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Lessons learnt from embodied GHG emission calculations in zero emission buildings (ZEBs) from the Norwegian ZEB research centre

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ABSTRACT

The objective of this work is to present, evaluate and discuss the calculation methodology and embodied greenhouse gas (GHG) emission results from zero emission building (ZEB) case studies from the Norwegian ZEB research centre, to extract design drivers and lessons learnt. In all, two virtual models, and five ZEB pilot buildings are assessed; consisting of three residential, two office and two school buildings. The embodied GHG emission results show that the building envelope (ca. 65%) and production and replacement of materials (ca. 55–87%) are the main contributors to total emissions across the Norwegian ZEB case studies. Although difficult to draw definitive conclusions, this work builds upon the current body of knowledge on embodied GHG emissions in Norwegian ZEBs, and provides some practical indications for embodied GHG emission calculations and reduction strategies in future Norwegian ZEB and zero emission neighbourhood (ZEN) projects.

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1. Introduction

Life cycle assessment (LCA) is a well-established methodology used for the environmental assessment of buildings [1]. Due to the long lifespan of buildings, operational energy use has traditionally been identified as the main contributor to high GHG emissions in buildings [2]. However, because of increasingly stringent energy requirements and improved energy efficiency, the significance of emissions from operational energy has decreased [1,2]. In contrast, environmental impacts from the production, construction, maintenance, replacement and demolition phases are gaining significance [1]. This trend is even more pronounced in zero emission buildings (ZEBs), whereby the embodied emissions associated with building materials contribute to a large proportion of total greenhouse gas (GHG) emissions of a building [3]. Consequently, there is a growing interest in addressing embodied material emissions and choosing low-carbon products when designing ZEBs [4,5].

The objective of this work is to present, evaluate and discuss the calculation methodology and embodied GHG emission results from ZEB case studies from the Norwegian ZEB research centre, to extract design drivers and lessons learnt. In addition, this work begins pinpointing important measures for reducing embodied material emissions and simplifying embodied emission calculations for future ZEBs and for the new Norwegian research centre on zero emission neighbourhoods (ZEN) in smart cities.

The paper begins by outlining significant background literature, and the in-house ZEB methodology used in life cycle embodied GHG emissions of Norwegian ZEBs. This is then followed by the methodology used for evaluating and discussing the ZEB case studies. The ZEB case studies are then described. The GHG emission results are presented to deduce lessons learnt and design drivers. These findings are discussed, and final remarks are drawn in the conclusion.

2. Background

The Norwegian ZEB research centre has developed a Norwegian ZEB definition and guideline for ZEBs with an ambition for achieving zero GHG emissions from the life cycle of buildings [6,7]. According to the definition, a net ZEB can be achieved by offsetting greenhouse gas (GHG) emissions from the entire life cycle of the building through the generation of onsite renewable energy [6,7]. The ZEB research centre's definition is very ambitious; therefore, a stepwise approach of using ambition levels has been developed to allow flexibility for different types of buildings and local boundary conditions [6,7]. The lowest ambition level is ZEB-O÷EQ, which is equivalent to all emissions relating to energy use for the operation of a building (O), excluding the energy use for appliances and

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equipment (EQ), shall be compensated for with onsite renewable energy generation. ZEB-COMPLETE is the highest ambition level whereby all emissions related to the entire life cycle of a building (including construction (C), operation (O), production and replacement of building materials (M), maintenance, replacement and repair in the use phase (PLET) and deconstruction, transport, waste processing and disposal at end-of-life (E)) shall be compensated for with onsite renewable energy generation [6,7].

The ZEB research centre has evaluated two concept buildings (virtual building models) and nine pilot buildings considering different design strategies and material choices to achieve a net zero emission balance for the agreed upon ZEB ambition level. The most efficient design strategies and material choices for achieving low embodied emissions identified through the pilot projects are; area and material reduction, application of reused and recycled materials, using materials with low embodied carbon, sourcing local materials, and adopting materials with high durability and a long service life [8].

The ZEB ambition levels have proven useful in the development of ZEB concept and pilot projects, because they have increased transparency, are comparable with other projects, and have contributed to important learning outcomes for emission reduction measures [8,9]. The methodology developed by the ZEB research centre has been used by different stakeholders in the Norwegian building industry [9,10], not only to understand and evaluate the emissions from ZEBs, but also to consider different emission reduction measures [9]. However, the ZEB case studies highlight how challenging it can be to focus on embodied emission reduction, especially during a complex project process [11,12]. This is because, decisions regarding design and material alternatives are based on many criteria including technical properties such as load bearing capacity, fire safety, durability and sound proofing properties; as well as data availability, cost and time issues [11]. Challenges during the project can also include unforeseen changes in the design and construction phases, such as unexpected ground conditions or new design requirements. Furthermore, many construction professionals consider life cycle GHG emission calculations time consuming and complex, especially in relation to data collection [1].

During the past 8 years, the ZEB research centre has focused on developing solutions at the individual building level. However, focusing on individual ZEBs has been challenging and even difficult to achieve energy and emission targets, either because the energy demand and associated embodied emissions cannot be sufficiently reduced, or because of limited access to onsite or nearby renewable energy [8]. The centre has also highlighted the importance of transitioning from individual ZEBs to wide scale zero emission neighbourhoods and communities to effectuate global climate and energy related goals [13,14]. Optimisation at the neighbourhood level can reduce system-wide energy demand, use of a higher share of renewable energy due to the integrated nature of cities (including transport and infrastructure) and reduction of GHG emissions. Thus, the new Norwegian research centre on zero emission neighbourhoods (ZEN) in smart cities aims to enable the transition to a low carbon society by developing sustainable neighbourhoods with zero GHG emissions [15].

Previous studies have evaluated the effect of various GHG emission reduction strategies on low-energy houses in a Norwegian context, and found that GHG emissions may be reduced by approximately 20% if low embodied carbon materials are chosen [16,17], by about 20% if reuse and recycling is planned for [18,19], by about 10% if material loss at the construction site is optimised [20], by about 10% if buildings are designed to be low maintenance [20], and by about 10% if the building is designed to have a robust energy system [20]. Some studies have also shown that embodied GHG emissions can be reduced by up to 40% if biogenic carbon storage of wood is considered [21], by up to 30% if concrete contains reactive magnesium or calcium silicates [22], and by 5% if a green roof is implemented [20,23,24]. In contrast, the Norwegian ZEB case studies have not previously been analysed with the purpose of extracting important design drivers and lessons learnt on low embodied material emission design for buildings. However, some simplified comparisons have been carried out [8,25–27].

This body of work is illustrated through selected examples from the Norwegian ZEB concept studies and pilot buildings for three building typologies, namely residential, office and school building, as shown in Table 1. Both Haakonsvern office and Skarpnes residential development have been excluded from this assessment since they both have a ZEB-O ambition level, and do not assess embodied material emissions. Powerhouse Brattørkaia and Zero Village Bergen have also been excluded from this assessment since they are still in the planning and design phases, and have not yet been built. Zero Village Bergen will also become a pilot area in the new ZEN research centre.

2.1. ZEB GHG calculation methodology

The ZEB research centre has developed an attributional life cycle assessment (LCA) methodology to quantify the life cycle CO_{2eq} emissions from the ZEB case studies [6,7]. An excel-based LCA tool [42] has been developed in accordance with international LCA standards (ISO 14040 and ISO 14044) following the four main steps: i) goal and scope, ii) life cycle inventory (LCI), iii) environmental impact assessment and iv) interpretation of the results [43,44]. The tool has been used in life cycle GHG emission calculations for each of the ZEB case studies. The goal of the LCAs for the ZEB case studies has been to evaluate, quantify and provide an overview of the life cycle GHG emissions of the building to achieve a net ZEB balance. Across the ZEB case studies, a functional unit of $1m^2$ of heated floor area (BRA) over a reference study period of 60 years has been considered. The system boundary has been defined in accordance with the modular life cycle system as defined in EN 15978: 2011 [16] and the scope of the ZEB ambition levels [6,7], see Fig. 2.

The modular life cycle system measures the cradle-to-grave impacts from four main life cycle stages [45]: product stage (A1-A3), construction stage (A4-A5), use stage (B1-B7) and end-of-life stage (C1-C4). In addition, the optional stage (D) is defined to account for the potential positive impacts of processing or reusing materials after end-of-life. In the different ZEB ambition levels, operational energy use (O) corresponds to life cycle module B6, Materials (M) correspond to life cycle modules A1 – A3 and B4 for the production and replacement of building materials. Construction (C) corresponds to life cycle modules A4 and A5, for transport from the factory to the construction site, and installation activities, respectively. The end-of-life (E) phase corresponds to life cycle modules C1 – C4 which include the demolition, transport, waste processing and final disposal of building materials, whilst the use phase (PLET) corresponds to the remaining life cycle modules, B1, B2, B3, B5 and B7 for use, maintenance, repair, refurbishment and operational water use, respectively. Life cycle module D is used to document emission compensation from onsite, renewable energy generation [6,7].

Operational energy use is either calculated through specific input data for energy simulations in calculation software such as SIMIEN [46] or IDA-ICE [47] in the design phase, or measured in terms of net energy need (kWh) on-site during the use phase. Previous research at the ZEB research centre has determined a conversion factor for the Norwegian electricity grid, that considers the decarbonisation of the European power systems towards 2050. This emission factor corresponds to 132 gCO_{2eq} per kWh of electricity [48,49]. It is acknowledged that the ZEB emission factor for electricity is sensitive to multiple factors, such as time, location, and

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