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From Zero Energy to Zero Power Buildings: A new framework to define high-energy performance and carbon-neutral buildings

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ABSTRACT

The definition of Zero Energy Building (ZEB) has often been controversial both in regulation and research. This work explores a new evaluation framework introducing the Zero Power Building (ZPB) concept, a novel method that studies the relationship of buildings to the physical boundary, weighting system and analysis timeframe, approaching performance assessment at reduced time intervals. The methodology proposed in this paper showcases how the limitations of the ZEB can be overcome by adopting the ZPB concept on a reference commercial building. The case study was analysed under two different scenarios, with and without an electric storage system. The application of the ZPB concept on an hourly basis poses a challenge to the case study performance, considering both final energy use and CO_2 emissions. Specifically, the building commonly accepted as a ZEB turns as a ZPB for only 54.76% of annual hours and as carbon-neutral building for 55.58% of annual hours. The paper presents an innovative methodology that aims to assist in the design and operation of future buildings, as well as provide guidance for policymakers and regulators. The findings emphasize the significance of using dynamic assessment strategies to accurately evaluate the buildings performances and enable meaningful comparisons in various contexts.

Introduction

Buildings energy performance has been a topic that has attracted particular attention within the scientific community for several years [1]. The global need to inhabit energy and environmentally performing buildings is now more than ever a consolidated necessity [2]. Various studies have aimed to accurately describe building performance through new calculation methodologies and innovative definitions. The energy balance calculation methodology has played a crucial role in evaluating energy performance and identifying specific building types, such as Zero Energy Buildings (ZEBs) [3]. However, debates and discussions persist regarding the interpretation of the ZEB concept and associated calculation methods, both from scientific and regulatory perspectives.

Within the European Union, there is currently no universally agreed-upon method for defining ZEBs, as each member state has its own regulations. Approximately 60 % of member states have implemented the definition of (nearly) Zero Energy Buildings in their legal documents [4], based on the European Energy Performance of Building Directive [5] and its recasts [6,7]. This lack of harmonization makes it challenging to compare buildings labeled as ZEBs, particularly when considering specific factors that assess not only energy performance but also environmental and economic impact [8].

Another limitation is the comparison between designed and operational performances of ZEBs. It is crucial to minimize the discrepancy between these conditions when evaluating a ZEB effectively. Despite these limitations, the definition of ZEB has not undergone significant changes over time. Therefore, understanding the current consensus on this concept is essential to avoid ambiguity and facilitate the implementation of ZEB projects [9].

Furthermore, ZEB performance is typically measured using various indexes to determine energy efficiency and self-sufficiency. A literature analysis and review of the state of the art in this field will provide an overview of the current understanding of ZEB definitions and performance indexes, identifying research gaps that drive further innovation in the construction industry. This understanding is crucial for promoting sustainable development and mitigating the adverse effects of climate change [10].

Motivation and aim of the work

The definition of ZEB proposed so far has left numerous gaps and

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Nomenclature

Acronyms

ZEB	Zero Energy Building
DOE	Department of Energy
DC	Direct Current
EPBD	Energy Performance of Building Directive
ZPB	Zero Power Building
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
EU	European Union
PE	Primary Energy
NEEE	Neutral Exported Electrical Energy
RER	Renewable Energy Ratio
OREF	Overall Renewable Energy Fraction
PV	Photovoltaic
TMY	Typical Meteorological Years
US	United States of America
BESS	Battery Energy Storage System
CO_2	Carbon Dioxide

Symbols

E	Energy, expressed in kWh
E	Export
I	Import
G	Generation
L	Load
P	Power, expressed in kW
Δt	Time interval, expressed in hour
i	i-th time interval
j	j-th supplied energy flow
k	k-th demanded energy flow
J	Total number of supplied energy flows
K	Total number of demanded energy flows
f	Weighting factor – specific
w	Weighting factor – generic

Subscripts

bal	Balance
sup	Supply
dem	Demand
b	Boundary
imp	Imported
exp	Exported
ren	Renewable
P	Primary
nren	Non-renewable
eq	Equivalent

interpretations that have not allowed its correct application and dissemination. To date, there are numerous frameworks but few applications able to validate them. Without a structured approach it is impossible to compare two ZEBs in different locations or context. The need for a framework that highlights the boundary conditions of a building is more than ever necessary to allow evaluations between two buildings or districts [11]. Therefore, motivations behind this work can be summarized as follows:

- Current analysis frameworks for high energy performance buildings do not often find practical applications.
- Comparing ZEB buildings is a complex process that usually does not produce reliable results.
- Buildings with high energy performance often have strong inconsistencies between calculated performance and monitored data.
- The current ZEB concept should be more flexible and not only focused on energy performance, allowing also an environmental or economic assessment of the building.

The lack of a generally accepted and recognised definition and framework, the possibility of comparing buildings in different contexts and the timeless gap between design and operation are topical issues that motivated the conduct of this work. On this basis, this work aims to analyse the current framework for defining and evaluating Zero Energy Buildings (ZEBs) and identify critical issues while proposing a new approach. The study focuses on analysing energy performance at short time intervals to better understand the dynamic nature of ZEBs. The proposed framework suggests transitioning from the controversial concept of ZEB to that of Zero Power Buildings (ZPBs), which places a high-resolution time step at the core of the analysis and reconsiders ZEB methods and definitions. Furthermore, the proposed framework seeks to go beyond the narrow concept of energy by introducing a more flexible definition that can meet the increasingly complex performance requirements of buildings (sustainability, emissions, costs, etc.). To test the effectiveness of this approach and highlight the importance of a ZEB's dynamic behaviour, a preliminary case study was conducted. Additionally, an improvement scenario was proposed, incorporating a battery energy storage system (BESS). The results were analyzed in terms of energy performance and environmental impact, showcasing the flexibility of the Zero Power Framework in defining and evaluating high-performance buildings and encouraging the transition from Zero Energy to Zero Power or Zero-Emission buildings. [12]. The concept of Zero Power Building that this paper aims to propose and introduce to the scientific community is intended to provide an answer to the highlighted questions still left open by the classical definition of Zero Energy Building.

State of the art

Multiple papers published in the past decade have focused on defining Zero Energy Buildings (ZEBs) and evaluating their performance. A recent overview by D'Agostino and Mazzarella [13] highlighted inconsistencies in ZEB definitions, including variations in metrics, primary energy conversion factors, and accounting methods for energy exported from buildings. The authors proposed a new index, the Neutral Exported Electrical Energy Index (NEEE), to account for electricity production from renewable sources. In an additional study [14], the same authors emphasized limitations stemming from conflicting choices regarding physical boundaries, energy balance, and weighing systems in defining ZEBs. Contextually, another analysis by Sartori et al. [15] identified five criteria to define ZEBs uniquely and revealed how certain performance parameters applied to a Norwegian ZEB could favor fossil fuels over renewables, raising critical concerns regarding ZEB definitions [16]. Similarly, Marszal et al. explored various criteria parameters and their implementation for ZEBs, discussing their advantages and disadvantages [17]. A consistent step forward was made by Sartori et al. [18], proposing a comprehensive definition framework for net ZEB in 2012, organizing evaluation criteria and emphasizing the absence of an internationally approved definition for ZEBs. They also differentiated the concept of energy balance between load/generation balance and import/export balance. Subsequently, several studies have focused on indices related to load matching and grid interaction as useful parameters for describing ZEB performance [19]. These indicators were used by Salom et al. [20] to test net ZEB performances, highlighting advantages and drawbacks. It was found that these indicators are most effective when analyzed at detailed time intervals, providing insights into the building’s performance at specific moments [21].

The achievement of a shared definition of ZEB has further incentivized the search for other performance indices dedicated exclusively to the exploitation of renewable resources [22]. The Renewable Energy Ratio (RER) [23] has been commonly employed to assess the proportion of renewable energy use in terms of primary energy. The application of this index allows to evaluate different design choices to exploit the renewable potential of a system [24] or even to evaluate the performance of innovative systems in comparison with traditional systems [25] in different climates [26]. The weaknesses of this index were analyzed by Panão [27], which proposed the Overall Renewable Energy Fraction (OREF) index, able to also take into account the off-site renewable energy [28].

The concept and definition of ZEB often revolve around primary energy requirements, which provide a comprehensive understanding of a building’s energy impact. However, studies analyzing the primary energy impact of ZEBs have yielded conflicting results, highlighting the challenges in transitioning from final use energy to primary energy calculations [29]. Furthermore, the dynamic evolution of weighting factors adopted for the assessment of primary energy needs is crucial in the design of a ZEB [30].

Many of the studies presented above derive from the results achieved in the IEA Task 40 / Annex 52, focused on the study of the definitions and concept of ZEB [31]. Despite approximately a decade passing since the task’s completion, a globally accepted definition of ZEBs has not been established, emphasizing the ongoing need to accurately describe and compare high-energy performance buildings.

Material and methods

From zero energy to Zero Power buildings

The methodology applied in this work starts from the concept of energy balance applied to a building [32], globally accepted as reported in Equation (1):

$$E_{bal} = \sum_{j=1}^{J} E_{\text{sup},j}\cdot w_{\text{sup},j} - \sum_{k=1}^{K} E_{\text{dem},k}\cdot w_{\text{dem},k} \quad (1)$$

where E_{sup} ed E_{dem} represent the energy supplied or demanded by any j-th and k-th energy flow involved in the analysis, respectively. To account for different energy types, a weighting system represented by the factors w is incorporated into the balance. The balance output, denoted as E_{bal}, represents the quantity needed to resolve the energy balance, and its unit depends on the chosen weighting system. In the context of the ZEB concept, the unit is typically (primary) kWh. Equation (1) establishes the basis for defining the concept of Zero Energy Building and its interpretations as follows:

$$\begin{array}{lll} nearly\ ZEB & if & E_{bal}\lesssim 0 \\ net\ ZEB & if & E_{bal} = 0 \\ plus\ ZEB & if & E_{bal} > 0 \end{array}$$

Equation (1) is currently used to determine if a building meets the criteria for being a Zero Energy Building (ZEB). However, this definition has significant weaknesses that lead to misleading and non-rigorous applications. Three key aspects contribute to these limitations:

1. **Physical boundary**: The definition lacks clear boundaries for the energy balance, resulting in different considerations and outcomes. Choosing a specific boundary b is crucial and serves a particular analysis purpose.
2. **Weighting system**: Establishing an appropriate metrics system is necessary for comparing buildings with different energy sources. This requires consistent weighting factors w that align with the defined boundary and analysis timeframe.
3. **Analysis timeframe**: Determining the analysis time interval is crucial for studying a building. The chosen timestep (Δt) influences the reliability and realism of the results. It can span the entire building life cycle or focus on smaller intervals, with implications for the previous two aspects. This work emphasizes the importance of shorter analysis time intervals to properly assess the building’s continuous evolution.

Table 1 summarizes the variables involved in a building balance, which should be specified unambiguously in order to conduct an unbiased performance assessment.

The analysis of a building’s performance should be based on three fundamental “pillars” identified: physical boundary, weighting system, and analysis timeframe. The choice of the boundary determines the purpose of the analysis, the weighting system establishes the evaluation metrics, and the analysis timeframe determines the level of dynamic detail. The weighting system is particularly important as it enables the comparison of different energy flows and expands the concept of Zero Energy Building to include emissions and economic considerations [33].

Table 2 summarizes the implications of the weighting system in defining Zero Emissions/Carbon-Neutral or Zero Cost Buildings. With recent regulatory developments aiming for a carbon–neutral building stock, there is a clear need to update the traditional definition of ZEB and develop a comprehensive framework to accurately assess a building’s performance across multiple aspects beyond energy. This applies both in the U.S. [34] and in Europe [35].

The current definition of ZEB is exclusively focused on the energy aspect of the building and also takes certain boundary conditions for granted. The physical boundary considered for a ZEB is the entire building site, with the goal of studying the import/export balance. The chosen metric to define a ZEB is primary energy, specifically its non-renewable share. Finally, the building balance is conducted on a monthly or annual basis [36]. These specific choices limit the variables involved and can be summarized as follows:

- Physical boundary: Building Site (purpose: import/export balance)
- Weighting metric: Non-renewable primary energy
- Analysis timeframe: year/month

By applying these boundary conditions to Equation (1), the non-renewable energy balance is obtained, where the supplied flows are represented by the building energy export (exp) and the demanded flows by the imported energy flows (imp), described by Equation (2). Furthermore, the generic weighting factor w is replaced by the conversion factor into non-renewable primary energy $f_{P,nren}$, selected as a reference metric.

Table 1

Building energy balance boundary variables.

Physical boundary (b)		Weighting metric (w)	Analysis timeframe (Δt)
Physical boundary	Purpose		
Building envelope	Envelope performance	Final use (carrier: x)	Life cycle
Building energy systems	Load matching	Primary energy	Lifetime
	Energy systems efficiency	CO_2	Year
Building Site	Import/Export balance	$CO_{2,eq}$	Month
	Grid interaction	Cost	Day
District	District interaction		Hour
Grid			Sub-hour

Table 2

Weighting system metrics involved in the assessment of the built environment.

Weighting metric	Nomenclature	Unit	Purpose	Concept
Final use	–	kWh	Energetic assessment	Zero Energy Building
Primary energy	f_P ($f_{P,ren}$, $f_{P,nren}$)	kWh_P/kWh		
CO_2	f_{CO2}	kg_{CO2}/kwh	Environmental assessment	Zero Emission Building (Carbon-Neutral Building)
$CO_{2,eq}$	$f_{CO2,eq}$	$kg_{CO2,eq}$/kWh		
Cost	c	€/kWh	Economic assessment	Zero Cost Building

$$E_{bal} = \sum_{j=1}^{J} E_{\exp,j} \cdot f_{\mathrm{P,nren},j} - \sum_{k=1}^{K} E_{\mathrm{imp},k} \cdot f_{\mathrm{P,nren},k} \qquad [\mathrm{kWh_P}] \tag{2}$$

To ensure accuracy and consistency with the real performance of the building, Equation (1) needs to be modified to incorporate the reference physical boundary (*b*) and the time interval used to solve the balance. The time variable is crucial as it accounts for time-dependent energy flows and weighting factors. By defining a reference time interval (t_{ref}) and an analysis timeframe (Δt), the energy balance can be solved and analyzed in detail, as represented by Equation (3).

$$t_{ref} = \sum_{i=1}^{N} \Delta t_i \qquad [\mathrm{hr}] \tag{3}$$

where Δt is a fixed analysis timeframe and t_{ref} is the total evaluation reference time, made up of a total number *N* of *i*-th Δt intervals.

According to this approach it is possible to move from the concept of energy to that of averaged power over an analysis interval Δt, integrating the energy flows in each *i*-th interval related to the fixed analysis interval Δt, using Equation (4).

$$\overline{P}_{\Delta t_i} = \frac{E_{\Delta t_i}}{\Delta t} = \frac{1}{\Delta t} \int_{(i-1)\Delta t}^{i\Delta t} P(t)dt \qquad [\mathrm{kW}] \tag{4}$$

By substituting Equation (4) to the initial concept of ZEB exposed in Equation (1), it is possible to obtain the definition of averaged power balance, represented by Equation (5). This evaluation method allows to overcome the limits of the classical energy balance in terms of boundary *b*, of weighting system *w* and above all in terms of temporal variation, that in the classical ZEB approach considers $t_{ref} = 1$ year and $\Delta t = 1$ year/month.

$$\overline{P}_{bal,t_{ref}} = \sum_{j=1}^{J} \sum_{i=1}^{t_{ref}/\Delta t} \overline{P}_{j,\Delta t_i}(t) \cdot w_j(t) \Big|_b - \sum_{k=1}^{K} \sum_{i=1}^{t_{ref}/\Delta t} \overline{P}_{k,\Delta t_i}(t) \cdot w_k(t) \Big|_b \tag{5}$$

where $\overline{P}_{bal,t_{ref}}$ is the balancing power of the system across the boundary *b*. Equation (5) represents the tool that authorizes the transition from the concept of Zero Energy to that of Zero Power Building (ZPB). The ZPB framework unequivocally defines the conditions adopted to solve the averaged power balance of a building, ensuring a consistent application of the three analysis "pillars". Again, the unit of measurement in Equation (5) is variable depending on the weighting system adopted for the analysis.

The method proposed in this work wants to focus on the temporal detail of the analysis (variable Δt in the balance), which addresses the limitations encountered in the literature regarding the concept of ZEB. After defining an analysis boundary *b*, the application of Equation (5) allows to explore the building performance in a different perspective, highly variable over time, switching from the classic concept of (nearly) Zero Energy Building to a more complete concept of (nearly) Zero Power Building. This transition opens up to different design strategies of energy systems and new considerations on weighting factors.

The weighting system

To perform an accurate averaged power balance is necessary to consider comparable energy carriers. This requirement has led to the use of weighting systems in studying buildings, starting from the very first concept of energy balance reported in Equation (1). The purpose of a weighting system is to ideally convert different forms of energy into common and comparable metrics.

When assessing the environmental and sustainable impact of energy flows, the conversion factor into CO_2 is commonly used, considering the carbon dioxide emissions associated with the generation, transformation, and dispatching processes [37].

The characteristics of weighting factors are variable in space, time and direction of production, as specified in Equation (6). While for space and time it may seem more obvious, the dependence of weighting factors on their direction is often overlooked.

$$f_P, f_{CO_2} = f(space, time, direction) \qquad [\mathrm{kWh_P/kWh}],\ [\mathrm{kg_{CO_2}/kWh}] \tag{6}$$

To ensure consistency within the ZPB framework, a suitable weighting system must be employed, considering variability in terms of time, space and direction [38]. For this reason, the environmental impact analysis proposes conversion factors in kg of CO_2, based on the following boundary conditions:

- Space: U.S. Midwest region (case study location).
- Time: hourly detail.
- Direction: asymmetrical.
- Carrier: electricity.

These choices allow for the evaluation of dynamic changes in weighting factors, converting electrical energy flows into corresponding CO_2 emissions. Fig. 1 illustrates the trend of the f_{CO2} factor used in subsequent analyses, sourced from the U.S. Energy Information Administration's (EIA) hourly electric grid monitor [39]. EIA makes available real-time hourly data gathered through the form EIA-930 (Hourly and Daily Balancing Authority Operations Report) that collects hourly electric system operating data from electricity Balancing Authorities (BAs) in the contiguous United States. To calculate the CO_2 emissions intensity of load, EIA methodology associates estimated emissions with the transfer of electricity between BAs using a multi-regional input–output model (MRIO) [40]. The graph in Fig. 1 depicts the average CO_2 emissions rate per kWh generated or consumed in the U.S. Midwest region. It considers the direction of energy flows, with production-based averages reflecting generation and emissions within the region, while consumption-based averages account for emissions associated with imported or exported electricity [41]. The analysis emphasizes that the impact of a generated kWh differs from a consumed kWh, highlighting the significance of considering the direction in the analysis. The study employs the avoided burden approach to assess the impact of onsite renewable production. This approach weights an energy flow produced from on-site renewables using the generation conversion factor, indicating how each on-site kWh produced avoids the generation of one kWh from traditional sources. Conversely, a consumed kWh is weighted based on the CO_2 emission intensity associated with consumed electricity.

The adoption of a dynamic assessment with a reduced time interval for evaluating a building's performance cannot only consider the energy quantities involved in the balance. In fact, the role of the weighting system is crucial in the evaluation process. The use of a dynamic weighting system with a temporal detail consistent with the weighted energy quantities gives the evaluation process a totally different meaning, which is more accurate and representative of reality.

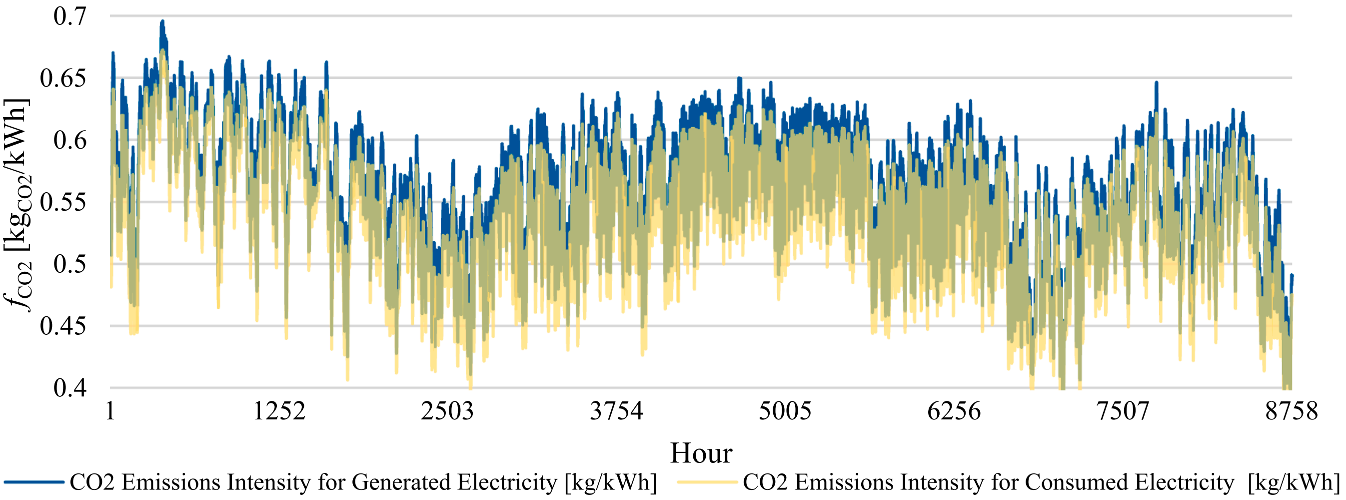

Fig. 1. Weighting conversion factor for CO_2 emission intensity for generated and consumed electricity in the U.S. Midwest region [39].

Case study application

The study of the transition from ZEB to ZPB through the proposed methodology was applied to a numerical case study. A reference building was chosen according to the US DOE Commercial Reference Building [42], considering a small office building type designed with the ASHRAE 90.1-2013 template. Building main characteristics are summarized in the Appendix Table A.1.

The model was built considering Minneapolis, Minnesota (MN) as representative city, using the TMY2 climate reference file from Rochester International Airport, MN. The climate zone is 4b according to the ASHRAE classification, corresponding to the Dfa category of the Köppen classification [43], thus indicating a humid continental weather [44].

The building HVAC system was considered fully electric, capable of meeting winter and summer energy needs. The building and system models were developed using EnergyPlus. Additionally, two on-site renewable energy systems were modeled:

1. A south-facing rooftop photovoltaic (PV) generator, with specific characteristics detailed in Table A.2.
2. An electrical battery energy storage system (BESS) connected to the PV system, sized to meet approximately 25 % of the building's average daily electrical demand. Key characteristics of the BESS are provided in Table A.3.

The electrical storage operates using a direct current (DC) bus type with an inverter and DC storage. Charging and discharging of the storage are controlled based on the building's power demand, considering on-site generation. Only excess generation beyond on-site consumption is stored (legacy behavior). Fig. 2 illustrates the defined balance boundary and energy flows involved in the building assessment.

The analysis boundary *b* includes the traditional grid-dependent energy generation systems (HVAC system) and on-site grid-independent renewable generation systems (PV Generator + Storage). This type of boundary condition, often known as site boundary, is designed to focus on the load matching of the building, and to verify the mutual

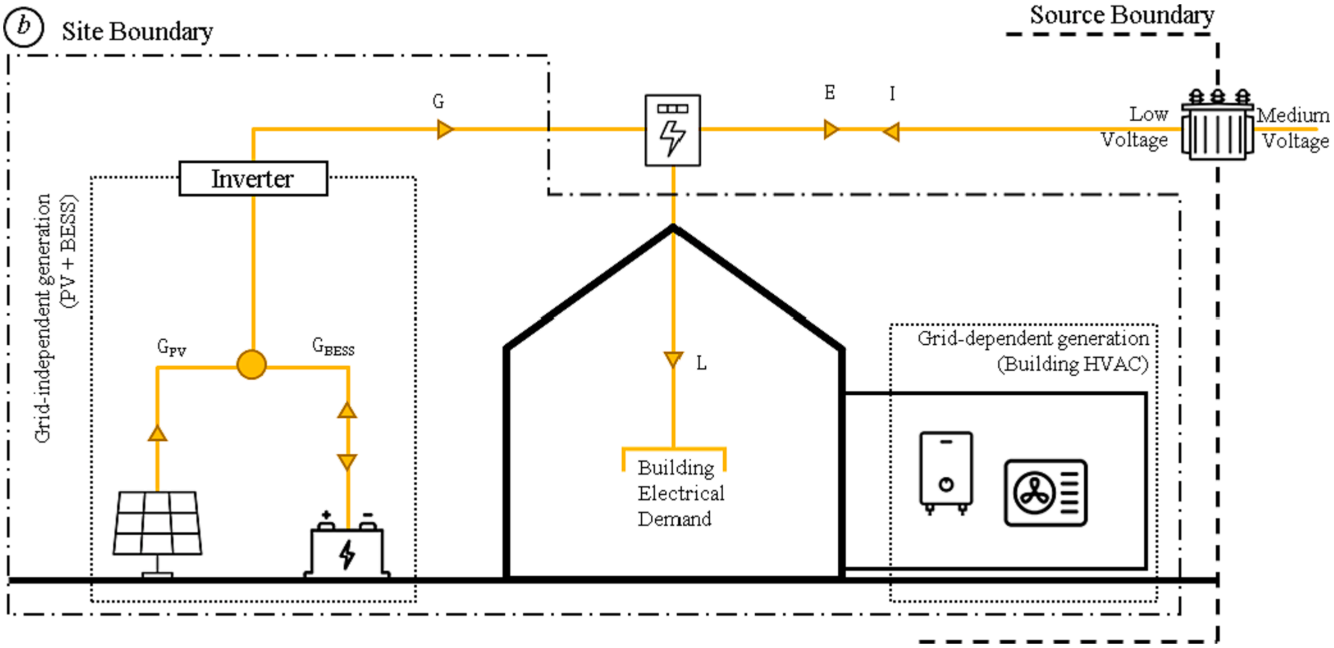

Fig. 2. Definition of the balance boundary setup and energy fluxes involved.

relationship between the building and the electricity network. The energy flows within this analysis boundary include:

- On-site generation system energy, G, which comprises energy produced by the PV array (G_{PV}) and energy involved in the BESS charging and discharging processes (G_{BESS}).
- Energy purchased/imported from the grid, I.
- Surplus energy produced but not consumed on-site (exported), E, which is fed back into the electricity grid.
- The building load, L, which describes the building energy utilization.

Thus, the electrical energy demand of the building, L, is described by Equation (7), considering all the energy fluxes involved.

$$\mathrm{L} = \mathrm{G} + \mathrm{I} - \mathrm{E} \qquad [\mathrm{kWh}] \tag{7}$$

According to the details specified in this section, two different simulation scenarios were generated to test the effectiveness and impact of the Zero Power Building assessment methodology. The first scenario consists in the installation of the onsite photovoltaic generation system only, the second instead couples the PV system with the electrical storage system. To emphasize the application of the ZPB approach, the energy performance of both scenarios was analyzed at different time intervals, ranging from a full year to individual hours. The results, presented in the following section, aim at analyzing the performance of the two scenarios following the concept of ZPB, highlighting their strengths compared to the classic definition of ZEB.

Results

Results summary

This section examines the results obtained from applying the Zero Power Building (ZPB) methodology to the two presented case study scenarios. Both scenarios include the building envelope and HVAC systems within the physical boundary, to analyze load matching in different configurations [45]. The analysis encompasses long periods (year and months) compared to hourly results, representing the transition from ZEB to ZPB.

Regarding the weighting system, this study explores two paths to assess the potential of the Zero Power approach:

- The first part of the results (Section ZPB approach on the final energy use) focuses solely on electrical final energy use as the primary energy carrier, without employing a specific weighting system.
- The second analysis (Section ZPB approach on weighted energy flows) concentrates on the building's environmental impact. A dynamic weighting system is employed, weighing energy flows based on CO_2 emissions. The hourly results incorporate the weighting factors described in Section The weighting system.

The outcomes provide valuable insights for various purposes and goals. Instead of claiming one solution as superior, the analysis showcases the significant potential of the proposed methodology for evaluating building performance.

ZPB approach on the final energy use

The relationship between onsite consumption and production was analyzed by comparing the supplied and demanded energy flows, starting from the definition of energy balance and averaged power balance discussed in Equations (1) and (5), respectively. In the specific case of this analysis, the energy flow supplied to the building is represented by the onsite energy generation (G), while the demanded energy flow is represented by the building load (L). By adopting this specific physical boundary, it is possible to rewrite the Equations that define the ZEB and the ZPB, using Equations (8) and (9).

$$E_{bal} = \sum_{j=1}^{J} E_{\mathrm{sup},j} \cdot w_{\mathrm{sup},j} - \sum_{k=1}^{K} E_{\mathrm{dem},k} \cdot w_{\mathrm{dem},k} = \mathrm{G} - \mathrm{L} \qquad [\mathrm{kWh}] \tag{8}$$

$$\begin{aligned} \overline{P}_{bal,t_{ref}} &= \sum_{j=1}^{J} \sum_{i=1}^{\frac{t_{ref}}{\Delta t}} \overline{P}_{j,\Delta t_i}(t) \cdot w_j(t) \Bigg|_b - \sum_{k=1}^{K} \sum_{i=1}^{\frac{t_{ref}}{\Delta t}} \overline{P}_{k,\Delta t_i}(t) \cdot w_k(t) \Bigg|_b \\ &= \sum_{i=1}^{t_{ref}/\Delta t} \overline{\mathrm{G}}_{\Delta t_i}(t) - \sum_{i=1}^{t_{ref}/\Delta t} \overline{\mathrm{L}}_{\Delta t_i}(t) \qquad [\mathrm{kW}] \end{aligned} \tag{9}$$

The relations set out above involve approximations, including:

- The supplied and demanded energy flows are unitary and already aggregated in the large areas G and L, respectively. Therefore $J = K = 1$.
- The weighting factors w were assumed equal to 1, as this analysis focused solely on the final energy use of the electric energy carrier.

The analysis considered varying time intervals (Δt) ranging from 1 year to 1 h, with a total reference time interval (t_{ref}) of one year. The results differed depending on the chosen Δt, with annual and monthly intervals aligning closely with the ZEB definition Equation (8), while daily and hourly intervals better represented the ZPB approach Equation (9), emphasizing the dynamic aspect.

Fig. 3 illustrates the relationship between supplied (G) and demanded (L) energy flows for each time interval of analysis. The graph compares the two scenarios investigated and displays different time intervals. The y-axis represents on-site energy generation (G), while the x-axis represents the building energy load (L). The theoretical net Zero Energy Building (ZEB) line indicates when on-site energy production matches the building's energy demand. Points above the net ZEB line indicate positive energy balance (E_{bal}) or power balance ($\overline{P}_{bal}$) conditions. The figure also reports the percentage of intervals in which the building functions as a ZEB, depending on the time interval.

The annual analysis shows that both scenarios qualify as Zero Energy Buildings (ZEBs) since their on-site electricity generation exceeds their demand. However, when the analysis timestep is reduced, they no longer meet the ZEB criteria. On a monthly basis, both scenarios achieve the ZEB target for only 6 months (50 %). Daily analysis reveals that Scenario 1 reaches the target for 181 days (49.59 %) while Scenario 2 achieves it for 183 days (50.14 %). Notably, the hourly analysis demonstrates that Scenario 2 outperforms Scenario 1 significantly, meeting the ZEB target for 4797 h (54.76 %) compared to 2564 h (29.27 %). This highlights the impact of analysis timestep on ZEB performance. The concept of Zero Power Building emphasizes high-resolution timestep analysis to capture a building's dynamic behavior. Without this approach, both scenarios would yield similar results on an annual or monthly basis, both qualifying as ZEBs without distinction. However, the results indicate that Scenario 2 performs better, benefiting from electrical storage. The energy flows involved in the building's balance are illustrated in Fig. A.1, showcasing the average daily behavior for each month. Specifically, the energy demand trend (L) is compared to total on-site production (G) and on-site production from the PV generator (G_{PV}). In Scenario 1, the difference between G and G_{PV} is solely due to the inverter's efficiency, whereas Scenario 2 demonstrates the effect of energy storage.

The energy balance of both scenarios was compared on different time intervals in Figs. 4 and 5. The left axis compares on-site energy generation (G) with building energy load (L) on a logarithmic scale. The right axis depicts the Load matching factor, which indicates the percentage of energy demand met through on-site production, as defined in Equation (10). In some cases, the Load matching percentage can exceed 100 %,

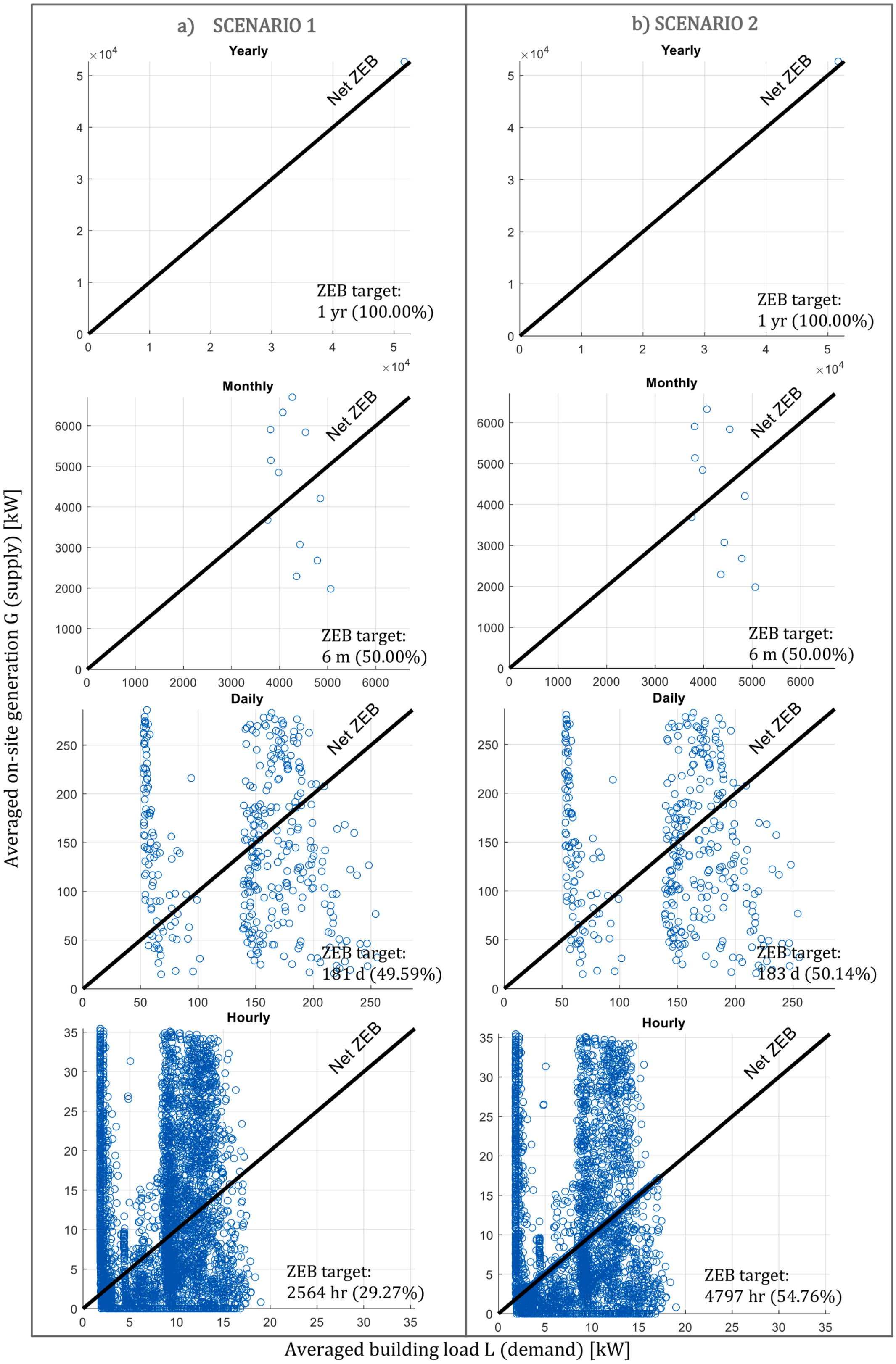

Fig. 3. ZEB and ZPB balance concept applied to case study Scenario 1 (a) and 2 (b).

indicating that on-site energy production has surpassed the energy demand within the given time resolution.

$$Load\ \ matching(\Delta t) = \frac{\mathrm{G}}{\mathrm{L}}\cdot 100 \qquad [\%] \tag{10}$$

Fig. 4 depicts the behavior of the building on a typical summer evening, (June 20th, 6:00 pm). While there are no significant differences between the two scenarios on an annual, monthly, or daily basis, the hourly behavior is noteworthy. Scenario 2 achieves the ZEB target with a load

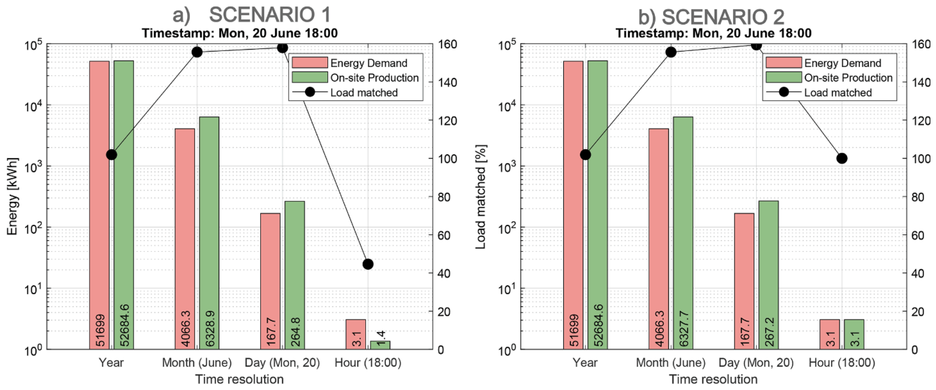

Fig. 4. Summer energy balance and load matching comparison on different time resolutions for Scenario 1 (a) and Scenario 2 (b).

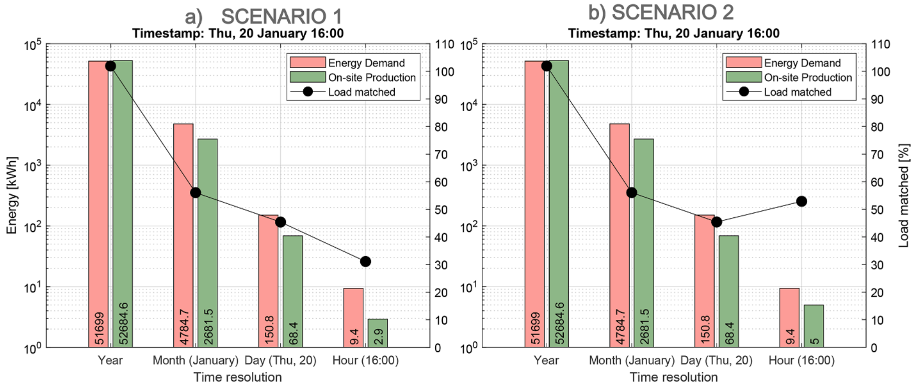

Fig. 5. Winter energy balance and load matching comparison on different time resolutions for Scenario 1 (a) and Scenario 2 (b).

matched percentage of 100 % during the analyzed hour. When considering larger time intervals, both scenarios meet and exceed the ZEB target. In contrast, Fig. 5 illustrates the behavior on a typical winter afternoon (January 20th, 4:00 pm). In this case, both scenarios only reach ZEB target when considering the annual balance. Monthly, daily, and hourly balances indicate load matching values lower than 60 %. Nonetheless, the hourly analysis provides more detailed insights into the building's behavior, demonstrating that Scenario 2 achieves higher load matching (53 % vs 31 %), which would have been overlooked with a larger time resolution.

ZPB approach on weighted energy flows

This section describes the environmental impact of the buildings in terms of CO_2 emissions, by adopting the weighting system described in Section The weighting system. Theoretically, the application of the boundary conditions to carry out this analysis allows us to rewrite Equations (1) and (5) again, using Equations (11) and (12), respectively.

$$E_{bal} = \sum_{j=1}^{J} E_{\text{sup},j}\cdot w_{\text{sup},j} - \sum_{k=1}^{K} E_{\text{dem},k}\cdot w_{\text{dem},k} = \text{G}\cdot f_{\text{CO}_2} - \text{L}\cdot f_{\text{CO}_2} \qquad [\text{kg}_{\text{CO2}}] \tag{11}$$

$$\begin{aligned}\overline{P}_{bal,t_{ref}} &= \left.\sum_{j=1}^{J}\sum_{i=1}^{\frac{t_{ref}}{\Delta t}} \overline{P}_{j,\Delta t_i}(t)\cdot w_j(t)\right|_b - \left.\sum_{k=1}^{K}\sum_{i=1}^{\frac{t_{ref}}{\Delta t}} \overline{P}_{k,\Delta t_i}(t)\cdot w_k(t)\right|_b \\ &= \sum_{i=1}^{t_{ref}/\Delta t} \overline{\text{G}}_{\Delta t_i}(t)\cdot f_{\text{CO}_2,\text{sup}}(t) - \sum_{i=1}^{t_{ref}/\Delta t} \overline{\text{L}}_{\Delta t_i}(t)\cdot f_{\text{CO}_2,\text{dem}}(t) \qquad [\text{kg}_{\text{CO2}}]\end{aligned} \tag{12}$$

where f_{CO2} represents the conversion factor into CO_2, used as the weighting factor w. In particular, Equation (11), which describes the classical energy balance on an annual basis, uses an annual static f_{CO2} conversion factor, equal to 0.606 kg_{CO2}/kWh, based on the US national average provided by the Emissions & Generation Resource Integrated Database (eGRID) EIA-1605(b) form [46]. In the average annual approach, both supplied and demanded energy quantities have been weighed by the same conversion factor. On the other hand, Equation (12) adopts a dynamic weighting system on hourly basis, consistent with the methodological approach proposed by the ZPB framework, variable in space, time and direction.

The two proposed results in this section have different weighting systems, addressing both the dynamic aspect and the specific geographical area. The annual analysis uses a constant conversion factor that represents the limitations of the traditional approach for evaluating ZEB buildings [47]. The hourly analysis, on the other hand, adopts a conversion factor specific to the case study's geographical area, and differentiates supplied from demanded energy flows. This again highlights how the dynamic analysis of a building's weighted performance (whether CO_2 emissions or primary energy) loses its value if the corresponding weighting factor does not follow the same time resolution as the energy carrier.

Fig. 6 compares the two scenarios on an annual and hourly basis. The results show that the hourly analysis better assesses the impact of the BESS system installed in Scenario 2. In the annual analysis, both scenarios achieve zero emissions by balancing the weighted energy demand with the emissions avoided through the weighted energy supplied. However, in the hourly analysis, Scenario 1 only achieves zero emissions for a smaller portion of the year (29.84 %), while Scenario 2 with the BESS system reaches the carbon neutral target for a larger portion of the year (55.58 %).

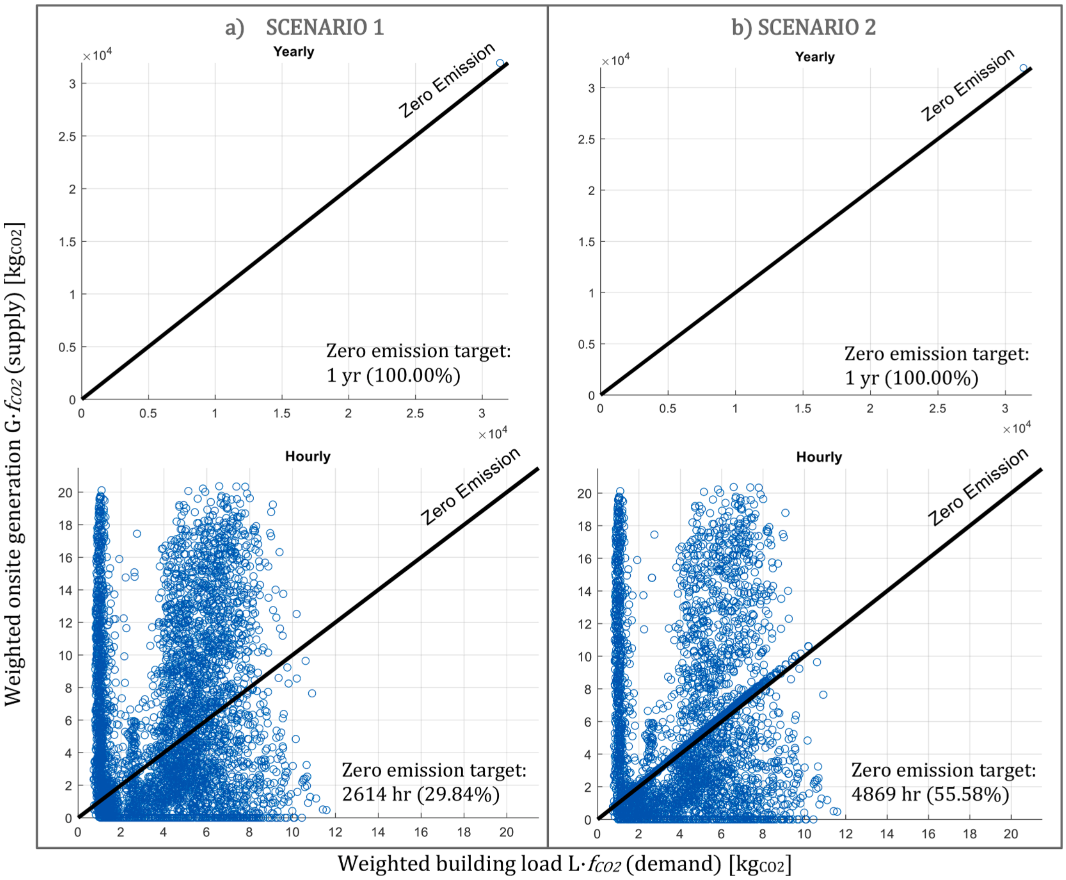

Fig. 6. Weighted ZEB and ZPB balance concept for case study Scenario 1 (a) and 2 (b).

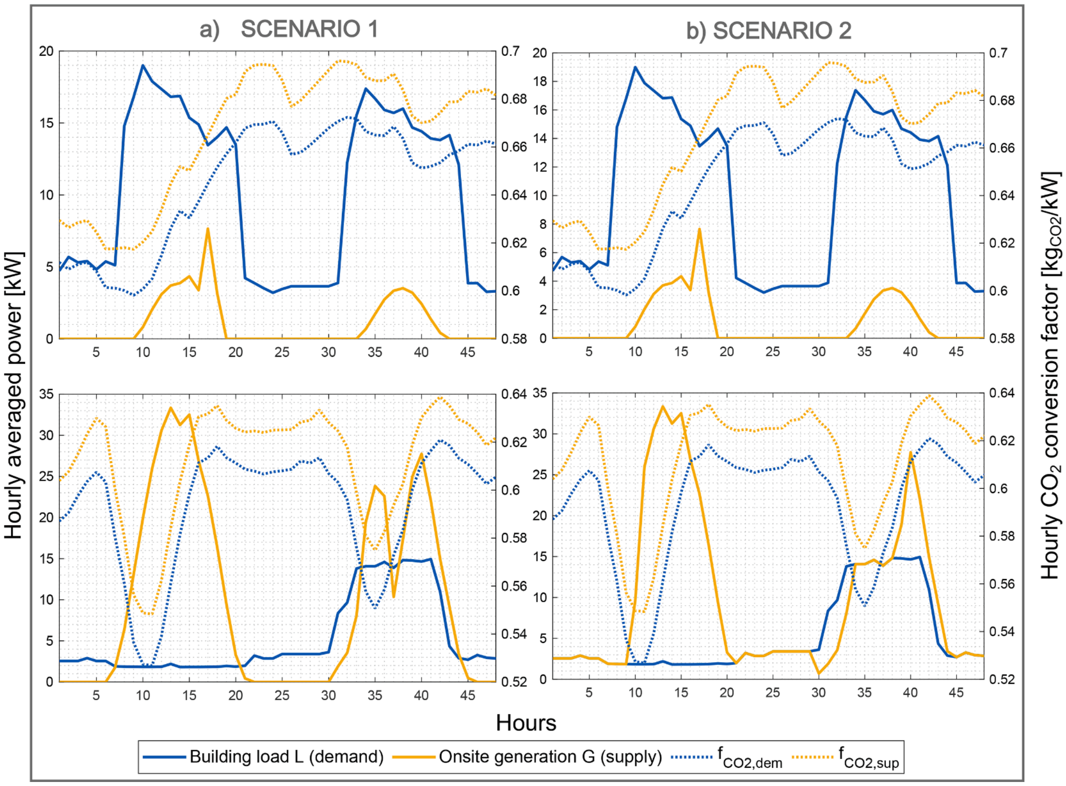

Fig. 7. Dynamic trend of onsite energy generation (supply) and building load (demand), with the respective CO$_2$ conversion factors.

An important result emerges from this first analysis. From the annual static point of view the weighted results in terms of emissions faithfully follow the final energy results of Section ZPB approach on the final energy use. However, the hourly results show slight differences with respect to their counterpart in final energy, mainly due to the use of asymmetric dynamic weighting factors, capable of differently valuing the direction of the energy flow considered. Additionally, the results would be further influenced if different energy carriers were involved.

The dynamic impact of variables involved in the averaged power balance is analyzed to better understand the application of the ZPB concept. Fig. 7 compares the case study scenarios focusing on two days (48 h) representing the winter (top of the figure) and summer (bottom of the figure) seasons. The graph shows the dynamic trend of the hourly demanded (blue line) and supplied (yellow line) power on the left y axis, combined with the dynamic trend of the CO_2 conversion factors reported on the right axis. During the winter reference period, both scenarios perform similarly as the onsite generation cannot fully satisfy the building's load, totally self-consuming the energy produced.

However, during the summer period, the impact of the BESS system in Scenario 2 is significant. The on-site power generation better matches the building's load profile, leading to different results in the weighted energy flows. Analyzing the results at an annual level would yield similar outcomes for both scenarios. However, the detailed approach of the ZPB methodology allows for a single-hour analysis, which highlights the positive match between supplied and demanded energy. Scenario 1, without energy storage, experiences excess on-site production during the summer season, resulting in fewer hours with a positive averaged power balance. The installation of a BESS system is appropriately valued in achieving the net-zero emission target, which the traditional definition of ZEB would not capture based on monthly or annual averages.

In both reference periods, it is observed that the CO_2 conversion factors for supplied flows are consistently higher than those for demanded flows. This indicates that energy consumed from the external power grid has a greater environmental impact, considering not only the generation but also the transmission and dispatching processes. The use of a dynamic weighting system allows for an accurate assessment of the building's performance and supports its design and operation. It is evident that the CO_2 conversion factor decreases during the day due to the influence of renewable sources on the external power grid. This detail, crucial to the ZPB approach, can guide important decisions in regulating and managing a building's energy systems, aiming to minimize its environmental impact [48].

Conclusion

This work addresses the inconsistencies of the Zero Energy Building (ZEB) concept and proposes the concept of Zero Power Building (ZPB), which focuses on high-resolution time intervals for analysis. The ZPB framework emphasizes the importance of considering the time evolution, physical boundaries, and primary resources of energy flows in a building. Numerical applications on a case study demonstrate the advantages of the ZPB concept in accurately assessing energy performance. The use of a detailed analysis timeframe enables a better understanding of energy usage, particularly in the integration of renewable energy systems. It allows for the incorporation of complex thermal models and facilitates informed decisions in design and optimization strategies [49]. The work also highlights the potential benefits of electric storage systems and emphasizes the need for a dynamic evaluation approach that can evaluate design alternatives and support early-stage design choices. The results underscore the importance of different temporal approaches in evaluating building performance and show the improvement achieved through hourly analysis compared to the traditional annual energy balance.

This work has introduced the novel concept of ZPB and proposed a new analysis framework to overcome the criticalities linked with the concept of ZEB. The following main results have been achieved:

- The current method of evaluating ZEB buildings leads to conflicting results that do not allow comparison between buildings.
- The Zero Power Building concept describes the realistic performance of a building, analyzing it under specified and unambiguous boundary conditions in terms of physical boundary, weighting system and analysis timeframe.
- The results of the Zero Power Framework describe buildings as dynamic entities and allow to open numerous definitions of dynamic parameters to support current regulations and innovative assessment procedures.

A further relevant outcome of the application of the ZBP methodology is the disclosure of numerous possibilities for innovative optimization scenarios, based on dynamic energy assessments. The concept of Zero Power Building, with its variations depending on the weighting system adopted, fits perfectly into contexts of multi-objective optimization [50], capable of considering different weighting systems in order to find optimal solutions in terms of energy, environment or cost [51]. In possible future implementations of this work, the proposed analysis framework can be integrated into optimization algorithms in order to support informed decisions for stakeholders involved in the design choices on different levels [52].

The imperative for data availability at reduced temporal intervals, such as on an hourly or sub-hourly basis, constitutes a pivotal challenge for the widespread implementation of the suggested methodology, particularly in the context of evaluating weighting factors, that necessitates a multifaceted information base. Nevertheless, the presented methodology demonstrates utility in two primary applications depending on the nature of the dataset in question:

- Retrospective analyses (backward-looking), which do not necessitate real-time data but enable accurate assessment of past behaviors. Illustratively, this could involve scrutinizing emissions from a building over the preceding year or its entire lifecycle.
- Prospective analyses (forward-looking), which mandate access to real-time or forecasted data. Although the latter category may appear somewhat far from present circumstances, it is intriguing to consider how the proposed methodology might harmonize with AI-driven algorithms to optimize a building's operational behavior in real time. This optimization could lead to minimization of primary energy consumption, emissions, and costs, or enhancements in its grid interaction. These areas of investigation, which are well-documented in the existing body of literature, serve as a vital launchpad for subsequent advancements in this field of inquiry.

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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.

Data availability

Data will be made available on request.

Appendix A

Appendix A collects details regarding the results achieved in Fig. A1, and describes the technical choices implemented in developing the model of the building and related energy systems (Table A1, Table A2, Table A3).

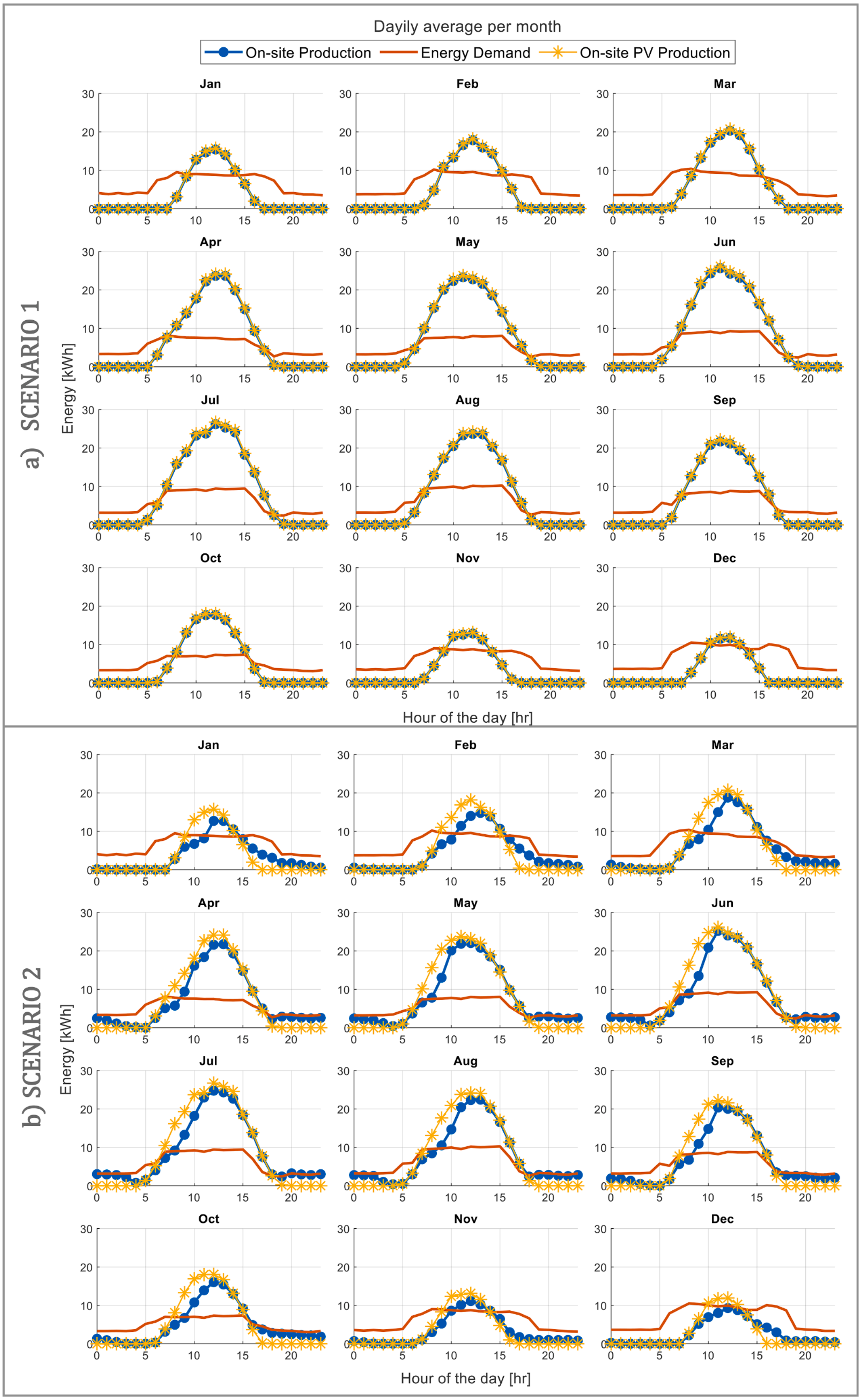

Fig. A1. Daily averaged on-site production and energy demand for each month for Scenario 1 (a) and Scenario 2 (b).

Table A1
US DOE Reference Building Case Study.

Building Model	US DOE Commercial Reference Building
Building Type	SmallOffice
Template	90.1-2013
Climate Zone	ASHRAE 169-2013-6A
Representative City	Minneapolis, Minnesota
Total conditioned building area	511 m^2
Thermal zones	5 (1 core, 4 perimeters)
Reference TMY2 Weather	Rochester International Arpt, MN

Table A2
PV Generator model (EnergyPlus object details).

Model	PV Generator
Surface Area	Roof facing South
Fraction in Surface Area with Active Solar Cells	88 %
Cell Efficiency (fixed)	20 %
Inverter efficiency (fixed)	98 %
EnergyPlus main object	PhotovoltaicPerformance:Simple

Table A3
BESS model (EnergyPlus object details).

Model	Electrical Storage
Nominal Efficiency for Charging	100 %
Nominal Efficiency for Discharging	100 %
Maximum Storage Capacity	30 kWh
Initial State of Charge	0 kWh
Maximum Storage State of Charge Fraction	0.96
Minimum Storage State of Charge Fraction	0.00
Inverter efficiency (fixed)	98 %
EnergyPlus main object	ElectricLoadCenter:Storage:Simple

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