A consistent taxonomic framework : towards common understanding of high energy performance building definitions

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Title

A consistent taxonomic framework: towards common understanding of High Energy Performance Building definitions

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Abstract

The rising interest in High Energy Performance Buildings (HEPBs) has led to an inflation of definitions and related terminology to describe them, characterised by (sometimes subtle) differences and overlaps in performance requirements. The wide variety of HEPBs is well worth discussing our approach in distinguishing between them and ensuring common interpretation. Two important tasks we are facing now are the delineation and classification of HEPB-(sub)types as this is considered to be a critical precondition for generating market trust and understanding regarding the definitions between the broad range of stakeholders involved. This article presents a taxonomic framework, based on an extended set of relevant key performance indicators and related boundary conditions to report on -and compare- the performance level of HEPBs. The importance of these core indicators and boundary conditions is outlined by means of existing HEPB-definitions. The resulting taxonomic framework acts as a tool to identify differences and similarities in the HEPB-definitions, which is for instance suitable for the establishment of an adequately complete sets of guidelines, consistent project descriptions and correct categorization of HEPB-(sub)types, contributing to future consistent and complete communication. The framework is designed to be flexible and allows for future expansion. The applicability of the framework is furthermore tested by means of a selection of existing HEPB-definitions.

Highlights

- A harmonised definition framework for High Energy Performance Buildings is lacking.
- Decisive criteria to categorize a High Energy Performance Building are collected.
- A consistent taxonomic framework for High Energy Performance Buildings is proposed.
- The applicability of the taxonomic framework is tested.

Keywords

High Energy Performance Building definitions; performance level; core indicators; energy-related metrics; harmonized taxonomy; classification framework

Word count

9145 words

List of abbreviations

BEI: Building Efficiency Index
BEN: Almost Energy Neutral
BITS: Building Integrated Technical Systems
BREEAM: Building Research Establishment Environmental Assessment Method
$CO_{2(eq)}$: Carbon Dioxide (equivalent)
dB: Decibels
DHW: Domestic Hot Water
DOE: U.S. Department of Energy
DOE: U.S. Department Of Energy
ELF or LF: (Electrical) Load Factor
EPB: Energy Performance of Buildings
EPBD: Energy Performance of Buildings Directive
EPC or EnPC: Energy Performance Coefficient
ESCO: Energy Saving Company
EUI: Energy Use Intensity
GBPN: Global Building Performance Network
GHG: Greenhouse Gas
GRIHA: Green Rating for Integrated Habitat Assessment
HEPB: High Energy Performance Building
HPB: High Performance Building
HVAC: Heating, Ventilation and Air Conditioning
IEA: International Energy Agency
KPI: Key Performance Indicator
LEED: Leadership in Energy and Environmental Design
nZEB: nearly Zero Energy Building
NZEB: Net Zero Energy Building
PEB: Positive Energy Building
PED: Positive Energy District
PEF: Primary Energy Factor
PHA: Passive House Alliance
PHI: Passive House Institute
PV: Photovoltaic
REC: Renewable Energy Certificate
REHVA: Representatives of European Heating and Ventilation Associations
RES: Renewable Energy Source
UKGBC: UK Green Building Council
ZCB: Zero Carbon Building
ZEB: Zero Energy Building
zEPI: zero Energy Performance Index

€/m²: Euros per square meter
J_{ex}: Joule exergy
kWh_{ep}/m^2: kilowatt hour primary energy per square meter
Sej/J: emergy per unit energy
Sej/kg: solar emjoules/ kilogram

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1. Introduction

Several countries are setting targets to help alleviate the depletion of non-renewable resources and deterioration of our environment by the building sector [1,2]. This leads to an increased demand for High Performance Buildings (HPBs). The disperse set of actors and the continuous evolution in research and application of HPB-principles, results in an avalanche of related terminology to categorize these buildings, such as (net/nearly/plus) Zero Energy/Carbon emission Buildings (ZEBs or ZCBs), climate-sensitive buildings, passive houses, active houses, solar houses, autarkic buildings, green buildings etc. [3–7].

The lack of proper distinction between various HPB-definitions to compare their performance level has become clear in recent years [2]. HPB-procedures can be highly refined, often in accordance with specific standards, dealing with all kinds of details and provide a solution to (a set of) socio-environmental issues (e.g. energy demand, carbon emissions, water consumption, etc.), however not all to the same extent. The requirements and terminology for defining a HPB differ considerably [4,5,8,9] and has proven to be subject to ambiguity [2,8,10,11]. This indicates the need to identify the characteristics of HPB-(sub)types, relative to each other. Many articles and research projects describe and evaluate the HPB-types in a different manner and sometimes no exact definition is used [12–14]. HPB-terminology is furthermore no static matter. As language is transient, the HPB-concepts may change subtly over time [15]. Many HPB-definitions are furthermore revised for consistency and shortcomings on regular basis [7,13,16] e.g. to comply with the available technical knowhow, often resulting in subtle nuances in the HPB-definitions. This results in decreased understanding of the HPB-definitions.

As the definition of HPBs can greatly influence the design and implementation principles, it becomes crucial to unambiguously define the HPB-requirements and provide consistent related terminology to control the design, construction, operation and evaluation principles of the building [2,17]. Without proper and clear description of the HPB-types -and subtypes in the HPB-definitions, all parties involved must attempt to decipher the intentions of the communicator and risk using the definitions and related prerequisites interchangeably [15]. As a consequence, disputes occurring over contracts that involve the development of these buildings are inevitable [18]. This ambiguity might furthermore be an obstacle that a court or arbitrator must reconcile when determining whether the performance or breach actually occurred [15], possibly leading to financial implications.

The discussion around the HEPB-definitions has become more specific in the last decades [11,19] and research has been conducted about the decisive criteria in these HPB-definitions. The focus in this paper is on High Energy Performance Buildings (HEPBs), which are a subcategory of HPBs and characterized by the energy-related metrics to define their performance level. The majority of HEPB-definitions raises questions regarding one or more of the following criteria:

- The focus of the balance to define the performance level of the building (energy demand, carbon emissions, energy cost, etc.)
- The application and calculation period for the balance
- The accepted energy supply options and end-use categories in the balance

- The connection to the energy infrastructure to obtain the required balance
- The final balance
- The quality assurance strategy

Only one universally accepted definition to completely describe all HEPB does not exist [7,17,20,21]. Establishing only one generic definition would imply reporting on the requirements that have to be met in a non-detailed way, which would work counterproductive [22]. It is for instance not possible to completely understand and distinguish between all HEPB-subtypes, solely based on the overall focus of the balance to define the performance level of HEPB, as these buildings can differ greatly in various other areas as well (application and calculation period, accepted energy supply options, etc.). Compiling other areas in the definition, such as information on the connection of the building to the energy grid, would allow to distinguish between HEPB-(sub)categories in a more detailed manner, e.g. distinguishing a ZEB from a Net Zero Energy Building (NZEB), thereby allowing to understand the performance level of the HEPB-subtypes better. Furthermore, if the requirements to reach a certain HEPB-subtype are too non-binding, lax or open-ended, they will not stimulate to reach specific performance targets [23]. The definition should furthermore also leave space to adapt to the specific conditions and climate of the building [7,23]. The accuracy of the method should be in proportion with the limits and uncertainty in input data [22]. This also implies that the most accurate, complete and state of the art methods are not necessarily the most appropriate method for a specific application [22,24]. It is, however, reasonable to provide a limited set of fairly generic, overarching and non-detailed HEPB-definitions that merely function as supplements to categorize definitions of HEPB subtypes, without jeopardizing the real comprehensibility of the subtypes.

The multitude of slightly different HEPB-definitions calls for a manner to safeguard their comprehensibility during a long period of time. Whilst some researchers have attempted to compare two or more definitions (e.g. [6,13,25–29]), such attempts are not exhaustive and are also static in nature, thus not able to keep up with the pace of new emerging definitions. Ideally, the identification of HEPB-(sub)types should be easy and efficient, as it should be used by multiple different users [30]. With these observations in mind, this article aims at examining the seemingly interchangeable terminology, by capturing the differences and similarities in their performance level. A consistent taxonomic framework is presented as a dynamic tool to differentiate between the various definitions for HEPBs on the basis of a set of relevant Key Performance Indicators (KPIs) and related boundary conditions. The centralised taxonomic framework is designed to allow for consistent use of comprehensive HEPB-definitions, to enable clear communication and promoting the uptake of taxonomic changes as a result of progress in the techno-economic fields of HEPBs in a straightforward and effective way.

2. Capturing differences in HEPB-definitions

This part of this paper explores a set of diverse sources for HEPB-definitions, including legislation, official publications by federal governments and several organisations that provide third party verification, to explore the importance of the implementation of specific performance criteria and boundary conditions in the HEPB-definitions.

The criteria for the categorisation of HEPBs according their performance level can be described by means of KPIs and related boundary conditions (as indicated in Figure 1). The KPIs and boundary conditions, presented in this article, are in the first place based on literature in which various types of high energy performance case study buildings are categorized (among which [7,17,28,31–33]) and in which HEPB-definitions are explained and compared (e.g. [8,9,34–37]), supplemented with previous research on relevant KPIs and boundary conditions (e.g. [2,38]).

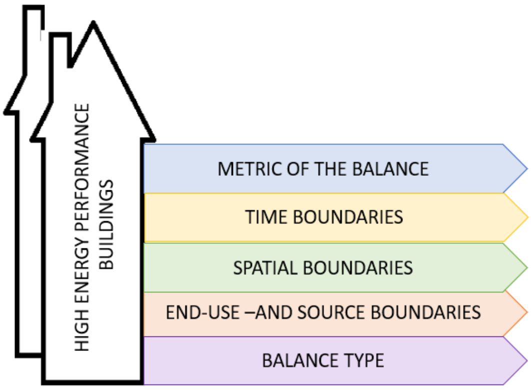


Figure 1: KPIs and related boundary conditions as main parameters for the determination of the performance level of HEPBs.

2.1. Metric of the balance

The **metric** (e.g. energy demand, carbon emissions, energy cost, etc.) is used to assess the final balance in many HPB-definitions. This final balance is characterized by consumption and production of the metric. In CoLab Low Carbon buildings, the balance is characterized by carbon emissions as a main metric [14]. Some HEPB-types are characterized by more than one metric. In the UK Green Building Council's (UKGBC) Zero Carbon Building (ZCB)-definition, comfort levels are also evaluated, aside from carbon emissions [16], unlike the name suggests. At first sight, a green building [39–41] and the JPI Urban Europe Positive Energy Districts (PEDs) [42] have for instance not much in common. However, these HPB-types are not completely different in scope. Instead, they are both an integral part of an approach towards sustainable urbanization. Within one category of metrics, such as the 'energy-metric', further distinction is possible. Defining the metric as 'energy' is not specific enough to capture the specific scope in the definition, as many variants of the energy-metric exist. The primary energy metric in REHVA's nZEB definition [43] is for instance different from the delivered energy metric of a Swedish nZEB [44], despite the fact that they are both referred to as an nZEB. To be able to clearly identify the scope of the HEPB-(sub)types, the metric of the balance should be described in a detailed manner to avoid ambiguity.

2.2. Time boundaries

The **time span** has an effect on the considered end-uses and energy sources in the balance and the period over which these components are balanced. The UKGBC's ZCB-definition introduces a set of definitions, explicitly considering various time spans over which the balance could be considered. Distinctions is made between the 'Construction, Operation and Whole Life net ZCB', affecting the final balance of the carbon metric [16]. The carbon balance of a UKGBC's 'Construction Net ZCB' is defined by the net carbon emissions that are associated with the building's product and construction stages up to practical completion. The 'Operational Net ZCB' is defined as a building in which the carbon emissions are associated with the building's operational energy on an annual basis. A third category, the 'Whole Life Net ZCBs', have a balance that is defined by the carbon emissions of the building's construction and operational phase (including maintenance, repair, refurbishment and water use), the end-of-life (demolition, waste and disposal) and the beyond the lifecycle (carbon savings from material re-use). The latter approach encourages design for flexibility, adaptability and disassembly to minimise end-of-life impacts [16]. Without mentioning the time boundaries in the HEPB-definition, this distinction may not be clear.

The **time steps,** used to verify the final balance of a HEPB, may vary as well, impacting the reported performance level [45]. The overarching EPB standard (EN ISO 52000-1 [46]) provides various option for the time spans of the final balance verification, among which hourly, monthly, seasonal and yearly. The choice is made between monthly and hourly in the national calculation procedures of most European member states [22]. This is in contrast with the EPB implementation of Sweden for nZEBs and in the 3-Liter House [47], for which the final energy balance of the building is based on the actual (measured) energy consumption.

2.3. Spatial boundaries

The **spatial boundaries** for the final balance of the metric are essential to identify the type of end-use, and production flows across the boundary. The boundaries for this balance have an impact on the reported overall performance level of the building. The boundaries for EXCESS' PEB focusses more on a single building [48], whereas the spatial boundaries of the JPI Urban Europe's PED are set in a way that the performance level of the complete urban neighbourhood is considered [42]. The spatial boundaries of a Passive House are set in a manner that they only consider the usable living area into account, whereas most standards on low energy buildings usually deal with the total area of the building [49]. The UKGBC considers ownership as a basis for the determination of the on-site processes [16]. The portfolio owner may therefore demonstrate net zero carbon across the entire project that is under their control (typically landlord areas), even if single building units that are part of the portfolio do not actually achieve the net zero carbon balance individually. An individual tenant may in this sense also demonstrate the same balance for the complete rented areas under their control [16].

2.4. Type of end-use

The **end-use categories** that are included in the energy balance of an Active House are especially related to the building (including heating, cooling, ventilation, lighting, Domestic Hot Water (DHW), auxiliary energy and the embodied energy) [50,51]. This is in contrast with a the 3-Liter House in which only heating end-uses are considered for the verification of the performance level of the building [47]. The performance level of the Active House is therefore difficult to compare to that of the 3-Liter House. Electric mobility is furthermore in many cases not considered, as it exceeds the spatial boundaries of the building. In some definitions, it is explicitly stated that electric mobility is not part of the final balance of the metric. This is for instance the case for the UKGBC net ZCB [16]. However, in the JPI Urban Europe PED-definition, the spatial boundaries are defined in a manner that mobility is included in the total final balance [42]. Information on the end-uses and production flows in the final balance is essential to obtain an idea regarding the comparability of the performance level of HEPB-subtypes.

2.5. Final balance

The relevance of making a distinction between **qualitative and quantitative definitions** can be illustrated using the passive house as an example [52]. The passive house definition, as developed by the Passive House institute (PHI) in Germany [53], is assessed on the basis of threshold values for space heating and cooling energy demand, renewable energy production, airtightness and comfort values [52,54,55]. When looking at this definition in a qualitative manner, it can be understood that this final threshold values should be met to a large extend by means of passive design measures [53]. If the passive house definition is solely interpreted qualitatively, one might think that this term refers to a house with no active systems [20] and in case the definition is solely interpret quantitatively, the passive requirements are neglected.

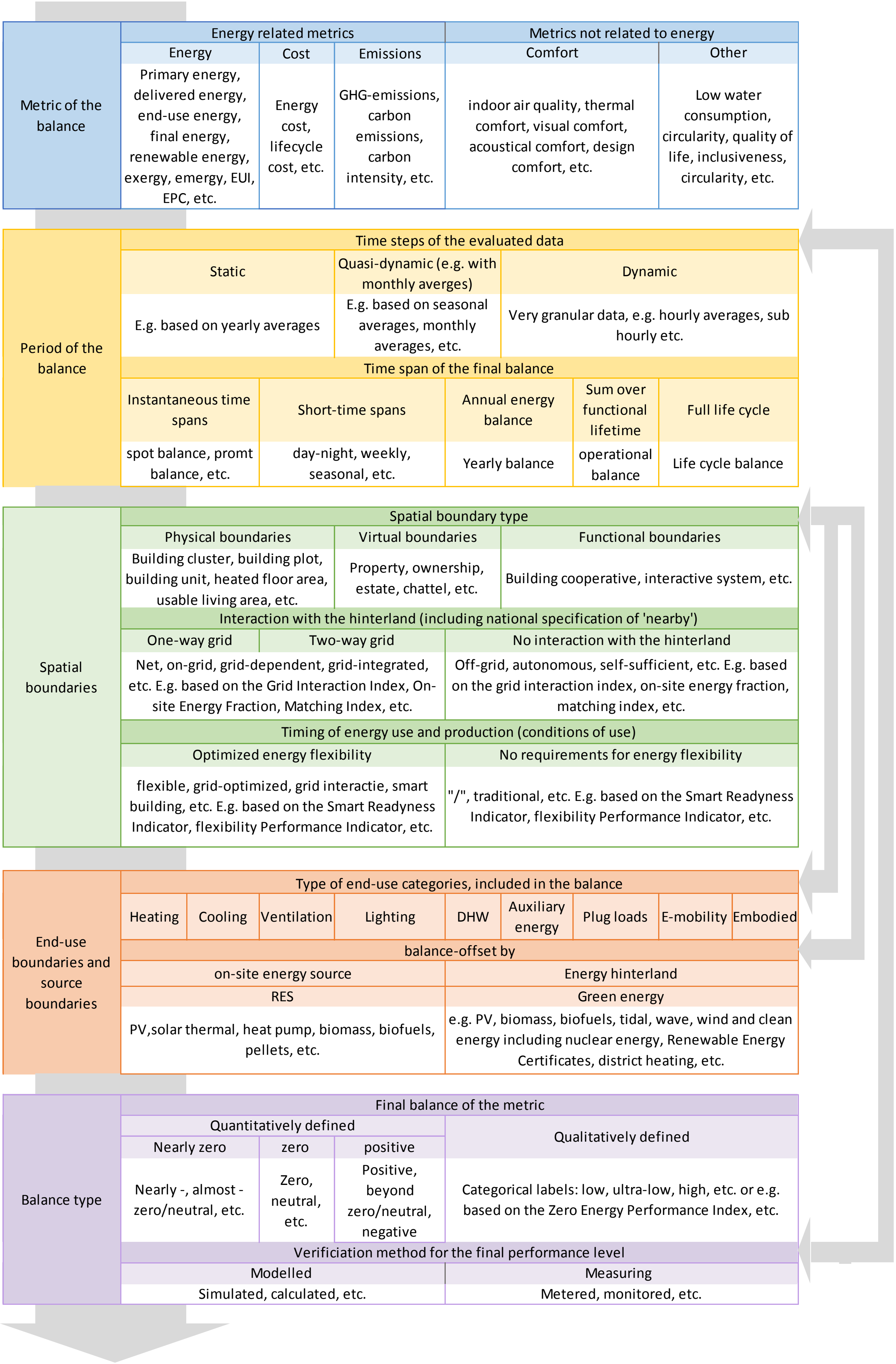
The balance between consumed and produced quantities of the metric on-site can also be subject to different interpretations. The **final balance** of the heating and cooling loads, as well as the final balance of the total primary energy demand of the PHI Passive House and a 3-Liter House [47] is low, however, not zero [55]. This is for instance in contrast with the required zero energy balance of a DOE ZEB [43].

2.6. Need for a consistent and reliable taxonomic framework for HEPBs

Without explicit specification of a complete set of KPIs and related boundaries, direct comparison between these buildings becomes problematic and may lead to incomplete or false conclusions regarding the performance level of the buildings, which is confirmed in literature (among which [2,25,56]. The aforementioned examples of HEPB-types are used to illustrate the variety of HEPB-types and the domains in which they may differ. The differences may not be visible without specifying them. Apart from the aforementioned definitions, many more HEPB-examples exist that can be used to demonstrate the risks of insufficient or incomplete communication on the performance indicators and boundary conditions in the HEPB-definitions [31]. A consistent and reliable framework for the categorization of HEPB-definitions requires the implementation of all of these areas to avoid future miscommunication and erroneous conclusions after comparison to e.g. benchmarks or the performance level of other buildings.

3. Taxonomic framework for HEPBs

A taxonomic framework is proposed that aims to support in drawing up definitions or classifying definitions (or rating schemes) for comparison of their performance level (Figure 2). The taxonomic frame in this paper, primarily focusses on buildings that contribute to reducing the energy consumption and increasing the performance level on the energy-derived metrics. In addition, an outline is given on how HPB-concepts that are not solely defined by energy related metrics would fit into this taxonomic framework. The various indicators and boundary conditions which are included in the frame are furthermore discussed. The proposed taxonomic framework also provides some terminology that can be found in the definitions, functioning as an indication on how they could fit in the framework or an impetus to further expansion of the framework.



Metric of the balance	Energy related metrics			Metrics not related to energy	
	Energy	Cost	Emissions	Comfort	Other
	Primary energy, delivered energy, end-use energy, final energy, renewable energy, exergy, emergy, EUI, EPC, etc.	Energy cost, lifecycle cost, etc.	GHG-emissions, carbon emissions, carbon intensity, etc.	indoor air quality, thermal comfort, visual comfort, acoustical comfort, design comfort, etc.	Low water consumption, circularity, quality of life, inclusiveness, circularity, etc.

Period of the balance	Time steps of the evaluated data		
	Static	Quasi-dynamic (e.g. with monthly averges)	Dynamic
	E.g. based on yearly averages	E.g. based on seasonal averages, monthly averages, etc.	Very granular data, e.g. hourly averages, sub hourly etc.

Period of the balance	Time span of the final balance				
	Instantaneous time spans	Short-time spans	Annual energy balance	Sum over functional lifetime	Full life cycle
	spot balance, promt balance, etc.	day-night, weekly, seasonal, etc.	Yearly balance	operational balance	Life cycle balance

Spatial boundaries	Spatial boundary type		
	Physical boundaries	Virtual boundaries	Functional boundaries
	Building cluster, building plot, building unit, heated floor area, usable living area, etc.	Property, ownership, estate, chattel, etc.	Building cooperative, interactive system, etc.

Spatial boundaries	Interaction with the hinterland (including national specification of 'nearby')		
	One-way grid	Two-way grid	No interaction with the hinterland
	Net, on-grid, grid-dependent, grid-integrated, etc. E.g. based on the Grid Interaction Index, On-site Energy Fraction, Matching Index, etc.		Off-grid, autonomous, self-sufficient, etc. E.g. based on the grid interaction index, on-site energy fraction, matching index, etc.

Spatial boundaries	Timing of energy use and production (conditions of use)	
	Optimized energy flexibility	No requirements for energy flexibility
	flexible, grid-optimized, grid interactie, smart building, etc. E.g. based on the Smart Readyness Indicator, flexibility Performance Indicator, etc.	"/", traditional, etc. E.g. based on the Smart Readyness Indicator, flexibility Performance Indicator, etc.

End-use boundaries and source boundaries	Type of end-use categories, included in the balance								
	Heating	Cooling	Ventilation	Lighting	DHW	Auxiliary energy	Plug loads	E-mobility	Embodied

End-use boundaries and source boundaries	balance-offset by	
	on-site energy source	Energy hinterland
	RES	Green energy
	PV,solar thermal, heat pump, biomass, biofuels, pellets, etc.	e.g. PV, biomass, biofuels, tidal, wave, wind and clean energy including nuclear energy, Renewable Energy Certificates, district heating, etc.

Balance type	Final balance of the metric			
	Quantitatively defined			Qualitatively defined
	Nearly zero	zero	positive	
	Nearly -, almost - zero/neutral, etc.	Zero, neutral, etc.	Positive, beyond zero/neutral, negative	Categorical labels: low, ultra-low, high, etc. or e.g. based on the Zero Energy Performance Index, etc.

Balance type	Verificiation method for the final performance level	
	Modelled	Measuring
	Simulated, calculated, etc.	Metered, monitored, etc.

Figure 2: Outlines of a taxonomic framework for HEPBs.

3.1. Metric of the balance

The metric of the balance is an important aspect in the definition as it captures the overall project goals and the intentions of the investors [7]. Drivers for investments in HEPBs, in most cases, have the ambition to ensure a secure energy supply, provide access to clean energy or financially affordable energy [57]. The two metrics that are most often associated with the energy balance are energy cost and emissions [7,58,59]. Apart from the aforementioned, other green building indicators can possibly be seen as metrics (e.g. comfort, water management, land-use etc.) [7]. These metrics are either (semi-) dependent or independent from the energy metric. The energy-dependent metrics are obtained from the energy balance, using weighting systems (Figure 3). The energy-independent metrics are a result of non-energetic green building indicators [60,61]. The hybrid category of semi-energy-dependent metrics combines both energy-dependent and independent metrics (e.g. buildings that are assessed based on the 'exergy'-metric). In addition, the context of energy-independent metrics is provided. The focus for HEPB projects may in the first place be on one metric. However, it is possible to consider multiple metrics for the balance, e.g. indoor air comfort in low energy buildings, resulting in multi-objective design strategies.

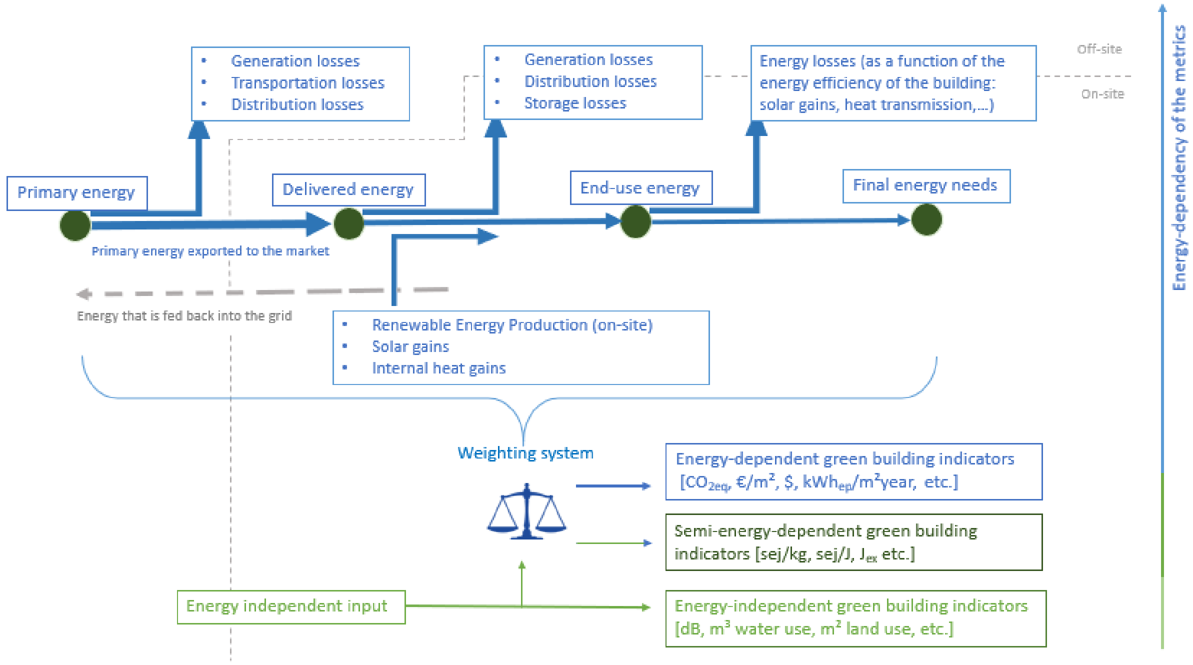


Figure 3: Schematic illustration of the transformation of primary energy into useful, final energy needs, adapted from [7,11,62–65] *with suggestion for off-site and on-site boundaries.*

3.1.1.Energy

For the determination of the performance level of a building, energy needs are often used as a metric for comparison. The HEPBs with 'energy' as a main metric are often referred to as '(Net/Nearly/beyond/... Zero) Energy Buildings'. The energy needs of the buildings can be determined in various ways. Distinction is needed between zero source and zero site energy [25,62]. This distinction is reflected in the two popular understandings of the energy metric, namely primary energy and delivered energy. Primary energy as a metric of the balance allows to take into account the difference between the final energy needs and the source energy to cover for it [27,66] (see Figure 3). This metric is commonly used [3,5], as the regulatory focus in building codes is often on this metric [5,62]. Using primary energy as a metric for the balance is especially possible during the early design phase of the building, whereas the final energy needs and end-use energy is easier to asses when monitoring the building in its operational phase.

For the transformation of final energy into primary energy, Primary Energy Factors (PEF) or conversion factors are needed [67]. These factors represent the amount of primary energy that is required per unit of final energy [63] and are based on pre-defined, regional or national weighted averages or specific on-site production values that reflect reality [68]. These factors depend on a multitude of considerations (e.g. national energy mix, climate,…) and may reflect political preferences, rather than solely scientific or engineering understandings [7]. PEFs may for instance have a direct effect on the competitiveness of certain technologies, depending on the energy carrier. Furthermore, various calculation methods exist to determine these conversion factors [69]. The lack of information regarding these factors leads to difficulties in comparing HEPB-types. This is especially problematic on international level. When specifying the exact metric of the balance, it is therefore essential to provide information on the calculation methodology or type of conversion factors as well. On European level, standardized tables are provided for reporting these factors in a structured and standardized manner (e.g. the choice of numerical primary energy factors and the respective rating methods) [22]. This is a first step towards harmonization and increasing transparency, to enable comparison and exchange of information on best-practice examples.

Delivered energy is the metric of the balance that is easiest to understand and implement [27,63]. The balance of this metric can easily be verified by means of the utility bills [70]. This metric has, however, two important drawbacks: the fact that conversion and transportation losses are neglected and ignorance of the quality of the different types of energy [32]. The energy balance can furthermore be transformed into other, closely related energy metrics. The Energy Use Intensity (EUI), reflects for instance the building's energy use, normalized by the size of the building (usually the total floor area). Another example is the Energy Performance Coefficient (EPC or EnPC), which is a dimensionless metric that considers the yearly energy consumption and on-site renewable energy production [71].

3.1.2. Cost

The measures that are taken to achieve a HEPBs may have a significant influence on the global cost of the building [65]. Building owners are typically interested in low or even zero energy cost buildings, using energy efficiency measures and installing renewable energy systems to reduce the energy cost during the operational phase of the building [70]. The global cost of these buildings usually consists of the initial investment cost, the annual cost, the disposal cost and the GHG-emission cost [66].

The operational energy cost balance can easily be verified by means of the utility bills. Calculations of the energy cost in the early design phase of the building are however challenging [27]. The energy prices (and investment costs) not only change in time, but can also differ internationally. The feed-in tariffs and purchase tariffs depend largely on the national context and approach towards these buildings and sometimes private agreement between building owner and the utility grid [32]. Reaching the zero energy cost level can furthermore be challenging due to (fluctuations in) utility rate structures that compensate for the energy to be exported to the grid, which often not allow for the energy cost balances to go below zero on an annual basis [70].

3.1.3.Emissions

Another set of HEPB-definitions focusses on the emissions that are a result of the achievement of a certain energy balance. Emissions are an appropriate metric for the HEPB-definitions when high priority is given to climate change response [5]. Within the category of low emission building, focus is mostly on carbon dioxide (CO_2) [3,5,72], as it is seen as the main GHG that is responsible for the climate change [73].

3.1.4. Green building indicators

In addition to the energy-related concept, the focus of the definition can also be on other (energy-unrelated) concepts, such as water use, acoustic comfort and the effects of the building on the natural landscape. Sustainability is worldwide no single defined concept [74]. It is a time-dependent concept [64] and interpretations are constantly added [64]. When focus is on broader sustainability targets, the design of an HPB in general results in reducing or completely avoiding the depletion of critical resources (e.g. energy, water, land, raw materials), prevention of environmental degradation, caused by the infrastructure throughout the life cycle of a building, the creation of a build environment that is liveable, comfortable, safe and productive [75]. This is often achieved through a collaborative approach [64,76].

HPB-definitions that have such broad sustainability indicators, are often referred to as ‘green buildings’, ‘ecobuildings’ or ‘sustainable buildings’ and in this article categorized under ‘HPBs’. These terms are often used interchangeably, but are in fact not all synonyms [20]. Green buildings and ecobuildings are considered to aspire to achieve sustainability but do not necessarily achieve this level [15]. In this sense, it is true that HEPBs (such as low energy, carbon or cost building projects) are a step towards the achievement of the green or even sustainable building status.

The energy-related metrics can be combined with broad sustainability indicators, resulting in the hybrid semi-energy-related metrics. An example is the ‘emergy’-metric (energy and material flows), which is a method that accounts for the environmental resource use, both directly and indirectly related to a construction [77]. The quantity of materials and other flows (e.g. lands use, energy and human labour) are considered in the balance of this metric [77–79]. Another example is the ‘exergy’-metric, used to quantify all energy and material needs for a building, both for the construction aspects and operational phase of the building [80]. These metrics are complementary to embodied energy use [77].

3.1.5.Comfort

Comfort requirements are inherent boundary conditions to energy related metrics, however certainly not always considered as an additional requirement in HEPB-definitions [7,81]. The possible comfort considerations in the HEPB-design concepts are spread throughout the domain of health, well-being and productivity. They can generally be categorized in five groups, as shown in Figure 4 [17]. The inclusion of multi-objectives in the HEPB-design (e.g. comfort consideration as secondary requirements, apart from the reduction of energy-weighted metrics), contributes to a holistic design approach. Whether or not comfort requirements are met, impacts the reported performance level of a building.

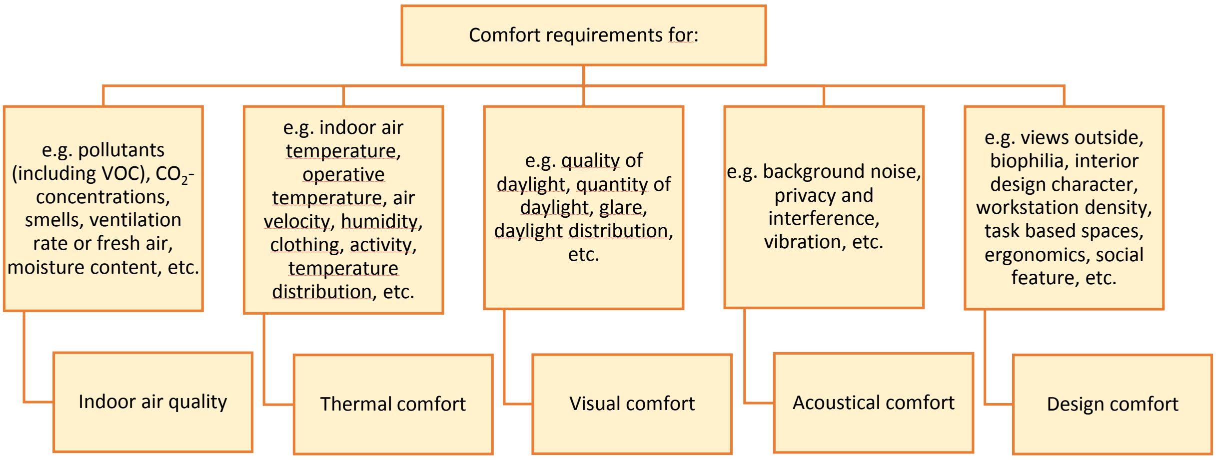


Figure 4: Classification of comfort requirements, adapted from [17,82,83].

3.2. Time boundaries

The time boundaries of the balance can be defined by the time steps (also referred to as sampling -or recording time [84]), used in energy measurements or calculations, and the time span over which the balance is considered.

3.2.1. Time steps of the evaluated data

Technologies that are applied to meet the performance requirements of HEPB-types are dynamically interacting with variations in weather and operation conditions (e.g. thermostats, occupation, energy needs, mechanical ventilation, window blinds, weekend operation, heat pumps, solar panels, etc.). The inclusion of dynamic effects has a prominent effect on the reported performance level [22] and requires small time steps in the verification methodology. The required time steps depend on the desired data accuracy and on the monitoring equipment that is used [84]. The time-approach is in many cases considered as a direct result of variations in the time steps for the determination of the final balance [7,33,85–87].

Distinction can be made between the static -, quasi-dynamic-, and dynamic time-approach for the calculations and measurements to obtain the final balance [22]. The static approaches are characterized by low-granularity of the input data, which could for example be based on yearly averages [7]. The input data and time steps of the quasi-dynamic approach have a higher granularity, e.g. based on seasonal averages or monthly averages. The high granularity of the dynamic approach is typically a result of hourly or even sub-hourly calculations or measurements.

Simple monthly balances are sufficient to investigate the seasonal performance of buildings, whereas daily and hourly fluctuations need higher granularity [88–90]. A monthly calculation method contains correction or adjustment factors that are predefined in a statistical manner to reflect the dynamic effects. These factors are usually based on a large set of dynamic building simulations with e.g. daily variations of weather conditions and conditions of building use. The quasi-dynamic and static methods have lost their transparency and robustness due to the necessity to introduce an increasing number of correction or adjustment factors. Ensuring good comparability of the building’s performance levels, requires information regarding such correction factors [22]. The dynamic approach does not rely on a large set of correction factors, but the challenge in this method lies in avoiding the need for too many input data from the building as this data is sometimes not available. The increased amount of input data also introduces more uncertainties, easily leading to a decreased accuracy of the final balance of the metric [22]. The method furthermore requires more expertise and a higher computational cost.

For energy-related and semi-energy related metrics, weighting factors (e.g. energy prices) are ideally adapted within the same time steps as the rest of the verification, enabling for instance to assess dynamic pricing mechanisms [91,92]. Information regarding the time steps and which whether weighting factors are adapted to these time steps is therefore suitable information in detailed definitions on HEPB-subtypes.

3.2.2.Time span of the final balance

The time steps of the evaluated data should be distinguished from the time span of the considered balance. Both monthly and sub-hourly data can for example be used to obtain a mean final balance that is spread over the time-period of one year. The time steps are in this sense monthly or sub-hourly (quasi-dynamical or dynamical) defined, whereas the time span is the period of one year. The time steps of the balance can be shorter or equal to the time span of the measurements or calculations.

Carrilho da Graça [93], Sartori et al. [7] and Voss et al. [89] highlighted the implications of the time span definition for the final balance in the assessment of the building's compliance with a certain HEPB-definition. Literature reports on four main options for the timespan: (i) full life cycle of the building, (ii) the operational time of the building, (iii) annual balance or in special situations (iv) the short time spans, namely seasonal, monthly, hourly or even sub-hourly balances [7,32]. An additional time span category are the 'one time' or 'spot' balances. These balances are useful for constant metrics or to detect instantaneous conditions [7] (e.g. assessing the PV-system performance and failures under clear sky conditions) [84]. The short time spans reflect short durations (e.g. weeks, day-night differences, etc.). These time spans provide information about the time-dependent behaviour of the HEPBs. The long-time spans consists of the yearly, operational and full life cycle balance. These balances are relevant to assess metrics that are influenced by variances in conditions (e.g. weather variations, user behaviour or operating conditions). HEPB-definitions and policies usually focus on the sum of the metric over the functional lifetime [94].

The balance can be made during a specific time span (e.g. annual balance) and then afterwards extrapolated to a larger time span (e.g. sum over the functional lifetime). Literature mentions the annual balance as a typical and often used balancing period, as it enables to include the seasonal variations [32,48,70,95]. In case the temporary mismatch between the supply and demand has to be examined, the hourly time span is suggested [48]. The spot balance, on the other hand, can be used to derive pieces of information on a longer time span in case they are used to measure time-constant metrics. The output can, in such cases, be repeated to obtain the trend over a longer time span [84].

3.3. Spatial boundaries

The traditional distribution model that is characterized by the one-way delivery of electricity and the related definitions for upstream and downstream have become obsolete and is now challenged by local generation and decentralised means [38]. In smart city projects, the production and consumption model is more complex with regards to design, operation and maintenance principles, combined with the introduced new key elements such as Renewable Energy Sources (RES), energy storage, data management and prosumers [38]. In some definitions, energy management practices, such as energy storage (which can be both physical [96–98] and virtual [99–101]) are an imperative part to provide in sufficient comfort levels. The old production/consumption model should be replaced by the current, more complex model that is defined by storage and data management possibilities, central (renewable energy) production systems and synergies between a group of buildings and the energy grid [38]. The energy grid, in this sense, is very broad and should not be limited to the electricity-grid. This conception of the 'grid' is sometimes referred to as 'hinterland' and includes e.g. other energy carriers for heat and cold such as biomass, biogas, syngas, etc. [38]. To indicate the difference between buildings projects that need the hinterland to balance the metric and building projects that operate on an autonomous basis, spatial boundaries become paramount [7,27,38,66,88], possibly supplemented with information on grid interaction and the timing of the energy use and production.

3.3.1.Spatial boundary type

The spatial boundary can be defined as the interface between the building (or in some cases cluster of buildings that show synergies [7]) and the hinterland [88]. This boundary results in the differentiation between on-site and off-site systems in the load/generation balance [88]. An accurate description between on-site and off-site boundaries is strongly debated internationally, and may therefore differ in various definitions. Three dimensions for the spatial boundaries are suggested: (i) physical, (ii) virtual and (iii) functional dimensions for the determination of possible synergies with the hinterland.

Production, storage and consumption options are considered physically on-site, if situated in, under or adjacent to the building or cluster of buildings. This is in line with the interpretation of the Global Building Performance Network (GBPN) [102]. What cannot be classified under the aforementioned, is part of the off-site physical boundary category. In line with the physical interpretation of the spatial boundaries, a vehicle is considered to be an on-site end-use category that is included in the final balance of the metric unless this vehicle is used outside of the physical boundaries of the building. If the vehicle is used outside of the physical boundaries, the energy flow is seen as exported energy trough transmission to or from the hinterland. Following the same idea, renewable energy production can be seen as physically on-site in case the fuels are harvested on-site. Otherwise it is seen as delivered energy [43].

Sartori et al. [7] and the Zero Carbon Hub [103] argue that on-site energy flows should not be located on the physical building site itself. If these investments are financed by the building owner and contribute to the balance of the metric of the building, they could also be categorized under on-site building systems. This need is reflected in the definition that was proposed in the +CityxChange project [38] and resulted in the virtual dimension for the determination of on-site boundaries. The virtual dimension limits the building(s) in terms of contractual boundaries and provides the possibility to include for instance production infrastructure that is situated outside of the geographical boundaries, however, owned by the building(s) holder. Building systems that are owned by or rented to a third party (e.g. energy service companies or ESCO's [104]) during the period in which they contribute to the balance of the metric of a building can be excluded from the on-site boundaries in case the boundaries are set in a virtual or contractual manner.

The additional functional dimension limits the HEPB in terms of functional units that contribute to the balance of the buildings' metric. This interpretation limits on-site production, storage and consumption systems to those that directly contribute to the balance of the metric without being blended with the energy mix from the hinterland for transportation. This manner, district heating, as an independent entity, is considered a functional part of the HEPB and can could therefore be an on-site production unit. However, in physical terms, it would not be considered on-site [38]. This stresses the importance of the awareness regarding the three dimension that define the spatial boundaries in HEPB-definitions.

3.3.2. Interaction with the hinterland

Renewable energy is often locally generated, changing the traditional unidirectional centralized energy hinterland system towards a bi-directional decentralized system with smaller production plants and multiple prosumers [105]. Therefore, distinction is made between one-way grids in which energy is either only exported to -or imported from the hinterland to the building and the two-way grid which features both import and export to and from the grid [7]. When a building interacts with the energy hinterland, it is furthermore valuable to specify whether or not the source energy comes from near or far away. With this regard, additional information on the national specification of nearby is essential, as this can be country-specific [22].

After the type of boundaries are set, it can be verified whether the building interacts with the hinterland to obtain a certain final balance. Buildings that are characterized by a neutral or beyond neutral balance without needing the energy grid, are referred to as autonomous buildings. These buildings are neither bidirectional, nor unidirectional connected to the energy hinterland. This type of buildings are also indicated as 'self-sufficient', 'stand-alone' or autarkic buildings [6,29,32]. If these buildings cannot produce or store a sufficient amount of the metric (e.g. renewable energy, carbon capture, etc.) at any moment in time to meet the envisioned balance, it will either need to rely on the hinterland or needs investments in on-site energy storage technologies (physical and/or virtual) to bridge the mismatch between production and consumption. Buildings that are dependent on the hinterland at some moments in time, are referred to as 'grid integrated', 'net zero' or 'net neutral' buildings and still need the hinterland to obtain a certain balance [27,29,32,33,106]. In older definitions [29,94], buildings are considered off-gird if they only need the hinterland as a backup solution. However, this would be contradictory to the strictest sense of the spatial and time boundaries during periods of time when the hinterland needs to be addressed.

The interaction of the HEPBs with the energy grid is essential information in the definitions [48]. It is in some cases explicitly calculated. The grid interaction index, for instance, represents the standard deviation of the net export energy within one year, normalized by the highest absolute value [89]. In other cases, the net export energy is calculated as the difference between the export and the import energy between the energy hinterland and the building. Other indicators exist as well, such as the on-site energy fraction or the matching indexes for different energy carriers [107]. These factors are only relevant when data is available for at least one year with hourly or sub-hourly time resolution [48].

3.3.3. Timing of the energy use and production

The increased share of RES to the energy mix, leads to challenges in planning and controlling the energy production, transmission and distribution [105]. To support the transition to renewable energy systems (which is characterized by intermittent energy production) together with the growing electricity demand, there is a need for an adjustable demand, based on the available generated power [105,108,109]. Energy flexibility refers to the potential to adjust the energy demand and supply on the basis of external requests [105,109,110], which can be utilized for stabilizing the energy grid or maximize self-consumption of on-site RES [111]. The utilization of advanced control systems, such as demand response, load shifting, heat pump and tank storage combo, energy cost and renewable energy generation that is based demand shifting, increases the energy flexibility of a building [105,110,111]. The extent to which a building is energy flexible, provides useful information about the impact of the HEPBs on the energy hinterland, thus influencing the performance level of the building [109]. An example of a parameter to quantify energy flexibility is the Flexibility Performance Indicator, as proposed by Arteconi et al [109].

3.4. End-use boundaries and source boundaries

In HEPB-definitions, differences can be found in terms of the energy end-usages that are taken into account, e.g. heating, cooling, plug loads, etc. The end-use boundary, also referred to as balance boundary [7], is used to determine whether certain energy end-uses are included or not included in the final balance of the metric. Furthermore, information on the included energy sources for the balance of the metric is of value in the HEPB-definition.

3.4.1.Type of end-use categories considered in the balance

The importance of defining the end-uses that are considered for the final balance of the metric, is multiple times confirmed in other articles and reports on HEPB-definitions and assessment strategies [7,29,32,112]. The end-use categories that are considered in the balance are still a subject of debate in the HEPB-definitions [11]. To guarantee clarity about the meaning of the performance level of the HEPB-types, information about the included end-use categories in the final balance of the metric is crucial.

The first attempts of HEPBs were zero thermal buildings [32,94,113–115]. These buildings were designed to solely decrease the space heating or cooling loads to a zero energy level (although in a few instances, DHW-loads were included in the balance as well) [32]. In other approaches, only the end-uses that are characterized by electricity as an energy carrier are accounted for in the assessment of the HEPB [116,117]. Presently, end-use categories that are typically considered are building related end-uses: HVAC, domestic hot water (DHW), lighting and other Building Integrated Technical Systems (BITS) [3,7].

Plug loads, auxiliary components and embodied energy are often excluded from the final balance [3,118]. The reason to ignore plug loads in the final balance of the metric can be explained by the fact that it is not considered permanent in the buildings [2]. In most evaluations, the energy consumption by HVAC systems are considered an inseparable mix, whereas in other evaluations primary equipment is included by means of a rule-of-thumb addition that accounts for the auxiliary equipment [119]. However, sometimes, auxiliary energy is not incorporated in the end-use category to which it contributes [118], although its contribution to the total end-uses can be high and is likely to increase, even as primary equipment is showing vast improvements in energy efficiency [119].

The balanced end-use categories are affected by the considered time boundaries. The final balance of the metric is primarily related to the contribution of the end-uses during the operational phase of the building project [120,121]. Many definitions exclude embodied energy from the HEPB-definition and only consider the operational phase of the building [3,94]. A possible reason for only covering the operational phase of the buildings in de definition is the absence of an accurate method to calculate the end-use category that is related to the construction and demolition phase [122].
However, others, among which Hernandez and Kenny [33], suggest that the energy balance should take into account the embodied energy (energy that is related to the materials and consumed during the building’s construction and use phase (e.g. embodied energy) [65] and demolition phase during the full life cycle of the building) [32,33]. As the share of energy demand and contribution to GHG-emissions of buildings in HEPBs is reduced significantly, the impact of the embodied energy becomes increasingly important in the total balance of the metric [33,94,123–125]. In a low energy building, the embodied energy share can for instance reach 26%-57% of the total final balance and in (nearly or net ZEBs even 74%-100% [126].

E-mobility is becoming increasingly popular [127] and provides the option to store energy, needed for peak shaving. The e-mobility end-use category is affecting the balance of the metric, increasing energy flexibility of the building and decreasing grid-dependency [26]. Introduction of this end-use category in the final balance of the metric is therefore valuable. Other end-uses (e.g. rain water treatment) may be included in the balance of the metric as well, which are typically a prerequisite to comply with sustainable certification schemes, such as LEED [40], GRIHA [128] and BREEAM [41] [129].

3.4.2. Balance-offsets

Analogous to the end-use categories, HEPB-definitions can differ with regard to energy-source categories, taken into account in the final balance [31]. Specifying the source categories that are included in the balance, and the hierarchy according to which they should be implemented is for some cases crucial information to determine the performance level of a building [48]. A first distinction can be made between on-site energy sources and the energy hinterland. The spatial boundaries play a role in this distinction.

Some HEPBs are named after the RES that have been installed in the building, e.g. photovoltaic ZEB, wind ZEB, photovoltaic-solar nearly ZEB, etc. [6,130]. These buildings are characterized by very specific energy-source categories, such as PV, wind, PV-solar. The specific energy-sources can be grouped (e.g. biomass, biofuels, hydroelectric, etc.). Without information regarding what is, or is not included in the considered source categories, the HEPB-definition can be insufficiently complete to differentiate between certain HEPB-types. With this regard, it can be useful to indicate the specific types of energy sources (e.g. biomass, biofuels, wind, PV, etc.) that are considered within the balance.

The time-dimension and spatial boundaries that are taken into account have an impact on the included source categories, which can be demonstrated with biomass as an example. The CO_2-emissions that are being captured in the biomass are returned to the atmosphere through combustion, leading to a zero increase in CO_2-emissions. However, when considering the whole lifecycle of a building, the origin and therefore also transportation radius of the biomass has an impact on the final balance. In case the harvest, transport, production process and delivery of the biomass are included in the balance as a result of the chosen time-dimension, the final balance could be 'nearly zero', not reaching the neutral carbon emissions balance [131]. In case part of the resultant additional CO_2-emissions are produced outside of the spatial boundaries, the balance can even be 'nearly net neutral'.

3.5. Final balance of the metric

In many HEPB-definitions, the final balance plays a decisive role in the given HEPB-category of the building. Some HEPB-definitions are solely descriptive (referred to as qualitative definitions), whereas others are quantitative, characterized by threshold values [20,71]. Furthermore, the verification of this final balance can either be based on the actual or predicted performance or a combination of both.

3.5.1.Quantitative versus qualitative definitions

In case the final balance of the HEPBs is accompanied with relative benchmark to comply with a certain HEPB-definition, they are referred to as quantitative definitions. Benchmarks are suitable for the assessment of HEPB-projects in other regions with similar climates, political views, similar occupancy schedules, etc. However, the biggest drawback of a benchmarking method is that this definition can only be used properly outside of these boundaries, in case the benchmarks are adapted to local conditions [7]. New and different concepts are needed that are inter alia geo-climatically and geopolitically adapted to be applicable in other regions as well. Garcia et al. [132] proposed fixed, relative targets as a basis for the determination of the performance level of buildings, rather than fixed maximum values in order to obtain an outcome that is most suitable for international comparison. In this manner, the impact of the local conditions on the used weighting system, can be introduced, along with the metric.

When the balance of the metric reaches the zero level, a ‘zero’ or ‘neutral’ status can be granted (e.g. ZEB) [20,25,133,134]. The balance of HEPBs that does not reach the neutral level, yet demonstrates a significant progress towards this level, can, analogously be referred to as ‘nearly zero’ or ‘nearly neutral’ [20,134]. Balances surpassing the zero level, are often marked as ‘positive’ or ‘beyond zero energy’ (Figure 5) [135].

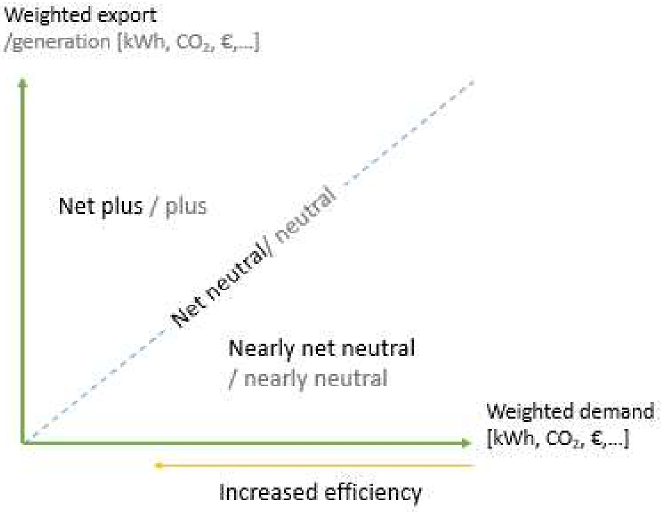


Figure 5: Graphical representation of the final balance of the metric, adapted from [28,88].

3.5.2.Qualitative definitions

The qualitative, descriptive definitions can be used to indicate the quality of the final balance. The final balance in qualitative definitions often comes in the form of categorical labels (e.g. poor, typical, good, high, etc.) or as a quality judgement of the final balance (e.g. low, high, etc.). Another example of a qualitative alternative for the quantitative zero energy balance is the Zero Energy Performance Index (zEPI). This index is used to indicate how likely a building is to be net zero. In case this value is smaller, the building is more likely to be net zero. More qualitative rating types can be found in [71]. The main advantage of the qualitative definition is that it can easily be adapted to updates, e.g. to comply with national energy performance requirements. A disadvantage to the qualitative definition is that they result in interpretations that are difficult to compare to each other (e.g. when the required ratio is different), even though they stem from the same concept [8].

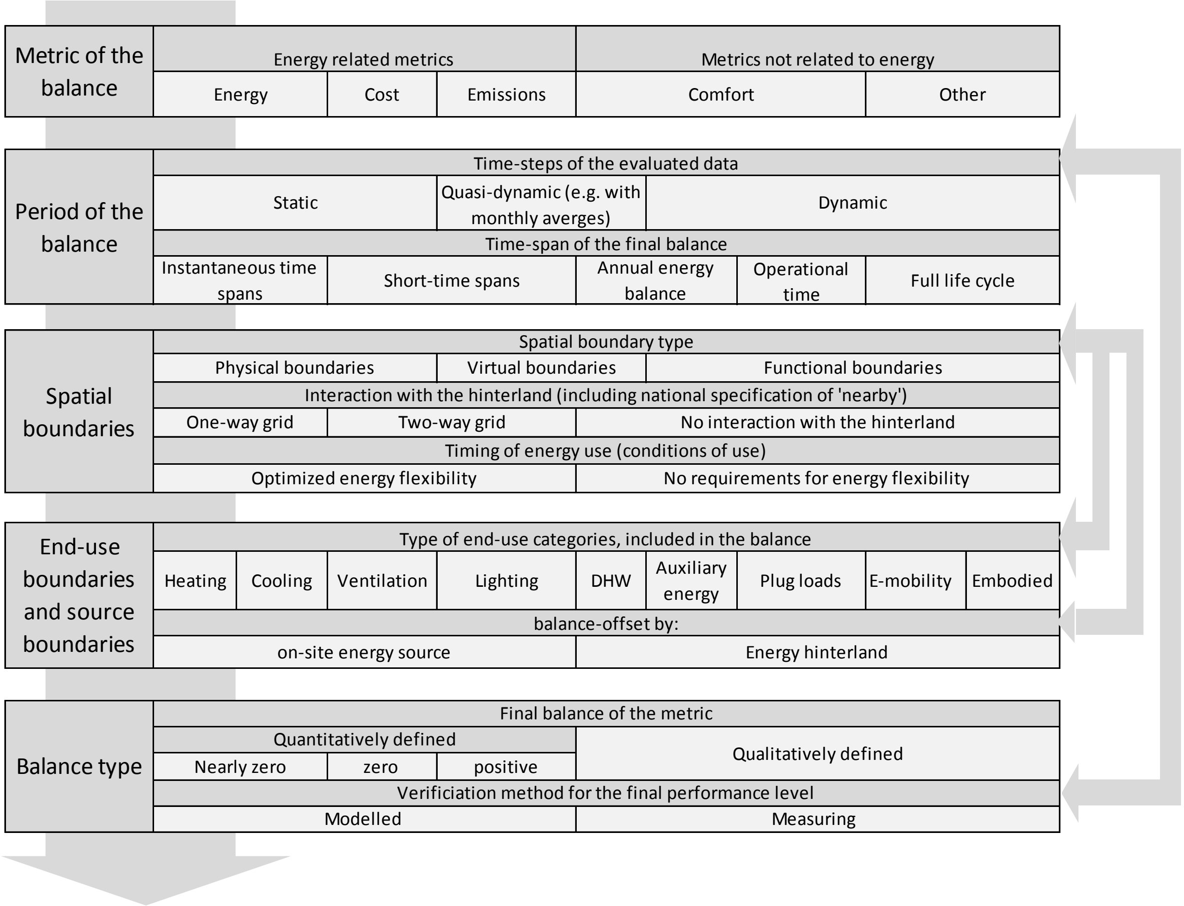
3.5.3.Verification of the performance levels

Two popular approaches for assessing the performance level of a building are: through metering the actual building’s performance or through calculation and numeric simulation. Metering the performance level of a building allows for an efficient collection of detailed actual building information (e.g. energy peaks, medians, extremes, seasonal variations and outliers) [136]. Metered data depends on stochastic variations, such as weather conditions, user behaviour, etc. This limits the conclusions that can be drawn from them as for the complete operational phase of the building. However, when predictions of the balance of the metric are needed, building energy models can be used. The accuracy of these simulation models can be somewhat lower than it is for (carefully) performed measurements. This is often caused by (i) rules of thumb that result in mere estimations of the energy needs of the building and (ii) the parameters that are difficult to estimate, e.g. occupant's behaviour [137]. These models can be calibrated to increase the accuracy by means of environmental and building monitoring equipment that is widespread [137]. This increases the reliability of the final balance of the metric.

3.6. Discussion

Ambiguity regarding core indicators and boundary conditions for the calculation of the performance requirements for HEPBs, makes it difficult to compare the status of the HEPB-market in different countries and regions [138]. The proposed taxonomic framework aims to capture these core indicators and boundary conditions and is expected to increase understanding of HEPB-definitions.

For the comparison of a set of case study definitions, the framework was used in a simplified manner (Figure 6), allowing for a fast, yet meaningful comparison of the definitions. It furthermore illustrates the flexibility of the framework for future adaptations without reducing comprehensibility of the outcome. The simplification is obtained by excluding the set of suggestions that have been made for further refinement (as illustrated in the white brackets of the framework in Figure 2).



Metric of the balance	Energy related metrics			Metrics not related to energy	
	Energy	Cost	Emissions	Comfort	Other

Period of the balance	Time-steps of the evaluated data				
	Static	Quasi-dynamic (e.g. with monthly averges)	Dynamic		
	Time-span of the final balance				
	Instantaneous time spans	Short-time spans	Annual energy balance	Operational time	Full life cycle

Spatial boundaries	Spatial boundary type		
	Physical boundaries	Virtual boundaries	Functional boundaries
	Interaction with the hinterland (including national specification of 'nearby')		
	One-way grid	Two-way grid	No interaction with the hinterland
	Timing of energy use (conditions of use)		
	Optimized energy flexibility	No requirements for energy flexibility	

End-use boundaries and source boundaries	Type of end-use categories, included in the balance								
	Heating	Cooling	Ventilation	Lighting	DHW	Auxiliary energy	Plug loads	E-mobility	Embodied
	balance-offset by:								
	on-site energy source	Energy hinterland							

Balance type	Final balance of the metric			
	Quantitatively defined			Qualitatively defined
	Nearly zero	zero	positive	
	Verificiation method for the final performance level			
	Modelled	Measuring		

Figure 6: Simplified template of the taxonomic framework that was used to test the applicability on a set of HEPB-definitions.

A set of eight HEPB-definitions are classified in the taxonomic framework to visually illustrate the variety in performance level and to test the applicability, ease of use of the framework and the quality of the outcome. A first visual comparison already demonstrates the differences in terms of their performance level. This is illustrated by placing the filled-in frameworks next to each other in miniature (Figure 7).

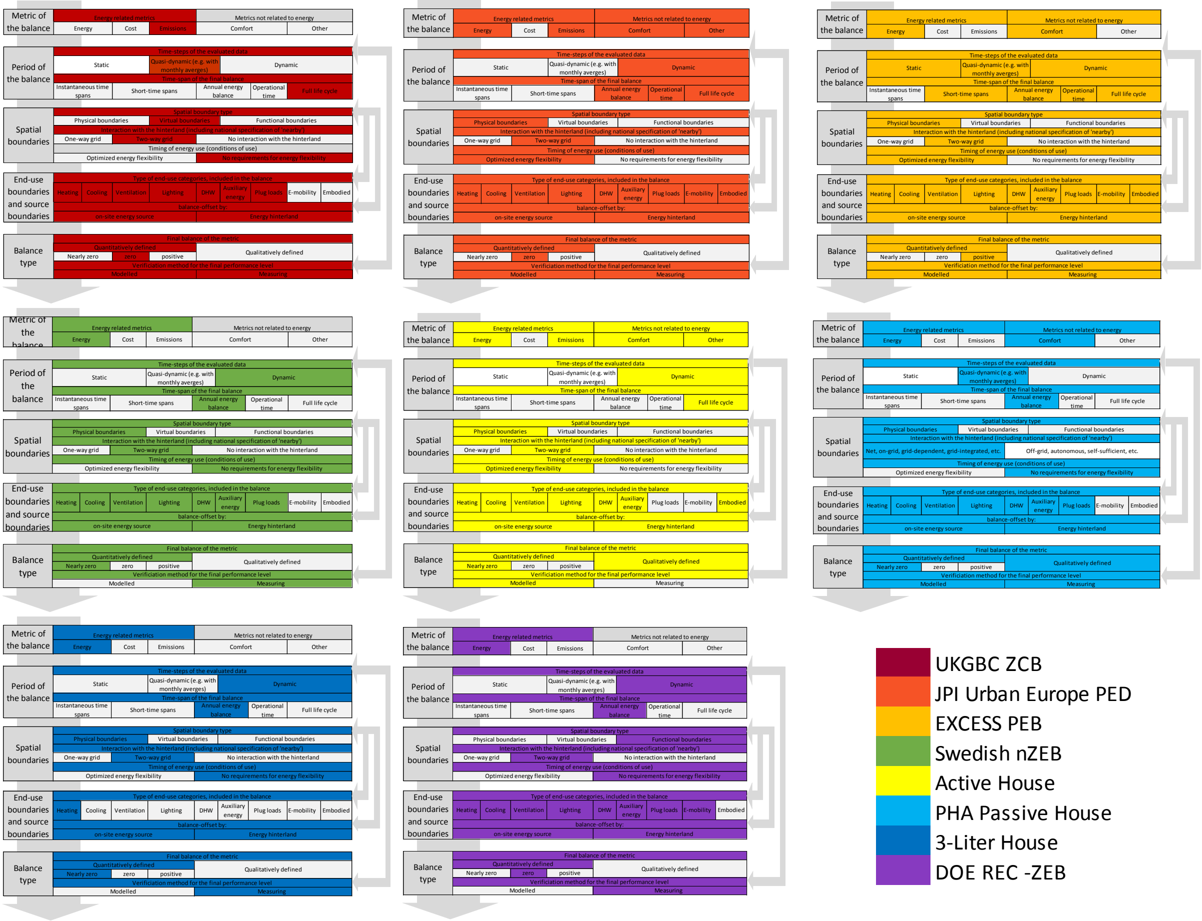


Figure 7: Possible classification of HEPB-types in the taxonomic framework [16,43,44,47–49,51,139,140].

The boxes that are in compliance with the performance requirements of a definition are coloured. In case no information is provided on the KPI and preconditions, all boxes are coloured for that KPI or boundary, therefore allowing any possible infilling. Some definitions remain very generic (e.g. EXCESS PEB [48] and the Active House [139]), recognizable by the large amount of coloured boxes within each category of KPI or boundary condition, whereas other definitions are more specific, such as the Swedish nZEB [44]. Generic definitions provide the opportunity to classify or group a large number of more in detail defined HEPB-subtypes.

It was found that taxonomic classification of the buildings is in some cases hampered by inconsistent terminology. Hence, consistent terminology on all areas is essential for correct classification in the framework when aiming at decreasing erroneous interpretations of HEPB-types.
Changing terms and the disuse of the replaced definitions, could lead to increased difficulties in current and future understanding of differences in HEPB-approaches [20]. As a result, the HEPB-definition may be misunderstood. In such a case, the framework allows to communicate the changes in the definitions in a clear and simple way, by inserting the new and the old definition, showing differences and overlaps.

The framework allows to compare HEPB-definitions in a straightforward manner. Without reading every bracket, differences and similarities between HEPB-definitions already become visible by observing and comparing the coloured brackets of the filled-in taxonomic frames to each other. It is suggested to use the simplified framework (as pictured in Figure 7) as a basis for a first graphical distinction, if necessary followed by a more detailed analysis of selected cases. The framework is furthermore suitable for refinement through elaboration on each given KPI ad boundary. Suggestions for such refinement are included in the extended framework of Figure 2 (within the white brackets). The accomplished detailed subcategory for the KPI or boundary (e.g. for the energy metric: primary energy, delivered energy, end-use energy or…) can be filled in the energy-bracket, an extra row for further division in sub-categories could be added for every KPI or boundary or an additional framework for every overarching group of HEPB-definitions could be provided that focusses on in-depth-categorization.

4. Conclusions

The wide variety of HEPB's is well worth discussing our approach in distinguishing between HEPB-(sub)types and ensuring their common interpretation. Two important tasks we are facing now are the delineation and classification of HEPB-(sub)types. An integrated taxonomy on HEPB-definitions gives priority to HEPB-(sub)types delineation, rather than the creation of new terminology for already existing and emerging HEPB-(sub)types. The need for delineation of HEPB-(sub)types is critical, apart from the production of accurate inventories, as the HEPB-design and operation principles depend partially on those inventories and our knowledge of HEPB-(sub)types. Erroneous boundaries to define HEPB-(sub)types can lead to incorrect design and operation principles. A radical change is essential to prevent worsening over-abundance of both synonyms and names of doubtful applications concerning the creation of names. Some stakeholders in the HEPB-industry have already collaborated and achieved to successfully adopt an integrative approach to the HEPB-taxonomy. It is however essential for the whole discipline to evolve.

Defining one open, overarching definition for all HEPBs would work counterproductive as the definition would not allow estimations of the performance level of the building to be in proportion with the required and possible robustness. One overarching, generic definition alone to define a HEPB, would therefore result in decreased understanding of the performance requirements of various HEPB-subtypes. Alternatively, more detailed definitions are possible for HEPB-subtypes. An essential characteristic of these more detailed definitions is that they are suitable for clear interpretation, exact reproduction and meaningful comparison. Miscommunications or problems regarding comparability and reproduction of the performance level of HEPBs are usually a result of an incomplete or ambiguously defined set of KPIs and boundaries in the definitions for HEPB-subtypes.

In this work, a consistent taxonomic framework is proposed that includes an extended set of KPIs and boundary conditions to distinguish the various definitions of HEPB-(sub)types, as an answer to the large variations in HEPB-definitions and the resultant lack of understanding and comparability between them. The framework allows to identify the variances in the performance level of the multitude of HEPB-subtypes. For the categorization of the HEPBs, a complete set of KPIs and related boundary conditions has proven to be a strong tool. The suggested framework explicitly considers: the metric of the balance, the time boundaries, the spatial boundaries, the end-use and source boundaries and the balance type. The framework allows to compare HEPBs in a fast, straightforward and visual manner and to identify the definitions of HEPB-subtypes that belong to the same ‘family’ of definitions.

We propose the framework to act as a basis for the global understanding and development of complete HEPB-definitions and consistent related terminology. A taxonomic frame with a complete set of KPIs and boundary conditions for the categorisation of HEPB-types is expected to decrease miscommunication regarding HEPB-definitions, avoiding for instance possible legal consequences that are related to erroneous interpretations of certain HEPB-concepts. The frame can furthermore help to raise awareness about the variety in strategic approaches and HEPB-concepts in professional education. By publishing a consistent and clear taxonomic framework for HEPBs, building professionals, service providers, building owners and policy makers are better provided to help increase the HEPB market uptake, quality and profitability of HEPBs. The organisational advantages are related to the increased knowledge regarding some HEPB-types and the consequential speed at which the sector is moving towards a high-performance building market. It furthermore enables efficient communication of good practice on specific HEPB-concepts around the world, for instance facilitating clear and holistic databases that help to get an overview of the HEPB stock in an efficient manner. It is therefore essential that the integration of an HEPB-taxonomy is seen as a crucial precondition for common understanding of HEPB-definitions to solve the gap in communication between all stakeholders.

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