kgCO_2eq/m^2$.y in Tokyo. This increase can be contributed to utility grid intensity and time of use variations in study locations. Study locations with higher nighttime carbon emission intensity in the utility grid benefit more from the BESS.

Moreover, the study considered net metering with transfer of excess electricity produced back to the utility grid, creating a favorable operating scenario in terms of operational emissions. Future studies should consider the variations in emissions in the absence of net metering and when degradation in operational performance of BESS over time is factored in.

Based on study findings, developing net zero building standards with storage requirements could accelerate the adoption of BESS to drive decarbonization in built environments. In 2024, the State of Virginia mandated the installation of energy storage to improve grid reliability [75]. Although this policy was developed for the utility companies in the region, policymakers can scale down similar codes for buildings to standards mandated by the California Energy Commission. These standards, created in 2022, include BESS requirements for new high-rise multi-family buildings with photovoltaic systems [76]. Similarly, the recent clean energy and resilient transition plans from European Union like European Green Deal [77], REPowerEU [78],and Clean Industrial Deal [79] sets strategies to transition from traditional energy sources to renewable energy sources to reduce greenhouse gas emissions. The study results could be used to drive these transitions and wider integration og BESS into these plans to achieve maximum potential of renewable energy sources in reducing greenhouse gas emissions. Furthermore, providing financial incentives such as tax credits or low-interest financing could allow building owners to bridge the initial installation costs of BESS.

4.2. Strengths and limitations

This study focused on improving self-consumption and supporting low-carbon operation in net zero energy residential buildings by integrating plug-in BESS. The comparative approach with multiple scenarios with various energy ratings provides an optimized energy storage design with a more effective supply and demand matching for the reference net zero energy residential building. Additionally, the building performance was evaluated using dynamic grid emission factors for each hour [80], adding to a more accurate and granular understanding of building operational emissions, and aligning it better with carbon neutrality goals in the built environment. Therefore, global decarbonization goals are directly addressed by bridging a critical gap in the existing literature by linking energy efficiency metrics to carbon neutrality, adding to the originality of this work. However, the study does have some limitations. Future research covering various geographic locations and climate zones should account for regional and national variations in building codes. This would help to create how energy use patterns and peak loads could vary in the study locations considering local behavior and cultural influences. However, the proposed methodology of using uniform schedules across the study locations still ensures a comparable analysis as the relative cross-location pattern would be broadly similar. Additionally, the simulation model was calibrated for the original location of the reference building. Future research should carry out location-specific calibrations considering occupancy, system schedules, and climate variability, provided field measurement data is available. Furthermore, TMY data from 2009 to 2023 should be compared with historical emission factors for a more accurate depiction of reference building performance based on the availability of data.

4.3. Implications for practice and research

The baseline reference building model follows the NZEB definitions outlined in [81], where electricity export to the utility grid occurs when onsite electricity generation exceeds building energy consumption. However, the conventional net metering framework, which allows exported electricity to offset imported electricity, has come under increasing scrutiny due to its financial and infrastructural implications. Many countries and regions have begun shifting towards policies that promote self-consumption of onsite-generated electricity while discouraging reliance on net metering. This shift is evident from recent regulatory changes in the Netherlands, which will phase out net metering incentives starting January 1, 2027 [82]. Similarly, Germany is adopting policies that support self-consumption [83], while in the United States, states such as Arizona, California, and Hawaii have revised net metering frameworks by reducing compensation rates or transitioning towards self-sufficiency models [84]. These evolving policies underscore the necessity for alternative strategies that maximize onsite renewable energy utilization, such as integrating BESS to optimize self-consumption, particularly during nighttime when photovoltaic generation is unavailable.

Considering dynamic grid emission data sources, Electricity Maps [42] list national Transmission System Operators (TSOs) and public databases as the primary sources of their dynamic grid emission data. However, it is essential to acknowledge that the statistical processing methods or assumptions used across national TSOs may vary depending on the study locations. Other viable data sources for dynamic grid emissions for the study locations include Hydro-Québec for Quebec in Canada [85], European Network of Transmission System Operators for Electricity (ENTSO-e) for European countries like France, Germany, and Italy [86], D-Sharing that provides data for 10 power grids from Japan [87,88], Carbon Intensity platform developed by National Energy System Operator in the United Kingdom [89], and Emissions & Generation Resource Integrated Database (eGRID) developed by Environmental Protection Agency (EPA) in the United States [90].

Comprehensive BESS life cycle assessment (LCA) [91], considering raw material extraction, manufacturing processes, operational performance, recycling applications, and end-of-life disposal strategies should be a critical research direction for the future. Lifecycle emissions from plug-in BESS may offset some operational benefits. Existing studies from [92] provide energy paradigm-shifting approaches in the context of vehicle-to-everything interactions, battery circular economy, and battery cascade utilization for lifecycle carbon intensity quantification towards achieving net zero batteries. Additionally, [93] proposed a database on the lifecycle carbon footprint of batteries, from raw materials to recycling, based on a generic methodology to support policymakers. According to the study, in China, these values varied from 0.0119 US$ to 0.0574 US$.

Similar studies for varying climates in the G7 Countries are essential to support the transition into sustainable built environments. As such, battery costs play a critical role in the feasibility of demand-side applications that integrate photovoltaic systems with BESS. The break-even costs are influenced by BESS sizing and capacity, photovoltaic system sizing, building type, and BESS degradation according to [94]. High BESS costs currently limit the profitability of integrating photovoltaic systems with BESS, although focusing on the factors described below could improve economic feasibility [94]. Similarly, studies from [95] found that increased battery size improves self-consumption and reduces grid-dependence regardless of the tariff types. However, the economic viability of BESS should be improved with financial subsidies, since the payback period exceeds the life period [95].

A rigorous comparative analysis of BESS scenarios against non-storage models will provide valuable insights into their economic viability, environmental trade-offs, and global warming potential (GWP). The increasing availability of cost-effective storage solutions further emphasizes the importance of these evaluations. According to the Bloomberg New Energy Finance report [96], the cost of lithium-ion batteries declined to $139 per kWh in 2023, marking a 14% reduction from 2022. The demand for batteries is projected to grow by 53% annually, driven by increasing applications in both stationary energy storage and electric vehicles [96]. These trends suggest that energy storage solutions will become integral to residential and commercial buildings, providing resilience against grid fluctuations, and improving local energy reliability.

Additionally, comparative performance analysis of plug-in BESS with interventions like demand-side management, hybrid storage, and vehicle-to-home is necessary for informed decision-making. Beyond lithium-ion storage, future studies should investigate the feasibility and performance of alternative energy storage technologies, including flywheels, thermal energy storage systems, and hydrogen-based storage [97]. Each of these technologies presents distinct advantages and limitations in terms of energy efficiency, response time, and environmental impact. The integration of advanced control strategies, such as machine learning-driven predictive optimization [98] and adaptive energy management systems, can further enhance the operational efficiency of energy storage in NZEBs. By leveraging real-time data analytics and dynamic forecasting, buildings can optimize energy dispatch, mitigate peak load demand, and improve grid stability. Additionally, the role of decentralized energy networks and peer-to-peer energy trading in future NZEB applications warrants further exploration. As distributed energy resources become more prevalent, advanced block chain-enabled energy trading mechanisms can enable surplus energy sharing among buildings, reducing dependency on centralized grids while improving overall energy efficiency.

The combination of energy storage solutions, intelligent energy management, and innovative energy trading models can improve urban energy systems and fostering greater sustainability. This can further add to resilience in the built environment with other passive building renovation strategies against extreme weather events [99]. Future studies should also focus on developing hybrid storage solutions that integrate multiple energy storage technologies to balance cost, efficiency, and longevity. A multidisciplinary approach incorporating climate-responsive architecture, grid-interactive smart technologies, and material science will be crucial in advancing next-generation NZEBs. By addressing these emerging challenges, research can drive meaningful innovations that accelerate the transition towards self-sufficient, low-carbon, and resilient built environments in line with Sustainable Development Goals [100,101].

5. Conclusions

Rapid urbanization alongside warming climates highlights the need for energy-efficient buildings with minimal environmental impact. The NZEBs have emerged as a key solution for reducing energy consumption and operational emissions. However, as this study highlights, net zero energy does not always equate to net zero operational emissions. The magnitude of operational emissions depends on the share of low-carbon energy in the utility grid and diurnal variations in carbon intensity. This is particularly crucial for residential buildings, where nighttime energy demand is high, coinciding with the intermittency of photovoltaic systems. Integrating plug-in BESS is essential for enhancing self-consumption and reducing utility grid dependence by improving 24/7 carbon-free energy values. This study examined NZEB performance across eight locations in G7 countries, covering four distinct climate zones. It assessed variations in electricity use, operational emissions, and low-carbon energy operations under different BESS capacities compared to baseline without BESS. Findings revealed that plug-in BESS increased overall electricity use intensity across all study locations due to losses during charging and discharging cycles. However, it significantly reduced nighttime electricity use intensity, shifting peak demand away from the utility grid.

The effects on operational emissions varied by location, influenced by diurnal carbon intensity patterns. Cities like Berlin, with higher nighttime dynamic grid emission factors, experienced reduced operational emissions, while cities like Tokyo, with higher daytime dynamic grid emission factors, saw an increase. The study also evaluated the role of plug-in BESS in improving low-carbon operations using 24/7 carbon-free energy metrics. Results showed that carbon-free electricity use increased by up to 32.3% in Tokyo, which has a carbon-intensive grid, while in Paris, where the grid is already a low-carbon grid, the improvement was only 1.8%. This demonstrates that BESS integration is particularly beneficial in regions with high fossil fuel dependency but has a limited impact where the grid is low-carbon intensive. These findings highlight the necessity of grid-responsive energy management strategies to optimize plug-in BESS deployment. While plug-in BESS enhances energy self-sufficiency and reduces peak grid load, its effectiveness in lowering emissions depends on local grid conditions. Therefore, a comprehensive approach that integrates technological advancements, policy support, and grid decarbonization efforts to optimize its potential of plug-in BESS in residential buildings is necessary.

CRediT authorship contribution statement

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

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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Data availability

Data will be made available on request.

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