Zero Energy Building (ZEB) definitions – A literature review

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1. Introduction

It is difficult to find a building, which can be named the first Zero Energy/Emission Building (ZEB). One of the reasons could be that maybe ZEB is not a new concept for a building, it is just a modern name for buildings, from times before district heating and electricity, heated with wood or straw and lighted with candles and domestic animals?

Nevertheless, in the late seventies and early eighties appeared few articles, in which phrases *'a zero energy house*', '*a neutral energy autonomous house*' or '*an energy-independent house*' were used. It was the time when the consequences of the oil crisis became noticeable and the issue of the fossil fuels sources and the energy use started to be discussed. However, those papers were mainly focusing on the energy efficient technologies and passive solutions implemented in the building. Furthermore, only energy demand for space heating, domestic hot water and cooling were accounted in the 'zero', hence were they in fact buildings with zero energy use?

Over the decades, in many articles and research projects number of ZEB's were described and evaluated, however almost for each case the ZEB was defined different or sometimes even no exact definition was used. Recently, the lack of common understanding and common definition for ZEB became noticeable and the world wide discussion has begun. There are many studies available, in which authors tried to propose different definitions for ZEB depending on:

- how the zero energy goal is achieved
- what is the building – grid interaction
- unequal energy qualities in the energy balance
- what are the project boundaries for the balance?

The main objective of this paper is to describe and evaluate existing ZEB definitions. Based on this work are highlighted the issues, which should be resolved before developing new ZEB definition.

2. Different approaches for the ZEB concept based on literature review

The reviewed literature has indicated that there is wide diversity among ZEB definitions. Thus the definitions are divided into a number of groups in order to spotlight the most important topics for the discussion before formulating a ZEB definition.

First approach raises the issue of what should be equal to zero in the ZEB definition. Should it be primary energy, end energy, CO_2 emissions, exergy or maybe energy costs?

In the report, written in 2006 by Torcellini, et al., authors use the general definition for ZEB given by The U.S. Department of Energy (DOE) Building Technologies Program: *"A net zero-energy building (ZEB) is a residential or commercial building with greatly reduced energy needs through efficiency gains such that the balance of energy needs can be supplied with renewable technologies."* However they also point out clearly undefined "zero": *"Despite the excitement over the phrase "zero energy," we lack a common definition, or even a common understanding, of what it means."*

Furthermore, in the paper authors indicate that the definition of Zero Energy Building can be constructed in several ways, depending on the project goals, intentions of the investor, concern about the climate changes and greenhouse gas emissions or finally the energy costs. Taking into consideration all the above mentioned scenarios Torcellini, et al. (2006), distinguish and point out four most commonly used definitions:

- ***Net Zero Site Energy****: A site ZEB produces at least as much energy as it uses in a year, when accounted for at the site.*
- ***Net Zero Source Energy:*** *A source ZEB produces at least as much energy as it uses in year, when accounted for at the source. Source energy refers to the primary energy used to generate and deliver the energy to the site. To calculate a building's total source energy, imported and exported energy is multiplied by the appropriate site-to-source conversion multipliers.*
- ***Net Zero Energy Costs:*** *In a cost ZEB, the amount of money the utility pays the building owner for the energy the building exports to the grid is at least equal to the amount the owner pays the utility for the energy services and energy used over the year.*
- ***Net Zero Energy Emissions:*** *A net-zero emissions building produces at least as much emissions-free renewable energy as it uses from emissions-producing energy sources.*

The distinction among the ZEB definitions made by Torcellini, et al. (2006) is also brought up in various publications "The Potential Impact of Zero Energy Homes", 2006, Torcellini, et al.*(2006), "Centerline", (2008), Noguchi, (2008), Kilkis, (2007), Voss, (2008).

Kilkis, (2007) in his work refers to Torcellini, et al. (2006) however, in the discussion on ZEB definitions, he takes slightly another direction. Kilkis indicates that in balancing the "zero" both quantity and quality (exergy) of energy should be taken into consideration, since only by using exergy we are able to assess the complete impact of the building on the environment. Therefore, author proposes a new definition for the ZEB a Net-Zero Exergy Building and defines it as: "*… a building, which has a total annual sum of zero exergy transfer across the building-district boundary in a district energy system, during all electric and any other transfer that is taking place in a certain period of time".*

At the same time Mertz, et al. (2007) and Laustsen, (2008) distinguish only between zero energy and zero emission building. In the definition for zero energy building authors do not point out if primary or end energy should be used in the balance, they just emphasize that energy use should be equal energy production.

Second approach is also connected to the balance, however this time is posed a question what energy demands should be included in the balance.

In the seventies and eighties, when large part of energy use in the buildings was mostly due to the heating (space heating and domestic hot water) in publications devoted to Zero Energy Building, in the definitions only heat was accounted in the zero. One of the definitions focusing only on heating demand is e.g. the definition given by Esbensen, et al. (1977): "*With energy conservation arrangements, such as high-insulated constructions, heat-recovery equipments and a solar heating system, the Zero Energy House is dimensioned to be self-sufficient in space heating and hot-water supply during normal climatic conditions in Denmark. Energy supply for the electric installations in the house is taken from the municipal mains."*

On the other hand, in number of papers total energy demand of a building is fully dominated by electricity demand, thus in the ZEB definition only electricity is considered. One of the reasons for this situation is simply the lack of district heating in many countries, however this issue is not commonly mention in the definition, which makes it imprecise. As an example can be presented the ZEB definition given by Gilijamse, (1995): "*A zero energy house is defined here as a house in which no fossil fuels are consumed, and the annual electricity consumption equals annual electricity production. Unlike the autarkic situation, the electricity grid acts as a virtual buffer with annually balanced delivers and returns"* and Iqbal, (2003): "*Zero energy home is the term used for a home that optimally combines commercially available renewable energy technology with the state of the art energy efficiency construction techniques. In a zero energy home no fossil fuels are consumed and its annual electricity consumption equals annual electricity production. A zero energy home may or may not be grid connected"*

Nevertheless, in the scientific publications do exist ZEB definitions including both heating and electricity demand in total energy demand as an example is Lausten, (2008) definition: "*Zero Net Energy Buildings are buildings that over a year are neutral, meaning that they deliver as much energy to the supply grids as they use from the grids. Seen in these terms they do not need any fossil fuel for heating, cooling, lighting or other energy uses although they sometimes draw energy from the grid."*

In some ZEB projects focus not only on the operating energy demand but also on energy embodied in the building construction and materials. One of example of such a project can be BedZED - neutral carbon eco-community near London. Morbitzer, (2008) points out: *"…where possible, BedZED is built from natural, recycled or reclaimed materials. All the wood used has been approved to be sourced from sustainable resources, and construction materials were selected for their low embodied energy and were sourced within 35-mile radius of the site if possible."*

In the prevailing literature is the strict distinguish between definitions for off-grid ZEB and on-grid ZEB. The main difference between those two approaches is that, the off-grid ZEB does not have any connection to the utility grid, thus it does not purchase energy from the external sources and the boundaries for the balance calculations are within the building. In other words the building offset all required energy by producing energy from RES. As the on-grid ZEB is also energy producing building, but there is a possibility for both purchasing energy from the gird and feeding it back to the grid. This division is also noticeable in the ZEB definitions.

Among many definitions for the off-grid ZEB in the literature as an example of this type of ZEB can be definition given by Laustsen in 2008 for International Energy Agency (IEA) (Laustsen, 2008):*"Zero Stand Alone Buildings are buildings that do not require connection to the grid or only as a backup. Stand alone buildings can autonomously supply themselves with energy, as they have the capacity to store energy for night-time or wintertime use."*

Studies with clear definition for grid-connected ZEB belong to e.g. Gilijamse, (1995), Parker, et al. (2001), Iqbal, (2003), Laustsen, (2008) and the definition, which indicates the best the main features of this kind of ZEB is formulated by Laustsen, (2008): "*Zero Net Energy Buildings are buildings that over a year are neutral, meaning that they deliver as much energy to the supply grids as they use from the grids. Seen in these terms they do not need any fossil fuel for heating, cooling, lighting or other energy uses although they sometimes draw energy from the grid"*

The ZEB definitions can be also grouped according to what type of renewable energy source will be utilized, since main concept of zero energy building is the independence of fossil fuels. By renewable energy sources can be understood: solar thermal, solar photovoltaic (PV), biomass and wind or wave energy. In the prevailing literature ZEB definitions are not focus on one particular

renewable technology. However among studies describing existing ZEB cases the most commonly applied technologies are solar thermal and photovoltaic: Esbensen, et al. (1977), Saitoh, (1984), Saitoh, et al. (1985), Stahl, et al. (1995), Voss, et al. (1996), Gilijamse, (1995), Karmer, (2007), Mertz, et al. (2007), Parker, et al. (2001), Rosta, et al. (2008), "Riverdale NetZero Project-Edmontom, Alberta", (2008), Noguchi, et al. (2008) etc. Charron, (2005) gives even a definition for zero energy solar homes: "*Homes that utilise solar thermal and solar photovoltaic (PV) technologies to generate as much energy as their yearly load are referred to as net-Zero Energy Solar Homes (ZESH).*"

A good ZEB definition should also indicates, what is the supply-side of the renewable energy sources. According to Torcellini, et al. (2006) there are two options: on-site supply or off-site supply. Within the on-site supply authors distinguish building footprint and building site separately. Within the off-site supply the building either uses RES available off-site to produce energy on-site, or purchase off-site RES. Tocellini, et al. (2006) propose a hierarchy of preferred application of renewable energy sources:

Table 2. ZEB Renewable Energy Supply Option Hierarchy Torcellini, et al. (2006)

Option Number	**ZEB Supply-Side Options**	**Examples**
0	Reduce site energy use through low-energy building technologies	Daylighting, high-efficiency HVAC equipment, natural ventilation, evaporative cooling, etc.
On-Site Supply Options		
1	Use renewable energy sources available within the building's footprint	PV, solar hot water, and wind located on the building.
2	Use renewable energy sources available at the site	PV, solar hot water, low-impact hydro, and wind located on-site, but not on the building.
Off-Site Supply Options		
3	Use renewable energy sources available off site to generate energy on site	Biomass, wood pellets, ethanol, or biodiesel that can be imported from off site, or waste streams from on-site processes that can be used on-site to generate electricity and heat.
4	Purchase off-site renewable energy sources	Utility-based wind, PV, emissions credits, or other "green" purchasing options. Hydroelectric is sometimes considered.

3. Discussion

The Zero Energy/Emission Building is a complex concept thus the development of one ZEB definition applicable for all case is not a simple task. As presented in the literature review, there are many approaches to the ZEB definition and each of them spotlights different aspects of ZEB. Those issues have served to create a list of the main topics, which should be considered, when developing a new net ZEB definition.

First and probably the most important is the issue of the balance:

- what are the units of the balance (final energy; primary energy; exergy; energy costs or maybe CO_2 emission)
- which energy demands are in the balance: only the energy needed for operating the building, or also the energy use connected with occupants behavior (cooking, appliances, lighting etc.) is included?
- if the embodied energy in the construction should be accounted in the balance?

When looking at the general practice for calculating the energy use of a building, the most commonly used unit is the primary energy. This unit allows taking into consideration the difference in the generation and distribution of 1 kW of electricity and 1kW of heat or natural gas and thus express better the actual building energy use. Using the energy costs could make it almost impossible to design a building, which would be a ZEB through its entire lifetime. Since the energy prices not only differ between counties but also change in time and moreover the relative difference between prices of different fuels may vary over time. So a building could be ZEB only at the time when it is design. Final energy is the easiest unit to implement and understand, but on the other hand quality of the different kinds of energy if fully neglected. CO_2 emission could be also a unit, but for a second definition of Zero Emission Building.

The second question regarding the energy demands should not be difficult to answer, because if a building is named zero energy building, then zero should refers to both demands at the same time. In order to evaluate total building environmental impact embodied energy should be taken into account in the balance. However, it can significantly difficult and extend calculations especially in early design phase, when many values are yet unknown.

Another question for the discussion is to distinguish between off-grid and on-grid ZEB and if net zero approach is only focus on grid connected cases or not? From the literature review it can be noticed that the word ‘net’ is more often used in the definitions for grid connected ZEB to emphasize the interaction with the utility grid. Assuming, that net zero approach includes only on-grid ZEB, in the developed definition the regulations of the building-grid interaction should be well described, since this connection ought to be beneficial for both sides. Unfortunately, the studies describe mostly how positive it is from the building neglecting the gird situation.

Furthermore, one more topic for the discussion is the requirements, if the ZEB definition should include specific requirements it terms of:

- maximum allowed energy use,
- minimum indoor environment quality (temperature and IAQ)
- type and application of renewable energy sources?

In number of publications devoted to ZEB, similar path to achieve ZEB can be noticed. Firstly, the reduction of energy demand using energy efficient technologies and afterwards utilization of

renewable energy sources (RES) to supply remaining energy. This is the most logical approach to reach ZEB. Nevertheless, as Laustsen, (2008) points out: "*In principle this can be a traditional building, which is supplied with very large solar collector and solar photo voltage systems. If these systems deliver more energy over a year than the use in the building it is a zero net energy building."* In order to avoid and eliminate this kind of ZEB a fixed value of maximum allowed energy use could be a good solution.

In the literature the topic of indoor environment quality is almost fully neglected in the ZEB definitions, though it is an important issue. On the one hand it would be very beneficial from general point of view, that all ZEB would use the same values. It would be much easier to evaluate and compare ZEB between each other. On the other hand, giving so detailed criteria in the ZEB definition could significantly limit its usefulness in many cases. Since, different values can be used depending on building type, country, applied standard and local climate conditions. A good solution could be a guidance or suggestion which standards or values should be used.

In prevailing ZEB cases descried in the literature solar energy (solar thermal and photo voltaic – PV) is mostly common used RES. It follows from the fact that, firstly it can be easily implemented in the building construction (no extra space besides building footprint is needed) and secondly it is the best developed RES technology for small-scale application. However, there are cases, in which another RES than solar energy would be more beneficial or easier to use, so why the ZEB definition should impose a certain type of RES?

When the above mentioned questions, mostly related to general ZEB definition, are answered, then comes the matter if this one general definition is enough to include all cases? Focusing only on a single building brings already difficulties. There are different buildings types, which have different purpose and requirements and this diversity may not be covered by one definition. Thus, while developing the ZEB definition it should be considered that maybe it will be more suitable to develop separate definition for residential and non-residential buildings. The same issue appears when taking into consideration a single building and a community situation. Is one general definition sufficient for a building and at the same a group of buildings?

Finally, a question of different climates and thus different design criteria can be posed, if it is feasible to design and construct ZEB all over the world according to the same definition? Those topics are the key issues/questions, which should be solved while developing a new ZEB definition.

4. Conclusion

The above literature review and discussion about ZEB definition lead to the list of key questions, which should be taken into consideration when developing new ZEB definition.

1. **What should be the units of the balance?** – *Primary energy, CO2 units, cost, exergy...*
2. **What type of energy use should be included be the balance?** – *Energy demand for building operation, energy use related to users (DHW, appliances, lighting) and/or embodied energy*
3. **What requirements could be included in the new definition?** - *maximum energy use? Minimum indoor environment quality (temperature and IAQ, (day)light)?* T*ype and application of RES (only on-site or also external)? Building induced mobility?*
4. **Can one general definition include all cases?** - *different building types, a single building and a community situation, different climates, both for on-grid and off- grid*
5. **Should there be any requirements for building-grid interaction?** *Effect on peak load, storage capability, time building can "survive" disconnected to the grid.*

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