

Article

Positive Energy Building Definition with the Framework, Elements and Challenges of the Concept

Mia Ala-Juusela *, Hassam ur Rehman , Mari Hukkalainen  and Francesco Reda

VTT Technical Research Centre of Finland Ltd., Tekniikantie 21, 02150 Espoo, Finland;
hassam.rehman@vtt.fi (H.u.R.); mari.hukkalainen@vtt.fi (M.H.); francesco.reda@vtt.fi (F.R.)

* Correspondence: mia.ala-juusela@vtt.fi

Abstract: Buildings account for 36% of the final energy demand and 39% of CO₂ emissions worldwide. Targets for increasing the energy efficiency of buildings and reducing building related emissions is an important part of the energy policy to reach the Paris agreement within the United Nations Framework Convention on Climate Change. While nearly zero energy buildings are the new norm in the EU, the research is advancing towards positive energy buildings, which contribute to the surrounding community by providing emission-free energy. This paper suggests a definition for positive energy building and presents the framework, elements, and challenges of the concept. In a positive energy building, the annual renewable energy production in the building site exceeds the energy demand of the building. This increases two-way interactions with energy grids, requiring a broader approach compared to zero energy buildings. The role of energy flexibility grows when the share of fluctuating renewable energy increases. The presented framework is designed with balancing two important perspectives: technical and user-centric approaches. It can be accommodated to different operational conditions, regulations, and climates. Potential challenges and opportunities are also discussed, such as the present issues in the building's balancing boundary, electric vehicle integration, and smart readiness indicators.

Keywords: positive energy building; PEB; energy balance; increasing share of renewables; occupants' well-being; socio-technical framework; user engagement



Citation: Ala-Juusela, M.; Rehman, H.u.; Hukkalainen, M.; Reda, F. Positive Energy Building Definition with the Framework, Elements and Challenges of the Concept. *Energies* **2021**, *14*, 6260. <https://doi.org/10.3390/en14196260>

Academic Editor: Gerardo Maria Mauro

Received: 23 August 2021

Accepted: 22 September 2021

Published: 1 October 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Positive energy buildings can have a significant contribution to the efforts for mitigating climate change, by providing also the surrounding community with renewable energy, while ensuring a good living and working environment for its own occupants.

1.1. Building Sector's Contribution to Decarbonisation Goals

In our attempt to reach decarbonization and climate change mitigation goals, we need to look for all potential means, preferably starting from the most effective ones. The building sector accounted for 36% of final energy demand and 39% of energy-related carbon dioxide (CO₂) emissions in 2018 [1]. Hence, improving the energy efficiency of buildings and reducing related CO₂ emissions is one of the energy and climate strategy spearheads when targeting to mitigate climate change [2]. In the EU, this challenge is addressed among others in the European Commission's Energy Performance of Buildings Directive (EPBD), which regulates that all new buildings in EU countries need to be nearly zero energy buildings (NZEBs) by the end of 2020 [3]. European Commission has defined NZEB as "a building that has a very high energy performance", in which "the nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby" [3]. However, each EU country has its own definition for NZEBs, which consider the local operating environment and climate [4]. This results in

varying practices in realizing NZEBs among EU countries. The variety is even bigger when considering worldwide views on zero-energy buildings, e.g., the definition by the U.S. Department of Energy, according to which NZEB is “an energy-efficient building where the annual delivered energy is less than or equal to the on-site renewable exported energy” [5]. Although these definitions may seem very similar at first sight, a deeper analysis reveals that they include different terminology and boundary conditions.

While nearly zero energy buildings are the new normal in the EU, both the policy and the research continues to search for the next potential improvement steps. The European Strategic Energy Technology Plan (SET-Plan) targets to spur the development and deployment of low-carbon technologies [6], and the European Green Deal strives for Europe to be the first climate-neutral continent [7].

One of the next steps has involved the introduction of net-zero energy building (Net-ZEB), which has been widely addressed in recent literature and research work. The IEA SHC Task 40/EBC Annex 52 “Towards Net Zero Energy Solar Buildings” contributed significantly to defining net-zero energy buildings [8]. Sartori, Napolitano, and Voss [9] point out that the definitions for net-zero energy buildings also vary whether a building is connected to the energy grid or operates autonomously [9]. Cabeza and Chàfer carried out a thorough review of technological options and strategies towards zero energy buildings contributing to climate change mitigation [10]. Butera underlines the importance of integrated design, load matching, and occupants’ behavior in zero energy buildings [11]. Fast emerging ICT technologies create new options for better energy balancing, peak power reduction, enabling buildings and local energy assets to participate as virtual power plants through aggregators to the electricity markets. Better utilization and management of energy flexibility in buildings can create financial benefits for building owners and users [12].

These developments, when combined, lead to new possibilities for more sustainable and efficient buildings, and the introduction of positive energy buildings (PEBs) as the next phase. NetZEBs and PEBs are already widely under research, and a variety of examples is already emerging [13]. They mostly use similar technologies as NZEBs, but with an increased amount of different renewable energy production technologies integrated into the same building. As for the NZEBs, good energy efficiency should be a requirement also for the PEBs.

1.2. Other Benefits and Effects of PEB

The increased share of renewable energy produced in buildings targets to reduce the CO₂ emissions, and in this, PEBs have better possibilities to support the whole energy grid to be operated in a less polluting way through advanced energy balancing and by reducing peak power demands. PEBs can play a role in the paradigm shift foreseen in the development of low carbon energy systems [14] if buildings would start actively interacting with the grid to optimize the energy balancing, use of different energy sources, and energy storage. The flexibility offered by PEBs could also reduce or delay the needed investments in energy grids due to improved balancing and local supply, resulting in less need for transfer capacity. When designing the PEB and its control strategies, a decision needs to be taken if the PEB is primarily supporting the grid or striving for self-sufficiency. The business models are completely different for these two cases.

The need for better integration and management of the building’s energy system in relation to the connected energy grids brings both benefits and negative impacts to the energy grid and local energy system. The main difference between NetZEBs and PEBs is that NetZEBs could theoretically operate independently without the grid connection, assuming that the energy balancing is not an issue even in short time steps. The integration of NetZEB or NZEB with the grid has not been widely discussed, because it has not been so relevant. In PEBs, the grid connection is essential, as the building operates towards the grid as a prosumer (PROducer and conSUMER).

The users’ interaction and occupant behavior can have an important role in the overall energy performance of zero energy buildings [10,11]. Recently, the European Commission’s

Clean Energy for All Europeans Package also confirmed the crucial role of prosumers and their collective forms (energy communities) in the future energy system [15]. In PEBs, the role of users is even more advocated, as it has important effects on the flexibility that is available in the energy system.

Both NetZEB and PEB concepts increase the resilience of the building, thanks to the local renewable energy supply. Backup support, storage, and grid support enable to avoid and compensate blackouts and other grid failure situations. This would facilitate support of the building for a few days until the fault is resolved and normal operation of the energy system is restored.

It should be noted that the aim is not to transform all buildings into PEBs. The building stock transforms slowly over decades. Around 1% of new buildings annually either expand the building stock or replace the old building stock, and the current renovation rate is 1–2% per year in the EU [16]. The majority of the building stock will be old and inefficient still for quite some time, meaning that it is not foreseen that every building would be a PEB, but instead, PEBs are supporting to increase the share of renewable energy production in built environments, and to balance the local energy grids. While the main aim of NZEB and NetZEB is to limit the (non-renewable) energy demand of the building itself, the aim of PEB is to contribute to the surrounding built environment with zero-emission energy.

1.3. PEB—An Emerging Concept

A Scopus search showed that ‘zero energy building’ appeared around 2988 times, while the term ‘positive energy building’ appeared less than 70 times till August 2021 [17]. Most of the articles listed by the Scopus search are review articles and do not provide or propose a structured definition and framework on PEB that can act as a basis to build such buildings in European climatic zones. Few articles are discussing PEB for one region or country-specific situation, but again they are not defining the concept itself, rather just using the NetZEB concept or extending the NetZEB concept to measure or calculate the building energy systems performance, etc., specific to one country. There are no studies that provide a holistic or a broad PEB definition framework that extends the present NZEB that is applicable in different climatic zones of Europe. This shows that the term ‘PEB’ is still novel and needs to be defined to provide the basis and perspective. In order to facilitate the wide roll-out of PEBs, it is important to have a common understanding of the concept.

In this paper, the authors attempt to give a detailed definition of PEB, first exploring the terminology used for the definition of NetZEB and PEB concepts (Section 2), and then discussing the technical framework to be used for the PEB definition (in Section 3). Additionally, social and human-centric elements, which are not widely discussed in the literature referring to NZEBs and NetZEBs, but should be taken into account, are suggested in Section 4. A definition for PEB has been suggested in the context of the EXCESS project (an EU-funded research and demonstration project ongoing from 2020 until 2023 [18]), after a literature review and a thorough discussion by a team of experts in the field of energy-efficient buildings and renewable energy solutions [19]. The discussion was realized as a series of structured workshops and iterative telcos in order to clarify the key aspects to be addressed in the definition and exact formulations for those. This definition is presented in Section 5 as an example of the result when applying the framework in practice. Further issues in the development of PEBs are discussed in Section 6.

2. Terminology and Elements of the PEB Definition

The literature does not provide a clear definition for a positive energy building (PEB), but the NZEB and NetZEB definitions could be used as the basis for this. Sartori, Napolitano, and Voss [9] suggest a framework for the definition of NetZEB, which contains many relevant elements also for PEB definition. This chapter presents the terminology and the elements most often referred to in the literature discussing the NetZEB or PEB concepts, and some additional considerations concerning these aspects.

2.1. Boundaries

2.1.1. Physical Boundary of a Building

The physical boundary of the building is usually set on the building lot, which covers the site where the building is located, and where the on-site energy system is installed. It is important to highlight where renewable energy technologies can be installed. In line with the definition of the Energy community of Clean Energy Package [20], they can be placed within the building lot in accordance with the revised Renewable Energy Directive [21]. Instead, the revised Electricity Market Directive [22] does not tie the renewable energy technologies to the immediate proximity of the building lot.

PEB will have excess energy available, coming from the renewable energy systems within the boundary. This excess energy can either be stored onsite within the boundary or it can be sold to the grid outside the boundary. It is worth noticing that this energy has to come from renewable sources in order to comply with the emission reduction targets.

2.1.2. Balancing Boundary of the Building and Demand

The balancing boundary of the building refers to the energy load and generation elements of the building that are considered in the energy balance calculations. In the definition presented in this article, the included energy loads are heating (including space heating and domestic hot water), cooling, and electricity, including ventilation, fixed lighting, plug loads, and also for common uses in case of an apartment building (such as the lighting in common zones and elevators). The energy demand of wastewater treatment and of electric vehicles (EVs) are excluded from the definition presented in this article, since the infrastructure is nowadays most often separate from the building infrastructure [23]. The future prospects of EVs are further discussed in Section 6 below.

2.2. Exchange with Energy Grids and Naming of Energy Components

2.2.1. The Availability of Energy Grid

The energy grid refers to the supply channel or the medium through which energy such as electricity, heating, cooling, gas, or fuel is transferred. The grid can be either one way or two way. One way refers to the condition when energy is provided to the building, e.g., from the electricity grid, district heating, and cooling networks or from a natural gas network. The two-way grid refers to the channel that both provide energy to the building, but can also receive energy back from the building to the grid [9]. A two-way grid is a prerequisite for the positive energy balance of PEB. The two-way transfer of gas is currently not a widely used option but may become more general with the increased uptake of Power-to-Gas solutions.

2.2.2. Naming of Energy Components

Imported energy refers to the energy bought from the grid. This is the import of each energy carrier to the building: heat from district heating, cooling from district cooling, electricity, gas, fuels, etc. to the building site [9]. This is sometimes also called “delivered energy” [9,24].

Exported energy refers to the energy transferred from the building site to the grid. This is the export of each energy carrier: heating, cooling, and electricity (or even gas, as mentioned above) [9].

Energy supply refers to the onsite energy conversion from different renewable sources with technologies placed in/on the building or building site and technologies incorporated within the building elements [19]. In the literature, this energy component is also referred to as “generation” [9] or “production” [25]. The supply is specified for each energy carrier: heating, cooling, and electricity (or even gas). The supply may not be equivalent to the exported energy because it is partly used to cover the energy demand of the building.

Energy balance presents the relation of the energy supply and demand or import and export of the energy carriers, over the period of a year, month, or hour; e.g., in the NetZEB

concept, the weighted supply meets or exceeds the weighted demand over a year for each energy carrier [9].

2.3. Additional Aspects for PEB Concept

Reflecting from the present state of the art of the NZEB and NetZEB concepts, following are their main limitations when trying to apply them to PEB:

- The economic and user-centric perspectives are usually not the main part of the NZEB and NetZEB definition [3].
- The other energy demands of the buildings, for instance for common spaces, elevators, heat recovery, parking lot, or plug loads may not be considered in the calculation of the energy demand of the building [26].
- The NZEB concept does not often take into account the EV integration, although it may have an impact on the final energy demand of the building [26].
- The positive energy balance is not the requirement of the NZEB, although it can affect the grid and contribute to the reduction of emissions in the grid [3].
- Energy storage use on-site to improve self-sufficiency is usually not part of the NZEB concept [3].

3. Technical Approach to PEB

The technical framework provides the basis to build the definition for PEB. Technical criteria provide the ground to define, evaluate and compare different PEBs based on technical characteristics. These described criteria and frameworks have different options. The evaluation and the selection of the options become the methodology for developing the PEB definition. The framework presented below is built based on the combination of the literature review and discussions with experts from the EXCESS project (21 partners from 8 countries developing showcases of PEBs in Europe [18]).

3.1. The PEB Concept

Figure 1 shows the overall concept of the PEB. It gives the picture in terms of technical and social aspects. As the main purpose of a building is to support human activities in the building and its surroundings with the least possible cost and minimize negative effects on the environment, the economic, human, and social aspects must be considered in PEB along with the technical issues. Figure 1 shows the interaction of the components and grids, the building's balancing boundary, and the energy flows. This chapter presents the technical framework, while economic, human, and society-centric aspects are discussed in Section 4.

Figure 1 reveals the complexity of the PEB concept in the current technical framework: there are many different renewable technologies available, able to convert the energy from the renewable source into heating, cooling, or electricity, and even into gas in the near future. The availability of different two-way grids is also increasing rapidly, although electricity is still the most convenient way for two-way transfer in the majority of buildings. However there is a brisk development in the fields of two-way heating and cooling grids, (also referred to as 5th generation district and cooling grids or 5GDHC) [27,28]. Storage technologies are also increasing in terms of availability and variety, providing new opportunities for control strategies and business models [29,30]. The integration of electric vehicles (EVs), especially vehicle-to-grid (V2G) applications brings yet another factor in the equation. The key component however is the building itself: its ability to serve the needs of the users with as low energy demand and low environmental effects as possible. It requires energy-efficient building solutions, but also relevant control strategies and the ability of the building and its systems to react to the control signals.

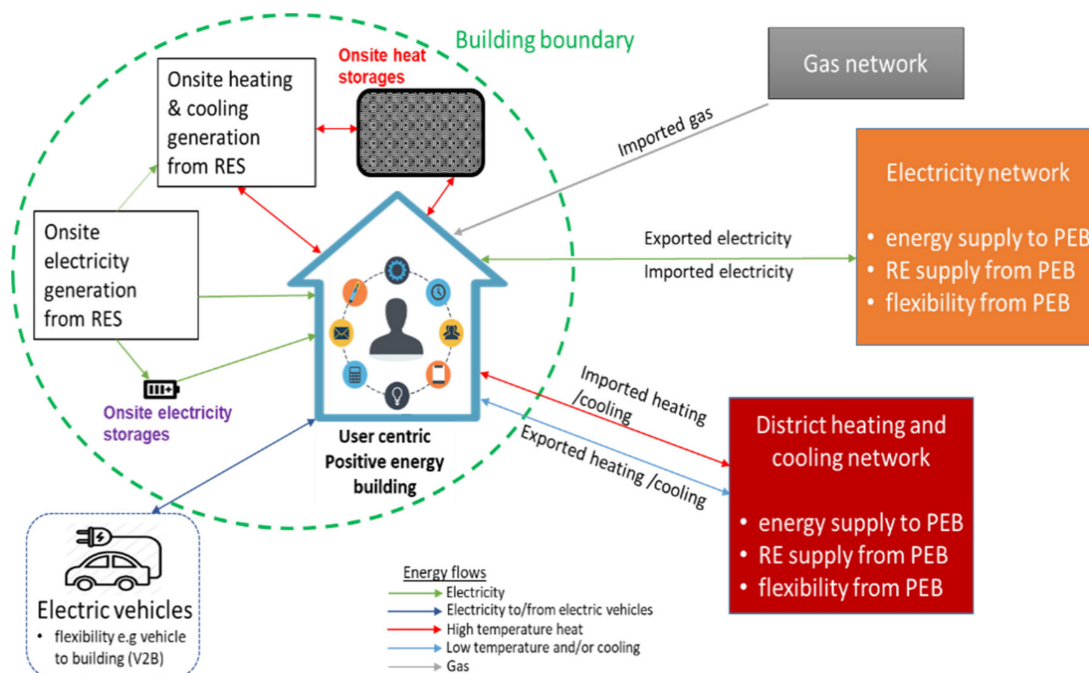


Figure 1. The positive energy building concept, in terms of technical- and social-centric approaches.

3.1.1. Energy Efficiency in Positive Energy Buildings

A high level of energy efficiency is a core requirement of a PEB. The literature suggests that implementing energy efficiency measures is the right way to achieve sustainable buildings and zero energy buildings [31] and the Clean Energy for all Europeans communication puts “energy efficiency first” [32]. These efficiency measures can be based on local and regional guidelines and regulations. The envelope properties have to be defined (e.g., U-values of roof, floor, walls, windows, doors, and airtightness) as well as minimum performance requirements for other components such as HVAC systems (COP, fan power, etc.).

The energy efficiency requirement in PEB can be based on cost optimality or a certain efficiency target level compared to the state of the art or reference [33,34]. The cost optimality target is part of the amended EPBD [3]. The efficiency target can also be set based on a demand reduction (e.g., 50%) compared to the state-of-the-art building with similar functionality.

3.1.2. Energy Supply from Renewable Sources

The PEB should have on-site renewable energy as the main energy source. In NetZEB, the onsite renewable energy generation should cover at minimum the energy demand of a building [35], but in a PEB, the requirement is to clearly exceed the demand.

In addition to simply requiring the use of a renewable source, different criteria can be used for placing the renewable options into order-related priority, e.g., to the cost, the local availability, or the suitability of the supplied energy towards the demand (heating, cooling, or electricity), based on exergy analysis [36,37]. For the off-site options, these selection criteria could also be related to the proximity of the renewable fuel source or the renewable plant, and even investments to low- and zero-carbon energy projects off-site might be taken into account (e.g., [38,39]).

3.2. Energy Balance in PEB

In positive energy building, the export of energy must be higher than the import of energy, either overall or separately for each energy carrier. Energy balancing aims at calculating the total import and export values of energy carriers in PEB.

The balancing can be carried out hourly, annually, or over several years. Usually, annual balance is considered as it can include seasonal variations [39]. In the PEB definition presented in this article, the annual balance for operational energy is suggested. In addition, the importance of life cycle assessment is mentioned (i.e., cradle to grave, discussed in Section 4). The energy balance is relatively easy to simulate during the building design. However, one challenge is how to define one year for assessing the performance of a PEB, as the years can be very different, and this will require methodology for transferring the operational energy values into a reference year. Moreover, it should be discussed how will it be addressed if the building complies with PEB definition in one year according to measurements, but not for the next two years, e.g., as a result of the weather conditions or user behavior, in case the calculations are not based on standard use and reference year. The standard use assumption should also give reasonable room for the user preferences, e.g., regarding thermal comfort.

In general, different weighting factors are often used to balance the energy flow for each energy carrier in PEB. The balancing can be carried out in many ways such as comparing renewable supply and energy demand during the year or import and export of energy to and from the grid during the year [9]. Each method has certain benefits and drawbacks. For instance, the demand and supply calculation is easier to apply and therefore widely used. It can be assessed by calculating or measuring the total annual demand of the building and then the total yearly supply onsite from renewable sources. However, the total annual level analysis does not give any insights on the performance during the year, e.g., at a monthly, weekly, or daily level. In addition, it can be valuable to give attention to the grid exchange as well, by estimating the import and export of energy via the grid. This kind of analysis requires, e.g., hourly values of the demand, supply, export, and import of energy for each energy carrier.

3.3. Energy Matching and Grid Interaction

It is worth noticing that all energy conversion, transport, and storage processes always induce losses, and consequently, additional costs and emissions, be it on the building site or on the grid level. Therefore, in addition to the annual energy balance between the demand and supply in PEB, the short-term matching of the demand and supply must be met primarily from renewable energy. Energy matching shows how well the on-site supply and demand are correlating in terms of timing. The short-term mismatch has to be met by an external grid or by the onsite storage. If the aim is high self-sufficiency, priority should be given to the onsite storage to meet the short-term mismatch. In any case, the negative impacts to the grid need to be minimized. In the PEB definition presented in this article, this was assured by including in the core definition the requirements of high self-consumption rate and high energy flexibility.

Additional performance indicators for energy matching can be defined to calculate the performance of the PEB. Many such indicators are discussed in detail in the EcxEED project [40] and also presented by IEA SHC Task 40/EBC Annex 52 “Towards Net Zero Energy Solar Buildings” [41]. These indicators provide basic information on the self-sufficiency level of the PEB and how well it is able to meet the onsite demand via renewables. In order to estimate these indicators, annual measurement with the minimum hourly resolution is needed. The choice of the indicators may also affect the design choices: you will get what you measure.

3.4. Flexibility of the Building as Support to the Energy Grid

Another target for a PEB can be to maximize the support for the grid, provided by the flexibility in the PEB. In this case, the PEB uses mainly its own RE but provides RE to the grid during periods when there is not enough RE available in the grid to cover the needs, as well as to offer a possibility to shift the demand on the PEB side or export the energy available from the on-site storage. Optionally, PEB can also import extra RE from the grid to the local storage in order to avoid the curtailment of renewable electricity. The

grid support can be provided with the same flexibility that is also useful for optimizing the energy flows in the PEB itself.

Additional means to utilize the flexibility of the PEB beyond the NetZEB and NZEB concepts include maximizing the export of energy from the onsite generation without storage integration. Another approach would look into the matching capability of the onsite generated energy and building integrated energy storage, targeting to achieve higher self-sufficiency and maximize the self-consumption of the onsite generated renewable energy. Further means for increasing the use of the flexibility of a PEB are discussed in IEA EBC Annex 67 [42], including demand response, load shifting, heat pump, and tank storage combination, energy cost-based demand shifting, and renewable generation-based demand shifting.

3.5. The Function, Space Use, and Usage Schedules in a Building

The purpose and the function of the building are also relevant for the definition, as these affect the required space use, indoor conditions, and the level of comfort. Buildings for public spaces, sports activities, schools, residences, offices, or hospitals have different requirements. The space use specifies how the space is being distributed among the users. In addition, the schedule of use is important for the balancing of energy demand and supply. Building purpose and use schedule can strongly affect the people density and how the peak hours and the peak demand occur in the building and how these relate to the availability of renewable energy. In addition, climatic conditions have to be identified to get a reference for the energy demand of the building.

3.6. Mobility and Electrical Vehicles in Relation to PEBs

Another factor that has been discussed in relation to the PEB framework is the integration of mobility in the buildings. The transport and mobility sector contribute to 27% of the emissions in Europe [43]. Therefore, many cities are developing policies and plans to reduce the emissions caused by mobility especially by fossil fuel-based transport [44,45]. The plan is to shift towards more electrified transport as they have lower operating emissions during their life cycle, provided that the electricity is generated from renewable sources [46]. The amount of electric vehicles is increasing rapidly: from 2 million electric vehicles by 2017 [47] to over 5 million by 2018 [48], and is expected to reach up to 44 million by 2030 [49]. Europe's clean energy package suggests providing at least 10 charging points in residential buildings [15].

Mobility has not been the focus of the concept of NetZEB. By integrating the EV with the PEB in this definition framework, the suggested PEB concept would assist cities to reduce their transport-related emissions. EV is included in the PEB definition to address the future challenges and provide flexibility both at the technical and policy level to integrate the energy demand of future mobility in the buildings.

An important aspect that must be considered with the integration of EV in the building is its impact on the total energy demand of the building, i.e., the place of the EV in the building boundary. If the building is importing more energy from the grid to meet the EV's demand, this would have an impact on the overall energy performance of the PEB. Although EV is considered as an environmentally friendly transport medium [47], its impact on the building performance could be negative. The demand of the EV can also be unpredictable and vary depending on the user's behavior. This may lead a building to have poor energy performance or may lead the building not to comply with the PEB definition [50]. As PEB is considering future technologies and EVs in the context to broadly solve the clean energy transition targets, therefore, it is important to define EV's placement in the PEB context. Moreover, the EV can be used as local storage to provide vehicle-to-building integration and provide flexible options within PEB, if needed.

4. Human and Society Centric Approach to PEB

In the NZEB and NetZEB concepts, most of the definitions [9,51,52] revolve around the technical features and characteristics. However, buildings are places where people spend most of their time [53]. Therefore, the human-centric approach is an integral part of the PEB definition, ultimately contributing to an impact on society. In PEB definition and framework, this approach is adopted to include the human and societal centric approach along with the technical approach. Moreover, economic aspects are considered.

4.1. Indoor Environment Quality

In the PEB definition presented in this article, a high-quality indoor environment is mentioned as an indispensable element in the PEB, securing the comfort and well-being of building occupants. The focus in the indoor environment is usually not considered in the NZEB concept [39], but merely considered as self-evident background.

The indoor environment quality (IEQ) includes the indoor air, thermal, acoustic, and visual quality. These factors also influence the perception of each other: A good visual environment improves thermal comfort and vice versa [54]. Indoor air quality requirement sets certain limits for carbon dioxide, volatile organic compound concentration, and airflow. Thermal comfort is affected by the air and radiant temperatures, their distribution, and air-flow rates, in addition to the person-related physical and psychological parameters (metabolism, clothing insulation, age, gender, personal history in relation to the thermal environment, etc.) [55–59]. The other elements that have to be considered are, e.g., daylight utilization and materials with good acoustic qualities. The comfort level of the users depends on many factors such as climate, tradition, culture, and functionality of the buildings [54,60].

User comfort is a primary objective for PEB and may not be compromised. This is a crucial element in order to address the EU policy priorities [15], which place the consumer at the heart of the energy system without compromising his comfort and the hygiene of indoor environments. Improved indoor environment leads to a higher rate of users' satisfaction based on their demand and behavior [61]. The indoor environment has a direct impact on the well-being of the building user, and it can even affect productivity in working environments [62,63]. Moreover, a certain level of control must be provided to the end-user regarding the indoor environment. According to several studies this also, in turn, affects the feeling of thermal comfort [64,65].

One thing highly likely to affect the thermal comfort of the building occupants in the future is the urban heat island effect, which is a result of the combined effects of increasing urbanization of the world population and global warming [66]. This phenomenon, increasing the need for cooling, could even be exacerbated by more frequent heatwaves. Therefore, in addition to limiting the cooling needs by sustainable design, it is important to take into account the planning of the PEB that the design should also limit the contribution to overheating of the urban environment. This could be achieved, e.g., by minimizing the waste heat of the air conditioning systems, release of solar energy by absorption-convection at the outer surfaces, and reflection towards the neighboring buildings.

4.2. User Engagement

Building users expect the building to communicate, react, and adapt to their requirements and needs in a flexible manner [67]. User engagement and acceptance have to be the central point of the framework and definition [61]. With the help of the internet and information and communication technology, the users can interact with the building management systems based on their comfort and other requirements. The users should have the means to communicate their preferences related for instance to temperature, lighting, and scheduling of various appliances to support the flexibility of the energy demand. These devices should have a user-friendly interface, through which the users can control the building and energy systems, and also obtain various feedbacks for instance on consumption profile, costs, saving of energy, air quality, conformance with standards,

compliance of functionality to the user requirements, or emissions caused by certain selections [68]. A minimum level of service should be included, with certain controls and some level of feedback or reporting in a user-friendly way (e.g., gamification). The data security and privacy of the users have to be ensured based on general data protection regulations when users are sharing data, personalized selections, and interacting with the devices (internet-of-things) [69].

Ideally, the users should of course be engaged already in the planning phase of the PEB, in order to increase the user friendliness of the design. Some new ways are suggested for realizing this, e.g., as part of regenerative design [70] or by utilizing artificial intelligence (AI) as a tool in the design process [71]. The design phase, however, goes beyond the scope of this article, which is limited to the core definition framework, essential terms, and items that a definition has to include so that PEB's core definition can be used in different climatic zones and its performance can be compared. The issues related to the building architecture, aesthetics, ICT, and user interface will be discussed in more detail in the future work of the authors, in relation to the demonstration buildings in the project. The guidelines formulated in the same project for local authorities also urge to include a wide variety of stakeholders in the development of PEBs: building owners and users, but also urban planners, architects, engineers and designers of energy companies, consultants, landowners, water companies, and environmental protection agencies [72].

4.3. Life Cycle Emission Considerations in PEB

Buildings are responsible for 35% of the carbon emissions in Europe. The target is to reduce the carbon emissions by 80% by 2050 in Europe [73], therefore, the emissions caused by the building sector have to be addressed. The emissions of the PEB must be minimized and the energy demand has to be as low as possible. CO₂ emissions reduction constitutes a true benefit and even motivation for the further uptake in PEB technologies in the building sector. PEB is expected to significantly reduce the CO₂ and other greenhouse gases and air pollutants (CO, NO_x, nanoparticle, non-combustible hydrocarbon) emissions related to heating, cooling, and electricity demand of buildings.

The environmental impacts of PEBs should be evaluated with a life cycle analysis, including the building material, technical installation of renewables, and the installation of the energy efficiency measures in the buildings. This would allow considering the emissions of the material and components of the buildings and renewables installed on the building with a cradle to grave approach. This includes the emissions of the building material and renewables during the installation, use, maintenance, and demolition [74].

The life cycle requirement is more difficult to achieve for an existing building being renovated into PEB, as it has already used a lot of energy before the renovation [19]. The way to approach this issue should be developed when setting the Key Performance Indicators (KPIs) for PEB. They could, e.g., be different for new and renovated buildings.

4.4. Economic Considerations in PEB

To reflect the whole picture, it is essential that the economic analysis of PEB focuses on life cycle costs, instead of only investment costs. The return on investment, payback period, and other economic KPIs should be identified for the PEB. The cost of energy efficiency and renewable technologies and various measurement technologies supporting the flexibility can be high, resulting in a longer payback period. On the other hand, the increased energy savings, emission reduction, and user satisfaction should be considered in the cost calculations. Moreover, with added value in the assets, it is expected that the value of the property may also increase, resulting in economic benefit to the building owners, investors, and city. Economic analysis can also consider the reduced risk of energy cost increase thanks to high energy efficiency and self-consumption [75].

The profitability of PEBs can have challenges, as e.g., Karunathilake, Hewage, Brinkerhoff, and Sadiq argue that reaching net-zero status at the building level is not feasible with the current resource potential and economic conditions, even though significant reductions

in both emissions and operational costs can be achieved with the hybrid renewable energy system [76].

A viable business model should be developed for the PEB with revenue streams from market transactions. The business model strongly affects the optimization strategies that are applied in the PEB: these are very different if the target is high self-sufficiency or maximum support to the grid or something else. The ownership of the business model and PEB will also strongly affect the value proposition and revenue streams. To mention a couple of very different options, the PEB business model could be owned, e.g., by a service provider, offering a livable, environmentally friendly building for the occupants and support to the grid operator, or by a local energy community targeting high self-sufficiency and offering flexibility and renewable energy source for the grid operator.

5. Positive Energy Building Definition

A definition for positive energy building was developed as the first step in the EXCESS project, based on a literature review described above, and extensive, structured discussions between the partners in a series of workshops, telcos, and e-mail exchanges. This definition is presented here as an example of the outcome of applying the framework presented above, and the considerations of the EXCESS team related to these topics. The EXCESS team consists of experts in the field of energy-efficient buildings and renewable energy solutions, committed to developing working solutions for PEBs. A full description of the process and the considerations of the individual aspects in relation to the literature is given in [19].

EXCESS defines a positive energy building as “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 renewable energy” [19].

The following aspects are included in this PEB definition:

- The EXCESS project considers mainly residential buildings, but looks also at the role of the building in a bigger context, especially through impact to the energy networks. When assessing the building, the energy needs for other than residential activities, e.g., commercial or public services are excluded, but the energy use for the shared spaces is included.
- The local generation includes the energy produced at the building lot, with technologies that are placed in/on the building or building site, as well as technologies incorporated within the building elements.
- The energy need components considered are electricity, heating and cooling. Heating includes both space and water heating. Electricity covers the lighting, plug loads, ventilation, and the electricity demands for the shared spaces such as the lighting in common zones and elevators.
- For renewables, the definition of renewable energy from the European RES (renewable energy sources) directive is adopted, which defines it as “energy from renewable non-fossil sources”, e.g., wind, solar, hydro, geothermal, or biomass [77].
- High self-consumption rate helps in minimizing both the emissions and the negative impacts to the grid. Demand response and energy storage solutions can be used as ways to increase the self-consumption rate.
- Indoor environment considers the elements of thermal, visual, and acoustic environment and indoor air quality.
- The life-cycle effects on costs and emissions should be taken into account in the planning and analysis of PEB.

Figure 2 shows the focus of the PEB definition and the most important elements in this context, based on the EXCESS partners’ inputs and the literature review.

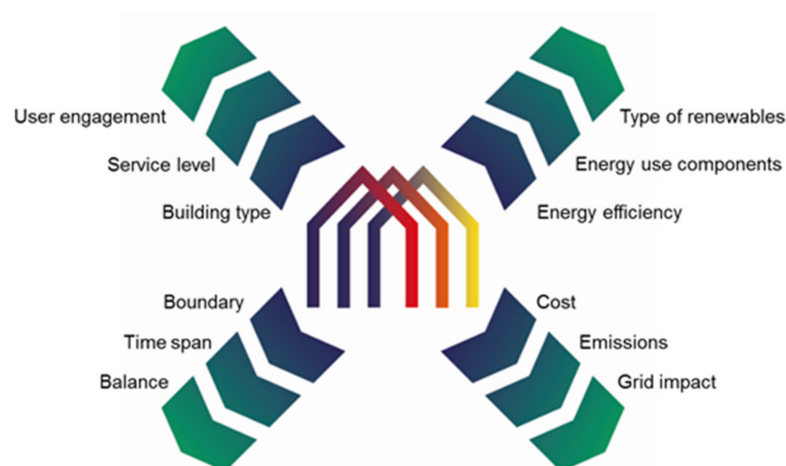


Figure 2. The central elements in the positive energy building definition presented in this article [19].

There was a general agreement among the EXCESS consortium that the energy demand of public spaces should also be included in the balance, e.g., public lighting and elevators. It was also concluded that only residential uses should be included (as in this definition the residential buildings are addressed) and EVs are considered only as an option for future integration. The PEB was defined at the early phase of the project (in early 2020), and the work continued further. The discussion still continues whether the plug loads will be included since measuring them is quite difficult in a building where residents are paying for their own energy bills. Yet, these measurements would be needed to verify if the building meets the Key Performance Indicators (KPIs) for PEB. The definition of the KPIs is the next step in the process. The PEB definition and KPIs will be verified through four demonstrations in the EXCESS project.

6. Discussion

As the PEB is an emerging concept, some considerations for the appropriate indicators and future developments are in place. The PEB definition suggests that several indicators need to be developed, including energy, cost, and user friendliness or comfort. The development of the indicators is the next step after the definition, but some aspects can already be pointed out. Generally, the PEBs may meet the criteria at different levels. Other aspects that need to be further discussed are the integration of EVs.

6.1. Primary Energy as Indicator

Primary energy factors represent the conversion efficiency of the energy from the primary source to the secondary or delivered energy carrier to the end user. They are widely used to convert the building energy demand into primary energy, which is later used to evaluate the building energy indicator performance as mentioned in the European building performance directive (EPBD) [52]. The use of primary energy factors as indicators for PEB is problematic because primary energy factors are set on a national level. They are different in different countries, because the energy sources, the energy generation units, and the distribution channels are different. Moreover, the status of the national energy transition programs may have impacts on them. As a consequence, it is difficult to compare the PEB performance internationally and to standardize such calculations especially in the context of PEB.

The EPBD however regulates that the energy performance certificate needs to provide information about “the actual impact of heating and cooling on the energy needs of the building, on its primary energy consumption and its carbon dioxide emissions” [3]. For a PEB, the CO₂ emissions would be a more suitable indicator, as the main reason for promoting PEBs in relation to the energy source is their contribution to decarbonization of

the energy system. (The other, non-energy source-related reasons are energy efficiency and well-being of the user.)

6.2. Different Ways to Categorise Positive Energy Buildings

There could be different types of PEBs according to the boundary of the building in the same style that is proposed by the European Energy Research Alliance (EERA) for positive energy districts (PED) [78]. According to EERA, the PED can be divided into three main categories based on the boundary, here applied to a building level:

1. Autonomous PEB: A self-sufficient building, in which all energy demand, supply, and storage components are within a defined building boundary. All the demand is covered by on-site renewables. Energy is not imported from the external grid, but excess energy can be exported to the grid.
2. Dynamic PEB: A building with a higher onsite renewable energy supply than the demand within the defined building boundary. A building is interacting with the grid and other buildings outside the boundary.
3. Virtual PEB: A building with virtual or no specific fixed boundary. The renewable energy sources and storage can be located outside the geographical building boundary. The onsite renewable energy and virtual generation sources should have a higher combined supply than the energy demand of the building.

It is important to identify the PEB boundary at the initial stage. The identification of the building's boundary can be influenced by many factors such as the geography of the city, the location of the building, local regulations, building type and construction, the available energy infrastructure, market and financial model, environmental conditions, etc.

Another approach is suggested by Ala-Juusela et al. [19] for defining different levels of PEBs, such as: (1) supply operational energy (basic PEB), (2) including EV charging (a very good PEB), and (3) level depending on time balance: balance over a year or hourly balance.

6.3. PEB as Energy Community

The definition presented in this article does not consider the ownership models of the renewable systems or the charges applied to the energy transmission inside the building site, although this is also very relevant for the applicable business model and the costs, as mentioned earlier. This is addressed, e.g., in the ongoing discussion related to energy communities. A recent publication by the Joint Research Centre made an overview of the activities, organization, and implications of energy communities as participants across the energy system [79], defining different forms of energy communities. Among them, it is worth mentioning two forms: an energy community within a housing company and an energy community crossing property boundaries. As for the first type, no network charges apply for the energy, which is generated and consumed within the site boundaries, if it does not cross the access point to the distribution network. This would be the most probable type for a PEB in an apartment building. While for the second form, a mutual electricity line across the involved sites' boundaries after the grid connection point would be needed and therefore payment of network charges and tariffs might apply according to general principles [79].

6.4. The Integration of EVs and Other Vehicles

The integration of vehicle-to-grid (V2G) EVs will change the grid interaction and the effects of PEBs on the grids quite profoundly. One of the main aims of PEBs is to minimize the negative effects to the grid and to reduce the need for transferring energy. If an EV is charged at the building location and feeding in electricity in another location (V2G) or vice versa, this does not require transfer capacity in the grid between these points. The use of the EV for storing and transferring energy is likely to stay as a marginal option for now, as it will affect the lifetime of the batteries in the EV, until new solutions start appearing for

the electricity storage that can better resist the charging and discharging, and have better storage efficiency.

Zhou, Cao, Hensen, and Lund systematically analyzed the energy integration and interaction between buildings and vehicles regarding different energy forms, advanced energy conversions, diversified energy storage systems, and hybrid grids' interactions [80]. Their analysis goes beyond electric vehicles, as it also includes other types (gasoline and gas or hydrogen-powered vehicles). They claim that a systematic interaction between the building's energy system and the transportation supports the energy systems to become more robust, reliable, and flexible [80]. Efforts are still needed in developing incentives and subsidies for vehicle owners for the depreciation of their vehicles when they participate in renewable and sustainable energy sharing networks, as well as in the standardization of interactive facilities [80]. The current challenges for the vehicle integration include the lack of hybrid (biofuel, hydrogen, and electrical grids) energy networks to expand grid capacity, static export costs, frequent grid power fluctuations, unpredictable schedule of vehicles, synchronized peak load of buildings and vehicles, and the availability of charging facilities and fuel stations [80].

6.5. PEB in Relation to Smart Readiness Indicator (SRI)

The EU has proposed to further develop and support the EPBD by establishing the smart readiness indicators (SRI) [81] for the building stock. This would allow to rate the buildings and, in particular, the PEB in terms of its smart readiness. The rating would show the capacity of the buildings in terms of their readiness to adopt and integrate future technologies such as electric vehicles, renewables, energy storage for flexibility and demand-side management, etc. Similarly, this would also show the ability of the building to adapt according to the occupant's requirements, improve the energy efficiency and optimize the systems, and adapt according to external signals for instance from the grid, to improve the energy flexibility of the building. It is expected that the PEBs could have the SRI scoring introduced, as PEBs should be able to adapt according to the surroundings and the user comfort. This scoring can provide a rating mechanism to evaluate and compare different buildings. Due to the user-centric approach and other technical features included in PEBs, they may have a high SRI score compared to other existing or new NZEB buildings.

7. Conclusions

The international efforts to reduce building-related carbon emissions have resulted in the introduction of energy-efficient buildings that mainly use energy from renewable sources. Until recently, these concepts have concentrated on the technological aspects and have aimed for a net-zero energy balance. Introducing positive energy buildings brings additional elements to the discussion. In the new concept, the interaction with the grid is more emphasized, drawing more attention, e.g., to the flexibility of the energy supply and demand. The emergence of electric vehicles and vehicle to grid solutions bring yet another factor to the equation. The central role of the users as beneficiaries and operators of the PEB is also worth considering when defining the concept. As the CO₂ emissions and costs in the operational phase are minimized with the PEB concept, the role of the life-cycle considerations is gaining more attention. A clear definition of the concept will facilitate the wider roll-out of the PEBs, as the stakeholders will have a common understanding of the goals.

This article presents a definition for a positive energy building, being “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, securing the comfort and well-being of occupants. The PEB is also able to integrate future technologies, such as electric vehicles, with the motivation to maximize the utilization of local renewable energy sources.

This definition for positive energy buildings is developed based on previous, existing concepts for nearly and net-zero energy buildings. In comparison to earlier energy-efficient building definitions, this PEB definition highlights the comfort and well-being of the occupants, the integration with the grid, and the energy flexibility of the building. A broader framework and criteria for PEBs are first presented. The PEB framework and definition are based on two aspects, technical and human and society centric.

The building must be designed and constructed in a way that it has high energy efficiency during the whole life cycle. It is imperative that the onsite energy supply comes from renewable sources. It is important to estimate the grid interaction and energy matching, as positive energy building interacts with the grid with a positive balance that must be accounted for, and negative effects to the grid need to be minimized.

The human and societal centric framework highlights indoor environment and quality, user engagement, and comfort. The life cycle effects of PEBs related to embodied energy, life cycle emissions, life cycle costs, and resilience are also reflected.

The article points out some of the aspects that are still under discussion or worth paying attention to in the future development of the concept and the indicators. With the new smart readiness indicators, the PEB can adapt to new challenges, such as the integration of electric vehicles, flexibility options, user comfort, and renewables. Some of the other challenges discussed are defining the building boundary, which can be influenced by many factors such as urban plans, geography, resources available, etc.

One interesting finding is the lack of commonly agreed and physically sound terminology for the different energy components (e.g., generation, production or supply, load or demand, use or need are used sometimes for same purposes, sometimes for different meanings). A recommendation, therefore, is to continue the work on harmonizing the terminology for the PEB concept and energy components, also in compliance with the underlying physics.

Future work includes the development and verification of the KPIs and studies to analyze the impact of the proposed definition in different European climates by calculating and simulating the buildings to estimate the potential technical and economic challenges, looking at the feasibility of the PEB as defined here.

It is critical to understand the multi-dimensional and interdisciplinary nature of a positive energy-building concept. This concept requires a joint and collaborative approach of different partners, stakeholders, and stockholders. It requires changes in the urban planning, technical, economic, academics, industry, societal and political level. PEBs can play a role in sustainable, low-carbon cities in the future.

Author Contributions: Conceptualization, M.A.-J.; methodology, M.A.-J., H.u.R., M.H. and F.R.; writing—original draft preparation, H.u.R. and M.A.-J.; writing—review and editing, M.H. and F.R.; visualization, H.u.R., M.A.-J. and F.R.; project administration, F.R. All authors have read and agreed to the published version of the manuscript.

Funding: The work was supported by the European Union's Horizon 2020 research and innovation program H2020-2019-2023 under the project name EXCESS [grant number 870157].

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors acknowledge all the project partners in EXCESS project.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

1. International Energy Agency. *2019 Global Status Report for Buildings and Construction*; Global Alliance for Buildings and Construction: Paris, France, 2019.

2. United Nations. *About the Sustainable Development Goals*; Department of Economic and Social Affairs, United Nations Sustainable Development: New York, NY, USA, 2018.
3. *Energy Performance of Buildings Directive*; European Commission: Brussels, Belgium, 2021.
4. *EU Countries' Nearly Zero-Energy Buildings National Plans*; European Commission: Brussels, Belgium, 2020.
5. Torcellini, P.; Grant, R.; Taylor, C.; Punjabi, S.; Diamond, R.; Colker, R.; Moy AECOM, G.; Kennett, E. *A Common Definition for Zero Energy Buildings*; The National Institute of Building Sciences: Washington, DC, USA, 2015.
6. European Commission. Strategic Energy Technology Plan. Available online: https://ec.europa.eu/energy/topics/technology-and-innovation/strategic-energy-technology-plan_en (accessed on 26 May 2021).
7. European Commission. *Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. The European Green Deal*; COM/2019/640 final; European Commission: Brussels, Belgium, 2019.
8. Solar Heating and Cooling Programme International Energy Agency-Solar Heating and Cooling | Task 40. Available online: <https://task40.iea-shc.org/> (accessed on 26 May 2020).
9. Sartori, I.; Napolitano, A.; Voss, K. Net zero energy buildings: A consistent definition framework. *Energy Build.* **2012**, *48*, 220–232. [CrossRef]
10. Cabeza, L.F.; Chàfer, M. Technological options and strategies towards zero energy buildings contributing to climate change mitigation: A systematic review. *Energy Build.* **2020**, *219*, 110009. [CrossRef]
11. Butera, F.M. Zero-energy buildings: The challenges. *Adv. Build. Energy Res.* **2013**, *7*, 51–65. [CrossRef]
12. Zhou, Y.; Cao, S.; Kosonen, R.; Hamdy, M. Multi-objective optimisation of an interactive buildings-vehicles energy sharing network with high energy flexibility using the Pareto archive NSGA-II algorithm. *Energy Convers. Manag.* **2020**, *218*, 113017. [CrossRef]
13. Jäger, A.; Tuerk, A.; Kaltenegger, I.; Trumbić, T.; Cantalapiedra, M.; Maass, E.; Allaerts, K.; Ala-Juusela, M.; Klobut, K.; Fatima, Z.; et al. *Deliverable 1.2 of EXCESS Project: Stocktaking of PEB Examples*; European Commission: Brussels, Belgium, 2019.
14. Manfren, M.; Caputo, P.; Costa, G. Paradigm shift in urban energy systems through distributed generation: Methods and models. *Appl. Energy* **2011**, *88*, 1032–1048. [CrossRef]
15. European Commission. Clean energy for all Europeans. *Euroheat Power* **2019**, *14*, 3. [CrossRef]
16. Artola, I.; Rademaekers, K.; Williams, R.; Yearwood, J. *Boosting Building Renovation: What Potential and Value for Europe?* European Parliament: Brussels, Belgium, 2016.
17. Elsevier, B.V. Scopus. Available online: <https://www.scopus.com/> (accessed on 11 August 2021).
18. European Union Commission EXCESS | Horizon 2020. Available online: <https://positive-energy-buildings.eu/> (accessed on 24 September 2020).
19. Ala-Juusela, M.; ur Rehman, H.; Hukkalainen, M.; Tuerk, A.; Trumbic, T.; Llorente, J.; Claes, S.; Tsitsanis, T.; Latanis, K.; Maas, E. *Deliverable 1.1: PEB as Enabler for Consumer Centred Clean Energy Transition: Shared Definition and Concept*; EXCESS: Espoo, Finland, 2020.
20. Jasiak, M. Energy communities in the clean energy package. *Eur. Energy J.* **2018**, *8*, 29.
21. European Union. Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources. *Off. J. Eur. Union* **2018**, *L 328*, 82.
22. European Parliament and the Council of the European Union. *European Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on Common Rules for the iNternal Market for Electricity and Amending Directive 2012/27/EU (Recast)*; European Parliament and the Council of the European Union: Brussels, Belgium, 2019.
23. Engel, H.; Hensley, R.; Knupfer, S.; Sahdev, S. *The Basics of Electric-Vehicle Charging Infrastructure*; McKinsey & Company: New York, NY, USA, 2018.
24. British Standards Institution. *BS EN 15603:2008. Energy Performance of Buildings. Overall Energy Use and Definition of Energy Ratings*; European Standard; British Standards Institution: London, UK, 2008; pp. 1–45.
25. *Trends and Projections in Europe 2018. Tracking Progress towards Europe's Climate and Energy Targets*; European Environment Agency: Copenhagen, Denmark, 2018.
26. D'Agostino, D. Assessment of the progress towards the establishment of definitions of Nearly Zero Energy Buildings (nZEBs) in European Member States. *J. Build. Eng.* **2015**, *1*, 20–32. [CrossRef]
27. Buffa, S.; Cozzini, M.; D'Antoni, M.; Baratieri, M.; Fedrizzi, R. 5th generation district heating and cooling systems: A review of existing cases in Europe. *Renew. Sustain. Energy Rev.* **2019**, *104*, 504–522. [CrossRef]
28. Boesten, S.; Ivens, W.; Dekker, S.C.; Eijndems, H. 5th generation district heating and cooling systems as a solution for renewable urban thermal energy supply. *Adv. Geosci.* **2019**, *49*, 129–136. [CrossRef]
29. Albawab, M.; Ghenai, C.; Bettayeb, M.; Janajreh, I. Sustainability performance index for ranking energy storage technologies using multi-criteria decision-making model and hybrid computational method. *J. Energy Storage* **2020**, *32*, 101820. [CrossRef]
30. Wang, K.; Qin, Z.; Tong, W.; Ji, C. Thermal energy storage for solar energy utilization: Fundamentals and applications. In *Renewable Energy—Resources, Challenges and Applications*; IntechOpen: London, UK, 2020.
31. Voss, K.; Musall, E. *Net Zero Energy Buildings: International Projects of Carbon Neutrality in Buildings: DETAIL Green Books by Karsten Voss (2013-02-28)*; C.H.Beck: Munich, Germany, 2013; ISBN 978-3-920034-80-5.

32. European Commission. A clean planet for all—A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy. *COM* **2018**, 773, 114.
33. Sartori, I.; Candanedo, J.; Geier, S.; Lollini, R.; Athienitis, A.; Pagliano, L.; Garde, F. *Comfort and Energy Efficiency Recommendations for Net Zero Energy Buildings*; International Solar Energy Society (ISES): Freiburg, Germany, 2016; pp. 1–8.
34. The Buildings Performance Institute Europe-BPIE. Cost Optimality – Discussing Methodology and Challenges within the Recast EPBD. Brussels, Belgium. 2010. Available online: <https://www.bpie.eu/publication/cost-optimality-in-building-renovations/> (accessed on 19 September 2021).
35. Atanasiu, B.; Despret, C.; Economidou, M.; Griffiths, N.; Maio, J.; Nolte, I.; Rapf, O. *Principles for Nearly Zero-Energy Buildings*; Buildings Performance Institute Europe: Brussels, Belgium, 2011.
36. Sala Lizarraga, J.M.P.; Picallo-Perez, A. *Exergy Analysis and Thermoeconomics of Buildings: Design and Analysis for Sustainable Energy Systems*; Elsevier: Amsterdam, The Netherlands, 2019; ISBN 9780128176115.
37. Li, H.; Svendsen, S. Energy and exergy analysis of low temperature district heating network. *Energy* **2012**, *45*, 237–246. [[CrossRef](#)]
38. Torcellini, P.; Pless, S.; Deru, M.; Crawley, D. Zero energy buildings: A critical look at the definition. In Proceedings of the ACEEE Summer Study, Long Beach, CA, USA, 14–18 August 2006.
39. Marszal, A.J.; Heiselberg, P.; Bourrelle, J.S.; Musall, E.; Voss, K.; Sartori, I.; Napolitano, A. Zero energy building—A review of definitions and calculation methodologies. *Energy Build.* **2011**, *43*, 971–979. [[CrossRef](#)]
40. Antonucci, D.; Pasut, W. *Key Performance Indicators (KPIs) and Needed Data. Deliverable 3.1 of ExCEED Project*; European Parliament: Brussels, Belgium, 2017.
41. Garde, F.; Donn, M. *IEA SHC Task 40/EBC Annex 52 Towards Net Zero Energy Solar Buildings: A Review of 30 Net ZEBs Case Studies. A Report of Subtask C. IEA SHC Task 40/EBC Annex 52 Towards Net Zero Energy Solar Buildings*; International Energy Agency: Paris, France, 2014.
42. Jensen, S.Ø.; Marszal-Pomianowska, A.; Lollini, R.; Pasut, W.; Knotzer, A.; Engelmann, P.; Stafford, A.; Reynders, G. IEA EBC Annex 67 energy flexible buildings. *Energy Build.* **2017**, *155*, 25–34. [[CrossRef](#)]
43. European Environment Agency. Indicator Assessment. Greenhouse Gas Emissions from Transport in Europe. Available online: <https://www.eea.europa.eu/data-and-maps/indicators/transport-emissions-of-greenhouse-gases-7/assessment> (accessed on 29 September 2021).
44. *Energy, Transport and Environment Indicators—2011 Edition*; Eurostat: Luxembourg, 2011; ISBN 9789279213847.
45. City of Helsinki. *Climate-Smart Helsinki—Towards More Sustainable City Planning. Brochure*; Helsinki City Planning Department: Helsinki, Finland, 2017.
46. Wang, B.; Xu, M.; Yang, L. Study on the economic and environmental benefits of different EV powertrain topologies. *Energy Convers. Manag.* **2014**, *86*, 916–926. [[CrossRef](#)]
47. International Energy Agency. *Global EV Outlook 2017: Two Million and Counting*; IEA: Paris, France, 2017; Available online: <https://doi.org/10.1787/9789264278882-en> (accessed on 20 December 2020).
48. International Energy Agency. *Global EV Outlook 2018*; IEA: Paris, France, 2018; Available online: <https://www.iea.org/reports/global-ev-outlook-2018> (accessed on 3 April 2020).
49. International Energy Agency. *Global EV Outlook 2019*; IEA: Paris, France, 2019; Available online: <https://www.iea.org/reports/global-ev-outlook-2019> (accessed on 22 December 2020).
50. Rehman, H.; Korvola, T.; Abdurafikov, R.; Laakko, T.; Hasan, A.; Reda, F. Data analysis of a monitored building using machine learning and optimization of integrated photovoltaic panel, battery and electric vehicles in a Central European climatic condition. *Energy Convers. Manag.* **2020**, *221*, 113206. [[CrossRef](#)]
51. D’Agostino, D.; Mazzarella, L. What is a nearly zero energy building? Overview, implementation and comparison of definitions. *J. Build. Eng.* **2019**, *21*, 200–212. [[CrossRef](#)]
52. *Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the Energy Performance of Buildings*; European Union: Brussels, Belgium, 2010.
53. Klepeis, N.E.; Nelson, W.C.; Ott, W.R.; Robinson, J.P.; Tsang, A.M.; Switzer, P.; Behar, J.V.; Hern, S.C.; Engelmann, W.H. The national human activity pattern survey (NHAPS): A resource for assessing exposure to environmental pollutants. *J. Expo. Anal. Environ. Epidemiol.* **2001**, *11*, 231–252. [[CrossRef](#)]
54. Leaman, A.; Bordass, B. Are users more tolerant of ‘green’ buildings? *Build. Res. Inf.* **2007**, *35*, 662–673. [[CrossRef](#)]
55. de Dear, R.; Brager, G.S. *Developing an Adaptive Model of Thermal Comfort and Preference*; UC Berkeley: Center for the Built Environment: Berkeley, CA, USA, 1998.
56. Bordass, B.; Cabanac, M.; Clements-Croome, D.; Cooper, C.; Davis, R.; Doggart, J.; Dorgan, C.E.; Duffy, F.; Farshchi, M.; Fisher, N.; et al. *Creating the Productive Workplace*; Clements-Croome, D.J., Ed.; E & FN Spon: London, UK, 2001.
57. Loftness, V.; Hartkopf, V.; Gurtekin, B.; Students Carnegie, G.; Hansen, D.; Hitchcock, R. Linking energy to health and productivity in the built environment evaluating the cost-benefits of high performance building and community design for sustainability, health and productivity. In Proceedings of the Greenbuild International Conference and Expo, Lawrence Convention Center, Pittsburgh, PA, USA, 12–14 November 2003.
58. Schweiker, M.; Shukuya, M. Comparison of theoretical and statistical models of air-conditioning-unit usage behaviour in a residential setting under Japanese climatic conditions. *Build. Environ.* **2009**, *44*, 2137–2149. [[CrossRef](#)]

59. Tokunaga, K.; Shukuya, M. Human-body exergy balance calculation under un-steady state conditions. *Build. Environ.* **2011**, *46*, 2220–2229. [[CrossRef](#)]
60. Humphreys, M.A. Quantifying occupant comfort: Are combined indices of the indoor environment practicable? *Build. Res. Inf.* **2005**, *33*, 317–325. [[CrossRef](#)]
61. Pastore, L.; Andersen, M. Building energy certification versus user satisfaction with the indoor environment: Findings from a multi-site post-occupancy evaluation (POE) in Switzerland. *Build. Environ.* **2019**, *150*, 60–74. [[CrossRef](#)]
62. Clements-Croome, D.; Bai-Zhan, L. Productivity and indoor environment. *Engineering* **2000**, *1*, 629–634.
63. Clark, D. *Information Paper-33: Productivity in Office Buildings. A Paper Referenced in a Book: What Colour is Your Building*; Cundall: London, UK, 2013.
64. Karjalainen, S. The Characteristics of Usable Room Temperature Control. Ph.D. Thesis, Aalto University, Espoo, Finland, 2008.
65. Smith, A.; Pitt, M. Sustainable workplaces and building user comfort and satisfaction. *J. Corp. Real Estate* **2011**, *13*, 144–156. [[CrossRef](#)]
66. *Analysis of Heat Waves Implications, Urban Heat Island Effects in Central European Cities and for Urban Planning*; World Bank: Washington, DC, USA, 2020.
67. Rodrigues, L.; Gillott, M.; Waldron, J.; Cameron, L.; Tubelo, R.; Shipman, R.; Ebbs, N.; Bradshaw-Smith, C. User engagement in community energy schemes: A case study at the Trent Basin in Nottingham, UK. *Sustain. Cities Soc.* **2020**, *61*, 102187. [[CrossRef](#)]
68. Huang, B.; Lei, J.; Ren, F.; Chen, Y.; Zhao, Q.; Li, S.; Lin, Y. Contribution and obstacle analysis of applying BIM in promoting green buildings. *J. Clean. Prod.* **2021**, *278*, 123946. [[CrossRef](#)]
69. European Union Commission. Regulation (EU) 2016/679 of the European Parliament and of the Council of 27 April 2016 on the protection of natural persons with regard to the processing of personal data and on the free movement of such data, and repealing Directive 95/46/EC (General Data Protection Regulation). *Off. J. Eur. Union* **2016**, *L 119*, 1.
70. Peponi, A.; Morgado, P. Transition to smart and regenerative urban places (SRUP): Contributions to a new conceptual framework. *Land* **2021**, *10*, 2. [[CrossRef](#)]
71. Sonetti, G.; Naboni, E.; Brown, M. Exploring the potentials of ICT tools for human-centric regenerative design. *Sustainability* **2018**, *10*, 1217. [[CrossRef](#)]
72. Hukkalainen, M.; Jaeger, A.; Ala-Juusela, M.; Llorente, J.; Villar, J.; ur Rehman, H.; Weibel, D.; Dewagtere, M. *Report on Making PEB Concepts Part of Local Authorities Planning Instruments*; EXCESS Deliverable 1.3; EXCESS: Espoo, Finland, 2020.
73. *A Clean Planet for all A European Strategic Long-Term Vision for a Prosperous, Modern, Competitive and Climate Neutral Economy*; European Union Commission: Brussels, Belgium, 2018.
74. Yohanis, Y.G.; Norton, B. Life-cycle operational and embodied energy for a generic single-storey office building in the UK. *Energy* **2002**, *27*, 77–92. [[CrossRef](#)]
75. Tuominen, P.; Seppänen, T. Estimating the value of price risk reduction in energy efficiency investments in buildings. *Energies* **2017**, *10*, 1545. [[CrossRef](#)]
76. Karunathilake, H.; Hewage, K.; Brinkerhoff, J.; Sadiq, R. Optimal renewable energy supply choices for net-zero ready buildings: A life cycle thinking approach under uncertainty. *Energy Build.* **2019**, *201*, 70–89. [[CrossRef](#)]
77. European Parliament. Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast). *Off. J. Eur. Union* **2018**, *2018*, 82–209.
78. European Energy Research Alliance EERA Joint Programme Smart Cities—SET-Plan Action 3.2. 2021. Available online: <https://www.eera-sc.eu/external-ccollaboration/set-plan-action-3-2.html> (accessed on 29 September 2021).
79. Caramizaru, A.; Uihlein, A. *Energy Communities: An Overview of Energy and Social Innovation EUR 30083*; Publications Office of the European Union: Luxembourg, 2020; ISBN 978-92-76-10713-2. [[CrossRef](#)]
80. Zhou, Y.; Cao, S.; Hensen, J.L.M.; Lund, P.D. Energy integration and interaction between buildings and vehicles: A state-of-the-art review. *Renew. Sustain. Energy Rev.* **2019**, *114*, 109337. [[CrossRef](#)]
81. Verbeke, S.; Aerts, D.; Reynders, G.; Ma, Y.; Waide, P. *Final Report on the Technical Support to the Development of a Smart Readiness Indicator for Buildings*; Publications Office of the European Union: Luxembourg, 2020.