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Near zero, zero and plus energy buildings: revised definitions

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Abstract

Here a survey of current definitions is the starting point to underline inconsistencies and critical issues, and to identify weak points. From these, distinguishing between energy and primary energy, with all its attributes, and between energy sources and energy carriers, a proposal of revised definitions of near zero, zero and plus energy buildings is formulated. This analysis is based on the use of the classic energy balance, but taking into consideration that a building is always a net energy consumer (it always produce entropy or destroy exergy). Special attention is then paid in clearly defining primary energy factors for energy carriers produced from renewable energy sources on site, nearby or far. Although the primary energy factors values have been fixed sometime by political reasons, a clear scientific definition is limiting them to a reasonable range these values, which at least do not violate the basic principles of thermodynamics. Finally, to clarify that a “plus” building cannot create energy but can just contribute to the local or regional electrical energy production by feeding the grid, a complementary energy index is then proposed beyond than required by the EPBD. This can overcome the questioning on the “negative” primary energy index that can be achieved by such building using some of current net ZEB definition. In this way is possible to spit the main function (and its quality) of a building from the secondary function (and quality) of being a distributed electric generator for the grid without losing any values and complying with the nearly Zero Energy Building definition of EPBD.

Keywords – ZEB, NZEB, nZEB, PEB, building, energy

1. Introduction

Near zero, zero and plus energy buildings are keywords appearing more and more on the press to qualify new buildings placed on the market and to underline their quality as environmental friendly buildings. But, despite a large debate on this item in the last 10 years, still there is no common general agreement on the technical meaning of such terms. The main question is what kind of building is the Zero Energy Building (ZEB). Then, if the zero is unambiguously defined, is simple to specify what does mean near or positive.

In short, a first trial to come up with a more clear and useful definition of ZEB was done in 2006 by Torcellini et al. in [1], but after stated that it is a building “with greatly reduced energy needs through efficiency gains such that the balance of energy needs can be supplied with renewable technologies”, they produced four different (sub)definitions: Zero Net Energy Building (ZNEB), Net Zero Site Energy Building

(NZSiEB), Net Zero Source Energy Building (NZSoEB), Net Zero Energy Cost Building (NZEC). All these different definitions have been introduced to account for different boundaries and metrics, which can be in turn more appropriate to the goals of designers, owners, organizations, etc.. Later, in 2008, ASHRAE, in its vision for 2020 [2], came up with a single definition choosing the NZSiEB among those listed before as the type of building which can be simply named NZEB. Thus the term ZEB was left aside to use the more clear NZEB term, which stresses with the attribute Net that such building can have a net zero energy balance on the site via two-way energy exchange with the power grid.

On the same route was the work done by the International Energy Agency (IEA) joint Solar Heating and Cooling (SHC) Task40 and Energy Conservation in Buildings and Community systems (ECBCS) Annex52 titled “Towards Net Zero Energy Solar Buildings”. Starting with a review of definitions on ZEBs in 2011, [3] [4], they came up with a “consistent definition framework” for NZEBs in 2012, [5], stressing the concept that “the term Net ZEB, Net Zero Energy Building, indicates a building connected to the energy grids”. But they went further ahead introducing the concept of nearly Net Energy Building (nNZEB) and Net Plus Energy Building (NPEB), [6].

In this scenario, which was mainly driven by technical and/or commercial interests, two main new actors were coming in partially changing the perspective. The European Union, through the recast of the European Directive on buildings energy performance, EPBD 31/2010 [7], introduced “by law” its definition of nearly Zero Energy Building (nZEB¹); while in 2014 the U.S. Department of Energy (DOE) Building Technologies Office contracted with the National Institute of Building Sciences (Institute) to establish definitions, associated nomenclature and measurement guidelines for zero energy buildings, with the goal of achieving widespread adoption and use by the building industry, [8]. The result this work is quite singular: because of the DOE Zero Energy Ready Homes program “had received feedback that concluded the term “net” was confusing to consumers”, “therefore, in striving for simplicity, consistency and to accentuate the core objective, DOE and NIBS selected the term Zero Energy Building (ZEB)” to indicate instead NZEBs (“However, it is recognized that the terms Net Zero Energy (NZE) and Zero Net Energy (ZNE) are in wide use and convey the same meaning as Zero Energy”).

The EPBD nZEB definition resulted to be too weak, leaving the Member State (MS) too degree of freedom in defining the application rules. The result is that today over 24 MS only few of them have a comparable practical definition of nZEB, [9]. Some MS have also mentioned in their National Plan [10,11] objective that goes beyond the nZEB requirements such as Positive Energy Buildings (PEB) in Denmark and France, Climate Neutral Buildings (CNB) in Germany and Zero Carbon Buildings (ZCB) in United Kingdom.

To support the definition of a common European framework, the European Commission (EC) has provided a mandate to the European Committee for Standardization (CEN) to review its technical standards “so that they become on the

¹ Note that nZEB is different than NZEB, n means "near", while N means "Net".

one hand unambiguous and compatible, and on the other hand a clear and explicit overview of the choices, boundary conditions and input data that need to be defined at national or regional level”, [12]. Because “such national or regional choices remain necessary, due to differences in climate, culture & building tradition, policy and legal frameworks”, [12], the resulting main standard, namely FprEN 15603:2014 (rejected at the formal vote) substituted by prEN ISO/DIS 52000-1:2015 (passed at public enquiry December 2015), is only informally addressing the nZEB definition in Annex H, as a methodological proposal, [13]. Meanwhile, for the same reasons, the European Federation of HVAC National Associations (REHVA) had started a task force on “Nearly Zero Energy Buildings”, which has published a comprehensive technical definition of nZEB as a compromise among different opinions, [14], [15].

This quick survey, limited to the main literature sources on ZEB, NZEB and nZEB, is clearly showing two principal issues: a) the different perspective and then characteristics of such buildings in the market-oriented U.S. DOE approach and in the “by law” constrained European Union approach; b) different meanings of near and positive attributes if a different zero reference is chosen (i.e. NZEB or off-grid or autonomous or self sustainable building).

2. U.S. DOE ZEB and E.U. nZEB

After [8], the former NZEB became for U.S. DOE just ZEB and it is defined as:

DOE-ZEB: *“An energy-efficient building where, on a source energy basis, the actual annual delivered energy is less than or equal to the on-site renewable exported energy”*

where:

- **source energy** is the site (building) energy plus the energy consumed in the extraction, processing and transport of **primary fuels** such as coal, oil and natural gas; energy losses in thermal combustion in power generation plants; and energy losses in transmission and distribution to the building site ;
- **building energy** is energy consumed at the building site as measured at the site boundary. At minimum, this includes heating, cooling, ventilation, domestic hot water, indoor and outdoor lighting, plug loads, process energy, elevators and conveying systems, and intra-building transportation systems.

To accommodate the collections of buildings where renewable energy resources were shared, three more definitions were added: Zero Energy Campus (ZEC), Zero Energy Portfolio (ZEP), Zero Energy Community (ZECo). These definitions are obtained from the ZEB definition just substituting the term building respectively with campus, portfolio and community, where:

- **campus** is a group of building sites in a specific locality that contain renewable energy production systems owned by a given institution;
- **portfolio** is a collection of building sites that contains renewable energy production systems owned/leased by a single entity;
- **community** is a group of building sites in a specific locality that contain renewable energy production systems.

To assess the energy performance, delivered (E_{del}) and exported (E_{exp}) energies through the site boundary for each energy type have to be measured or calculated. The source energy is then calculated from them using **source energy conversion factors** (r_i) from ASHRAE Standard 105. In DOE-ZEB accounting, the on-site renewable exported energy “*is given the same source energy conversion factor as the delivered energy to appropriately credit its displacement of delivered electricity*”. The ZEB site boundary could be around the building footprint if the on-site renewable energy is located within the building footprint, or around the building site if some of the on-site renewable energy is on-site but not within the building footprint. The ZEC site boundary allows for the building sites on a campus to be aggregated so that the combined on-site renewable energy could offset the combined building energy from the buildings on the campus. The ZECo or ZEP site boundary would allow a group of project sites at different locations to be aggregated so that the combined on-site renewable energy could offset the combined building energy from the aggregated project sites.

There is instead no any definition explaining what an **energy-efficient** building is, and a limitation on the ZEB label use: “the designation Zero Energy Building (ZEB) should be used only for buildings that have demonstrated through actual annual measurements that the delivered energy is less than or equal to the on-site renewable exported energy.”

In terms of source energy balance, the DOE-ZEB definition is then:

$$E_{source} = \sum_i (E_{del,i} \cdot r_{del,i}) - \sum_i (E_{exp,i} \cdot r_{exp,i}) \leq 0 \quad (1)$$

where:

$E_{del,i}$ is the delivered energy for energy type i ;

$E_{exp,i}$ is the exported on-site renewable energy for energy type i ;

$r_{del,i}$ is the source energy conversion factor for the delivered energy type i ;

$r_{exp,i}$ is the source energy conversion factor for the exported energy type i .

Conversely, the E.U. definition of nZEB, as reported in [7] art.2, sub.2 and art.9, sub.2(a), is:

EU-nZEB: “‘nearly zero-energy building’ means a building that has a very high energy performance, as determined in accordance with Annex I. 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”. “the Member State’s” shall detail “application in practice of the definition of nearly zero-energy buildings, reflecting their national, regional or local conditions, and including a numerical indicator of primary energy use expressed in kWh/m² per year. Primary energy factors used for the determination of the primary energy use may be based on national or regional yearly average values and may take into account relevant European standards”;

where no one of the important terms are directly defined as, for instance, the primary energy to be used in the numerical performance indicator (total, non-renewable or renewable) and the meaning of “nearby”. All quantitative definitions have been left to each MS as “*very high energy performance*” and “*a very significant extent by energy from renewable sources*”.

Using the CEN standard ad hoc developed for EPBD, EN 15603 [16], to assess the buildings energy performance, the corresponding primary energy use is calculated as:

$$E_p = \sum_i (E_{del,i} \cdot f_{P,del,i}) - \sum_j (E_{exp,j} \cdot f_{P,exp,j}) \quad (2)$$

where:

$E_{del,i}$ is the delivered energy for energy carrier i ;

$E_{exp,i}$ is the exported energy for energy carrier j ;

$f_{del,i}$ is the primary energy factor for the delivered energy carrier i ;

$f_{exp,i}$ is the primary energy factor for the exported energy carrier j .

Then, before 2019, each MS has to set up the maximum value allowed for the nZEB of the numerical indicator of primary energy use in kWh/m² per year, and after that, if A is a specified building area (useful, gross, etc.), the EU-nZEB is defined as:

$$EP_p = E_p / A \leq EP_{max}^{nZEB} = \max[E_p / A]_{nZEB} \quad (3)$$

where the upper limiting value shall be fixed using the “cost optimality” procedure provided by the European Commission [17]

Thus, a building that complies with the DOE-ZEB definition (1) may be also an EU-nZEB, while a building that complies with the EU-nZEB (3) could not be a DOE-ZEB. The first statement will be clarified later, while the second is evident.

3. Critical issues with U.S. DOE ZEB and related positive energy building definitions

The first issue can be identified in the loss of clarity and unicity when using (1) in association with Zero or Net Zero terms. U.S. DOE was choosing to change back from NZEB to ZEB because the term Net was unclear to the customers, but does not take care that is calling Zero something that mostly can be less than zero. This is just against the common customer understanding of zero.

Following this statement, a second issue is immediately coming out when we try to define a Positive Energy Building (PEB) (i.e. a building that use less delivered energy than exported on-site renewable energy): its source energy is negative! Again, this is in contrast with the common customer sense for which positive means greater than zero. In addition, we seemingly affirm that a ZEB or a PEB can “create” energy, violating the energy conservation principle. This is not a problem for experts who know the right answers, but it could be for customers, users and politicians. It would not be the first case that ZEB or PEB users are wasting more energy than conventional buildings users leaving all the time the windows open because the energy from renewable energy sources is “free of cost”.

The main issue is instead that this approach is not able really to assess the building energy performance quality. It is a common understanding that a valid energy intensity or quality index has always to be able to distinguish between buildings that do not have the same quality. It is possible to demonstrate that source energy, as calculated according to (1) with the same source energy conversion factors for both delivered and exported energy, regardless if from renewable or non-renewable energy sources, is not always able to do that.

Let to consider a full electric ZEB, as in the first example in [8], which has an actual annual delivered energy of 88 000 kWh and on-site renewable exported energy of 94 000 kWh electricity from photovoltaics, and let to assume that the heating system is just made of direct electric heaters. Using (1) with the same ASHRAE source energy conversion factors of 3.15 for electricity, the source energy is:

$$E_{source} = 94\,000 \cdot 3.15 - 88\,000 \cdot 3.15 = -18\,900 < 0 \quad (4)$$

Thus, this building is a DOE-ZEB or a Positive Energy Building.

Let now to consider exactly the same building with the same load situation but with water heaters supplied by a well water-to-water electric heat pump. In this case, if we leave the same PV field, the overall electrical energy production will be the same, but using a heat pump to cover the same thermal load the electricity consumption for heating will be much lower. Thus we resize the PV field in a way to maintain the same electrical energy difference between delivered and exported, i.e. 6 000 kWh. Assuming the actual annual delivered energy of 48 000 kWh and on-site renewable exported energy of 54 000 kWh electricity from photovoltaics, the source energy is still the same as before. Then we can argue that this method is non able to distinguish between different heat generation systems attributing the same performance index (the source energy in this case) to the building with the heat pump and to that with direct electric heaters. A second weak point is that these two “equivalent cases” are not at all equivalent from the electric grid fuel use point of view; this because, balancing the import-export at the site boundary, is not taken into consideration the highest loss experienced by the grid when carrying up and down more energy for the same net production from renewable energy sources.

This issue is mainly due to the use of the same source energy conversion factors for both the grid electricity and the on- site renewable exported electricity, i.e. the so-called substitution value approach.

If the aim is to transform the way building use energy and to achieve a rational and optimal use of all energy sources, this approach might fail because it is giving more importance to the net renewable energy delivered to the grid than to lower the building energy need and to increase on-site generation systems efficiencies. In fact, in principle and if the economic cost is not an issue, a building with two times higher energy need of another can have the same negative value of the source energy just using two times or more energy produced by renewable energy sources.

4. Critical issues with E.U. nZEB definition

The first issue with the EU-nZEB definition has been already underlined and is due to the voluntary lack of definitions, which attributes to MS the due to provide them.

The most important issue is instead with the metric and is related to the primary energy has to be used in the performance indicator. Being not specified total or non-renewable or renewable primary energy may be used. A simple reasoning can help to select among them what is the most compatible with the given nZEB definition.

The starting point is the definition of the Zero Energy Building in the framework of EPBD. Is it a net Zero Energy Building or not? There are two reasons supporting the negative answer. The first is that Net ZEB does not comply with the given nZEB definition because it is possible to have Net ZEBs which do not respect the request of “*very low amount of energy required*” which “*should be covered to a very significant extent by energy from renewable sources*”. It is quite evident that a building can be Net ZEB having a high amount of energy required partially covered by a high amount of non-renewable delivered energies if it is overproducing energy carriers from renewable energy sources and exports them. The second is more general and is related to the fact that the metric used to define the zero should not depend on local conditions, otherwise the zero is not unique. Also in this case it is evident that if (2) has to be zero the only possibility compatible with any possible positive values of the primary energy factors (which are by EPBD definition locally dependent) is that all delivered and all exported energy carriers have to be zero, i.e.:

$$E_p = \sum_i (E_{del,i} \cdot f_{P,del,i}) - \sum_j (E_{exp,j} \cdot f_{P,exp,j}) = 0 \quad \forall f_{P,del,i} > 0; \forall f_{P,exp,i} > 0 \quad (5)$$

$$\Rightarrow E_{del,i} = 0 \quad \forall i \quad ; \quad E_{exp,j} = 0 \quad \forall j$$

However, this is the definition of the off-grid or Autonomous ZEB. Thus, the reference zero for the EU-nZEB is the Autonomous ZEB. Once we have the zero, the nearly ZEB performance indicator is consistent with EU-nZEB definition if it is principle able to approach to such zero. If the total primary energy is used and if the energy conservation principle is respected, it is evident that being a building a net energy consumer (it is just destroying exergy or creating entropy dissipating high value energy to the environment at lower value) this performance index can never reach zero, neither in an ideal case. The use of renewable primary energy does make any sense being the EPBD goal the CO2 reduction. Thus it comes out the only possible consistent primary energy is the non-renewable one. Despite of that prEN ISO/DIS 52000-1:2015 [13] is suggesting to use the total. The total primary energy may be used, but not in the actual context. If we like to remark that energy saving has also to be applied to the renewable energy sources (very positive concept), the displayed goal has to be changed. The Directive has to be update and, instead of near ZEB, reference has to be made to **low or very low energy building**, because if we use total primary energy to qualify the performance never we can reach zero. Such choose has anyhow to drawback from the market point of view: net ZEB and Positive Energy Building do not exist anymore.

This result has in principle a strong implication on the primary energy conversion factors, which must only be referred to non-renewable primary energy. This is

compatible with the general goal of EPBD, the CO₂ emission reduction, related to the non-renewable energy use through combustion processes.

5. Primary energy conversion factors

We already stated that to be consistent with the EPBD nZEB general definition, the conversion factors must be applied only to non-renewable energy carriers (i.e. produced by non-renewable energy sources) to account for non-renewable energy sources use.

The remaining issues are then two: how to calculate their values and if the substitution value approach is consistent with the EU-nZEB definition.

The first issue is a false or just political issue. EN 15603:2008 and prEN ISO/DIS 52000-1:2015 are quite clear about the meaning of such coefficient and the definition allows unambiguous determination. By definition they are just applied only to energy carriers delivered or exported out of the site boundary (the assessment boundary for the building) to quantify how much of related primary energy has been used to produce and deliver such energy carrier. This determination could be difficult to achieve but it possible to do with the standard thermodynamics calculation. Of course the time variability of the losses chain from the source to the user may require updating their values on a short time base (the same as the energy performance calculation time base, from one hour to one year), but statistical analysis of specific energy carriers may help providing the most probable time profile. We do not have to forget that EPDB performance index for nZEB is just conventional and is the chosen way to push for having more performant building on the market. Thus, a conventional time profile for time variant primary energy conversion factor is something acceptable.

About the substitution value approach (to use the same conversion factors of the non-renewable deliver energy carrier for the renewable exported energy carrier), in the previous section about the DOE-ZEB, we have shown that such approach do not allow to distinguish between different on-site generation systems which realize the same net energy exchange (positive or negative, it is no matter). Thus, it must be avoided using zero for the on-site renewable energy carriers exported outside the site boundary. However, such approach kills the net ZERO concept applied to primary energy, which aims to valorize the distributed green electricity generation. Then it rises up a new question: how can be valorized the building that participates to the substitution of CO₂ based power generation feeding the grid with CO₂ free electricity, if the net ZEB concept has to be abandoned?

6. Alternative to the Net ZEB to account for the renewable energy export

From the foregoing it would seem that the given interpretation of the definition nZEB may penalize those buildings that produce energy carriers with the exploitation of renewable energy sources on site and that may export the overproduction contributing to the increase in the share of renewable energy used by the country. This is a non-issue if it is recognised that the EPBD performance indicator qualifies only the energy self-sustainability of a building and that the defining of the building's capacity to contribute to the production of zero CO₂ energy carriers for the benefit of the national energy system is another issue. Both aspects are important but need not be represented

by a single index, which takes away clarity to the results by mixing together such different objectives.

There is an additional motivation that should push to keep separate these aspects, besides the fact that the first is a property only of the building, while the second is a combined property of the building and of the energy system that it is connected to. In other words, a unique building property should not be confused with a combined property of the building and the energy system, which it is interconnected with.

Among other things, the aspects related to the issue of permission release and verification also motivate this differentiation. In fact, the building energy performance assessment and verification is usually in the responsibility of municipalities and real estate owners, in the sense that the related documentation is associated with the building permit and sales contracts and that performance verification is handled on Community level. Instead, the exchange of energy carriers between power producers and users, today limited to the electric energy carrier, is in the hand of electric grid Authority. The Grid Authority has then the need to manage local productions in order to avoid the collapse of the network to overload and excessive imbalances.

Ultimately, it is more efficient to separate the two features, introducing alongside the primary energy need, which defines the energy performance index, another index, which uniquely defines the building contribution to the regional/national zero CO₂ electric energy production. This “production” index must be under the Grid Authority control that in relation with the local grid capacity may or may not encourage / discourage this production in specific areas. In particular, being the objective the reduction of CO₂ production, this separation allows not only supporting and improving the exploitation of photovoltaic electricity, but also that produced by on-site cogeneration systems and exported to the grid. In the latter case, if for instance the building primary energy use is attributed only to the heating/cooling service, there is no primary energy consumption allocated to the exported cogenerated electricity and hence no CO₂ production.

It is then possible to define the index of contribution to the production of electricity from renewable energy or "CO₂-free" generators as:

CO₂ Neutral Exported Electrical Energy Index, NEEE:

“the share of export of CO₂ neutral electricity building production from renewable energy sources and from cogeneration systems per unit of useful area of the building, as:

$$NEEE = \left[\sum_{RES=1}^N (W_{RES,ren,exp}) + W_{CHP,exp} \right] / A \quad (6)$$

where

- $W_{RES,ren,exp}$ share of export of CO₂ neutral electricity building production from renewable energy sources exploited on-site;
- $W_{CHP,exp}$ share of export of CO₂ neutral electricity building production from thermal driven building cogeneration systems.

or the relative index defined as:

Percentage of CO2 Neutral Exported Electrical Energy per Primary Energy Need, NEEE%:

“yearly amount of CO2 neutral exported electrical energy to the grid and the overall yearly primary energy use of the building, E_p ,”; that is:

$$NEEE\% = \frac{NEEE}{EP} \cdot 100 = \left\{ \left[\sum_{RES=1}^N (W_{RES,ren,exp}) + W_{CHP,exp} \right] / E_p \right\} \cdot 100 \quad (7)$$

These two indices can be used to define incentives for buildings, which make a positive contribution to the national electric grid with CO2 free electricity, regardless their primary energy index. (i.e. if they are low or high energy-intensive building).

7. Revised nZEB definition

To overcome some of the underlined issues and to make clear to anyone (not only to experts) what nZEB means in the EPBD perspective a revised definition is given in the following based on few widely agreed statements:

- thermal and electric energy need reduced as much as reasonably possible (insulation, daylighting, thermal mass activation, etc.);
- service systems energy need reduced as much as economically feasible (heat recovery systems, increased efficiency of components and subsystems, etc.);
- building thermal and electrical energy use covered to a significant extent with the use of energy carriers produced on-site or nearby from renewable sources (solar thermal and PV systems, heat pumps, etc.);
- the provisions of point A, B and C must be obtained under the economic and/or financial sustainability (to comply with the cost optimality concept);
- the ability to be a distributed producer of CO2 neutral electricity for the network is not a nZEB requirement, but it can nonetheless be exploited separately with an appropriate index.

Following such statements the actual EU-nZEB definition can be rephrased as:

New-EU-nZEB: “*nearly zero-energy building*’ means a building that has a very high energy performance, as determined in accordance with Annex I. The nearly zero or very low amount of energy (**energy use**) required should be **obtained reducing as much as possible the energy need, compatibly with the use of building and ensuring the comfort and air quality, increasing as much as feasible the service systems efficiencies, and should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby**”. “the Member State’s” shall detail “*application in practice of the definition of nearly zero-energy buildings, reflecting their national, regional or local conditions, and including a numerical indicator of **non-renewable** primary energy use expressed in kWh/m² per year. Primary energy factors used for the determination of the **non-renewable** primary energy use may be based*

on national or regional yearly average values and may take into account relevant European standards”;

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