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Energy payback: An attributional and environmentally focused approach to energy balance in net zero energy buildings

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ABSTRACT

Net zero energy buildings (nZEBs) are understood as grid-connected buildings which do not require net inputs of non-renewable energy over a defined period of their life cycle. Energy requirements of nZEBs have until now been assessed based on the impact buildings have on the existing energy system. This paper introduces a new approach to nZEB energy balance that takes into account the actual amount of energy nZEBs require.

Energy balance methods previously proposed for nZEBs are illustrated in a new way and expressed in a series of equations based on a common terminology. Taking a different standpoint on the very logic that lies behind energy calculations; this article presents a new approach to energy balance in nZEBs. The paper highlights the important difference between preventing an increase in the demand for grid energy and ensuring that a building requires no net non-renewable energy. The authors argue that an energy payback approach constitute a more adequate way to tackle the environmental challenges nZEBs are meant to help solving, and to abide to a definition which stipulates that nZEBs should require no net non-renewable energy.

1. Introduction

The development of nZEBs often finds its root in the mitigation of greenhouse gas emissions, in particular in Europe [1]. Definitions for nZEBs are however sensitive to political, economic and energy security concerns. Concerns for environmental impacts other than merely climate change also play a role in the development of a sound definition for nZEBs.

Different approaches have been proposed to balance energy flows and greenhouse gas emissions associated with buildings. These approaches form one of the bases to assess what the appellation net zero energy/emission buildings stands for. Torcellini et al. [2] compared and proposed different types of ZEBs. The European Commission provided legal basis for certain aspect of a definition for nearly zero energy buildings in its recast of the energy performance of buildings directive (EPBD) [1], on which the European Council for an Energy Efficient Economy (ECEEE) provided useful comments [3–5] and which was reviewed in technical terms by Kurnitski et al. [6]. Sartori et al. [7] presented different criteria for the definition of net zero energy buildings: (1) boundary conditions, (2) crediting system, (3) net zero balance, (4) temporal energy match and (5) monitoring procedure. Voss et al. [8] proposed a road map to ZEBs presenting characteristics of the energy balance: (1) metric, (2) accounting, (3) system boundaries for balancing, (4) balancing period, (5) load match and (6) technology and grid integration. Marszal et al. [9] reviewed energy/emission calculation methods proposed for nZEBs in the framework of the International Energy Agency (IEA) SHC Task 40/ECBCS Annex 52: "Towards Net Zero Energy Solar Buildings" [10] and identified seven issues of special importance: (1) the metric of the balance, (2) the balancing period, (3) the type of energy use included in the balance, (4) the type of balance, (5) the renewable energy supply options, (6) the connection to the energy infrastructure and (7) the requirements for the energy efficiency and the indoor climate. All calculation methodologies where further compared to their respective national building codes [11]. Sartori et al. [12] presented a consistent definition framework for nZEBs, including aspects of the balance. These articles highlight a great variety in both the approaches and supporting energy balance methods. Organisations and countries also commissioned reports to define this new generation of buildings, e.g. the UK [13,14], Australia [15] and at the European level, the Building Performance Institute Europe [16].

This paper studies the logic on which energy balance methods proposed for nZEBs are based upon. It presents diagrams and equations which highlight this logic for a series of methods presented to the IEA SHC Task 40/Annex 52 [9,11] by a group of international experts. The implications of the different methods

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Table 1
Terminology & nomenclature.

Load	L_i	Total amount of energy required to operate a building. Depending on the building system's energy boundaries and renewable energy supply, the load - also called energy demand – can be significantly higher than the delivered energy.
Delivered energy	$E_{\mathrm{del},i}$	Total amount of energy (electrical, thermal, combustible, etc.) entering the building system's boundaries. The term delivered energy can be understood as the energy imported from the grid to the building.
Generation	G_i	Total amount of energy harvested from renewables. In most cases, this is electricity generated from renewable sources on-site or off-site, or thermal energy from heat pumps.
Exported energy	$E_{\mathrm{exp},i}$	Total amount of energy harvested from renewables and fed into the grid. The exported energy is that part of the generation which is exported to the grid, i.e. generation minus self-consumption. Self-consumption is the amount of energy harvested from renewables and used directly to cover building loads.
Embodied energy		
	$E^p_{\mathrm{emb,building}}$	Building embodied energy
	$E^p_{\mathrm{emb,RES}}$	Energy Embodied within a renewable energy supply system
Primary energy		The total energy required to deliver a certain quantity of end-use energy, it includes the energy required and lost in all processes associated with the provision of delivered energy. It is energy that has not been subjected to any conversion or transformation process [17]. It is the energy that is directly and indirectly required to extract, refine and deliver the fuel (end-use energy) [18]
Weighting factors		Factors used to weight against each other, using a specific metric, the different energy exchange of a building.
	$f^p_{\mathrm{del},i}$	Primary energy factor applied to the delivered energy
	$f^p_{\mathrm{exp},i}$	Primary energy factor applied to the exported energy
	$f^p_{\mathrm{load},i}$	Primary energy factor applied to the load
	$f^p_{NR,i}$	Non-renewable primary energy factor
	$f^p_{\mathrm{building},i}$	Building embodied energy factor

are discussed and a new environmentally-focused energy balance method is developed. This environmentally-focused balance follows an energy payback (i.e. attributional) approach rather than the avoided burden (i.e. consequential) approach followed by the other methods. Finally, case studies illustrate and compare the outcomes of the different methods.

2. Terminology

Equations developed in this paper are based on a common terminology that allows to easily compare the energy balance methods. The terminology presented in Table 1 generally follows European Standard EN 15603:2008 [17] and the recast of the Energy Performance of Buildings Directive (EPBD) [1]. The different variables are expressed for each energy carrier with the subscript *i*.

3. Basic parameters of energy balance

NZEBs need to fulfil a set of requirements. Once these requirements are fulfilled, a particular type of balance based on a given metric is done over a defined period, and for a defined set of boundaries, renewable energy supply (RES) options and grid interactions. Fig. 1 schematises the characteristics of the balance for nZEBs and provides an overview of the different parameters influencing the balance.

This paper studies the logic behind the balance independently from the other balance parameters. Energy and primary energy are used to illustrate the logical principles behind the balance methods. The methods introduced in this paper are generic and can be used with other metrics, e.g. GHG emissions, exergy [18] and cost, and over any defined balance period. The methods are also independent of the building system boundary. The system boundary dictates which type of energy is accounted for in the balance, e.g. building loads, user related loads, off-site energy demand directly related to the building users' activities (servers, transport, food, etc.), building embodied and end-of-life energy, etc. Furthermore, the models allow for any set of renewable energy supply and requirements, and are developed for grid-connected ZEBs, i.e. nZEBs.

4. Overview of energy balance types in zero emission buildings

The balance methods presented below can be used at the design stage or for the assessment of operating nZEBs. In its assessment form, the balance relies on monitored data for delivered and exported energy. In a design perspective, estimating self-consumption and accounting for embodied energy brings additional challenges. The design balance is therefore often based on estimated building *loads* and renewable *generation* of energy forms. Fig. 8 presents a good overview of the differences between a load/generation and a delivered/exported energy balance.

4.1. Method 1: a site balance

In this first method, the energy balance is done at the building site between delivered and exported energy. No conversion factor is applied to either energy flows. This type of balance, illustrated in Fig. 2, has been termed net zero site energy [2] or "ZEB Site". It is a simple, repeatable and consistent method based on direct

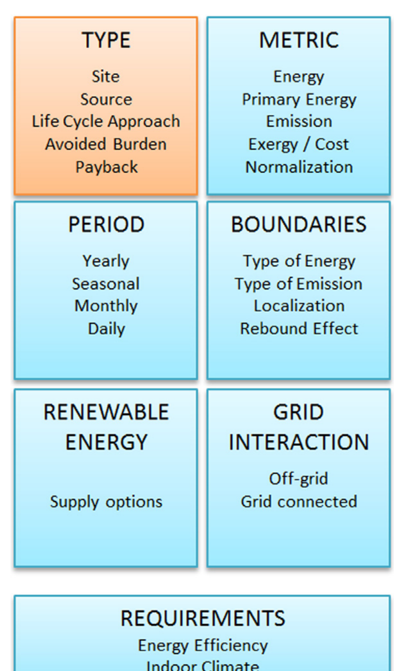

Fig. 1. Characteristics of nZEBs energy balance.