Sustainable Cities and Society 101 (2024) 105136

Contents lists available at ScienceDirect

Sustainable Cities and Society

journal homepage: www.elsevier.com/locate/scs

From Zero Energy to Zero Power Buildings: A new paradigm for a sustainable transition of the building stock

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A R T I C L E   I N F O

Keywords:
Zero energy building
Zero power building
Zero-emission building
Zero energy district
Zero power district
Energy performance of building framework
Building performance assessment
Dynamic performance assessment

A B S T R A C T

This research introduces an innovative method aimed at evaluating building energy performance within urban environments and communities, departing from the conventional Zero Energy Building (ZEB) concept and introducing the Zero Power Building (ZPB) framework. This approach, overcoming the limitations of the ZEB concept, offers a holistic definition in line with the goal of achieving a Zero-emission Building stock. By employing a power balance assessment coupled with dynamic Key Performance Indicators (KPIs), this methodology surpasses traditional techniques, providing a more accurate assessment of energy consumption and generation patterns. The method was applied to a district case study encompassing seven nearly Zero Energy Buildings (nZEBs), demonstrating its potential efficacy. Findings indicate how the proposed framework can accurately evaluate the integration of energy storage and sharing strategies, increasing the Zero Power target from 29 % to 51 % of annual hours. KPIs were also dynamically examined at the building and district level, introducing the concept of KPI accuracy and identifying pivotal hourly patterns to guide a sustainable transistion. The adoption of the Zero Power Building framework and the utilization of dynamic KPIs offer viable solutions to address conventional limitations in building energy assessments. This approach aids in guiding targeted energy efficiency measures aimed at fostering sustainable and Zero-emission Communities.

1. Introduction

The impact of buildings on global energy needs is undisputed (IEA - International Energy Agency, 2018), with the building sector currently accounting for 30 % of total primary energy consumption (IEA, 2022). Recent years have seen a focus on research and technological innovations aimed at reducing the energy impact and enhancing building energy efficiency to mitigate fossil fuel consumption (de Santoli et al., 2017). Emerging from these efforts are various approaches for achieving increasingly sustainable and energy-efficient buildings. Consequently, evaluating the impact of different solutions on building performance has become crucial. Literature has produced numerous methods and metrics, condensing building performance into a few key indicators. Legislative developments, such as the recasts of the Energy Performance of Building Directive (EPBD) in Europe, have defined the implementation of Zero Energy Buildings and shaped the sector's energy evolution (European Parliament, 2012; European Parliament, 2018). The ongoing discussions on the 3rd recast of the EPBD, part of the Fit for 55 EU package, have introduced the concept of Zero-emission Building, surpassing Zero Energy Buildings by ensuring that the residual energy needed doesn't produce on-site carbon emissions from fossil fuels (European Parliament, 2023). Though differences persist among the EU Commission, EU Parliament, and EU Council regarding its implementation, some key aspects are apparent. First, there is a noticeable shift from a static (monthly) energy assessment calculation step for buildings to a more detailed hourly or sub-hourly calculation approach. This shift aims to better capture the interplay between on-site renewable energy generation, consumption, and grid export. Moreover, reducing the timeframe used as the basis for achieving zero energy targets is crucial to avoid inaccuracies caused by compensations using monthly or annual energy measurements (cover-up effect). Such practices can result in misleading representations of Zero Energy Buildings (ZEBs) (Kurnitski & Hogeling, 2022).

In both research initiatives and national regulations, the energy balance stands as a fundamental tool for evaluating building performance, facilitating the comprehension of energy flows within a building's defined perimeter and offering diverse avenues for setting energy performance objectives.

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https://doi.org/10.1016/j.scs.2023.105136
Received 5 October 2023; Received in revised form 14 December 2023; Accepted 15 December 2023
Available online 16 December 2023

Nomenclature

Symbols

$\overline{P}$	Average power
a	Accuracy
b	Boundary
B	Building
D	Delivered
E	Energy
E	Exported
G	Generated
L	Load
P	Power
S	Surface
t	Time variable
V	Volume
w	Weighing factor
Δt	Time interval
ε	Accepted error

Subscripts/superscripts

bal	Balance
dem	Demand
i	i-th time interval
j	j-th supplied energy flow
J	Total number of supplied energy flows
k	k-th demanded energy flow
K	Total number of demanded energy flows
ref	Total reference time for analysis
ren	Renewable
shared	Shared energy
sup	Supply
target	Target value for KPIs
tot	Total (Renewable + Non-Renewable)
use	Used on site

Acronyms

(n)	Nearly/net
CCHP	Combined Cooling Heating and Power
EPBD	Energy Performance of Building Directive
HVAC	Heating, Ventilation and Air Conditioning
PEF	Primary Energy Factor
PV	Photovoltaic
RER	Renewable Energy Ratio
SC	Self Consumption
SS	sSelf Sufficiency
ZEB	Zero Energy Building

1.1. The zero energy building concept: definition limits and KPIs constraints

The most successful application of the energy balance is certainly the concept of Zero Energy Building (ZEB), in its meanings of net ZEB, nearly ZEB or plus ZEB. Practically, the definition of Zero Energy Building is the null result of the energy balance between the energy supply and demand. Defining the result of the balance as E_{bal}, the definition of ZEB is represented by Eq. (1), globally accepted from Kurnitski et al. (2011):

$$E_{bal} = \sum_{j=1}^{J} E_{sup,j} \cdot w_{sup,j} - \sum_{k=1}^{K} E_{\mathrm{dem},k} \cdot w_{\mathrm{dem},k} \tag{1}$$

where E_{sup} represents the energy supply, E_{dem} the energy demand, and w_{sup} and w_{dem} represent the weighting factors used to compare any *j*-th and *k*-th energy flows among all the supplied and demanded energy flows, *J* and *K* respectively.

Numerous strategies have emerged recently to achieve the Zero Energy Building (ZEB) target, defined as a structure capable of meeting its energy demands solely through renewable sources. The ZEB concept, defined by Eq. (1), remains unaltered over the past decade without revision or critical evaluation. Influential studies, such as those stemming from the IEA SHC Task 40 concluded in 2013, have shaped ZEB discussions (SHC – Solar Heating & Cooling Programme, & IEA – International Energy Agency, 2015). However, after almost a decade, the literature has lacked exploration or reassessment of the ZEB definition, leaving critical issues unresolved. The limitations of the ZEB definition primarily center on three aspects:

- **Physical boundary**. Altering the perimeter of energy analysis impacting building energy flows yields differing outcomes even within the same building.
- **Weighting system**. The choice of a weighting factor determines the energy balance metric. A static and generalist weighing system does not reflect the importance of this balance variable.
- **Analysis timeframe.** Eq. (1) defining ZEB relies on annual or monthly energy balances, failing to capture the dynamic behavior of buildings.

The limitations evident in the use of the energy balance also extend to the utilization of Key Performance Indicators (KPIs) supporting the definition of ZEBs. KPIs serve to condense complex energy performance into singular indicators, facilitating comprehension and evaluation of specific building characteristics. Similar to energy balance considerations, the indicators associated with the ZEB concept typically represent static performances averaged annually, employing fixed physical boundaries of analysis that fail to capture the true dynamic nature of buildings. Among the numerous KPIs used, this paper references Self Sufficiency (*SS*), Self Consumption (*SC*), and Renewable Energies Ratio (*RER*).

SS gauges a building's ability to function independently from external energy sources (Amato et al., 2021), formulated in Eq. (2) (refer to Fig. 2 for a clearer illustration of energy flows).

$$SS = \frac{\text{Energy generated and used onsite}}{\text{Energy load}} = \frac{\mathrm{G_{use}}}{\mathrm{L}} \tag{2}$$

SC delineates the proportion of an energy flow produced and directly consumed by the building itself (Gudmunds et al., 2020), using Eq. (3).

$$SC = \frac{\text{Energy generated and used onsite}}{\text{Energy generated onsite}} = \frac{\mathrm{G}_{use}}{\mathrm{G}} \tag{3}$$

RER assesses the proportion of renewable energy use within the building's energy balance (Musall & Voss, 2014). Its definition involves energy exchanges across source boundaries, necessitating the use of primary energy weighting factors, as per Eq. (4) (Kurnitski, 2013).

$$RER = \frac{G + \mathrm{D^{REN}}}{G + \mathrm{D^{TOT}} - \mathrm{E^{TOT}}} \tag{4}$$

where the superscripts $^{\mathrm{REN}}$ and $^{\mathrm{TOT}}$ indicate the energy share attributable to renewable or renewable plus non-renewable sources, respectively. Table 1 provides an insightful overview of presented KPIs relevant to building energy performance, outlining their distinct advantages and disadvantages in a comprehensive manner.

Table 1
Advantages and Disadvantages for adopted Key Performance Indicators (KPIs).

KPI	Advantages	Disadvantages
Self Sufficiency (*SS*)	• Measures autonomy from external sources. • Demonstrates on-site generation capacity.	• Simplifies energy autonomy without considering demand. • Focuses solely on independence from external sources.
Self Consumption (*SC*)	• Identifies directly utilized on-site energy. • Indicates efficiency of on-site consumption.	• Neglects surplus energy generated and not consumed. • Overlooks energy distributed back to the grid.
Renewable Energy Ratio (*RER*)	• Reflects the proportion of renewable energy used. • Evaluates renewable energy utilization.	• Depends on precise assessment of primary energy factors. • High energy exports alter its significance.

Studies in the literature, reviewed in the following section, have individually investigated limitations on the physical boundary, the weighting systems, and the time interval of the analysis, achieving important results towards the ZEB target.

1.2. Strategies to achieve zero energy target: literature review

The pursuit of Zero Energy Buildings presents a captivating yet intricate challenge within the realm of construction. This endeavor demands not only academic exploration but also the pragmatic implementation by designers. Recent strategies have primarily concentrated on addressing the constraints inherent in the definition of Zero Energy Buildings to achieve this ambitious objective. This section delineates pertinent findings from existing literature, which extensively examines the confines associated with Zero Energy Building paradigms highlighted in Section 1.1 — specifically, the delineation of physical boundaries, the establishment of weighting systems, and the temporal scope of analysis. The literature offers significant insights and pivotal strategies aimed at fostering energy-efficient and sustainable buildings to accomplish the goal of zero energy performance, however, focusing on individual critical aspects without ensuring a holistic approach.

The role of the physical boundary, often declined as the relationship between buildings and their districts is seen as a key strategy to achieve ZEB targets. For instance, Zhou et al. (2021) conducted a recent study using battery cycling aging strategies and flexible vehicles-to-buildings interactions to achieve a positive energy district target. By expanding the physical boundary of a single building, they achieved better overall performance. Similarly, Bruck et al. (2022) achieved a similar goal using different strategies, focusing on building envelope retrofitting, which is particularly crucial for buildings in colder climates. Many studies have considered district heating networks as a tool to achieve ZEB targets on a district scale. They explore various approaches, such as integrating solar thermal systems (Abokersh et al., 2021), using decentralized heat pumps in fifth-generation networks (Bilardo et al., 2021; Calise et al., 2022), integrating waste heat from thermal waste (Nihal et al., 2023; Reddick et al., 2020), and optimizing energy production and demand (Weinberger et al., 2021).Additionally, research has focused on the logic of electricity exchange within districts (Jokinen et al., 2022; Pinto et al., 2022), drawing attention to energy communities as a rapidly expanding reality worldwide (Bilardo et al., 2020; Lopes et al., 2016; Mittal et al., 2019). All these studies share the use of flexible physical boundaries of analysis beyond single buildings, which is foundational to the definition of ZEB. They demonstrate that limiting analysis to a single building would not yield the same performance results, confirming the significance of the physical boundary in defining ZEBs.

Regarding weighing systems in the ZEB concept, numerous studies emphasize the importance of valorising different energy flows in building balances and comparing buildings in various geographical contexts. Troup et al. (2020) explored the impact of conversion factors on building energy models, highlighting how spatial and temporal differences in electricity grids significantly affect weighting factors. Fumo and Chamra (2009) investigated managing Combined Cooling, Heating, and Power (CCHP) systems to ensure optimal weighting factor values and reduce primary energy consumption. Among the most widely used weighting factors for evaluating ZEBs, primary energy conversion factors are the most adopted. Bilardo et al. (2022) demonstrated significant variations in primary energy factors (PEF) for various European countries between 2000 and 2020, providing insights for future legislative developments in the ZEB concept. The dynamic impact of energy conversion factors also influences Life Cycle Assessment (LCA) analyses (Negishi et al., 2018). These studies underscore the importance of the energy weighting method in defining ZEBs and developing strategies for high energy performance buildings. The weighting system not only acts as a fundamental variable in the energy balance but also guides optimization strategies and fuel switching when multiple energy sources are present (Ferrara et al., 2015).

Regarding the analysis time frame, assessing the balance of buildings presents some challenges. Dynamic energy simulations of buildings are foundational in research but are less commonly applied at a legislative level (Pérez-Lombard et al., 2009). Several studies have shown that current assessments of energy performance certificates often deviate from reality (Figueiredo et al., 2018; Kelly et al., 2012), indicating the need for updates (Narula, 2013). In some cases, dynamic assessment tools have been applied in specific assessments in Australia to reduce building performance gaps (Kang et al., 2022). The scientific community agrees on the importance of dynamic energy evaluations to overcome limitations related to annual or monthly considerations (D'Agostino et al., 2022). Studies like Savolainen and Lahdelma (2022) explored the optimization of renewable sources with energy storages, conducting analyses at detailed time intervals of 15 min. Zhan et al. (2023) studied energy flexibility strategies to increase the self-sufficiency of a multi-zone office. Lu et al. (2022) emphasized the importance of evaluating the real-time energy imbalance, not just the annual zero balance, when assessing the energy flexibility of ZEBs.

Despite many studies focusing on specific aspects of ZEBs, there is a need for a broader and more applicable definition of high-performance buildings within a larger context, in line with the new concept of Zero-emission Building as stated by the 3rd EPBD recast. The interconnected variables of a building's energy balance require a comprehensive performance assessment method that considers their mutual relationship. The proposition put forth in this paper underscores the imperative necessity for a holistic approach in shaping future definitions and strategies for a sustainable transition of the building stock.

1.3. Aim of the work

Expanding upon the constraints concerning the establishment of a universally accepted definition for Zero Energy Buildings, this work aims to define a new framework for the analysis of high energy performance and Zero-emission Buildings. A novel concept termed Zero Power Building (ZPB) is introduced as a departure from the constraints linked to the Zero Energy Building definition, emphasizing both methodological aspects and practical applications. Section 2 delves into the methodological foundations of the Zero Power Building, outlining its definition and evaluation methods, which transcend traditional energy balance and static KPIs. In Section 3 the ZPB concept is applied to the performance assessment of an existing case study, consisting of 7 multi-family residential buildings. Section 4 collects the results achieved and compares the Zero Energy with the Zero Power approach, accommodating flexible boundary condition in terms of physical boundary and timeframe of analysis. This section scrutinizes the distinction between the physical boundaries of individual buildings and the encompassing district, exploring performance metrics across annual and hourly scopes.

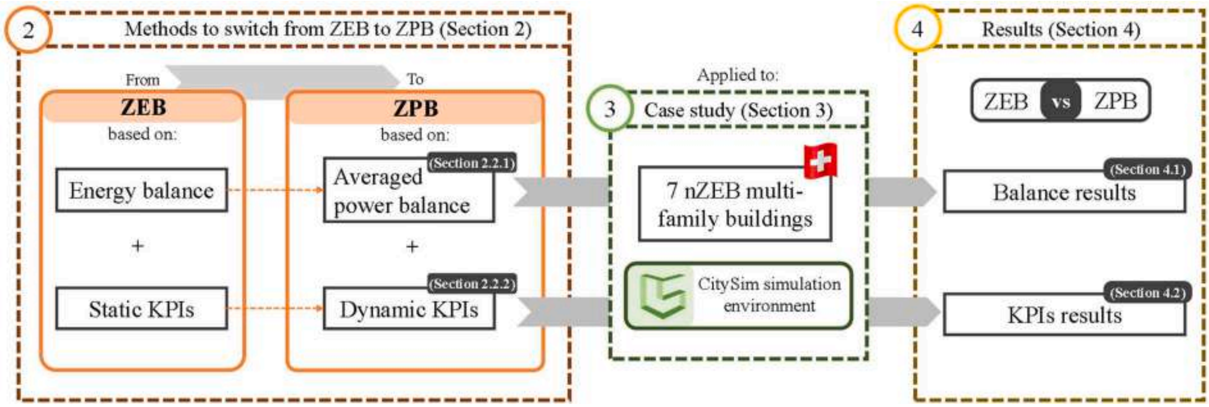

Fig. 1. Paper structure breakdown.

In Section 5 the achieved results are discussed, and the possible implications of the work are considered. Fig. 1 delineates the breakdown of subsequent sections for reference.

2. Methodology

2.1. From zero energy to zero power buildings: a new framework

Eq. (1) is the basis of the definition of Zero Energy Building. However, a more adequate expression of the same relationship should specify the physical perimeter of analysis of the energy balance (b) and the reference time of analysis t_{ref} for the j-th and k-th energy flow E. The result is expressed by Eq. (5).

$$E_{bal,t_{ref}} = \sum_{j=1}^{J} E_{j,t_{ref}} \cdot w_{j,t_{ref,w}} - \sum_{k=1}^{K} E_{k,t_{ref}} \cdot w_{k,t_{ref,w}} \tag{5}$$

In the classic ZEB definition, boundary b is identified as the import-export boundary, while t_{ref} is equal to a whole year. Additionally, a different analysis time interval for the energy flows (t_{ref}) and for the weighting factors ($t_{ref,w}$) should be specified, since they depend on different boundary conditions and might assume different evaluation timeframes.

Among the variables influencing the energy balance, time variable has an impact on all the others, since both the energy flows and the weighting factors are time dependent. As regards the variability of energy over time, it is necessary to re-evaluate the concept of energy through the integral of power P in the time interval Δt. Also considering the variability over the time of the weighting factor w, Eq. (6) is obtained to evaluate the weighted energy on the first interval Δt of a timeseries (form 0 to Δt), valid for any $j-$th supplied energy flow (same considerations applies for the k-th demanded flow).

$$E_{w_j,\Delta t} = \int_{0}^{\Delta t} P_j(t) \cdot w_j(t)\ dt \tag{6}$$

Considering a specific $i-$th time interval, Δt_i, the Eq. (6) assumes the generic meaning expressed in Eq. (7).

$$E_{w_j,\Delta t_i} = \int_{(i-1)\Delta t}^{i\Delta t} P_j(t) \cdot w_j(t)\ dt \tag{7}$$

Eq. (7) allows studying any weighted energy flow in a specific $i-$th interval, evaluating the trend over time of E and w. Therefore, Eq. (5) could be reformulated to study the energy balance for any $i-$th interval inside the total reference time of analysis t_{ref}, by summing each $i-$th analysis timestep, thus deriving Eq. (8).

$$E_{bal,t_{ref}} = \sum_{j=1}^{J} \sum_{i=1}^{t_{ref}/\Delta t} \int_{(i-1)\Delta t}^{i\Delta t} P_j(t) \cdot w_j(t)\ dt - \sum_{k=1}^{K} \sum_{i=1}^{t_{ref}/\Delta t} \int_{(i-1)\Delta t}^{i\Delta t} P_k(t) \cdot w_k(t)\ dt \tag{8}$$

Assuming to reduce the balance analysis time interval Δt, ideally tending to zero, Eq. (9) is derived, moving from energy balance to power balance evaluation:

$$\lim_{\Delta t \to 0} E_{bal,t_{ref}}(\Delta t) = P_{bal,t_{ref}} \tag{9}$$

The physical meaning expressed by Eq. (9) allows to evolve from the concept of (nearly/net) Zero Energy to that of (nearly/net) Zero Power. Thus, it is possible to physically argue the concept of the ZPB, i.e. a building capable of achieving high performance on a power balance, representing the building as a dynamic entity. The concept and definition of Zero Power Building is strongly dependent on the physical boundary b and on weighting factors w. It is therefore necessary that variables b and w are specified unequivocally for a correct application of the definition. Their definition will be specified in this work for a specific application to a case study.

2.2. Methods of analysis for zero power buildings

The definition of ZPB opens numerous possibilities for dynamic performance assessments for buildings. This section identifies two tools that can be used to evaluate a ZPB: i) the averaged power balance, understood as an evolution of the energy balance and ii) the KPI accuracy, interpreted as a development of the classical static KPIs.

2.2.1. The averaged power balance

In this new framework, the energy balance of the building takes on a different meaning. The annual or monthly energy balance, largely adopted to identify a ZEB, loses its usefulness. The ambition of the ZPB is to study the balance of energy flows over a time interval ideally tending towards zero. Considering a less idealistic time interval, such as the hourly interval, it is possible to evaluate the achievement of the ZPB target for each hour of a year. Following this approach, a building could only be considered a ZEB at certain instants in time. For this reason, it is useful to introduce the concept of averaged power over a time interval: given a fixed analysis interval Δt, the average weighted power in the $i-$th interval can be expressed using Eq. (10), valid for any $j-$th supplied energy flow (same considerations applies for the k-th demanded flow).

$$\overline{P}_{w_j,\Delta t_i} = \frac{E_{w_j,\Delta t_i}}{\Delta t} = \frac{1}{\Delta t} \int_{(i-1)\Delta t}^{i\Delta t} P_j(t) \cdot w_j(t)\ dt \tag{10}$$

In this work, the study of the hourly averaged power balance will be used as the first tool to evaluate the performance of a building within the

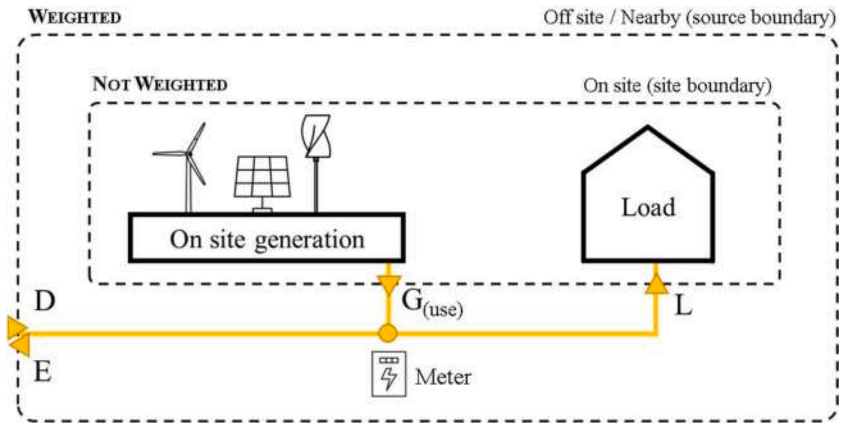

Fig. 2. Schematic of energy flows and reference boundaries in buildings.

Zero Power framework. Eq. (5) representing the energy balance of the ZEB can be studied in terms of averaged power according to Eq. (11):

$$\overline{P}_{bal,t_{ref}} = \sum_{j=1}^{J} \sum_{i=1}^{t_{ref}/\Delta t} \overline{P}_{w_j,\Delta t_i} - \sum_{k=1}^{K} \sum_{i=1}^{t_{ref}/\Delta t} \overline{P}_{w_j,\Delta t_i} \tag{11}$$

where $\overline{P}_{bal,t_{ref}}$ represents the weighted averaged power balance evaluated over the reference analysis time t_{ref}, using an analysis timestep Δt, for each j-th supplied and k-th demanded flow.

When it comes to evaluating the supplied and demanded energy flows in a building, the definition of the physical boundary has a strong impact on the results of the analysis. Main energy flows involved in the building balance are schematized in Fig. 2, identifying the building load (L), the onsite generation (G), the grid-delivered flow (D) and the grid-exported flow (E). For the sake of completeness, the energy flow generated and directly used on site (G_{use}) is also indicated. Depending on the building performance evaluation purposes, one analysis boundary is preferred over another. The figure shows two most used boundaries: the site boundary, which exclusively involves the flows generated and consumed on site by the building, and the source boundary, which involves the energy flows delivered and exported as external resources. The main difference between the two physical boundaries lies in the need to adopt weighting systems in the assessments over the source boundary, since energy flows from different sources are involved.

The fragility of the definition of ZEB also relies in the choice of a certain physical boundary adopted for the evaluation. Therefore, depending on the purposes of any building perforamnce analysis, the boundary should be declared to allow comparison between different scenarios and contexts.

2.2.2. Key performance indicators for (n)ZPB

The application of the Zero Power framework can be extended to KPIs and used for the dynamic evaluation of ZEBs, moving from static and annual indices to detailed dynamic distributions. This approach therefore makes it possible to study and improve buildings according to their realistic operation over time. Furthermore, the proposed framework is not limited to the exclusive application of KPIs to the single building. By manipulating the physical boundary, it is possible to consider energy flows that interact with a group of buildings or an entire district and consequently apply the definition of a KPI to a different perimeter. Considering *SS, SC* and *RER* as reference KPIs introduced in Section 1.1 through Eqs. (2)–(4), it is possible to study their dynamic evolution at each i th analysis timestep Δt_i using Eqs. (12)–(14).

$$SS_{\Delta t_i} = \frac{\int_{(i-1)\Delta t}^{i\Delta t} \mathrm{G_{use}}(t)\ dt}{\int_{(i-1)\Delta t}^{i\Delta t} \mathrm{L}(t)\ dt} \tag{12}$$

$$SC_{\Delta t_i} = \frac{\int_{(i-1)\Delta t}^{i\Delta t} \mathrm{G_{use}}(t)\ dt}{\int_{(i-1)\Delta t}^{i\Delta t} \mathrm{G}(t)\ dt} \tag{13}$$

$$RER_{\Delta t_i} = \frac{\int_{(i-1)\Delta t}^{i\Delta t} \left(\mathrm{G}(t) + \mathrm{D^{REN}}(t)\right)\ dt}{\int_{(i-1)\Delta t}^{i\Delta t} \left(\mathrm{G}(t) + \mathrm{D^{TOT}}(t) - \mathrm{E^{TOT}}(t)\right)\ dt} \tag{14}$$

The proposed method for the evaluation of KPIs within the Zero Power framework consists in the statistical study of the dynamic trend of the KPIs evaluated through a detailed analysis interval (hourly or sub-hourly). The distribution of the values assumed by the KPIs is therefore studied statistically, analysing the frequency of the distribution of the KPIs and their accuracy with respect to a reference value. The accuracy (a) of a given KPI, expressed by Eq. (15), replaces the concept of yearly averaged KPI.

$$\text{KPI accuracy } (\mathrm{a_{KPI}}) = \frac{\text{Number of KPI samples in acceptable interval}}{\text{Total number of samples}} \tag{15}$$

Again, adopting a consistent notation to consider the time variable, Eq. (15) can be expressed mathematically through Eq. (16).

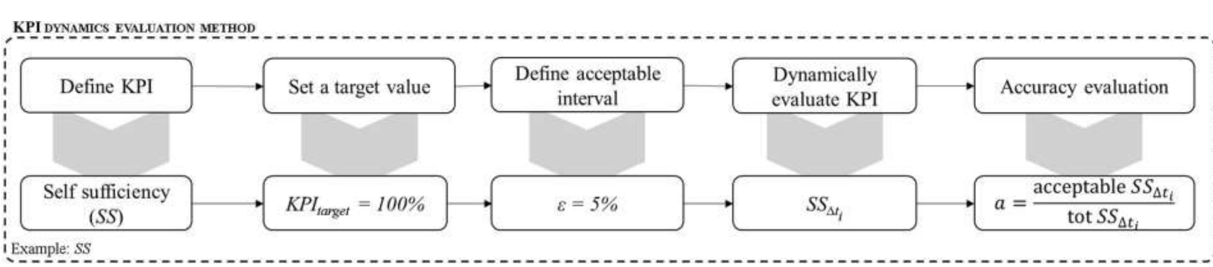

Fig. 3. KPI definition scheme in the ZPB framework.

Table 2
Conceptual transition from zero energy to zero power building performance.

Assessment methods	(n)ZEB	→	(n)ZPB
Balance	$E_{bal,t_{ref}}(\Delta t = month)$	→	$\overline{P}_{bal,t_{ref}}(t)$
KPIs	$\mathrm{KPI}_{t_{ref}}(\Delta t = month)$	→	a_{KPI}, KPI_i

$$a_{\mathrm{KPI}} = \frac{1}{t_{ref}/\Delta t} \sum_{i=1}^{t_{ref}/\Delta t} \left[\left| \mathrm{KPI}_i - \mathrm{KPI}_{\mathrm{target}} \right| < \varepsilon \right] \tag{16}$$

where $\mathrm{KPI}_{\mathrm{target}}$ represents the best achievable target value that the KPI can assume and ε represents the maximum error allowed between the $i-$th value of the KPI and the target value.

In the case of the KPIs proposed in this work, a reference value $\mathrm{KPI}_{\mathrm{target}}$ equal to 100 % is set, representing the best achievable performance, whereas maximum accepted error has been fixed to 5 %. In the Zero Power framework, Eq. (16) can be repeated for each KPI of interest. The procedure outlined in Fig. 3 defines the steps to achieve the accuracy assessment. The case of Self Sufficiency is given as an example in Fig. 3 to illustrate the framework.

Finally, Table 2 summarizes the transition from Zero Energy to Zero Power concept, identifying the different methods to evaluate its performance.

3. Case study application

After defining the methodological framework of the Zero Power Building concept, this section is dedicated to the presentation of a real existing case study. The proposed case study will be subsequently used to compare the ZEB and ZPB methodology.

The case study consists of a group of 7 nZEB buildings belonging to the same district and built in the village of Blatten-Belalp, in the canton of Valais in Switzerland. The district consists of multi-family residential buildings, built in 2010 as a holiday resort. Fig. 4 provides some real views of the case study, identifying the buildings involved.

Case study buildings are fully electric, solely relying on electricity as primary energy source. They are similar in terms of construction and intended use, with few differences in their exposure. Table 3 summarizes the main thermophysical characteristics shared by the buildings.

Space heating and domestic hot water are provided by ground source heat pumps installed for each building, integrated with photovoltaic (PV) systems installed on each roof, as shown in the model in Fig. 5. Table 4 instead collects the geometric characteristics and technical data of the buildings (numbered from B1 to B7).

A previous research study focused on the same case study, exploring energy performances (Rager et al., 2019). From the results previously achieved, the selected buildings comply with local regulatory requirements to be considered Zero Energy Buildings.

3.1. Simulation environment

Starting from the design data, the case study was modelled within CitySim environment (Kämpf, 2009). CitySim is an urban-scale validated simulation tool that allows an hourly simulation of the thermal and electrical loads of buildings, as well as their internal and surface temperatures and energy production from renewable sources (Mauree et al., 2017), necessary to implement the assessment tools set out in the methodology of this work (see Section 2) (Todeschi et al., 2021).

The virtual model was completed by defining hourly profiles of occupation, lighting and use of electrical appliances. The set point for heating is set at 20 °C, without cooling. All the design data needed to determine the thermal loads of the buildings was retrieved from the OSCARS research project (Rager et al., 2019). Afterwards, the model was upgraded with the integration of HVAC systems for heating and domestic hot water production. Each building is equipped with a geothermal heat pump serving two storage tanks on two different temperature levels (45 °C for heating and 60 °C for domestic hot water). Terrain profile has also been modelled, both in terms of the geometry of the ground (see Fig. 6) and external horizon.

Regarding weather data, different sources have been used. Through an on-site weather station, it was possible to measure the external temperature, relative humidity, solar radiation as well as wind direction and speed for the whole year 2017. These data were subsequently integrated with the weather data of the city of Montana weather station (Valais, Switzerland), through the use of the Meteonorm® software (Remund et al., 2020), concerning ground temperature, precipitation and cloudiness. The result was a climatic file built ad hoc for the next validation step of the model. Fig. 7 shows the daily variation of the external temperature trend (Fig. 7a) and of the daily beam normal irradiance (Fig. 7b), together with their average values (black lines).

3.2. Model calibration

The heating demand of the district model has been calibrated and validated through an annual monitoring campaign. During 2017, the hourly heating needs were acquired for each modelled building. A previous study (Dacos, 2017) focused on the calibration of the simulation model, using heating energy needs as a reference parameter. The

Table 3
Main thermophysical characteristics of the case study buildings.

Parameter	Value	Unit
External walls U-value	0.15	W/m^2K
Roof U-value	0.13	W/m^2K
Floors U-value	0.18	W/m^2K
Windows U-value	1.61	W/m^2K
Windows g-value	0.53	–
Infiltration rate	0.22	h^{-1}
Electrical appliances	70	MJ/m^2yr
Heating setpoint	2 0	°C
Walls reflectance	0.101	–

Fig. 4. Photographic views of the case study.[11]

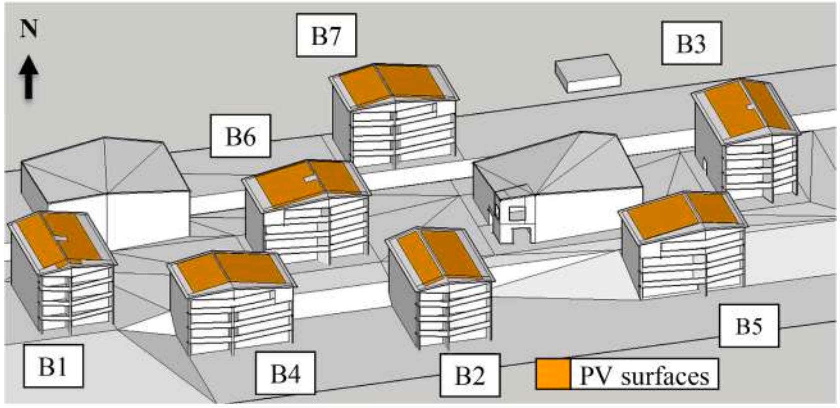

Fig. 5. Case study buildings with nomenclature and PV surfaces identification. Adapted from Dacos, (2017).

Table 4
Specific properties for case study buildings.

# Building	S_H [m^2]	V_H [m^3]	S/V ratio [-]	Thermal bridges losses [W/K]	Ventilation heat loss coefficient [W/K]	Glazing ratio [-]	Installed PV [kW]
B1	797	2521	0.32	79.18	341.61	0.46	26.52
B2	772	2590	0.30	76.87	333.84	0.47	23.80
B3	792	2535	0.31	78.28	452.43	0.44	25.74
B4	692	2311	0.30	69.89	259.69	0.41	24.48
B5	683	2311	0.30	67.90	244.42	0.41	24.48
B6	732	2247	0.33	71.63	274.78	0.43	26.78
B7	729	2260	0.32	71.39	291.31	0.43	27.30

Fig. 6. Building and ground modeling - detail from the case study. Adapted from Dacos, (2017).

parameters calibrated in the model involved infiltrations, occupancy profiles, equipment usage profiles and internal loads. All remaining design parameters were modelled according to the building characteristics set out at the beginning of Section 3. The process of calibrating the model parameters, limited to the heating demand, used initial values required by the Swiss technical standards SIA 380/1:2009 and SIA 2024, and then achieved calibrated values by means of the occupancy and utilization data of the building recorded during the monitoring campaign. The monitoring step was possible thanks to the support of the real estate company that manages the entire district. Table A1 in the Appendix groups the main parameters subjected to calibration for each modelled building. The calibration achieved excellent results: the heating demand on a yearly basis recorded a maximum error of 6.42 %, as shown in Table A2 in the Appendix.

3.3. Case study improvement scenarios

The numerical calibration process, which is not the subject of this paper, made it possible to achieve a calibrated model that represents the reference baseline for the application of the methodology proposed in this study. This foundational model was utilized to create two enhancement scenarios, aiming to assess their viability within the framework of the Zero Power Building methodology. These scenarios are outlined as follows:

- **Scenario 1** involved the integration of Battery Energy Storage Systems (BESS) in conjunction with the photovoltaic (PV) systems of individual buildings. The simulation entailed the installation of an identical electrical storage infrastructure across all buildings, preliminarily sized according to each building's electrical load. Table 5 presents the principal characteristics of the simulated batteries allocated to each building. The charging and discharging mechanisms of the storage system are governed by a control system that aligns with the building's power demand while considering any onsite power generation. Specifically, only surplus onsite generation is stored, following a legacy behavior. Furthermore, the BESS maintains a minimum State of Charge (SoC), potentially necessitating external energy sources for replenishment.
- **Scenario 2** involved implementing a unified district-wide Battery Energy Storage System (BESS) with provisions for energy sharing among buildings. To ensure an equitable comparison with Scenario 1, the district's BESS shared identical performance characteristics,

[1] Source: https://reka.ch/en/rekaholidays/reka-holiday-village-blatten-belalp

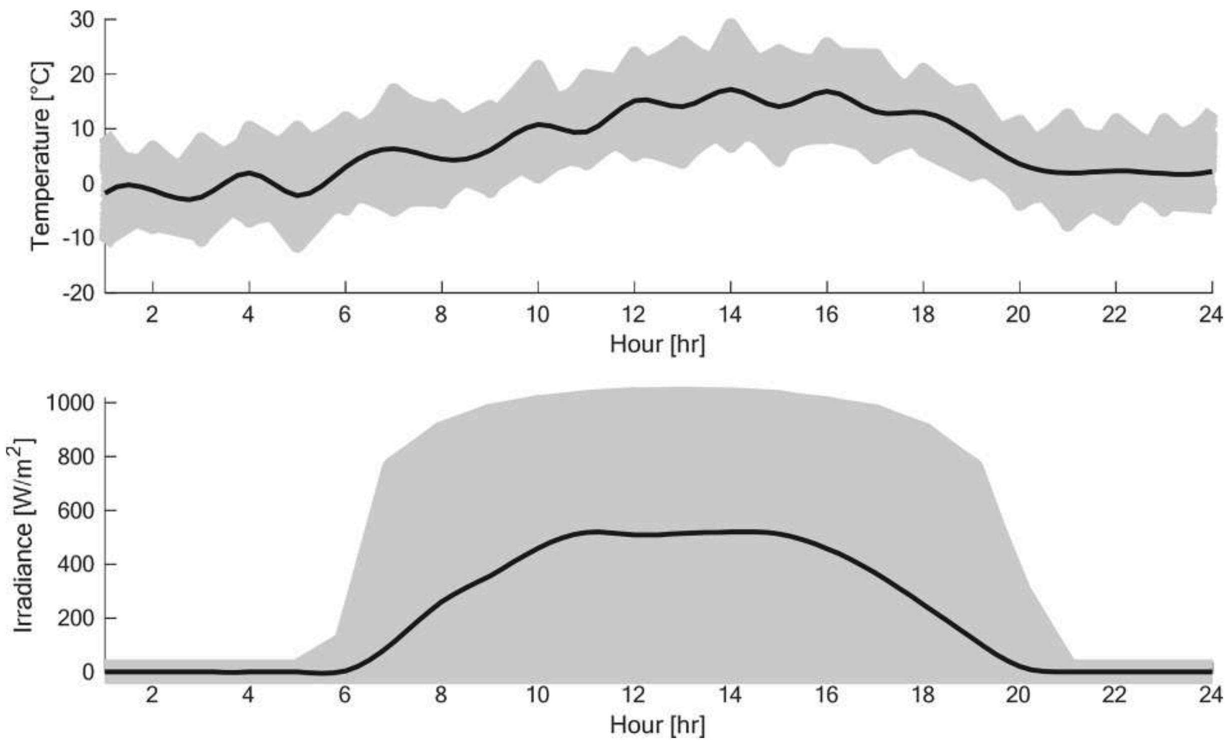

Fig. 7. Daily variation of the external temperature (a) and of the beam normal irradiance (b). Annual average values represented by the black lines.

Table 5
Main characteristics of BESS.

Parameter	Value	Unit
Total capacity	42	kWh
Charging efficiency	0.95	–
Discharging efficiency	0.95	–
Initial State of charge	0.5	–
Minimum State of charge	0.2	–
Drainage losses	0.05	–

Table 6
Summary of analysed scenarios.

	Baseline scenario	Scenario 1	Scenario 2
PV	Yes (Decentralised)	Yes (Decentralised)	Yes (Decentralised)
BESS	No	Yes (Decentralised)	Yes (Centralised)
Energy sharing	No	No	Yes

differing solely in capacity, which equated to the cumulative sum of all BESS units in Scenario 1 (7 × 42 kWh). Within Scenario 2, the introduction of a shared BESS allowed for potential electricity sharing among buildings within the district. In this context, the governing principle for energy exchange within the district was aimed at maximizing self-consumption, emphasizing energy sharing among buildings before prioritizing the charging of the shared BESS or exporting surplus energy to the external grid. In this simulation scenario shareable energy was evaluated on a district scale by Eq. (17), considering exported (E) and delivered (D) energy from each building B = 1..7.

$$E_{\text{shared}} = \min\left[\sum_{B} \mathrm{E_B}, \sum_{B} \mathrm{D_B}\right] \tag{17}$$

The model's implemented logic involves evaluating the shareable energy at each analysis timestep and distributing it proportionally among buildings exhibiting a positive energy demand. In Scenario 2, three distinct operational levels exist, each with its own priorities. In the energy production phase, the primary focus lies in optimizing district self-consumption through energy sharing among buildings. Subsequently, emphasis shifts to charging the shared Battery Energy Storage System (BESS) and, finally, exporting surplus energy to the external grid. During the prevalent consumption phase, priority reverts to enabling energy sharing, followed by discharging the shared BESS, and ultimately drawing energy from the grid.

Table 6 shows the 3 scenarios proposed in this work, which will be analysed in the next section using the Zero Power Building methodology. Furthermore, Fig. 8 schematizes the topology adopted for the two scenarios, highlighting the different positioning of the BESS and the possibility of sharing energy in Scenario 2. In addition, Site Boundary is displayed as the reference boundary for single building analysis, while

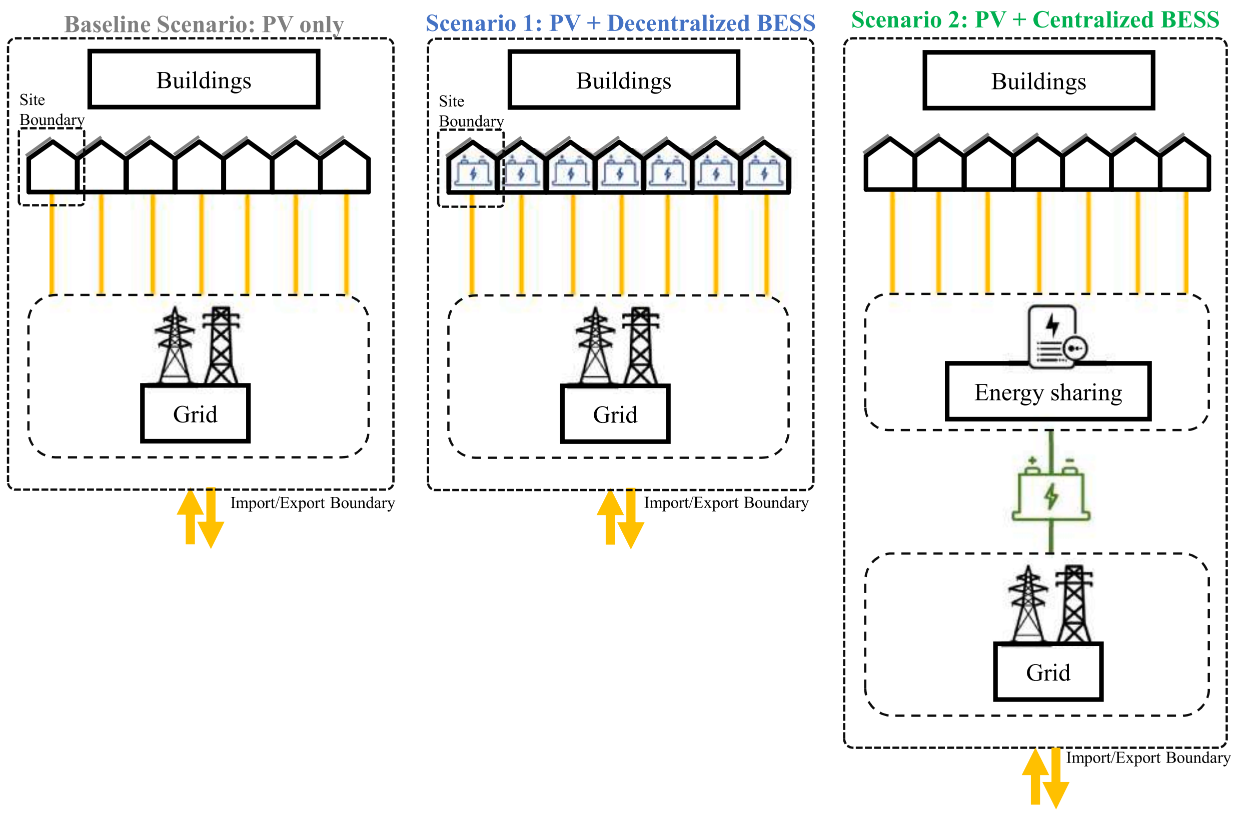

Fig. 8. Schematic comparison between topologies simulated in Baseline Scenario, Scenario 1 and Scenario 2.

Table 7
Boundary conditions variables adopted for the building balance study.

Objective	Boundary Physical boundary	Purpose	Weighting	Time detail
Energy/ Power balance study	Site boundary: building + onsite energy systems	Load/ generation balance	Final energy use on electricity carrier – no weighing	Year and Month (Energy) vs Hour (Average Power)

the Import/Export boundary is indicated as the reference boundary for the analysis involving the entire district.

4. Results

The results section delineates the findings derived from employing the two assessment methodologies expounded in Section 2.2, investigating the shift from a Zero Energy Building (ZEB) approach to the Zero Power Building (ZPB) framework. Section 4.1 focuses on the examination of energy and averaged power balances. Initially, the application of these tools was confined to a single building, facilitating a comparison between the Baseline and Scenario 1. Subsequently, the scope of analysis expanded to encompass the entire district, enabling a comprehensive comparison involving Baseline, Scenario 1, and Scenario 2. Given that

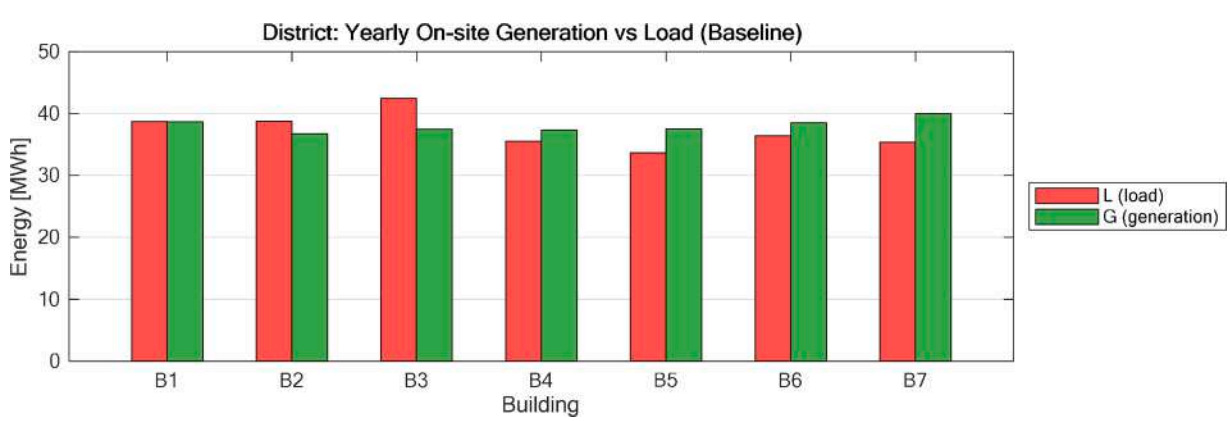

Fig. 9. Yearly energy balance (Load vs Onsite generation) for each building (Baseline).

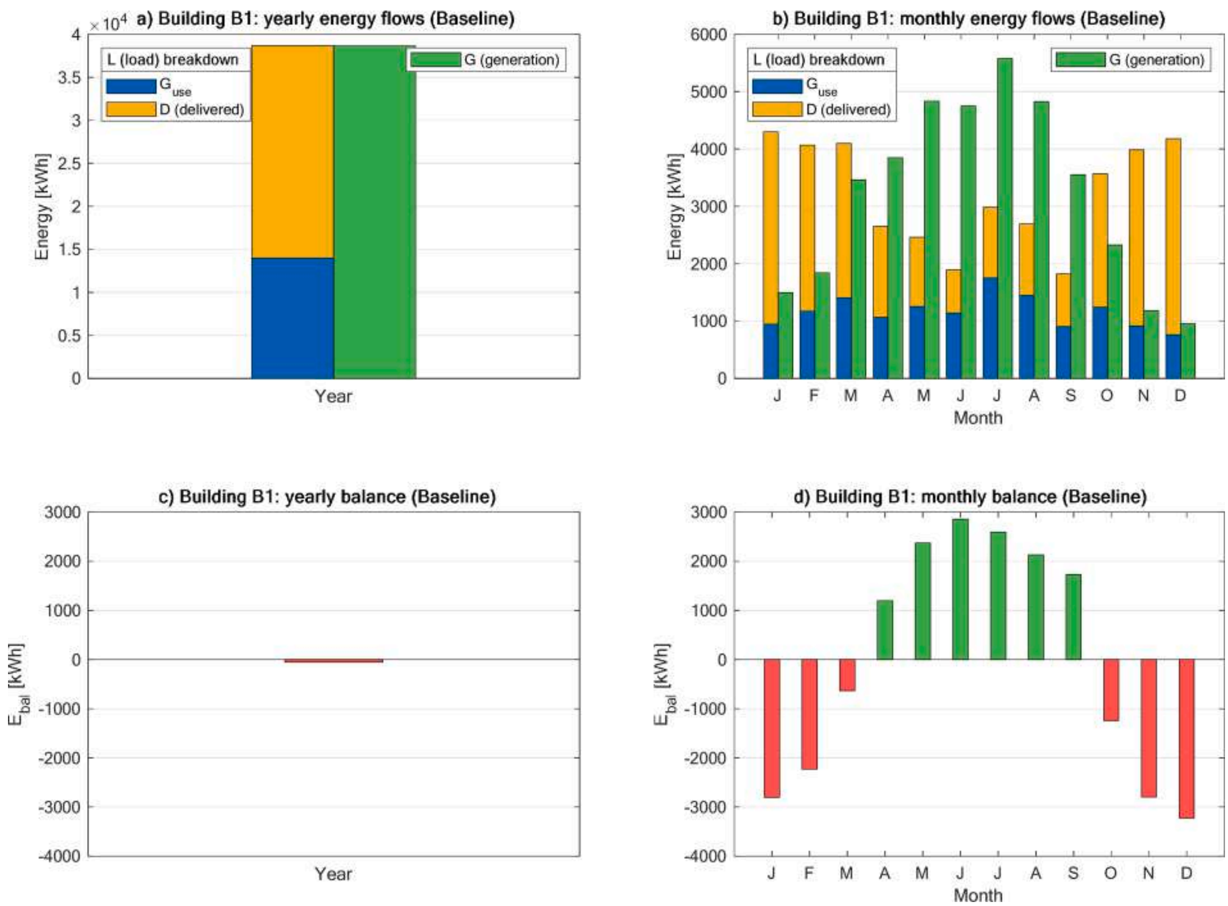

Fig. 10. Yearly and monthly energy balance analysis for B1 in the Baseline scenario.

Scenario 2 introduces a centralized district storage, maintaining a consistent analytical boundary becomes imperative to illustrate the adaptability of the Zero Power framework. Following this, Section 4.2 delves into investigating the influence of the proposed Key Performance Indicators (KPIs). Once more, the impact of the Zero Power approach is explored at the building level, contrasting KPIs and their accuracy between the Baseline and Scenario 1. Finally, the outcomes pertaining to a Zero Power District are elucidated, presenting the KPI results and accuracy at the district level, with Scenario 2 included in the comparison. Specifically, there's a proposed and highlighted distinct division between the analysis conducted on a single building level and the analysis conducted on a district level. This decision arises due to the nature of the energy sharing method employed in Scenario 2, which necessitates comparison through distinct physical boundaries of analysis. Consequently, embracing the Zero Power framework mandates defining a specific physical boundary of analysis for individual buildings (Site Boundary) and another for district analysis (Import/Export Boundary).

4.1. Energy balance vs averaged power balance: ZEB vs ZPB

The energy balance is the first tool adopted to evaluate the case study performance. For an unequivocal analysis, the balance variables are specified in Table 7. The physical boundary taken into consideration is the site boundary, which includes the building and its on-site generation systems. The purpose of this boundary is to study the load/generation balance. Since the analysis deals with fully electric buildings, the results are proposed in terms of final energy, using the electricity carrier. Therefore, no weighing systems are applied. Finally, the temporal detail of the analysis will focus from year and month (energy balance) to hour (average power balance).

Given the assumption of the analysis, Fig. 9 initially shows the result of the annual energy balance for the 7 buildings of the case study, for the reference baseline scenario, comparing the energy load (L) with the onsite energy generation (G). According to these results, all buildings can be defined as ZEB or nearly ZEB, since the onsite generation meets the building load.

Given the buildings' energy similarity, first analysis will only focus on building B1. Building B1 was chosen as the representative building of the district as its performance is close to the yearly breakeven between production and consumption (see Fig. 9), so that the divergences from the ZEB condition are as evident as possible (see Appendix A for buildings' energy demand details). Fig. 10 analyses the annual (Fig. 10a) and monthly (Fig. 10b) load and on-site generation of B1, separating the energy load into its shares of energy from onsite generation (G_{use}, blue bar) and delivered form the grid (D, yellow bar). Energy balance (E_{bal}) is also reported annually and monthly in Fig. 10c and d, respectively, highlighting a negative (red bars) or positive (green bars) result. On a yearly basis, building B1 can be considered ZEB, while monthly it behaves as a plus ZEB in the summer months, missing the ZEB target in the winter period (negative balance).

Fig. 11 presents findings pertaining to Scenario 1, centering on Building B1 and its incorporation of an electric storage system (BESS). Compared to the reference Baseline scenario, Scenario 1 performs worse in terms of both annual and monthly energy analysis. The BESS causes on-site generation to decrease due to charging, discharging, and drainage losses. Simultaneously, the building's energy load increases as it requires a minimum state of charge when on-site generation is unavailable. This leads to an overall energetic worsening.

The annual and monthly energy balance (Fig. 11c and d) further illustrates this decline, with an evident increase in energy demand (red bar) from the building on a yearly basis. Consequently, the building loses its ZEB status annually, although monthly performances remain

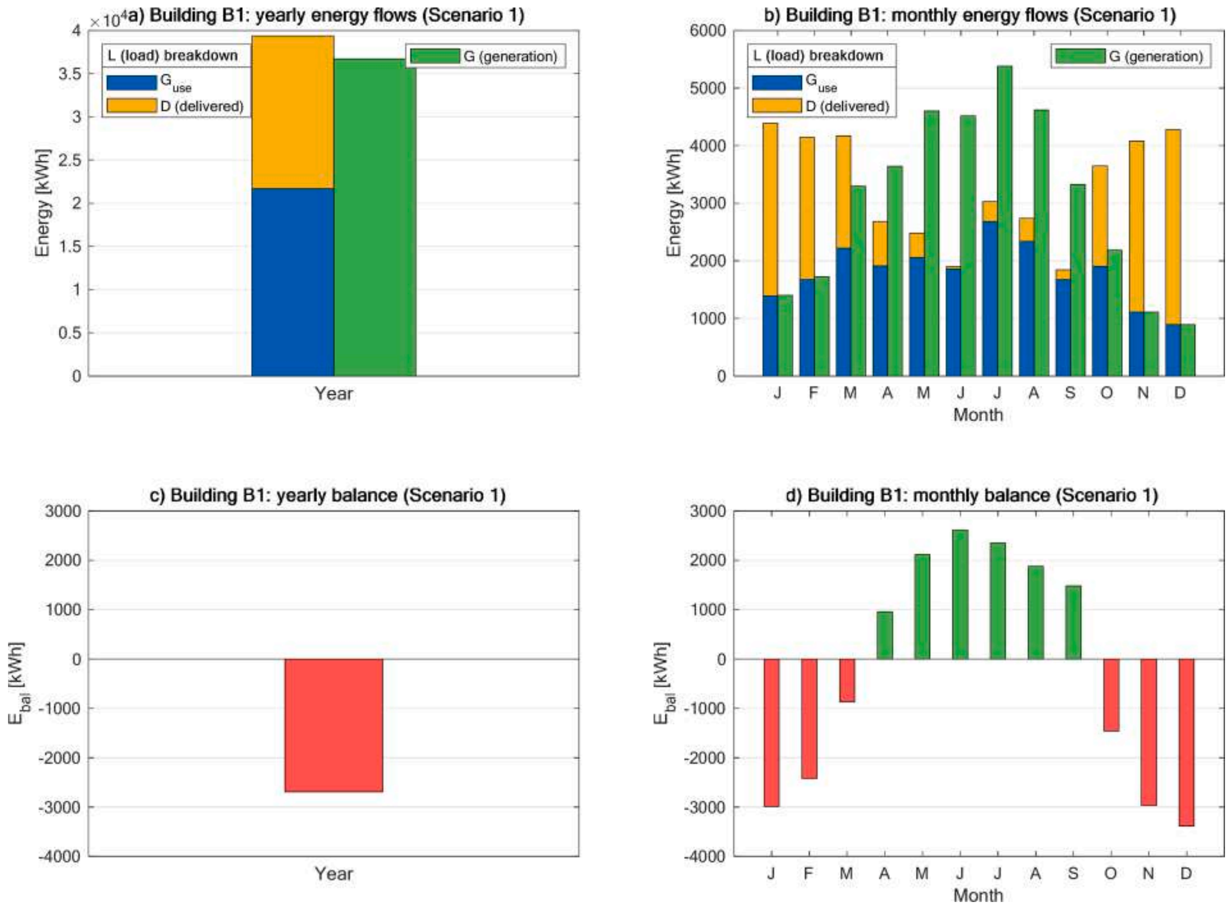

Fig. 11. Yearly and monthly energy balance analysis for B1 in Scenario 1.

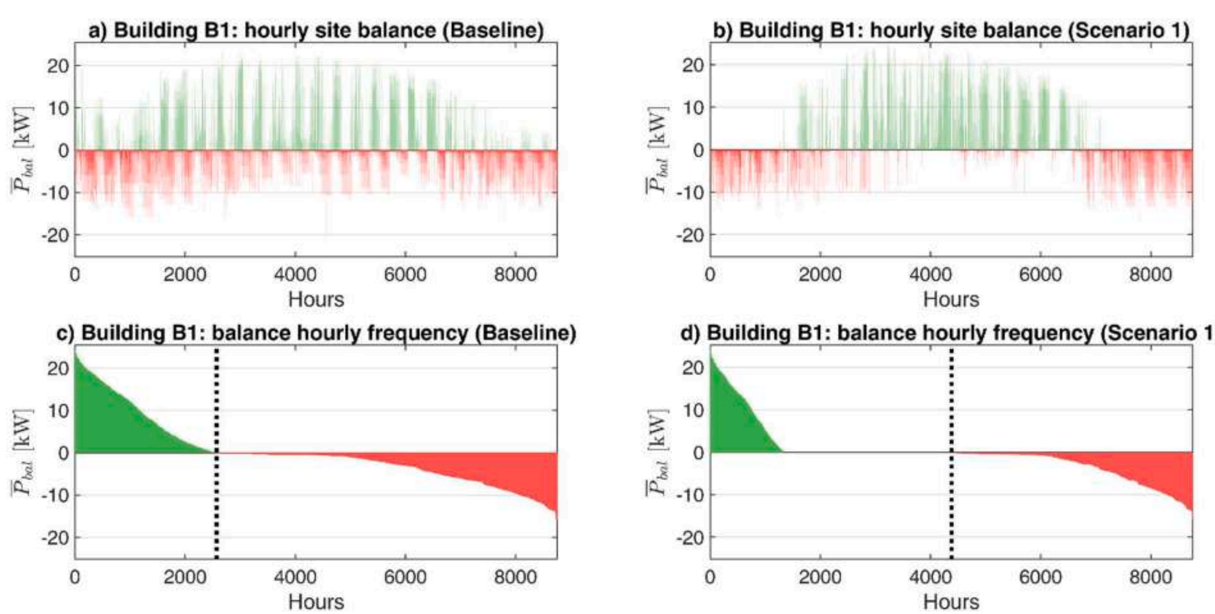

Fig. 12. Hourly average power balance for Baseline scenario (a) and Scenario 1 (b) with sorted representation (c-d).

similar to the previous scenario, showing seasonal variations.

The installation of the BESS brings benefits to Building B1 by significantly increasing the share of on-site energy consumption (G_{use}, blue bar) in Scenario 1. Although the overall energy balance might suggest that B1 loses its ZEB status, neglecting this improvement would be misleading. Using the Zero Power concept with a one-hour time resolution, Fig. 12 compares $\overline{P}_{bal}$ results between the reference Baseline scenario and Scenario 1. The averaged hourly power balance is represented for the entire year (Fig. 12a and b), along with its sorted distribution (Fig. 12c and d), using green and red bars for a positive or

Table 8
Boundary conditions variables adopted for the district balance study.

Objective	Boundary Physical boundary	Purpose	Weighting	Time detail
Energy/ Power balance study	Import/Export boundary: entire district	Import/ Export balance	Energy use on electricity carrier – no weighing	Year (Energy) vs Hour (Average Power)

negative balance, respectively.

The application of the Zero Power concept leads to different conclusions compared to the previous analysis using annual and monthly energy balances. Building B1 achieves the Zero (or plus) Power target for 50 % of the hours in Scenario 1, compared to only 29 % in the Baseline scenario. Additionally, this method allows analysis of how long the building can operate off the grid, which is vital for assessing potential power outages. The Baseline scenario enables approximately 2540 h per year (3.48 months) of off-grid operation, while Scenario 1 increases this to 4380 h (6 months). Conclusively, when considering the Zero Power concept, Scenario 1 performs better, and the installation of the BESS should be seen as advantageous for Building B1.

The presented case study shows that the ZEB approach doesn't properly credit the benefits of installing a battery energy storage system, revealing limitations and misleading information in its application. Instead, the Zero Power concept provides a more realistic and dynamic evaluation of a building's behavior.

Shifting focus to Scenario 2, the study involves the entire district to assess its energy performance, including energy sharing and storage. The ZPB methodology is still employed, but the physical boundary is extended to cover all seven buildings in the district. This change affects energy flows, and particularly the relationship between energy exported to the external grid and energy delivered from the grid to the buildings. The analysis now examines the import/export balance for the entire district, and the methodology's flexibility allows for adaptation to variations in the physical boundary, leading to the concept of a "Zero Power District". Table 8 provides updated boundary conditions for this analysis, supplementing the information in Table 7.

Fig. 13 compares three scenarios (Baseline, Scenario 1, and Scenario 2) using the Zero Energy concept analysis. Fig. 13a displays the annual imported and exported energy amounts, and Fig. 13b shows the E_{bal} for each scenario. The Baseline scenario is the only one with a positive energy balance (green bar), indicating it predominantly exports energy. On the other hand, Scenario 1 and 2 show negative balances, requiring more energy imports than exports (red bar). Furthermore, Scenario 2 has the highest need for grid-imported energy, around 20 MWh per year. While the definition of a Zero Energy district only applies to the Baseline scenario annually, the absolute values in Fig. 13a reveal that BESS systems (decentralized or centralized) have a positive impact, significantly reducing the district's dependence on the external grid.

The application of the Zero Power methodology yields different results for district performance in the proposed scenarios. Fig. 14 shows the sorted trend of $\overline{P}_{bal}$, indicating hours with prevailing export (positive balance) and import (negative balance). The dashed line represents hours when the entire district operates under "Zero Power" conditions.

Contrary to the annual energy balance findings, the ZPB methodology shows that the Baseline scenario achieves a positive balance for only 29 % of the annual hours (Fig. 14a). However, Scenarios 1 and 2 perform better, with positive balances for 45 % and 51 % of the hours, respectively (Fig. 14b and c). Additionally, the Zero Power approach quantifies the time the district can operate independently from the external grid: 2540 h (3.48 months) in the Baseline scenario, 4292 h (5.88 months) in Scenario 1, and 4468 h (6.12 months) in Scenario 2.

The proposed methodology shows that installing a centralized Battery Energy Storage System (BESS) with energy sharing (Scenario 2) is the most effective approach to achieving the Zero Power target. Scenario 2 not only performs better in terms of averaged power balance but also offers cost advantages compared to Scenario 1, as centralized storage systems have lower installation, maintenance, and operational costs than decentralized solutions. The methodology highlights the value of

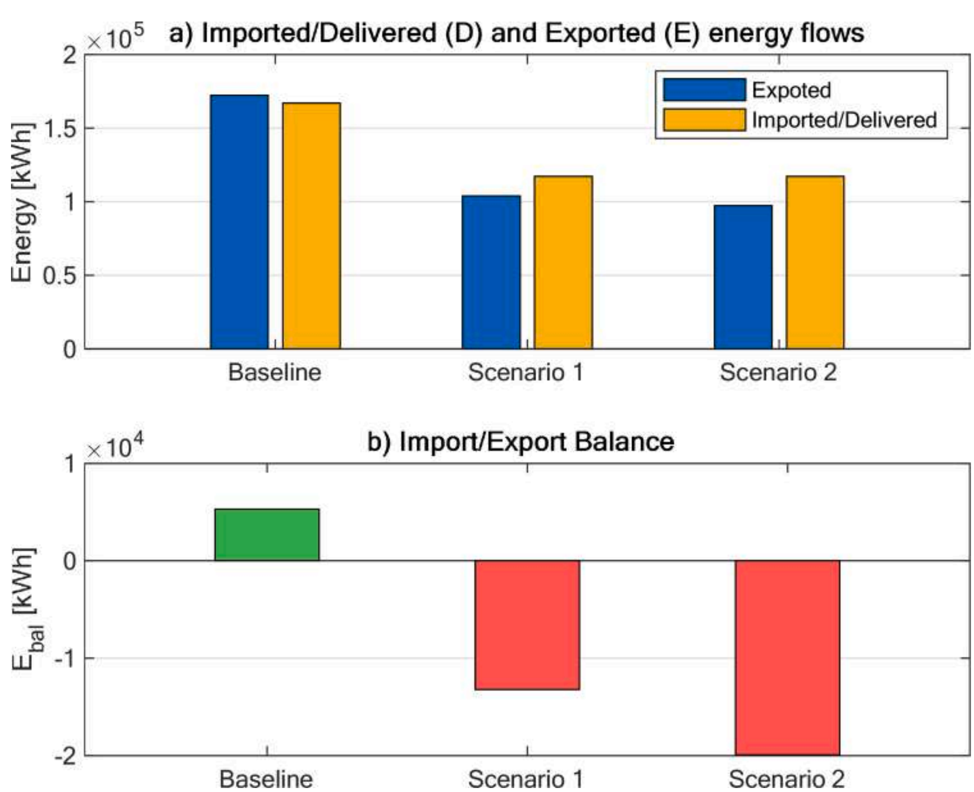

Fig. 13. Energy analysis of the district in the three scenarios: comparison between imported and exported energy (a) and annual energy balance (b).

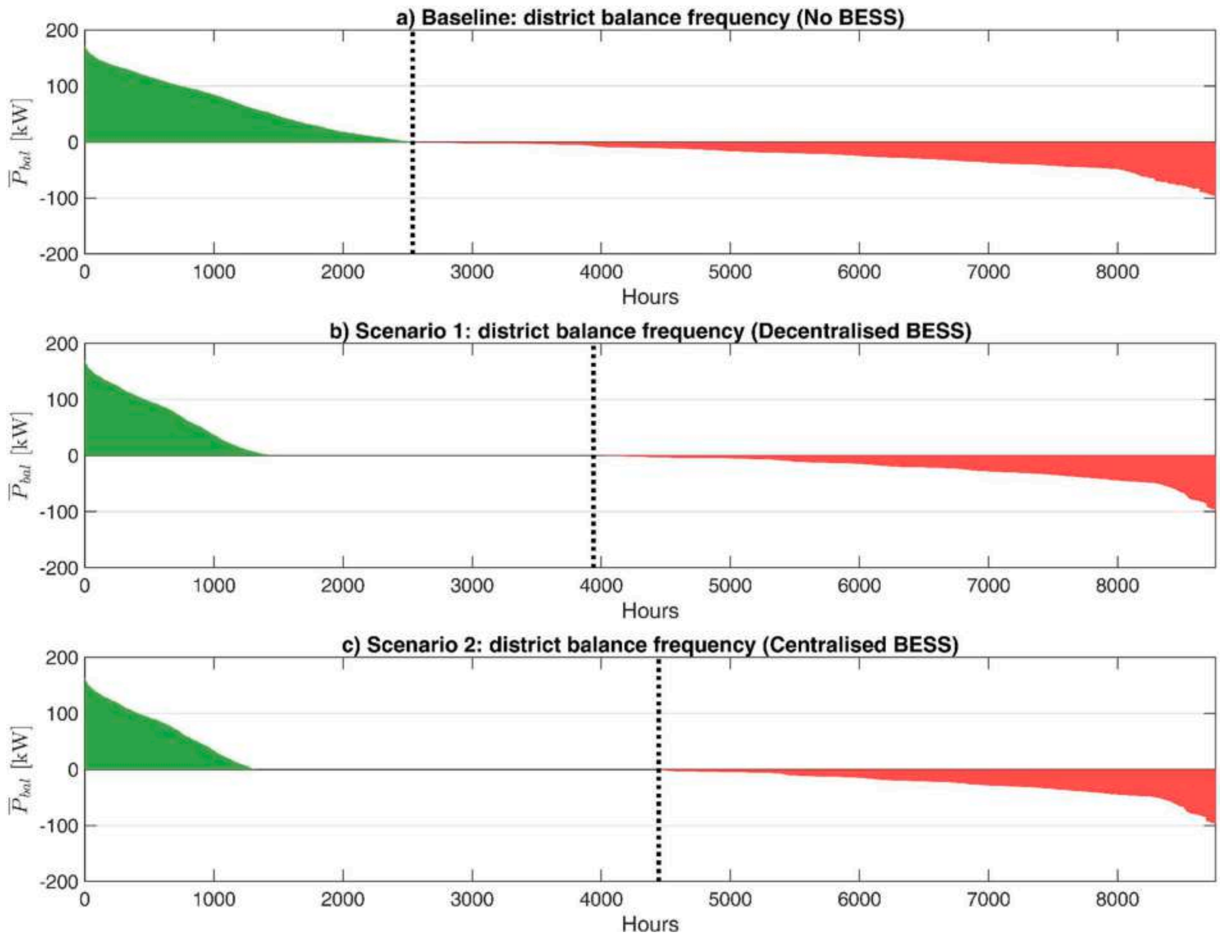

Fig. 14. Sorted trend of hourly average power balance for the Baseline scenario (a), Scenario 1 with decentralised BESS (b) and Scenario 2 with centralized BESS and energy sharing (c).

storage batteries, which were previously disregarded in achieving the Zero Energy target. Once again, the Zero Power concept challenges the traditional criteria for evaluating Zero Energy Buildings, considering not only individual buildings but also their interactions within a district context.

4.2. Dynamics KPIs: from ZEB to ZPB

This section focuses on analysing three Key Performance Indicators (KPIs) - Self Sufficiency (*SS*), Self Consumption (*SC*), and Renewable Energy Ratio (*RER*) - identified in Section 2.2.2. Weighting factors are applied to *RER* evaluation, since involves energy flows from external resources. Adopted weighting factors consider European average primary energy factors for electricity, according to EN ISO 52000–1:2018 (CEN, 2018) ($w_{nren} = 2.3$ and $w_{ren} = 0.2$).

Results are presented in Fig. 15, comparing the Baseline scenario (red bars) with Scenario 1 (green bars) for all buildings in the district. Scenario 1 outperforms the Baseline scenario in all indicators: *SS* improves by 20 %, *SC* by 22 %, and *RER* by 7 %. This contradicts the earlier analysis of the yearly energy balance in Fig. 10 and 11, indicating that the benefits of installing the BESS are perceivable when using the proposed KPIs. However, it is important to note that these performance indicators do not replace the definition of Zero Energy Building (ZEB) but rather complement it. They represent static performance averaged over a year and do not capture building dynamics. Throughout this analysis, a similarity in the performance of the case studies is observed, leading to a continued focus on building B1, representative of the district.

The proposed Zero Power Building methodology allows for a dynamic analysis of Key Performance Indicators (KPIs), providing insights into real building performance. Yearly heatmaps in Fig. 16 show the dynamic evolution of KPIs for the reference Baseline scenario (left) and Scenario 1 (right). The red color highlights hourly values within 5 % (ε) of the maximum value ($KPI_{target} = 100$ %), as established in previous Section 2.2.2. Overall, Scenario 1 demonstrates substantial improvements, giving valuable insights into KPI dynamics.

For Self Sufficiency (*SS*), Scenario 1 shows grid independence during central hours of the day and the summer season, extending self-sufficiency even during night hours with the help of the BESS (Fig. 16a and b). Self Consumption (*SC*) improves noticeably in Scenario 1, particularly during hours of lower solar radiation, suggesting a slight mismatch between PV generation and building load (Fig. 16c and d). Both *SS* and *SC* exhibit zero performance periods between day 200 and day 250, associated with null self-consumption ($G_{use} = 0$) and reduced loads, possibly due to building closures (see Figs. A1 and A2 in the Appendix).

Regarding the weighted KPI, Renewable Energy Ratio (*RER*) also improves in Scenario 1 compared to the Baseline (Fig. 16e and f). However, its dynamic trend is similar to *SS* due to the limited renewable share of electricity considered in the primary energy factors according to EN ISO 52000–1:2018. It is important to note that the results in Scenario 1 are based on preliminary BESS sizing without optimization procedures.

The dynamic analysis of performance indicators allows for the calculation of the accuracy of each Key Performance Indicator (KPI) with respect to an acceptable reference interval of 5 % from the target

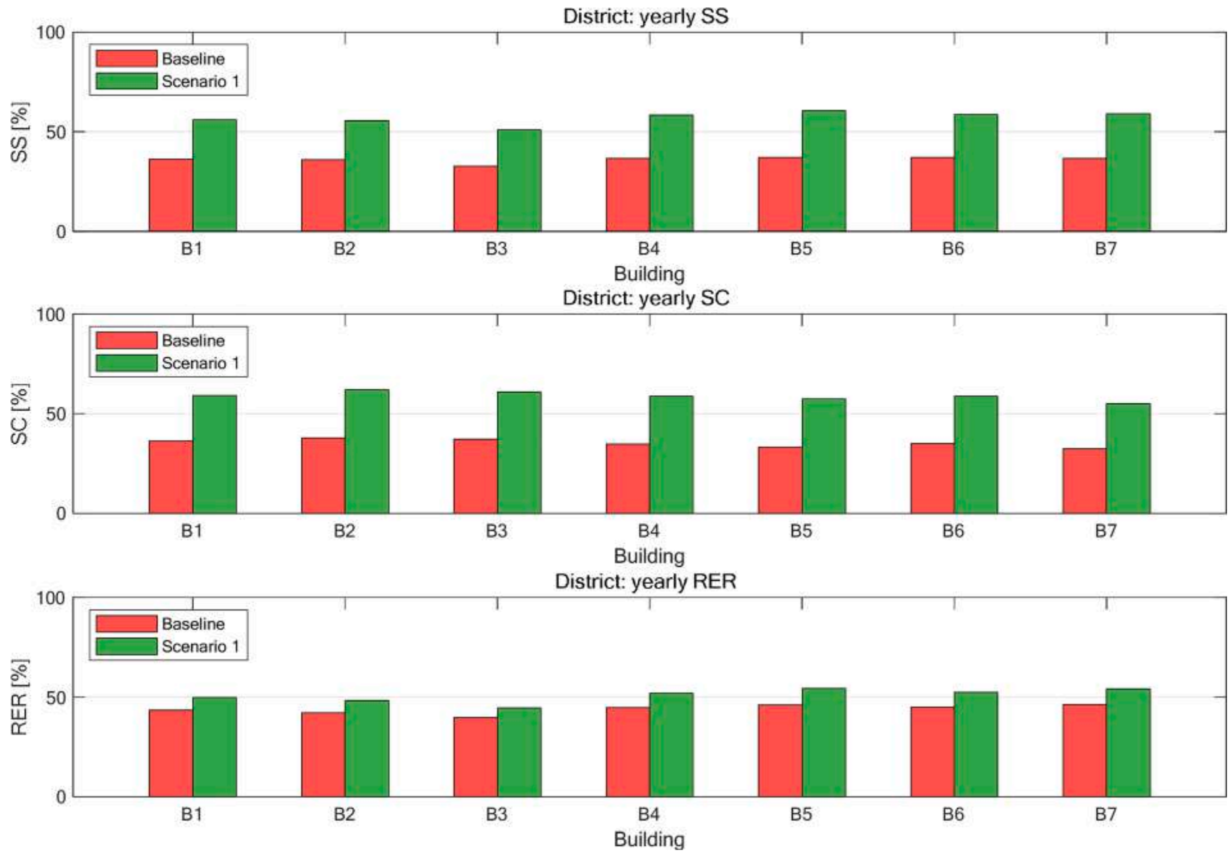

Fig. 15. Yearly KPIs for case study buildings.

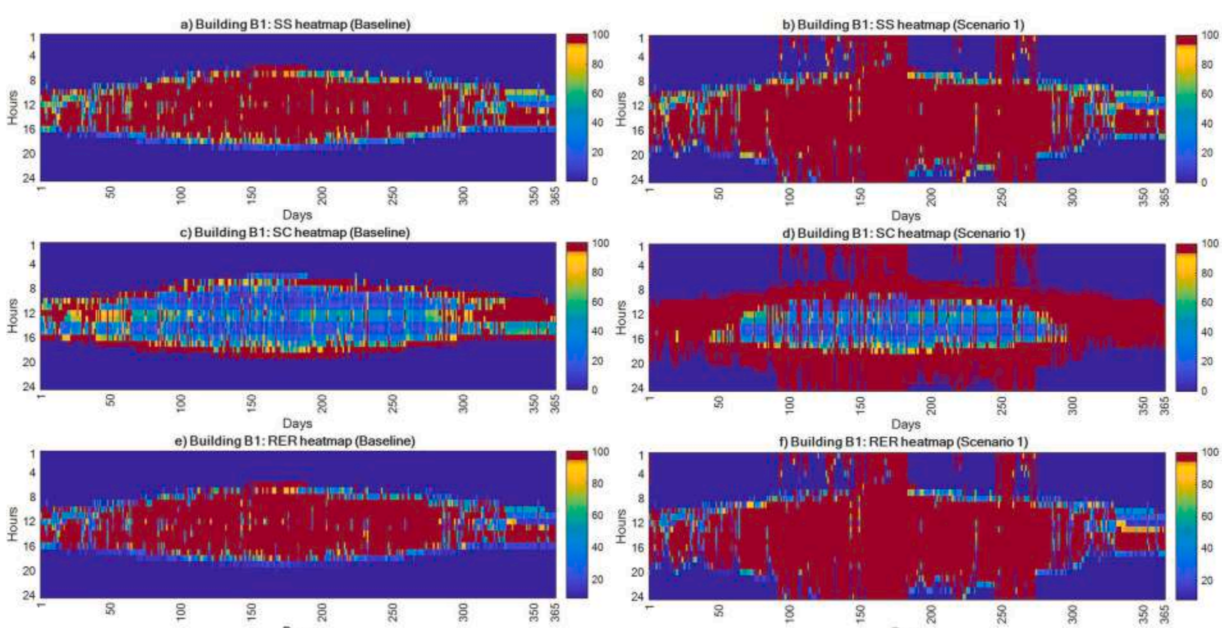

Fig. 16. KPIs heatmaps visualizing hourly fluctuation (y-axis) mapped across each day of the year (x-axis). KPIs comparison between Baseline scenario and Scenario 1: SS (a-b), SC (c-d), RER (e-f). Red area indicates acceptable values for accuracy calculation.

value (100 %). The concept of KPI accuracy, introduced in this work, is essential for understanding the percentage of time a KPI meets certain performance criteria and serves as a guiding indicator for design choices and optimization processes. Accuracy represents a synthetic performance indicator that complements the evaluation of annual KPIs by providing insights into the dynamic trends of the KPIs. The comparison between the Zero Energy Building (ZEB) and Zero Power Building (ZPB) approaches, as shown in Table 9, reveals significant improvements in both KPIs and accuracy when Baseline and Scenario 1 are compared.

In terms of Self Sufficiency (*SS*), annual KPI improves from 36.19 %

Table 9
Annual KPIs and their dynamic accuracy a.

Building: B1	KPI [%] Baseline	KPI [%] Scenario 1	a_{KPI} [%] Baseline	a_{KPI} [%] Scenario 1
SS	36.19	56.07	29.97	50.57
SC	36.24	59.15	13.77	45.03
RER	43.42	49.73	29.58	49.94

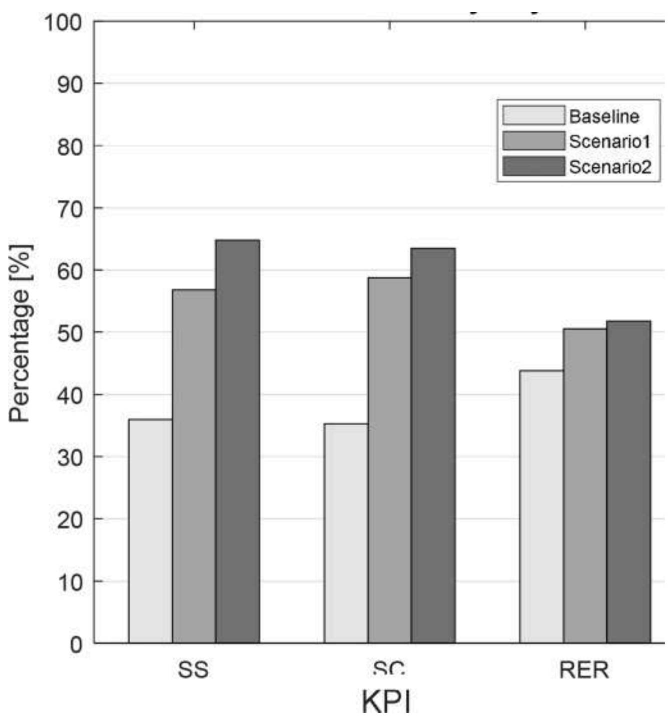

Fig. 17. Yearly averaged KPIs comparison in different scenarios over the district import/export physical boundary. 100 % is the maximum value achievable by the KPIs.

to 56.07 %, while its accuracy (a_{SS}) increases from 29.97 % to 50.57 %. Similarly, for Self Consumption (*SC*), the annual KPI improves from 36.24 % to 59.15 %, while its accuracy (a_{SC}) experiences a more substantial improvement, rising from 13.77 % to 45.03 %. For the weighted KPI, Renewable Energy Ratio (*RER*), although it undergoes a slight improvement from 43.42 % to 49.73 % in the annual KPI, shows a large margin of improvement in dynamic accuracy from 29.58 % to 49.94 %.

Static annual KPI assessment and dynamically assessed a_{KPI} accuracy represent different concepts that cannot be directly compared since they express different aspects of building performance. The accuracy parameter aligns more closely with the Zero Power Building concept, as it reflects the percentage of instances when specific performance metrics are achieved, considering building dynamics. In contrast, static annual KPI values are not applicable to the Zero Power framework as they do not consider building dynamics.

The analysis extends to the entire district, comparing the performance of Scenario 2 with the Baseline and Scenario 1. Again, the physical boundary is widened to include the entire district and study energy flows in the Import/Export boundary. Fig. 17 presents the results for each KPI on an annual basis.

Scenario 2 performs better than both the Baseline and Scenario 1 in terms of the defined KPIs. On average, Scenario 2 is 21 % better than the Baseline and 5 % better than Scenario 1. This indicates that the choice of centralized storage with energy sharing on a district level outperforms other solutions in terms of yearly KPIs. In particular, Scenario 2 exhibits the highest level of Self Sufficiency, making it the most independent from the external grid, consistent with the results obtained from the analysis of the averaged power balance.

The ZPB methodology was applied to analyze KPIs at the district level. Fig. 18 presents dynamic performance through yearly heatmaps with hourly detail. Overall, district-level performance closely resembles that of single buildings in terms of hourly patterns. The improvements achieved by installing storage batteries in Scenarios 1 and 2 are evident compared to the Baseline scenario. Comparing the two improvement solutions, Scenario 2 performs better in specific timeframes, particularly during the initial and final hours of each day, especially in the summer season. The graph highlights hours that reach the acceptable accuracy value in red, indicating when the performance meets the specified criteria.

The proposed methodology includes an hourly dynamic and accuracy evaluation of Key Performance Indicators (KPIs) at the district level. Table 10 presents the annual KPI values compared with their respective accuracy values. Scenario 2 achieves better performance, meeting the target values of each KPI for approximately 50 % of the hours in a year. The comparison between annual KPIs and accuracy values shows that Scenario 2 provides different performance improvements. Self Sufficiency (*SS*) and Renewable Energy Ratio (*RER*) exhibit similar progression in both annual KPI and accuracy. However, Self Consumption (*SC*) experiences a more pronounced relative increase in accuracy compared to the annual KPIs. This highlights the sensitivity of onsite energy production, mainly assessed by *SC*, to hourly analysis and the significant improvements that can be achieved with the use of storage batteries.

The dynamic approach supported by the ZPB concept confirms as a powerful tool for decision-making processes in early-stage planning phases, especially for achieving energy improvements through onsite resource exploitation, where storage systems can make a substantial difference.

In conclusion, comparing the results obtained from yearly Key Performance Indicators (KPIs) and accuracy values, the following points can be noted:

- Yearly KPI assessment provides a rough description of district behavior but may overstate realistic capabilities.
- Accuracy of a KPI, used as an alternative tool, highlights the dynamics of the district through a synthetic value, offering a more realistic perspective.
- The adoption of a centralized electrical storage on a district level with energy sharing proves to be the most effective solution based on the proposed energy assessment methodology. It significantly improves both the independence from the external grid and the utilization of onsite renewable resources.

5. Conclusions

This work proposes a new methodology to improve and overcome the concept of Zero Energy Building and its limitations. To this regard, the concept of Zero Power Building and its framework for application and evaluation at a community scale were presented and introduced. To encourage an upgrade for the ZEB definition, a realistic case study was selected, to which the ZPB framework was applied by means of two assessment tools: the averaged power balance and the KPI accuracy. The results demonstrated the weaknesses of the ZEB and how the ZPB can address them in line with the new principles of the 3rd EPBD recast. In conclusion, the outcomes of this work can be summarized as follows:

- The proposed definition of Zero Power Building overcomes the limits of the Zero Energy Building concept, in terms of physical boundary, weighting system and timeframe of analysis.
- Applying the current definition of ZEB leads to results that are not representative of reality, generating misleading indicators that confirm the gap between building design and operation.

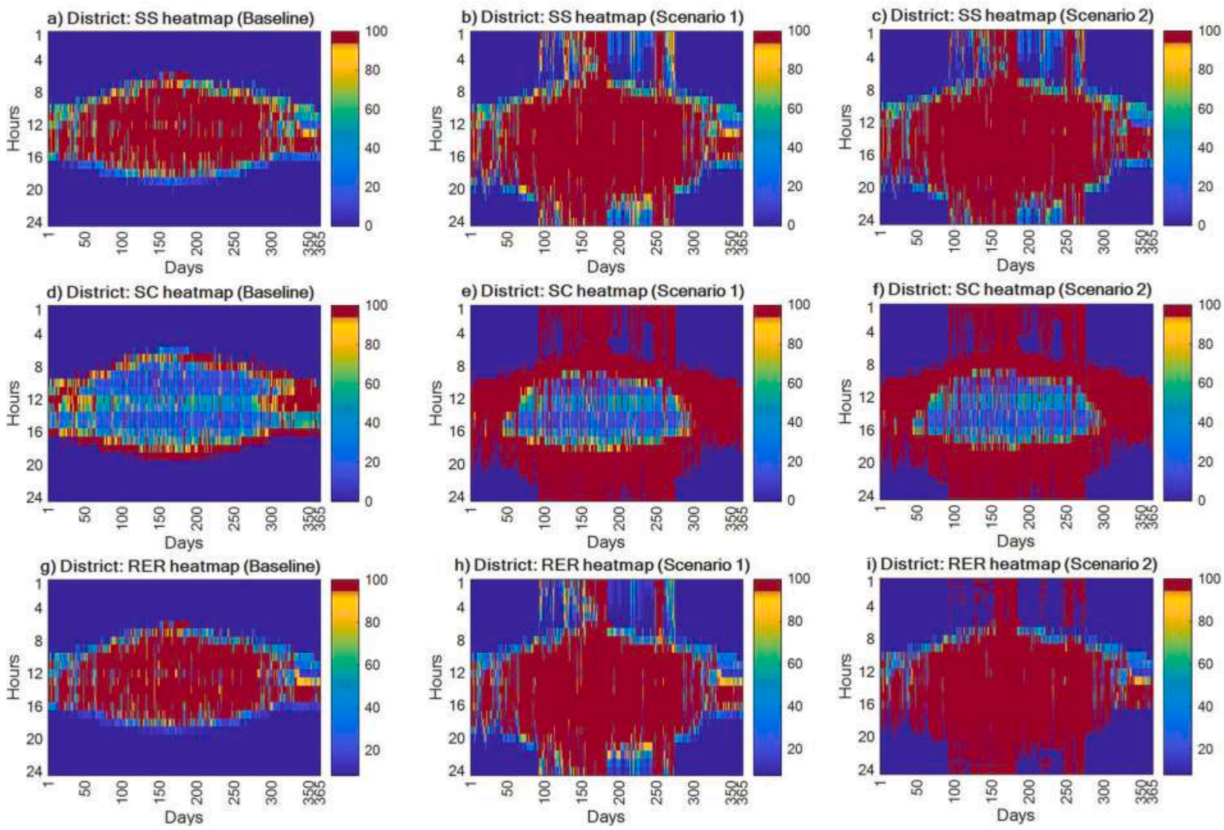

Fig. 18. KPIs hourly heatmap in different district scenarios: Baseline (a, d, g), Scenario 1 (b, e, h) and Scenario 2 (c, f, i). Red area indicates acceptable values for accuracy calculation.

Table 10
Annual KPIs and their dynamic accuracy a, on district level.

District	KPI [%]			a_{KPI} [%]		
	Baseline	Scenario 1	Scenario 2	Baseline	Scenario 1	Scenario 2
SS	35.96	56.82	64.76	28.55	46.74	51.43
SC	35.24	58.77	63.47	12.64	50.01	53.42
RER	43.81	50.55	51.80	27.99	45.49	49.74

- The dynamic evaluation methods proposed by the ZPB framework, such as the averaged power balance and the KPIs accuracy, are tools capable of approaching the real behavior of the building.

The results obtained from the methodological application illustrated in this paper have shown how a dynamic approach to the energy flow balance of a building can correctly assess energy storage and sharing performance. The case study district increased its Zero Power status from 29 % to 50 % of annual hours thanks to the implemented strategies. Regarding the selected KPIs, the dynamic approach was able to describe the accuracy of the achievement of Self Sufficiency (*SS*), Self Consumption (*SC*) and Renewable Energy Ratio (*RER*) targets, which increased from 28.55 %, 12.64 % and 27.99 % to 51.43 %, 53.42 %, 49.74 % respectively, due to energy storage and sharing.

Overall, the proposed work aims to raise awareness of the need for an update in the definition of ZEB, especially at a regulatory level, to favor a correct evaluation of the building stock and allow the comparison between buildings belonging to different contexts. Also, this approach might be a starting point to reconsider renovation and efficiency strategies towards decarbonization objectives.

Within the building energy efficiency and optimization practices, the Zero Power concept could open up important insights and analysis regarding building control and management systems, demand side management and optimization, advanced control algorithms and integration of renewable resources. All these practices, which are widely studied in building physics, need an appropriate evaluation method to understand their problems, potential and opportunities.

Finally, this work also demonstrated the applicability of the Zero Power concept at the district scale. The proposed method confirms how the definition of an appropriate physical boundary is fundamental according to the objectives to be achieved. On a district scale, the Zero Power methodology is applicable and confirms how the interaction between buildings belonging to the same district can be rewarded if properly evaluated.

5.1. Future developments

The outcomes derived from this study offer a singular perspective among the potential applications of the Zero Power Building (ZPB) framework. This work has only scratched the surface of the ZPB framework's possibilities by examining two improvement scenarios. However, the adaptability of this framework extends to a vast array of scenarios tailored to specific case studies, signifying a new direction in building performance assessment. Subsequent developments will inevitably delve into exploring the influence of varied strategies on the Zero Power Building concept. A comprehensive investigation into critical variables inherent to the Zero Energy Building (ZEB), such as delineating the physical boundary and refining weighing systems, remains an imperative aspect for further exploration within the ZPB framework. Additionally, the assessment tools introduced herein will undergo rigorous testing as means to support the initial design phase, seeking to bridge the gap between design and operation in the building sector (Biglia et al., 2021).

To achieve this, future developments of this work will endeavor to further reduce the analysis timeframe to the minute range (15 mins or less). This approach, consistent with the transition from Zero Energy to Zero Power Building, will strive to close the performance gap between design and operation. Moreover, it will seek to synchronize building performance evaluations with the energy billing, typically conducted by grid managers at sub-hourly intervals.

Finally, this work's prospective application extends to contributing to regulatory advancements in the sphere of energy assessment for forthcoming and existing buildings. Particularly, the Zero Power approach emerges as a pivotal tool supporting decarbonization and energy efficiency policies outlined in the latest recast of the European Energy Performance of Building Directive. Furthermore, the proposed framework integrates into the development of novel frontiers for energy and environmental certifications for buildings, offering a remarkably flexible assessment tool adept at accommodating diverse requirements from multiple certifying entities across different jurisdictions.

CRediT authorship contribution statement

Matteo Bilardo: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Jérôme H. Kämpf:** Conceptualization, Methodology, Supervision, Validation. **Enrico Fabrizio:** Formal analysis, Methodology, Supervision, Validation.

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

The authors do not have permission to share data.

Acknowledgments

The authors would like to thank all participants of the pilot and demonstration project "Solar Energy Supply in the Alps - REKA Blatten Tourist Village" for their support in collecting monitoring data for the case study of this paper (https://www.aramis.admin.ch/Grunddaten/?ProjectID=35214).

Appendix A. – Model data

A.1. Model calibration data

This section reports the main results obtained from the calibration process of the numerical models of the case study buildings. Although this process was not the subject of this paper, the main results that were subsequently used as a starting point for the applications in this paper are reported.

Table A1 shows the main thermophysical parameters that were subjected to the calibration phase, indicating the design starting values and those obtained following the model calibration.

The validation of the calibration process was carried out, for each building, on the basis of the daily heating demand. Table A2 shows the annual values simulated and monitored during the monitoring campaign.

Table A1
Model calibration data.

Building	Internal gains [W]		Infiltration [h^{-1}]		Occupancy (people*hr)		Occupancy profile	
	Design	Calibrated	Design	Calibrated	Design	Calibrated	Design	Calibrated
B1	1769.09	1727.25	0.22	0.41	153,300	133,371	SIA 2024	Monitored
B2	1713.60	1732.82	0.21	0.39	153,300	124,173		
B3	1757.99	1727.25	0.22	0.54	153,300	170,163		
B4	1536.02	1568.65	0.21	0.34	153,300	126,473		
B5	1516.05	1548.31	0.21	0.32	153,300	150,234		
B6	1624.81	1559.06	0.23	0.37	153,300	156,366		
B7	1618.15	1559.06	0.23	0.39	153,300	141,343		

Table A2
Yearly heating demand calibration results and error.

Building	Yearly heating demand [MWh]		
	Simulated	Monitored	Error
B1	17.523	17.719	−1.10 %
B2	17.643	17.551	0.52 %
B3	21.832	22.842	−4.42 %
B4	15.909	16.948	−6.13 %
B5	15.472	15.507	−0.22 %
B6	17.250	18.433	−6.42 %
B7	16.919	17.524	−3.45 %

A.2. Heating demand for buildings

Fig. A1 shows the hourly heating demand for each case study building simualted in this study.

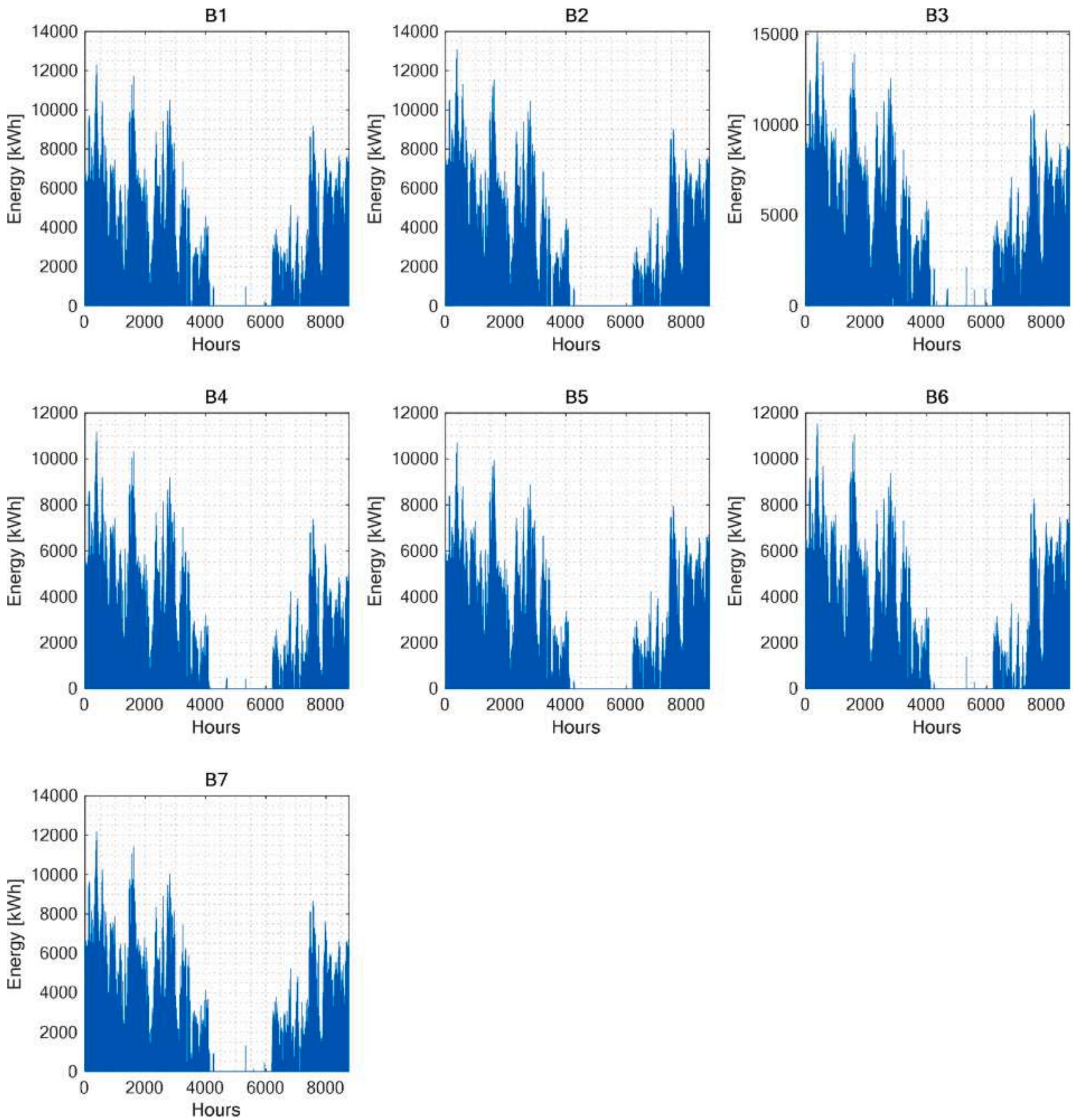

Fig. A1. Building hourly heating demand, expressed in kWh.

A.3. Internal gains for buildings

Fig. A2 shows the hourly internal gains for each case study building simualted in this study.

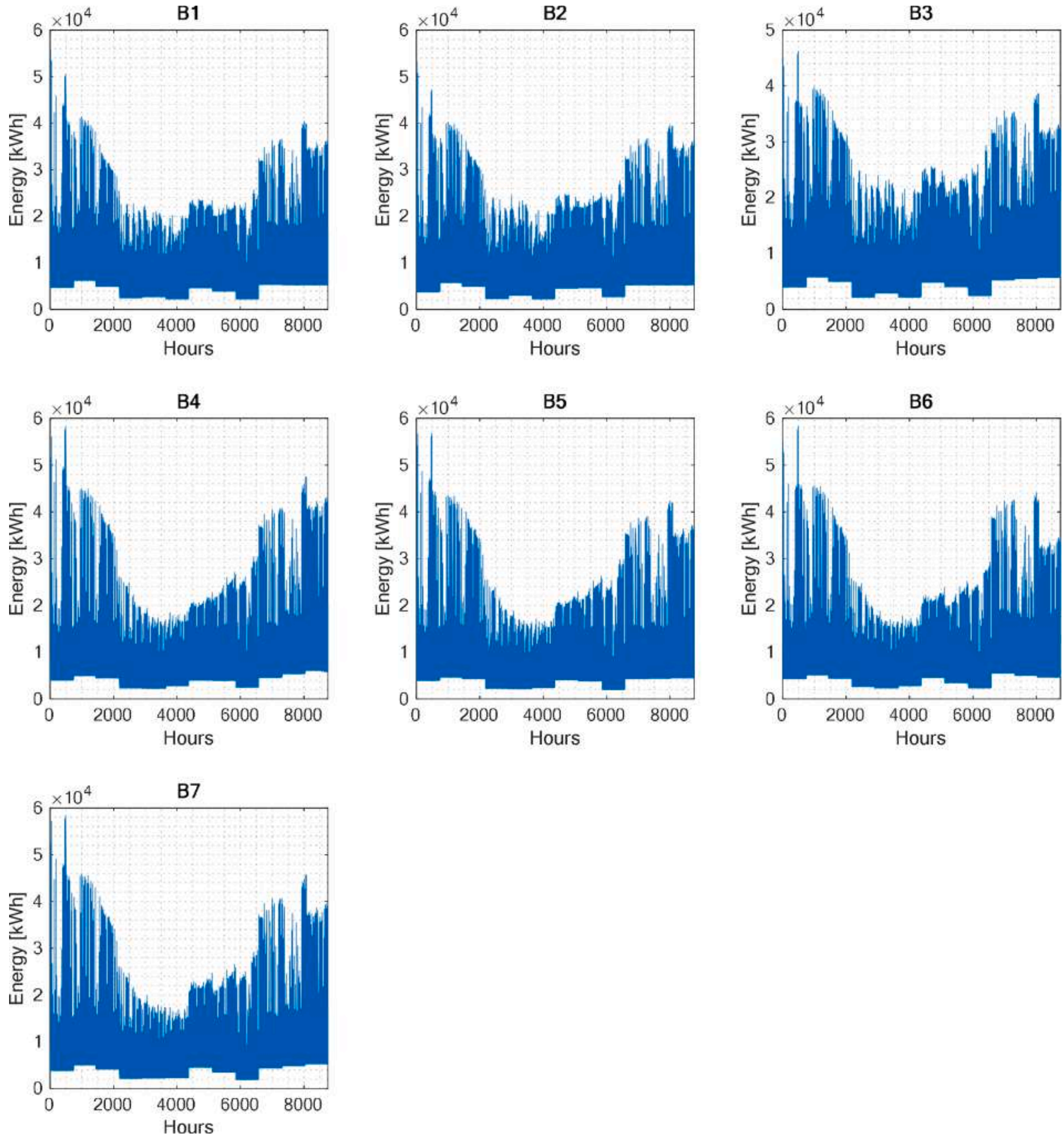

Fig. A2. Building hourly internal gains, expressed in kWh.

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