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Plus energy building: Operational definition and assessment

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ABSTRACT

Considering the amount of existing buildings, decarbonizing the building stock requires new buildings designed to reach the highest performance. The nearly-Zero Energy Buildings (nZEB) standard needs to be overtaken by Plus Energy Buildings (PEB) that presents the potential to produce more energy than the consumption over a specific period. Several studies investigated the potential of a building to achieve a plus energy balance, however, there is still a lack of a comprehensive and shared framework for designing and assessing the performance of a PEB. To cope with this issue, the authors identified a series of key aspects that needs to be stated in a consistent framework for PEB, and in particular: i) the balance contributions, ii) the physical boundaries, iii) the time span for the balance assessment, iv) the metrics for evaluating PEBs, v) the approach for evaluating load matching and grid interaction, vi) Indoor Environmental Quality and user satisfaction as added values of a PEB. The authors performed a comprehensive review identifying 82 papers dealing with PEB and deducing how the key aspects have been addressed. The literature overview provides the background for proposing an approach for the PEB definition and to introduce an operational assessment focused on providing the main statements focusing on PEB performance evaluation both during the design and operative phase.

1. Introduction

The building sector accounts for around 40% of the final energy consumptions and emits more than 30% of the greenhouse gas emissions in developed countries [1]. These figures have a direct impact on global warming, energy shortage and, in some cases, national security [2]. This concern has led to the establishment of various concepts, strategies, policies, standards, and regulations that aim to reduce building energy consumption and prompt sustainable construction.

Zero energy buildings (ZEBs) concept was established as a strategic target for new and renovated buildings and has become a part of the energy policy in several countries. For instance, all new buildings and deep renovations constructed in the European Union from 2021 must be at least nearly-Zero Energy Building (nZEB) as required by the Energy Performance of Building Directive (EPBD) and its ongoing revision [3,4], as a key strategy to decarbonize the building stock by 2050 in accordance with the revised EPBD 844/2018 [5]. Each Member State sets out the country requirements for standard nZEB according to the general indications established by the Directive.

Nowadays, thanks to the extensive research work to improve buildings performance and efficient technologies and equipment for the building sector, nZEB can be improved one step further to achieve the so-called Positive Energy Building. In this paper we refer to Plus Energy Buildings (PEB) instead, aiming at including in the definition other aspects than the positive energy balance relevant for the final user's satisfaction, such as a comfortable and healthy indoor environment.

As a general requirement, a PEB produces more energy than it consumes, and feeds RES-based energy to the grid, thus contributing to reducing the Green House Gas (GHG) emissions in the surrounding energy system. In this way, PEBs can support e.g., older buildings, where the transition to zero energy state would not be cost-efficient. In this perspective, PEBs represent a key step towards the decarbonization of the building sector. In particular, they shall contribute to reducing the energy grid congestion by providing a flexible energy asset that allows buildings and energy communities to act as integrated parts of the energy system and exchange energy (electrical, thermal energy, or other future energy carriers) among them or with the grid.

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PEB topic has received increasing attention in recent years, and it is foreseen to become part of the energy policy in several countries. Relevant studies can be found in the literature on existing and proposed definitions [6-11]. However, current PEB definitions are still quite generic and not yet standardized despite the complexity of the topic. A consistent definition is needed to allow countries to enact policies and national targets based on a clear and understandable concept. Otherwise, the scope of the definition may be biased and not appropriate as a basis for regulations and national policies. As key issues, it is important to understand what contributions to include in the energy balance and how to consider the Renewable Energy (RE) production to identify the most effective approaches towards the PEB target. This will be crucial for the future new building design as well as for determining the most effective strategies for renovation finding the balance between the installation of RE systems and the application of energy saving measures.

Therefore, there is still a need for a comprehensive and consistent framework that considers all the relevant aspects for evaluating the performance of a PEB, namely the physical boundaries, the balance contributions, the main metrics, the balancing period, and the amount of surplus energy. Such a framework can be foreseen as a cornerstone that would allow each country to define a coherent PEB definition harmonized with its political targets and specific conditions.

Consequently, the main aim of this study is to provide an overview of the current performance evaluation approach through a literature review on PEB and to propose a consistent definition framework. The introduced approach is developed in the context of the Horizon 2020 project "Cultural-E"[1]. This study first reviews the literature on existing PEB definitions and highlights the key aspects related to the energy balance evaluation and overall PEB performance analysis. The paper introduces the proposed approach of defining PEB in the Cultural-E project and identifies the key points to be considered in future research works. It is important to underline that the authors do not aim at giving a definition of the PEB, but the work outlines relevant aspects that a PEB definition shall consider in order to be consistent with the general scope of PEBs. Moreover, the paper investigates the concept of 'Plus' as an added value for the final users beyond positive energy balance by delivering sustainable buildings with accessible, comfortable, and healthy indoor environments, by supporting the takeover of e-vehicles, as well as by empowering final users toward energy savings practices.

2. Methodology for literature review

The literature review has been carried out by applying the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) checklist and flow diagram [12,13], which define a common framework for systematic reviews and *meta*-analyses for ensuring completeness and replicability of the reporting.

In particular, the collection of relevant literature was carried out by using the search engines, Scopus, ScienceDirect, and Google scholar. The literature analysis was based on the following definitions, used as keywords for the research: *Plus energy building(s), plus energy house(s), positive energy building(s), positive energy house(s), plus energy retrofit, plus energy renovation, positive energy retrofit, positive energy renovation.*

According to PRISMA, the authors define the following criteria for the eligibility of the studies:

1. Published in peer-reviewed academic journal or national/international conference.
2. Written in English.
3. Present balance between load and generation or import and export.

Moreover, since the aspects of interest deal with the identification of metrics and methodologies for assessing the performances of PEB, the following exclusion criteria were set up:

- Studies that do not present a balance between RE production and consumption.
- Studies focused solely on innovative solutions to improve energy savings or on improvements of technologies and systems without evaluating its effect on the final energy balance.
- Papers investigating the energy balance at a community, district, or neighborhood level [14-17].
- Cases with renovation to reduce energy consumption without deploying RE to offset the building need are not considered, e.g. [18,19], or without presenting the balancing metrics [20-22].

Finally, as the last condition, the authors excluded the works presenting one or more buildings that reach the target of nearly Zero or Net Zero Energy Building (nZEB or NZEB), only including the cases reaching a plus energy balance. The selection process following the PRISMA methodology is illustrated in Fig. 1.

The search was undertaken in October 2021 and resulted in 276, 382, and 2113 studies from Scopus, ScienceDirect, and Google scholar, respectively. Duplicate papers were identified and deleted. Studies were first reviewed and included/excluded based on the relevance of their title and keywords. Next, studies abstract was reviewed and preserved if the content fulfilled the inclusion criteria. Full papers were then assessed and maintained if the content satisfied the inclusion criteria. The identified appropriate papers were then categorized in chronological order [2,6,10,11,14,24–28,40–46,49,50,52–60,64–70,71–78,82–161]. A full review to extract the key parameters to evaluate PEB, such as metrics of balance, period of balance, type of energy use, type of energy balance, physical boundary, Load Matching (LM) and Grid Interaction (GI) indicators, was carried out. Finally, studies with a plus energy balance were retained and considered in further analysis. The final list comprised 82 articles included in the synthetic analysis (Fig. 2).

3. Literature trend analysis

3.1. General results

Fig. 3 illustrates the main overview of the building types described in the literature and the approach for the PEB performance analysis. About 72% of the studies investigated the potential of new buildings to achieve PEB, while the rest were retrofitted buildings towards the PEB target (Fig. 3 (a)) The overwhelming majority of the investigated buildings are residential (70%). About 11 % education, 7% offices, and 10% other building types. In addition, more than 70% of the reviewed studies investigated the potential to achieve plus energy target using numerical simulations (Fig. 3 (b)). This could be attributed to the fact that the PEB concept is still new, and there is a lack of case studies to perform experimental and real time monitoring investigations. In fact, most of the monitoring cases are related to building prototypes and exemplary cases within research projects [23-28].

As indicated in Table 1, the distribution of published studies shows that Europe plays a crucial role in the research and analysis of PEB, despite the other analyzed contexts, highlighting the relevance of the topic for the European Commission.

[1] https://www.cultural-e.eu/project-description/.

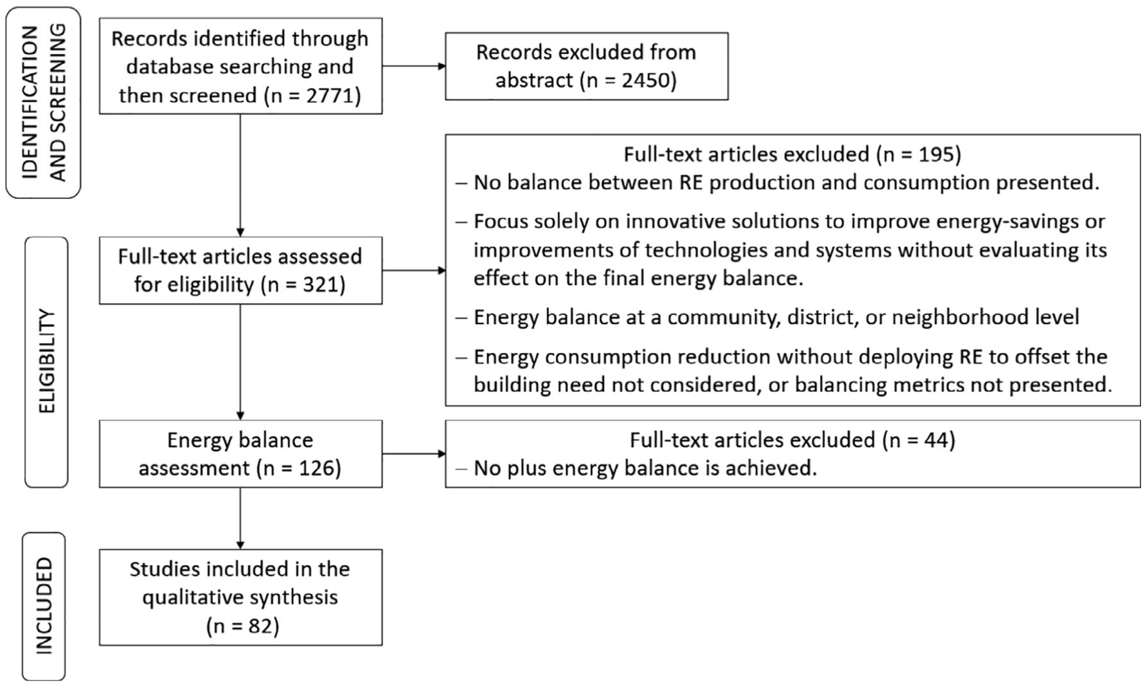

Fig. 1. Flow diagram showing the number of studies screened, assessed for eligibility, and included in the review.

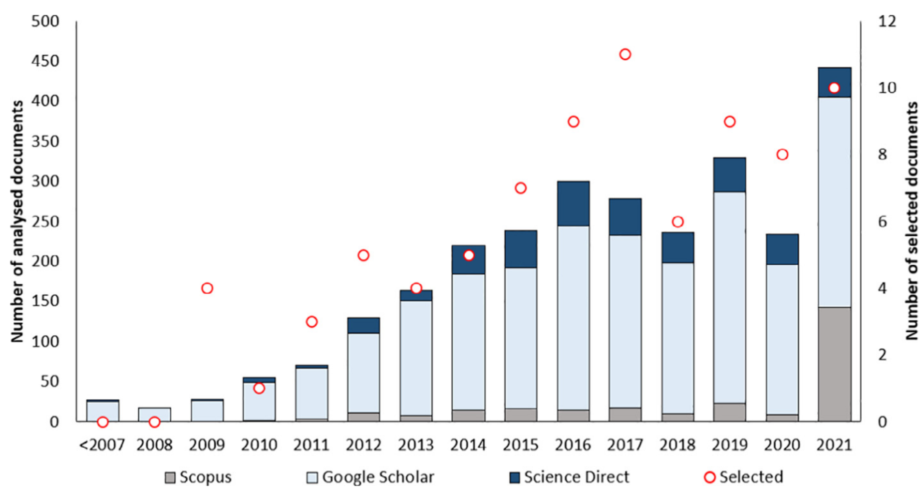

Fig. 2. Trends of number of documents per search engine and the number of selected documents for the present study.

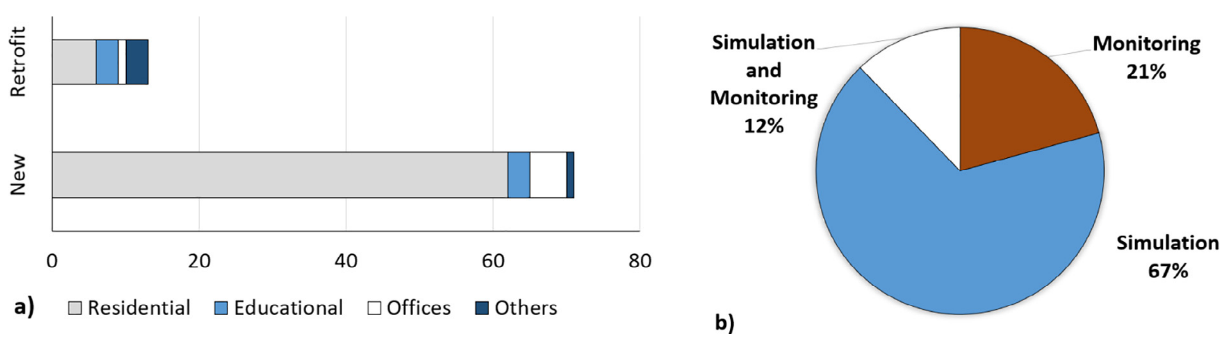

Fig. 3. Summary of the reviewed documents in terms of: (a) building type, and (b) type of performed investigation.

Table 1
Number of selected papers for each continent.

EU	Asia	America	Africa
56	14	8	4

Fig. 4 shows an overview of the main features of PEB balance as well as the indices adopted for the overall performance evaluation as identified in the literature analysis.

3.2. PEB – definitions, terminology, and concept of balance

PEB is a new concept, and its definition is currently in the spotlight of research and EU regulation development [29]. The energy balance should be evaluated by proper methodology, which specifies the type of energy demand, the Renewable Energy Sources (RES) and balancing period, as well as metrics and weighting system. Based on the reviewed articles, there is a variety of possible definitions and methods in the literature:

- *The simplest concept of a plus energy building is that it produces more energy on site than it uses on annual basis. This includes energy for heating, cooling, ventilation, lighting, and all devices that are plugged in* [6].
- *The net-plus balance means that the annual electrical energy surplus fed-in to the grid is greater than the annual electrical energy imported from the grid* [7].
- *A PEB could be one that produces more energy than is needed, and exporting it to other buildings or systems,* i.e. *'energy storage management or feeding the extra energy produced to the grid'*[8].
- *PEB is an energy efficient building that produces more energy than it uses via RES, with high self-consumption rate and high energy flexibility over a time span of one year* [30].
- *Energy-positive buildings and neighborhoods are those that generate more power than their needs. They include the management of local energy sources (mainly renewable,* e.g.*, solar, fuel cells, microturbines) and the connection to the power grid in order to sell energy if there is excess or, conversely, to buy energy when their own is not sufficient. They use ICT enabled low carbon systems and components such as advanced Heating, Ventilation and Air-Conditioning (HVAC) and highly efficient lighting. They are equipped with intuitive devices that not only meter the energy consumed but also provide real-time information (*e.g.*, on incentive pricing, deviations from standard consumption) to help people living in (or managing) these environments save energy while maintaining the desired comfort levels. They include plug-in electric vehicles infrastructures in order to facilitate not only clean transport but also alternative local energy storage* [9].
- *From the view of the housing association the energy plus apartment house was defined as a building where the tenants do not have to pay for the operating energy costs and can even use a possible financial surplus for other operating costs. However, from a technical point of view, an energy plus house produces more energy than is used to cover the loads of the building* [10].
- *Thiers and Peuportier* [11] *defined the PEB as a Net Zero source Energy Building.*
- *a positive energy building is an energy efficient building that produces more energy than it uses via renewable sources, with high self-consumption rate and high energy flexibility, over a time span of one year. A high-quality indoor environment is an essential element in the PEB, maintaining the comfort and well-being of the building occupants. The PEB is also able to integrate the future technologies, such as electric vehicles with the motivation to maximize the onsite consumption and also share the surplus RE* [29].

As can be noticed from the abovementioned definitions, the main difference between ZEB and PEB lays in the energy balance accounted during one year of operation. Nonetheless, the balance could also be computed for the whole lifespan of the building, by considering energy embodied in the materials and involved in the construction, retrofit and demolition phases of the building, following a life cycle approach. For instance, the *PowerHouse* [31] defines the PEB as:

- *a construction that, in the course of a 60-year period, will generate more RE than the total amount of required to sustain daily operations and to build, produce materials as well as demolish the building.*
- *A plus energy building that is built according to the PowerHouse definition prior to 2019 must produce more renewable, locally produced energy during the lifetime of the building, and must produce enough RE to cover the total embodied energy used for the production and transportation of the building materials used in the building. The local RE production must also cover the yearly net energy needs for operations, renovations, and demolition of the building. The local production of RE on the building is not required to cover the energy needed for plug loads in the building.*

3.3. Metric of balance

The metric adopted for weighting and comparing the different energy carriers of the building energy demand and production represents a key point in the assessment of PEB. To calculate the

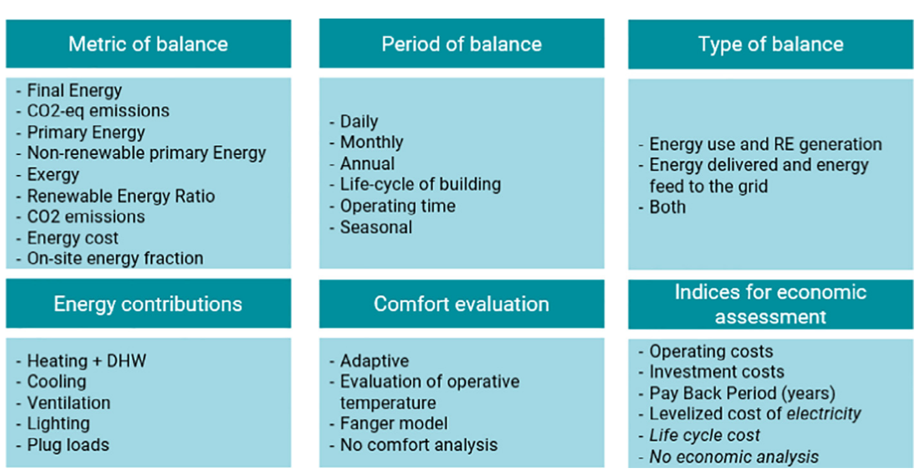

Fig. 4. Main features and indices identified in the analyzed studies.

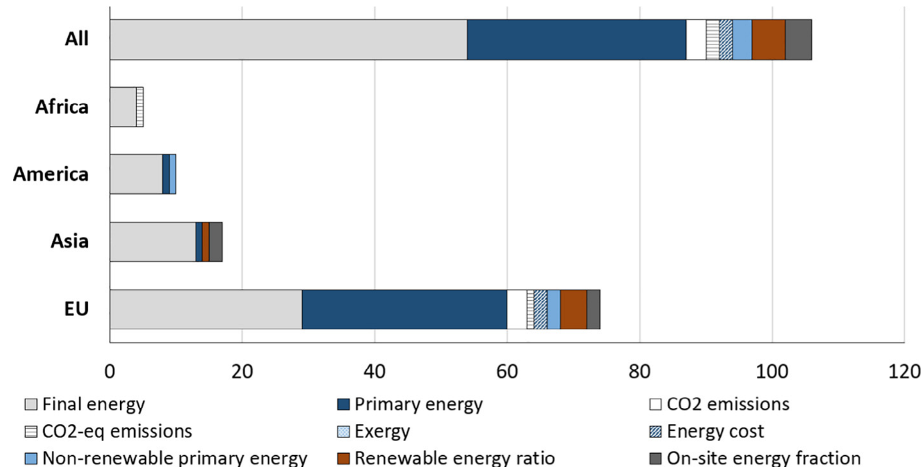

Fig. 5. Number of reviewed studies by country and metric of balance to evaluate the performance of PEB.

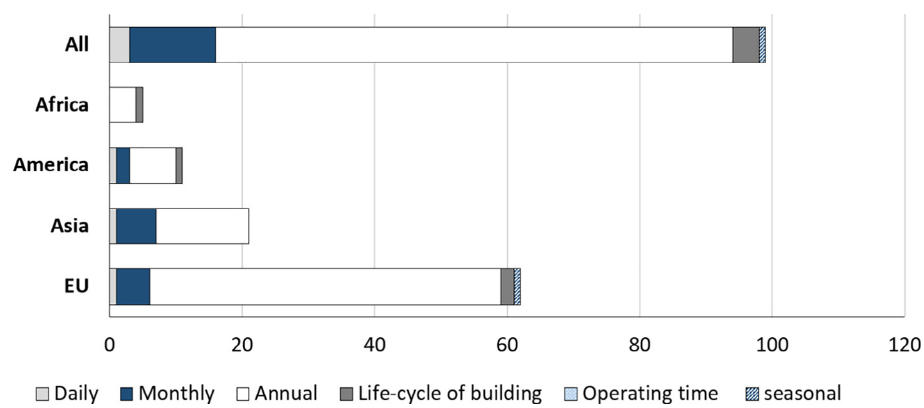

Fig. 6. Number of reviewed studies by country and time span used to evaluate the energy balance of the building.

energy balance of the building, all balance items need to be converted using the same metric. As previously shown in [32], the metric affects the relative value of each energy carrier and can therefore influence the required generation capacity as well as push end users to alter their choices on energy efficiency measures and energy fuels.

In the case of nZEB, there is a variety of balance metrics presented in the literature, such as final energy, primary energy [33], CO_2 equivalent emissions, exergy, cost of energy, the non-renewable primary energy balance [34], the *RE* ratio [34], on-site energy fraction [34]. Nevertheless, in the case of PEB, the reviewed literature indicates a clear focus on Final and Primary energy metrics (Fig. 5). Precisely, the primary energy metric is utilized more within the EU, since the EU has implemented regulatory use of primary energy factors in the energy policy framework while in the other contexts the performance evaluation is in terms of final energy. This is also because electrification of buildings is the most established practice outside the EU context. The indicators adopted by the works in Asia are more heterogeneous and include the *RE* ratio, non-renewable primary energy, and on-site energy fraction.

The primary energy considers the difference in generation and distribution by different energy carriers and can be adopted for comparison between consumption of products with the same functionality (e.g., heating) using different energy carriers (particularly electricity vs. fossil fuels). For decarbonization goals, savings in primary energy are more important than savings in final energy (e.g., electricity). For this reason, the EPBD [3] adopt primary energy as a metric, considering the national conversion factors. Nonetheless, it is worth noting that, as the share of *RE* in the energy mix is expected to grow considerably within 2030, primary energy conversion factors may not represent the actual conditions of power generation. In addition, the comparison among building energy performance in different countries is not reliable because conversion factors cannot be determined in absolute terms. The assessment of conversion factors are subject to a variety of methodological characteristics: temporal resolution, reference time frame, geographical boundaries, political strategies to promote or discourage the adoption of a technology or an energy carrier [35]. Using indicators dealing with weighted energy (primary energy, non-renewable primary energy) presents significant policy implications since the definition of the conversion factors is affected by national contexts and energy systems.

On the other hand, the final energy is a directly measurable metric, therefore transparent and easy to understand for building occupants. However, using it would lead to neglect conversion and transportation losses [1]. When more than one energy carrier is used, then the energy balance cannot be calculated since each energy carrier should be converted in the same metric.

3.4. Period of balance

It is defined as the period during which the building calculation is carried out to demonstrate when the PEB balance is achieved. The period of balance can vary significantly. In the case of ZEB, the commonly used balance is the annual one [33,34,36,37], some studies use a seasonal or monthly balance, and in some cases, an exhaustive full life cycle analysis of a building is performed. In the case of PEB, the same trends are noticed (Fig. 6). However, it

Table 2
Advantages and disadvantages of possible periods of balance extracted from [39].

Balancing period	Advantages	Disadvantages
Sub-annual: Monthly/ Seasonal	–RES dimensioned to better match the actual energy demand –It captures fluctuations of RES.	–Hard to meet plus energy balance for all the periods due to seasonal discrepancy between demand and generation.
Annual	–It complies with most building related regulation/standards –Easy to measure and verify	–Hard to capture mismatch between energy demand and RE production –Sensitive to user behavior
Operating lifetime	–It captures the annual variations in weather conditions It includes possible changes of occupants –It accounts start-up period of building systems.	–Long calculation procedure –Require continuous monitoring to be verified
Full life cycle	–It considers the embodied energy in the final balance.	–Diversity of boundaries options. –Lack of robust input data. –Lack of measurement and verification methods

is suggested that a yearly balance in the case of PEB would considerably limit the potential of a net-positive energy approach [38]. The authors correlate this to the considerable share of embodied energy as the operational energy is significantly reduced. Indeed, each balancing period has its advantages and drawbacks, which are summarized in Table 2.

The analyzed papers show a significant prevalence of annual balance that, in around 17% of the cases, is completed by monthly balance. It is interesting to note that both the life cycle and daily balance are less adopted, respectively only in four [40-43] and three studies [44-46]. Considering these two intervals, it would be more complex to reach the PEB target: on the one hand, having RE production sufficient to cover the building loads may be complicated on a daily basis (i.e. for PV in winter); on the other hand, setting up an energy balance considering the life-cycle perspective can be complicated for both predicting changes in building energy performances during the operation life and quantifying the embedded energies of the building components, including the end-of-life costs [47].

The annual balance seems to be the most practical and widely accepted calculation period to evaluate the final energy balance of a building, as the energy use may vary on a yearly basis due to several reasons i.e., climatic change, change in the number of occupants, change in building use.

The entire building life cycle can be an effective alternative for the annual balance when the embodied energy is included in the energy balance. Indeed, to evaluate this balance, it is important to define the boundaries ('Cradle to Cradle', 'Cradle to Grave', 'Cradle to Gate' and 'Gate to Grave' [48]) of the building life cycle.

Another option would be the monthly or seasonal balance. Although it is not popular within the building community, it may lead to better matching between energy generation and consumption because it is dimensioned to match the actual needs.

However, the balance over the entire life cycle would be not directly measurable and verifiable. And a monthly or seasonal balance would lead to an oversized RE generation system to face the seasonal variations.

3.5. Type of balance

The literature analysis showed two main approaches for assessing the energy balance: i) the balance between building loads and *RE* generation (load/generation), and ii) the balance between the energy delivered to the building and the energy feed to the grid (import/export). The balance focused on the building loads and generation is the most common approach and it is applied in 80% of the analyzed studies (Fig. 7). One of the main reasons is that the load/generation balance is the most suited to be integrated into existing building codes, which usually foreseen the calculation of the building energy load and the energy generated by renewable as performance indicators for building design and energy labelling. However, the import/export balance gives more complete information including the interactions between the building and the energy grid, and it can be easily monitored during operation by metering the building-grid interactions. On the other hand, performing a reliable balance between imported and exported energy during the design phase may be challenging since it requires detailed simulations for assessing the energy profile, evaluating the self-consumption potential, and, consequently, the energy fed to the grid. In fact, the detailed energy profile is strongly affected by the specific user behavior that is usually unknown during the

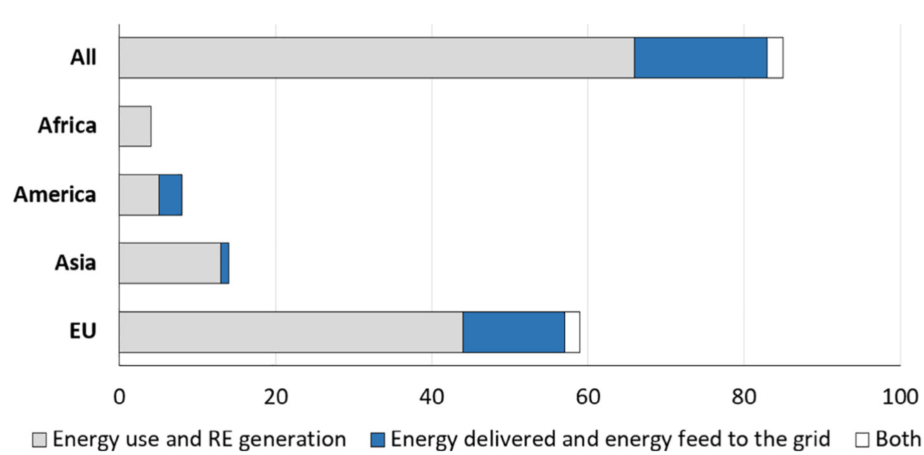

Fig. 7. Number of reviewed studies by country and type of energy balance.

Table 3
Advantages and disadvantages of each type of balance

Type of balance	Advantages	Disadvantages
Load/Generation	Suits better in existing building codes that are focused on calculating the loads.It is only necessary to add the calculation of the generation.	It completely overlooks the interaction with the grids. It does not consider thermal and electrical storages
Import/Export	gives the most complete information showing the interaction with the grids easy to prove during building operation through monitoring	Difficult to obtain in design phase because it requires estimates of self-consumption patterns and detailed simulation

design phase. The advantages and drawbacks of the two approaches are summarized in Table 3.

3.6. Type of energy use

The type of energy included in the energy balance is essential to calculate the balance between energy demand and *RE* generation. The reviewed articles show a tendency towards including the total energy use of the building by considering both the building and user-related energy, namely lighting and plug loads, that are included respectively in 88% and 68% of the studies (Fig. 8). Considering the contribution of user-related energy in the balance represents an important statement that has a high influence on sizing the renewables to be integrated. These contributions are significant in the overall consumption of a highly efficient building since the insulated envelope and efficient services lead to reduced HVAC and Domestic Hot Water (DHW) energy needs.

On the other hand, the plug loads are quite difficult to be estimated during the design phase, as shown in the studies that present also monitoring data. For instance, in [10], the building was built as a PEB, however, the monitoring campaign indicated that it could be PEB if only space heating was considered in the balance; while including ventilation and plug loads would lead to ZEB and nZEB, respectively. In [49], the building was designed as PEB, but in actual operation it performs as an nZEB because of increased energy consumption by the user, as a rebound effect of the foreseen high performances and renewable installation. Also in [50], the preliminary investigations using dynamic simulation show that the building can achieve plus energy balance, while in the actual operating conditions the monitoring campaign indicates that the building reaches only the nZEB target.

To cope with this issue, the renewable installed are usually designed to guarantee an adequate surplus of energy generation, that for the analyzed studies exceed the overall energy consumption of 48% on average.

3.7. Physical boundaries

The physical boundary primarily indicates what should be included in the energy balance, and secondly how to differentiate between on-site and off-site RE generation (i.e., the systems that are within the physical boundary are considered "on-site" and the rest are "off-site").

RE supply can be categorized into two main options for PEB: on-site and off-site supply. To establish which type of supply is applied by the building, it is crucial to introduce a clear definition of the physical boundary of the balance. For the on-site supply, the boundary can be considered as the building footprint or the building site [51]. For the off-site options, the building either purchase off-site RE sources, green energy, or CO_2 credits or uses RE sources available off-site to produce energy on-site. The overwhelming majority of the reviewed articles (80 studies) investigated the on-site RE as the main option to supply the required energy. This can be attributed to the continuous improvement of the PV panel efficiency, which is capable to generate an adequate amount of energy and enable effective integration of PV surfaces in building facades. As suggested in [32], RE supply options can be prioritized according to a mandatory hierarchy that considers the availability of resources, ownership, the performance of the grid in terms of energy mix and transportation, the distance of RE supply from the building, and the availability over building lifetime. The physical boundary could spread from household to building, and to building neighborhood. While the users would be more empowered, considering the boundary at the household level may not be feasible in cases where RE generation is shared among households. On the other hand, neighborhoods are considered in other definitions, as PEN and PED. Building type, usage, and location have a great impact on the potential of reaching PEB targets. For instance, a building in a rural area would have the potential for more local *RE* generation than buildings in urban and sub-urban areas due to more available spaces and less density of the built

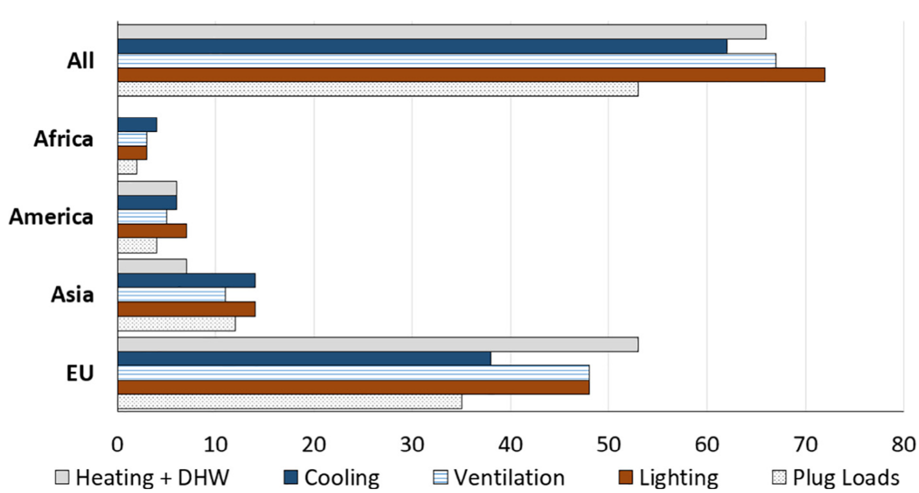

Fig. 8. Number of reviewed studies by type of energy use considered in the final balance.

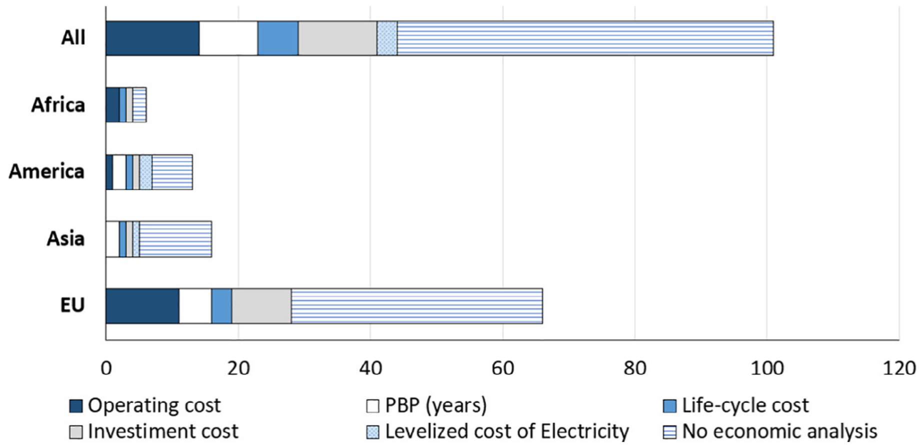

Fig. 9. Number of reviewed studies that performed economic assessment.

areas. Compact and high-rise buildings have less potential to produce energy on-site because of the limited area to install RE-based technologies. Besides, different building typologies such as commercial, school, or public buildings have different daily demands than residential buildings.

3.8. Economic and environmental assessment

Although the economic and environmental issues are of high importance, they are rarely considered alongside the energy evaluation in the reviewed studies. About 30% of the considered studies investigated the economic impact of PEB (Fig. 9) and applied the indicators as shown in Table 4.

Concerning the environmental analysis, it is performed in the 11% of the studies, with different level of completeness. Most of the studies [67,74,75] simply implement the evaluation of the CO_2 emissions due to the operational energy supply, by converting the energy consumption for heating, cooling, ventilation, lighting and plug loads in CO_2 emissions through conversion factors specific for each energy carrier. The other studies present more detailed environmental analysis, including the assessment of the embodied energy of the materials in terms of CO_2 equivalent emissions [11,66,69] and considering the building processes, including maintenance, dismantling and waste treatments [66]. Moreover, the evaluation of the water usage and the GHG mitigation is also considered as environmental indicators of PEB [64].

Nevertheless, main goal of PEBs is to contribute to the decarbonization of the building sector. Therefore, a sustainability assessment based on overall building life cycle is essential and shall include the total energy required for daily operations, user related consumption, and to build, produce materials as well as demolish the building.

According to the literature [76], two scenarios are foreseen. The first considers a 50-year lifespan [77]: the embodied energy for all building materials and components including the renewable system, the energy use during construction, the embodied energy for retrofitting (after 30 years) as well as end of life treatment, while the renewable system is assumed to be replaced after 30 years. The second scenario considers a 30-year lifespan [40], in this case the embodied energy for retrofitting and the replacement of *RE* system are not included.

3.9. Load matching and grid interaction

Load matching (LM) and Grid Interaction (GI) are characterized by a set of indicators that evaluate how the local energy generation compares with the building load and the energy exchange between the building and a power grid. LM indicators measure how much energy generation overlaps with load profiles, whereas GI indicators consider the unmatched parts of load and generation profiles, which involves an interaction with the grid as imported or exported energy. The identified LM and GI indicators from the reviewed studies and their brief definitions are reported in Table 5.

Although evaluating LM and GI is relevant for a PEB, to enable a sustainable integration with the energy system, the reviewed literature highlights that LM and GI are rarely considered when evaluating the potential of a building to achieve a plus balance they are included only in 6 studies (5 in Europe and 1 in America). The lack of studies in this field deals with the difficulty of retrieving reliable energy load and generation profiles and evaluating the plus-energy target by calculating the difference between the total generation and the total consumption on a monthly/yearly basis.

Third, a good dynamic matching both in grid interaction and load covering does not necessarily lead to a net or positive energy annual balance. Moreover, assessing LM and GI indicators requires complex and time-consuming simulation tools, which are not available to most building designers. Calculating these indicators requires information regarding the characteristics of the local energy generation system, the stochasticity of energy consumption, and the control of interaction among those systems, which

Table 4
Economic indicators used in the assessment of PEB.

Metric	Description	Reference
Investment cost	all costs that need to be covered until an energy efficiency measure is fully implemented	[6,40,52-59]
Operating cost	Expenses related to the normal operation of the building	[6,40,54-65]
Pay Back Period (years)	is the time it takes to cover investment costs => additional investment cost compared to baseline building (nZEB)	[6,36,53,66–70]
Life-cycle cost	the present value of the total cost of building usage for the whole calculation period	[40,59,72-74]
Levelized cost of electricity	cost of generating electricity at the point of connection to a load or electricity grid during the PV system lifetime and covers all system initial investments and operation and maintenance costs (O&M), including the replacement of PV system components when necessary	[36,67]

Table 5
Load matching (LM) and Grid interaction (GI) indicators and their brief definition.

Indicator name	Description	Reference
LM indicators: to describe the degree of the utilization of on-site energy generation related to the local energy demand		
Load cover factors or self-generation	The percentage of the energy demand covered by on-site RE production. Useful to investigate the influence of different strategies and measures of load modulation.	[36,44,46,78]
supply cover factor or self-consumption	The percentage of the on-site generation that is used by the building. It is a good indicator of when and how much of the on-site supply is self-consumed, and thus indicates the periods when building acts as supplier of energy	[36,44,46,78]
Loss of load probability	Percentage of time that the local generation does not cover the building demand. However, it does not provide any information about the amount of delivered electricity. It shows how often the on-site supply does not cover the on-site demand, and thus how often energy must be supplied from the grid	[78]
Behavior Ratio	Ability of a RE system to match in real-time the consumption.	[36]
GI indicators: to measure how the utilization of the grid connection is in relation to the building		
Peak power generation/exported	Normalized peak power value of the on-site generation/the exported energy.	[46,78]
Peak power load/delivered	Normalized peak power value of the load/the delivered energy.	[78]
Generation multiple	Ratio between peak values for exported/delivered energy or generation/load values. It relates the size of the generation system with the design capacity load.	[78]
Capacity factor	Ratio of the actual annual energy output to the amount of energy the PV array would produce if it operated at full rated installed power for 24 h per day for a year	[79]
Dimensioning rate	Peak power exchange over the connection capacity and should never exceed one for a well dimensioned connection	[36,80]
Connection capacity credit or power reduction potential	Percentage of grid connection capacity that could be saved compared to a reference case.	[80]
No grid Interaction Probability	The probability that the building is acting autonomously of the grid.	[46,81]

could be largely missing during the design phase or when using simplified calculation tools.

However, since plus energy buildings shall reduce the stress on the grid, it is important to complement the energy balance with an evaluation of the load matching between generated and consumed energy.

3.10. Indoor environment quality and user satisfaction

According to the current definition (EPBD 2010/31/EU) [5], nZEB shall provide an acceptable indoor environment, but no specific indicators or mean to measure and verify IEQ are requested.

As a result of this omission, none of the analyzed studies includes a comprehensive evaluation of IEQ, including thermal, visual, acoustic comfort, and air quality. Only 35% present the results of a thermal comfort analysis. Most of the research deals with a preliminary estimation of the thermal discomfort potential by comparing the predicted indoor temperature or operative temperature with ideal conditions (20 °C in winter and 26 °C in summer). Only a few works applied the Fanger model for assessing the comfort of the occupants [60,83-86], while only in Europe the adaptive comfort evaluation is applied [66,68,84,85,87,88] (Fig. 10).

Furthermore, IEQ requirements included in current standards (EN 16798–1:2019) derive from an attempt to relate occupant satisfaction with objective measurements. Therefore, they pursue ideal conditions that generally match with a subjective sensation of neutrality. However, occupant satisfaction with the indoor environment is also affected by a variety of cultural and social drivers that go far beyond the measurements of a set of environmental parameters [88].

To increase the appeal of PEBs towards final users and accelerate the market uptake of PEBs, PEB should deliver enhanced indoor environments pursuing occupants' satisfaction.

4. Proposed approach for a shared definition and assessment of PEB

According to the information collected within the literature review, this article proposes a general framework for defining and assessing the performances of a PEB. It is important to underline that the balance between load/generation, import/export, or in general, weighted supply/weighted demand, represents the core concept of a PEB definition.

Stated the considerable variability of existing approaches, the authors introduce an assessment level defined as'operational assessment,' which focuses on building design and operation application. The energy balance related to the operative assessment is based on measured or predicted final energy between load and generation related to each single energy vector. In addition, following a multifaceted concept of plus, key functional requirements of Plus Energy Buildings, related to the interaction with the energy grid, sustainability and users' satisfaction should be considered. The list of KPIs should address the overall energy and environmental performance, the dynamic matching between building own generation and load, the comfort and indoor environment quality.

4.1. Plus energy balance and metrics

As deduced by the analyzed literature, the positive energy target is considered achieved when the annual generated energy is greater than the annual energy load. According to the electrification trends, in most cases, the balance can be expressed in terms of final energy since only one energy carrier is involved. In case more energy carriers are involved, the balance can be expressed in terms of primary energy. In any case, each measured or predicted final energy use shall be explicitly declared to allow transparent and direct comparison among different buildings.

$$\textit{Net final energy balance} = \sum_{i}^{n} G_i - \sum_{i}^{n} L_i > 0 \quad (1)$$

where,G and L are the generation and load for an energy carrier (i).

The net balance in terms of Primary energy consumption is expressed as:

$$\textit{Net balance} = \sum_{i}^{n} G_i w_{g,i} - \sum_{i}^{n} L_i w_{l,i} > 0 \quad (2)$$

where w_g and w_l are the primary energy conversion factors for each energy carrier (i).

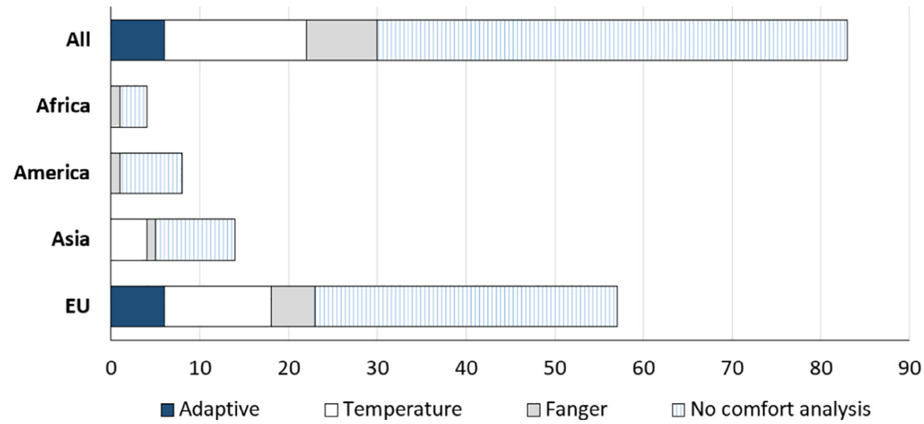

Fig. 10. Number of reviewed studies that performed thermal comfort analysis based on adaptive comfort model (adaptive), Fanger comfort model (Fanger), reference operative temperature (temperature) and no thermal comfort analysis (No comfort analysis).

The amount of surplus energy generated by the building shall be determined according to economic affordability and the viability of the installation of suitable *RE* generation systems.

Since the main objective of the operational assessment is to have measured and verified performance, a time span of one year is the most feasible to evaluate the energy balance and verify the plus energy target.

4.2. Plus energy balance items

The building operation represents the energy consumption for keeping the dwellings in livable conditions and includes the following energy uses: heating, cooling, ventilation, domestic hot water, lighting, auxiliaries, and plug loads. Including all energy uses in the balance ensures that the building has an energy production surplus to be shared with other buildings.

The full impact of the users is included by considering the plug-loads (i.e., the building appliances). This would contribute to empowering building energy end-users to reduce energy consumption and to change the mindset of designers from performance-driven to user-centered design.

Contributions from e-mobility, including the consumption at charging points within the building boundaries, could be considered in the balance but more discussion is needed for an effective application. In particular, e-mobility consumes energy outside the building footprint, and it could represent an additional energy carrier. Furthermore, consumption is related to the extent of travels which may vary considerably for different users and could be a considerable share of the energy balance. Even though an e-vehicle charge can provide flexible options to the building, too little is known on charging behavior patterns and the overall charging infrastructure is still under development.

Accounting for the user-related energy use in the balance may discourage, or prevent compact or high-rise buildings from being PEB, given that in these buildings the technical and economic viability for deploying RE could be limited. Thus, the definition of physical boundaries is another critical aspect to tackle.

4.3. Physical boundaries for plus energy generation

Since the operational assessment focuses on the building scale, the physical boundaries for RE generation are within the building footprint and can be extended to adjacent lots if there is a physical connection and direct control of RE generation system relying on:

- Ownership of the buildings or lots
- Neighborhood grid infrastructure
- Building management

In other cases, the assessment should refer to other existing Positive Energy Neighborhood or Positive Energy Districts definitions.

4.4. Added value of plus energy buildings

Besides the plus energy balance verification, PEBs shall ensure an added value to the environment and final users by providing:

- building flexibility to reduce the stress on the grid
- low carbon emission
- accessible, comfortable, and healthy indoor environments
- easy access to e-mobility

In this perspective, the energy balance should be complemented by a set of indicators/requirements that allow for a quantitative and objective evaluation of the above-mentioned aspects.

5. Conclusions

As a general requirement, PEBs shall produce more energy than they consume to compensate for the negative energy balance of surrounding buildings, thus contributing to the overall reduction of GHG emissions of the neighborhood. The uptake of PEBs represent a key step towards the decarbonization of the building sector. In particular, they shall contribute to reducing the energy grid congestion by providing a flexible energy asset that allows buildings and energy communities to act as an integrated part of the energy system and exchange energy (electrical, thermal energy, or other future energy carriers) among them or with the grid.

In practice, PEBs are described in the literature using a variety of terms and definitions whereas the assessment approaches are not consistent in terms of key issues to be considered while evaluating PEB. For instance, the balance contribution differs hugely among different definitions. In addition, the study reviewed and discussed the widely used metric for evaluating PEB, balancing period, the type of energy included in the balance, the type of balance, and the RE supply options, as well as other parameters related to the interaction between the building and the energy grid, as well as the environmental and economic aspects.

Intending to identify which PEB definition can better support the abovementioned purposes, the paper reviews the existing approaches for Plus Energy Building performance assessment, identifies key aspects on the definition of the energy balance, and systematically discusses their practical implications. Finally, the authors introduced an operational assessment methodology that can be applied to both building design and operation applications.

According to the operational assessment, the Plus Energy Building is an energy-efficient building that produces more final energy than it uses, including building operation and user-related consumption, via locally available *RE* sources over a time span of one year while ensuring the lowest CO_{2eq} emissions, high user satisfaction with indoor environment quality, good dynamic matching, according to economic affordability and to technical viability. The energy balance is based on measured or predicted final energy between load and generation related to each single energy vector. The energy generation shall be performed by *RE* systems located within building footprint and can be extended to adjacent lots if there is a physical connection and direct control of RE generation system relying on ownership of the buildings or lots, neighborhood grid infrastructure, and building management. Besides the plus energy balance verification, PEBs shall ensure an added value to the environment and final users by providing building flexibility to reduce the stress on the grid, low carbon emissions, accessible, comfortable, and healthy indoor environments, and easy access to e-mobility. The approach introduced within this work will be further developed for including strategies to assess and improve IEQ performances according to the needs of the users, that will be characterized according to geographical and cultural criteria.

A user-centered design approach needs to be adopted for PEB to provide a comfortable and healthy indoor environment for its occupants and raise their awareness of how daily practices and rhythms impact the building energy demand and its overall performance.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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