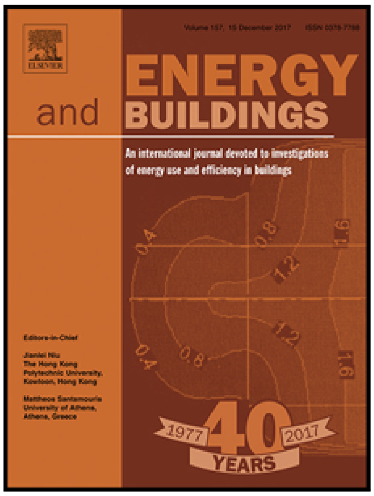

Lessons learnt from embodied GHG emission calculations in zero emission buildings (ZEBs) from the Norwegian ZEB research centre

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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.

Keywords: Design; Embodied GHG emissions; Zero Emission Building (ZEB); Zero Emission Neighbourhood (ZEN)

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 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.

Table 1. Selected examples from the Norwegian ZEB concept studies and pilot buildings.

Building Typology	**Case Study**	**Relevant Literature**
Residential	Single family house (SFH) concept study	[25, 28-31]
	Multikomfort house pilot building	[32]
	Living Laboratory pilot building	[26, 33, 34]
Office	Office concept study	[25, 35, 36]
	Powerhouse Kjørbo pilot building	[37, 38]
School	Campus Evenstad pilot building	[39-41]
	Heimdal high school pilot building	[12]

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 Figure 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].

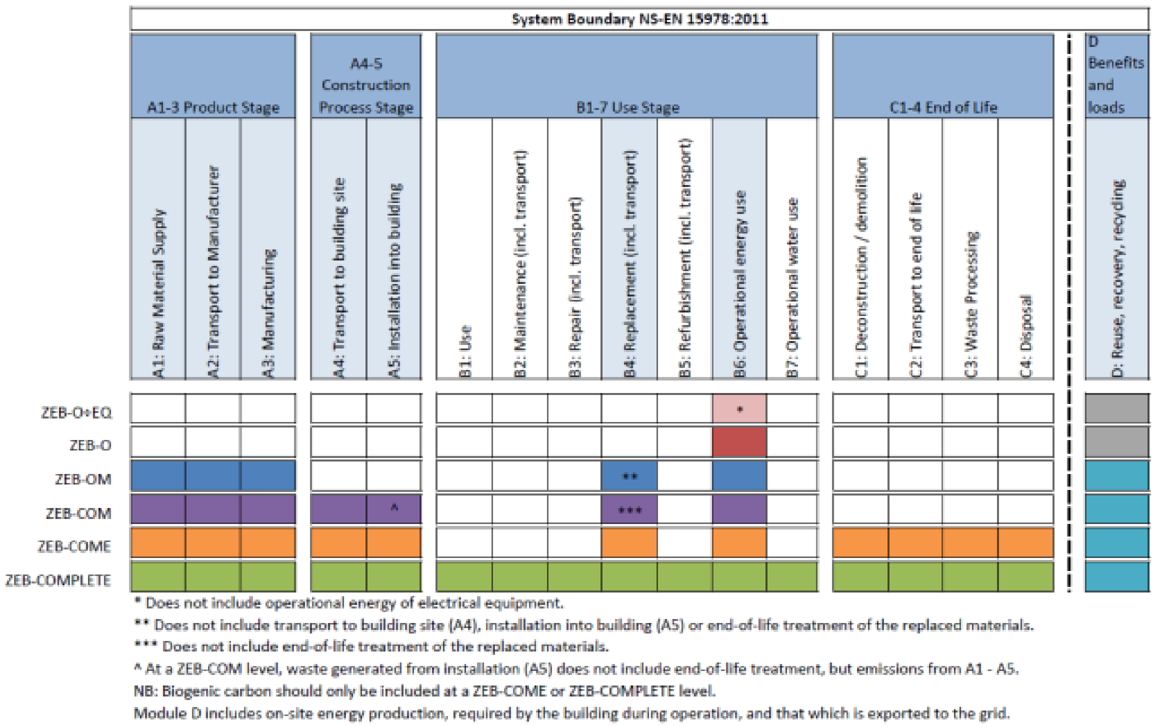


Figure 2. Description of system boundaries for LCA covered by the ZEB ambition levels [40].

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 national and European energy policies. Since this is already debated extensively in existing literature [48, 49], the matter is considered beyond the scope of this paper.

The life cycle material inventories for the ZEB case studies are structured according to the Norwegian standard NS 3451: 2009 table of building elements [50] 2-digit nomenclature (i.e. 21 groundwork and foundations, 22 load-bearing structure…etc.). This nomenclature is used to obtain an overview of the parts of the buildings that have been included in the studies, and to facilitate for structured and detailed comparisons.

Global warming potential (GWP) calculated in terms of carbon dioxide equivalents (CO_{2eq}) is used across all the ZEB case studies. Thus, the embodied material emissions are measured in terms of GWP ($kgCO_{2eq}/m^2/yr$), and are calculated according to the IPCC GWP 100-year method [51]. Focusing on GWP as an environmental indicator has the benefit of reducing complexity for decision makers, and more often than not correlates with other environmental impacts [41]. However, it also risks ignoring important environmental impacts that do not correlate with GWP, such as; toxicity, resource use, and resource depletion [1, 52]. Focusing on only one environmental indicator can potentially lead to problem shifting to other impact categories.

Data sources include environmental product declarations (EPDs) providing specific emission factors when the building material supplier is known, verified LCA reports from manufacturers, and generic emission factors from the life cycle inventory database Ecoinvent v3 when suppliers are unknown [53, 54]. It should be noted that EPDs use a different emission factor for electricity (during the production phase) compared to the ZEB emission factor for electricity (in the use phase), and that these emission factors have not been altered. Biogenic carbon has been excluded in GHG calculations for the concept and pilot buildings since the ZEB ambition levels of the case studies do not cover the whole life cycle of the building, biogenic carbon is only included at a ZEB-COME or ZEB-COMPLETE ambition level [6, 7]. Carbonation of concrete has not been considered at the Norwegian ZEB research centre.

Given a building reference study period of 60 years, it is assumed that no radical renovation or rebuilding takes place during the building service lifespan (except for Powerhouse Kjørbo which is a renovation project), and that building materials are replaced by buildings of identical technical performance at the end of their service lifetime [55]. The only exception to this rule is photovoltaic panels; whereby it is assumed that PV panels will be produced in a 50% more material/energy efficient way in 30 years' time [28, 35]. The estimated service lifespans of building materials and components are based on reference service lifetimes (RSLs) reported in EPDs, average values from SINTEF's design guidelines and product literature [53, 56].

3. Methodology

The methodology used in this paper is based on a quantitative and qualitative assessment of the calculation methodology and embodied GHG emission results from the Norwegian ZEB case studies. This method of assessment is chosen because of the vast differences in building typology, size, material, technology, construction method, location, and different strategies used to accomplish ZEB targets between the ZEB case studies, which makes it difficult to compare the ZEB case studies. This method has also been chosen to triangulate embodied GHG emission findings to cross-reference data and find points of convergence [57]. Therefore, a summary of the ZEB case studies is presented. Afterwards, the embodied GHG emission results for each ZEB case study are collected from published literature, and presented in terms of the functional unit for each life cycle module, each building part and in total for the whole building. The embodied GHG emission results have not been empirically harmonised since they all follow the ZEB GHG calculation methodology. However, although each case study follows the ZEB GHG calculation methodology, different LCA practitioners have carried out the calculations with varying objectives, system boundaries, data sources and levels of detail. Thus, there is a high degree of assumption and uncertainty in these results.

4. Case studies

At the ZEB research centre, the concept work started in late autumn 2011 with the analysis of two simplified virtual models; one office building (office concept), and one residential building (single-family house (SFH) concept) [28, 35]. As both concept studies are theoretical, they rely upon conventional building solutions, and do not consider material optimisation. The material inventory used in embodied material emission calculations is also limited. The results from the two concept studies demonstrate the demand for innovative and alternative solutions to reduce total embodied material emissions and achieve the defined ZEB ambition levels.

Subsequently, the Living Laboratory is the first ZEB pilot building to be built [26]. The Living Laboratory is a temporary single-family house with a multi-purpose demonstration experimental facility. Although the materials used have not been optimised in terms of embodied material emissions, the building incorporates innovative, state-of-the-art materials and technology to drive down emissions relating to the operational phase [26]. In contrast, the Multikomfort house is a demonstration and exhibition building, characterised by its sloping roof, glue laminated timber structure, natural stone and timber external facade, brick internal walls, and large glazing area [32]. Powerhouse Kjørbo is a renovated office building, which reuses the foundations and load-bearing structure directly in the refurbished building [37]. Campus Evenstad consists of an administration and educational school building, and has the highest ZEB ambition level out of the ZEB pilot projects (ZEB-COM) [40]. Heimdal high school is a larger school development project, and consists of a school building and sports hall [12]. The various ZEB case studies are illustrated in Figure 1. The complete material inventories, and results for each ZEB case study are well documented in the following ZEB reports [12, 26, 28, 32, 35, 37, 40] and include further details on data sources, assumptions, and uncertainties to increase quality and transparency. Key information about the case studies is summarised in Table 2.

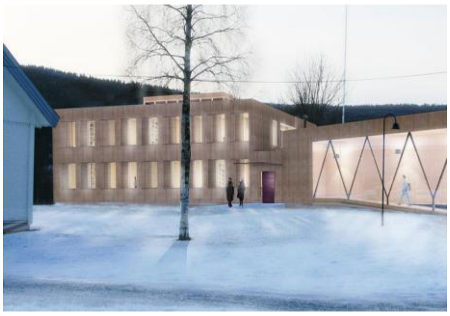
SFH concept [28]

Multikomfort house, Snøhetta

Living Laboratory [26]

Office concept [35]

Powerhouse Kjørbo, Snøhetta



Campus Evenstad, Ola Roald Arkitekter

Heimdal high school, Rambøll

Figure 1. Images of the Norwegian ZEB case studies considered.

Table 2. Matrix of building characteristics between the ZEB concept and pilot building case studies.

	SFH concept	Multi-komfort house	Living Laboratory	Office concept	Powerhouse Kjørbo	Campus Evenstad	Heimdal high school
References	[28]	[32]	[26]	[35]	[37]	[40]	[12]
General information							
Typology	Residential	Residential	Residential	Office	Office	School	School
Location	Oslo	Larvik	Trondheim	Oslo	Sandvika	Hedmark	Trondheim
Heated floor area	160 m^2	201.5 m^2	102 m^2	1980 m^2	5180 m^2	1140 m^2	26356 m^2
No. of floors	2	2	1	4	3 & 4	2	5
Completion	2013	2014	2014	2013	2014	2016	2018
ZEB ambition level	ZEB-OM*	ZEB-OM	ZEB-OM*	ZEB-OM*	ZEB-COM÷ EQ*	ZEB-COM	ZEB-O20%M**
Thermal properties (W/m^2K)							
U-value outer wall	0.12	0.11	0.11	0.12	0.13	0.12	0.07 - 0.13
U-value windows	0.65	0.75	0.65 - 0.97	0.75	0.8	0.8	0.8
U-value doors	0.65	0.75	0.8	0.75	0.8	0.8	0.8
U-value ground floor	0.07	0.08	0.1	0.11	0.12	0.13	0.05 - 0.10
U-value outer roof	0.1	0.0	0.1	0.09	0.08	0.10 - 0.12	0.08 - 0.10
Thermal bridges	0.03	0.03	0.03	0.03	0.02	< 0.02	< 0.02
Renewable electrical supply systems							
PV panels	69 m^2 η = 15.5% 22.75 kW_p	150 m^2 η = 15.5 % 22.75 kW_p	79 m^2 η = 15.8 % 12.48 kW_p	675 m^2 η = 15.4% 22.75 kW_p	1556 m^2 η = 20.4 % 312 kW_p	None	1937 m^2 η = 21.2% 375.4 kW_p
CHP	None	None	None	None	None	40 kW el	Ca. 50 kW el
Renewable thermal supply systems							
Solar thermal collectors	11.5 m^2	16.8 m^2	4.2 m^2	28.7 m^2	None	None	None
Heat pump	Air-to-water 7 kW	Geothermal 3 kW	Geothermal 3 kW	Geothermal 38 kW	Geothermal 2 x 64 kW	None	Geothermal Ca. 180 kW
CHP	None	None	None	None	None	100 kW heat	Ca. 80 kW heat

Ventilation and air conditioning							
Type	Mechanical mixing	Mechanical mixing	Hybrid mixing	Mechanical mixing	Mechanical displacement	Hybrid mixing	Mechanical mixing and displacement
Annual average temperature efficiency (sensible heat)	85 %	87 %	85 %	86 %	70 – 75 %	85 %	93 %

* The ZEB ambition level is not necessarily achieved, but represents level of documentation for that building.

** Covers GHG emissions associated with operational energy and only 20% of GHG emissions from materials (A1-A3, B4) and transport (A4).

5. Results

The embodied GHG emission results are summarised in Table 3 according to NS 3451 table of building elements and EN 15978 life cycle modules [45, 50].

Table 3. Summary of the GHG emissions results for the ZEB concept and pilot building case studies.

	SFH concept	Multi-komfort house	Living Laboratory	Office concept	Powerhouse Kjørbo	Campus Evenstad	Heimdal high school
References	[28]	[32]	[26]	[35]	[37]	[40]	[12]
GHG emissions per building element ($kgCO_{2eq}/m^2/yr$)							
21 Groundwork and foundations	1.47	0.69	1.05	0.57	0	0.76	0.33
22 Load-bearing structure	0.14	0.16	0.65	0.41	0.04	0.24	1.79
23 Outer walls	1.32	1.09	3.47	1.55	1.35	1.06	0.59
24 Inner walls	0.37	0.53	0.42	1.25	1.31	1.23	2.23
25 Floor structure	0.38	0.61	0.77	1.83	0.89	1.09	1.78
26 Outer roof	0.43	0.23	5.54	0.07	0.47	1.63	0.80
27 Fixed inventory	-	-	0.43	-	-	0.003	-
28 Stairs and balcony	0.00	0.03	3.07	0.03	0.03	0.28	-
29 Building, other	0.65	-	-	-	-	-	-
31 Sanitary	-	-	0.03	-	-	0.12	-
32 Heating	-	-	0.71	-	-	0.09	-
36 Ventilation and air conditioning	0.05	0.20	0.10	0.43	0.26	0.19	1.21
39 Appliances	-	-	1.92	-	-	-	-
43 low voltage supply	-	0.15	-	0.12	0.11	-	-
44 Lighting	-	-	0.004	-	-	1.26	-
49 Electric other (PV)	2.15	1.78	5.33	2.04	2.11	0.00	0.98
62 Person and goods transport	-	-	-	-	0.01	0.90	0.04
69 Other installations (STC)	0.23	0.50	-	0.06	-	-	-
Electric car	-	1.60	-	-	-	-	-
GHG emissions per life cycle module ($kgCO_{2eq}/m^2/yr$)							
A1-A3	5.25	4.34	12.11	6.33	3.77	6.41	6.97
A4	-	0.23	2.02	-	0.02	0.30	0.23
A5	-	-	1.21	-	0.23	1.53	-
B4	1.95	1.68	9.16	2.12	1.82	1.95	2.69
B6	5.05	4.6	-	4.35	2.85	1.62	3.58

C1	-	-	-	-	0.23	-	-
C2	-	-	-	-	0.06	-	-
C3	-	-	-	-	0.02	-	-
C4	-	-	-	-	0.43	-	-
D	-9.21	-12.5	-15.4	-4.34	-5.82	-22.9	-3.56
Total GHG emissions (A1-C4) ($kgCO_{2eq}/m^2/yr$)	12.25	10.85	24.5	12.80	9.43	10.48	13.47
Emission data source	Design phase	Design phase	As built phase	Design phase	As built phase	As built phase	Design phase

The results show that the scope of embodied GHG emission results reported varies between case studies, dependent on the level of detail recorded in the life cycle inventory and the ZEB ambition level set. For example, the SFH concept study has a ZEB-OM ambition level, and therefore only reports embodied emissions from life cycle modules A1-A3, B4 and B6; whilst Campus Evenstad has a ZEB-COM ambition level and reports embodied emissions from life cycle modules A1-A5, B4 and B6. Because Powerhouse Kjørbo is a renovation project, the entire life cycle has been reported. Similarly, all case studies have a minimum of building elements reported (21, 22, 23, 24, 25, 26, 36 and 49). However, some case studies include other building element components relevant to that case. For example, Powerhouse Kjørbo, Campus Evenstad and Heimdal high school include emissions from lifts (62 person and goods transport), whilst Multikomfort house includes emissions from running the family's electric car.

It should be noted that the life cycle embodied emission calculations have been carried out parallel to the development of the ZEB methodology, and by various LCA specialists. Therefore, the placement of emissions according to NS 3451 table of building elements experiences some deviation. For example, embodied emissions for solar thermal collectors are placed under '69 other installations' for the two concept studies and Multikomfort house, but under '49 electric other' in the Living Laboratory.

5.1. Embodied GHG emissions per life cycle module

The life cycle embodied GHG emission results for each case study are summarised in Figure 3. The results show that the largest contributor to high embodied emissions across the ZEB case studies is material emissions (M) from the production and replacement phases (A1-A3 and B4) contributing approximately 55-87% to total GHG emissions, the operational phase (O or B6) contributes approximately 14-42%, the construction phase (C or A4-A5) contributes approximately 2-15%, whilst the end-of-life phase (E or C1-C4) contributes approximately 8% to total GHG emissions. This shows that embodied emissions associated with the production and replacement of materials is the main contributor to total life cycle GHG emissions across the Norwegian ZEB case studies.

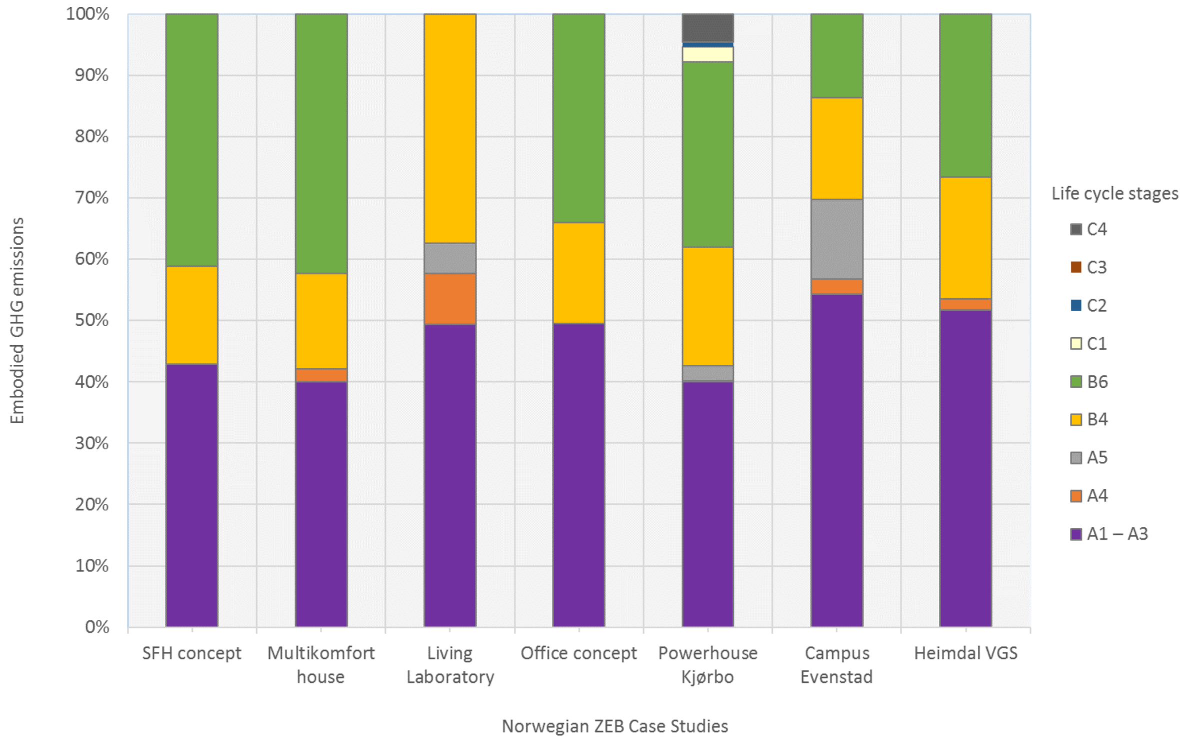


Figure 3. Embodied GHG emission results per life cycle module for each ZEB case study.

In the ZEB concept studies and most of the pilot buildings, the construction phase (A4 - A5) is either neglected (SFH, office, Multikomfort house and Heimdal high scool) or calculated based on assumptions (Living Laboratory and Powerhouse Kjørbo). However, the construction phase emission results from Campus Evenstad are based on real data collected from the construction site, and show that embodied construction emissions (1.5 $kgCO_{2eq}/m^2/yr$) are similar to operational energy use emissions (1.6 $kgCO_{2eq}/m^2/yr$) [40].

5.2. Embodied GHG emissions per building element

The building element GHG emission results are summarised in Figure 4, the dotted line indicates the proportion of embodied GHG emissions that belong to the building envelope. The results show that the largest contributor to high embodied emissions across the ZEB case studies is the building envelope, contributing on average 65% to total GHG emissions. Of these emissions, approximately 13% originate from the groundwork and foundations, 7% from the load-bearing structure, 26% from the outer walls, 19% from the inner walls, 19% from the floor structure and 16% from the outer roof. The second largest contributor to GHG emissions is '49 Electric other' which covers the PV systems, and contributes on average 20% to total GHG emissions. This is followed by the building services (sanitary, heating, cooling and ventilation) contributing on average 9% to total GHG emissions.

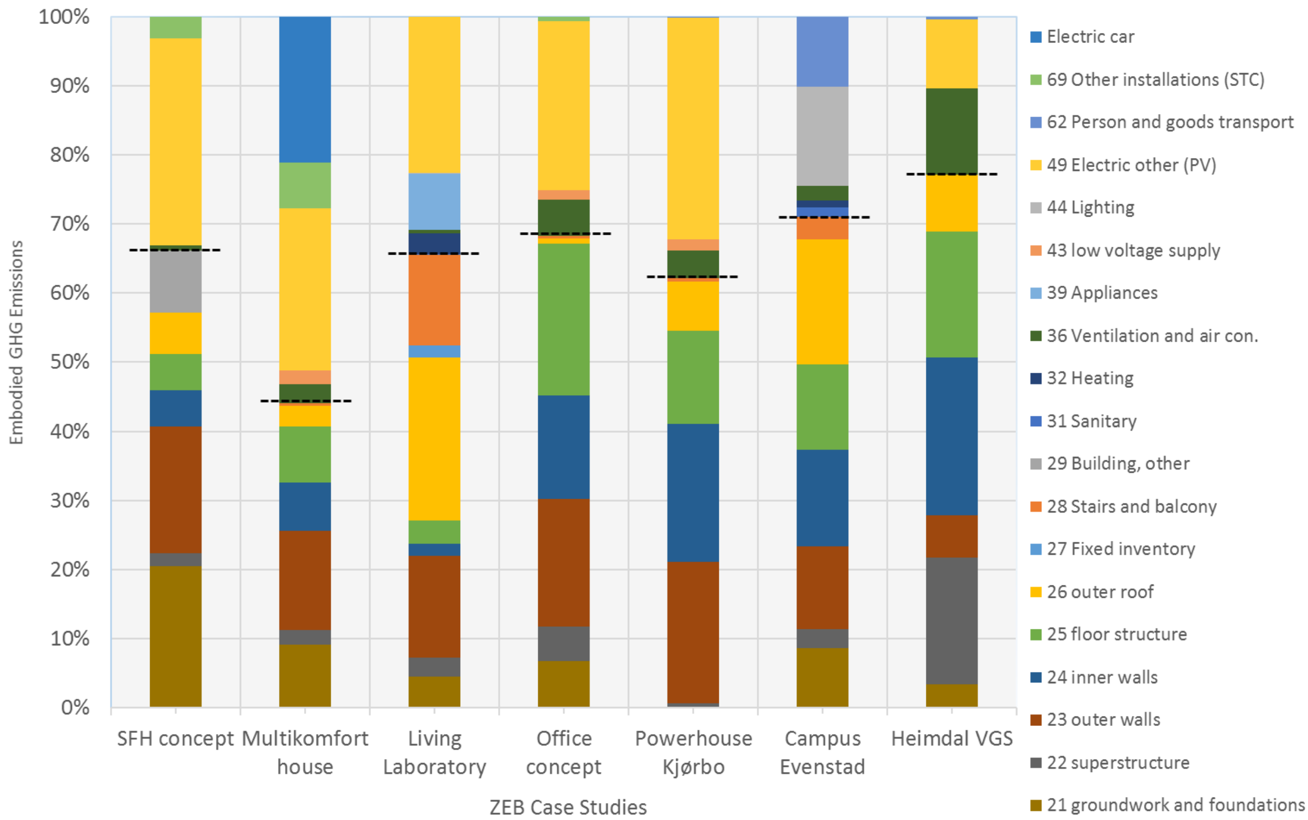


Figure 4. GHG emission results per building element for the ZEB case studies.

6. Discussion

This article presents and evaluates the calculation methodology and embodied GHG emission results of the Norwegian ZEB case studies to extract design drivers and lessons learnt. The results show the building envelope (ca. 65%) and production and replacement of materials (ca. 55-87%) are the main contributors to total GHG emissions across the Norwegian ZEB case studies. The results from Campus Evenstad highlight the significance of construction phase emissions in ZEBs, compared to emissions from operational energy use. Emissions from operational energy use in Campus Evenstad have been optimised and reduced through using a bio-based combined heat and power unit onsite. In contrast, the construction phase emissions utilise a high degree of fossil fuels through the combustion of diesel in construction machinery. In addition, the construction phase emissions occur during a short space of time (1 year), at the beginning of the building's life span; compared to operational energy use emissions which take place over a 60-year period. Since these operational energy use emissions occur over the lifetime of the building, and since the ZEB emission factor for electricity considers existing climate change mitigation targets and the decarbonisation of the electricity grid, the results show a depreciation in embodied operational energy use emissions averaged over time [58]. Therefore, detailed construction phase emission calculations have similar emissions to operational energy use in Campus Evenstad. Given the high concentration of emissions from the production, construction and replacement of building materials across the ZEB case studies, embodied emission reduction measures in ZEBs should focus on material use in the early design and construction phases to reach GHG mitigation goals of the near future.

6.1. Calculation methodology

This body of work is based on a quantitative and qualitative assessment of the calculation methodology and embodied GHG emission results of the Norwegian ZEB case studies. This method of assessment was chosen because of the vast differences in building typology, size, material, technology, construction method, location, and different strategies used to accomplish ZEB targets between the ZEB case studies, which has made it difficult to compare the ZEB case studies. The results have not been empirically harmonised, but they all follow the ZEB GHG calculation methodology. Although each case study follows the ZEB GHG calculation methodology, different LCA practitioners have carried out the calculations with varying system boundaries and data sources. This is partly because the ZEB research centre continuously revised the Norwegian ZEB definition guideline and calculation methodology according to relevant national and international frameworks, and experiences gained from the ZEB pilot projects. This means that there have been methodological improvements running parallel to the development of the ZEB pilot projects, which has in turn been challenging for the various stakeholders involved in the ZEB pilot projects. For example, the modularity principles defined in EN 15978 were adopted and used in defining the system boundaries of the different ZEB ambition levels, as previously demonstrated in Figure 2. This includes the exclusion of emissions relating to the transportation of construction workers in life cycle module A5 [18, 21]. However, a forthcoming Norwegian standard, prNS 3720, which describes a method for GHG emission calculations for buildings [23] includes emissions from the transportation of construction workers in life cycle module A5, and a new life cycle module (B8) for the transportation of people during the use phase. Thus, the transport of construction workers in life cycle module A5 was included in the system boundary for Campus Evenstad, and the inclusion of life cycle module B8 is being considered for the definition guideline currently being developed for the research centre on zero emission neighbourhoods (ZEN) in smart cities.

It is thought that the current scope of embodied GHG emission calculations used in the ZEB research centre is a good starting point for embodied GHG emission calculations in ZEN; however, the ambition levels and system boundaries should be revised to incorporate transport and infrastructure. This could be achieved by expanding the scope of NS 3451 table of building elements to include the outdoor nomenclature (e.g. 71 adapted terrain, 72 outdoor construction, 73 outdoor heating, ventilation and sanitation, 74 outdoor electric power, 75 outdoor telecommunications and automation, 76 roads and courtyards, 77 parks and gardens, 78 outdoor infrastructure and 79 other outdoor), and for the scope of life cycle modules to include the transport of construction workers in life cycle module A5, and the proposed life cycle module B8 for transport of people during the use phase. It would also be useful to encourage inclusion of the whole life cycle in the calculation methodology as a minimum requirement for the ZEN research centre, to avoid omissions or problem shifting of emissions. It may also be useful to include multiple iterations of GHG emission calculations (e.g. reference, design, as built, and in use phase calculations) to clearly document emission reduction savings during the design and construction processes. This is an emission reduction strategy that became apparent towards the end of the ZEB research centre, and has been adopted in the Norwegian FutureBuilt project. Futurebuilt is a ten-year programme (2010-2020) with a vision of developing carbon neutral urban areas and high-quality architecture [59]. The aim is to complete 50 pilot projects – urban areas as well as individual buildings – with the lowest possible greenhouse gas emissions [59]. This is achieved by freely documenting embodied GHG emissions from the pilot projects; against a reference building, at the design phase, at the as built phase, and during the use phase. This is accomplished by using the Norwegian GHG emission calculation tool klimagassregnskap.no [60].

Although each case study follows the ZEB research centre's GHG calculation methodology, different LCA practitioners have carried out the calculations with varying system boundaries and data sources. This is partly because of a lack of communication between LCA experts when it came to interpreting the Norwegian standard NS 3451 table of building elements as a system boundary. The standard provides a clear overview and description of the different parts of a building. However, the standard is subject to a certain degree of interpretation. For example, the floor structure in the Living Laboratory was placed under three different categories; the load-bearing trusses were placed under '22 superstructure', the floor build-up was placed under '25 floor structure', and the under-floor heating system was placed under '32 heating'. In contrast, the entire floor construction in the SFH concept study was placed under '21 groundwork and foundations' because a raft foundation was used. Thus, it is difficult to directly compare emissions arising from these two floor constructions on the building element level. Similarly, there has been uncertainty between LCA practitioners on where to place energy generation technologies in the table of building elements, especially when these technologies are integrated into the fabric of the building. For example, embodied material emissions for building integrated solar thermal collectors are placed under '69 other installations' for the two concept studies and Multikomfort house, but under '49 electric other' in the Living Laboratory. Thus, there is a high degree of assumption and uncertainty when comparing emission results per building element. In the future, it is recommended to include clear descriptions of what is included under each building part in emission calculations. It could also be useful to finetune the GHG calculation methodology by standardising system boundaries at the building element level, including a clear reporting format, and quality assuring results for case studies via an independent verifier.

Focusing on global warming potential (GWP) as an environmental indicator has the benefit of reducing complexity for decision makers, and more often than not correlates with other environmental impacts [41]. However, it also risks ignoring important environmental impacts that do not correlate with GWP, such as; toxicity, resource use, and resource depletion [1, 52]. Focusing on only one environmental indicator can potentially lead to problem shifting to other impact categories. Biogenic carbon and carbonation of concrete are other topics which are not covered properly by the ZEB calculation methodology. Biogenic carbon is largely excluded from the ZEB case studies, since none of the assessments have a ZEB-COME or ZEB-COMPLETE ambition level, that consider the whole life cycle of a building. Similarly, the carbonation of concrete was not considered in the ZEB calculation methodology. Incorporating the carbonation of concrete in calculations, can help reduce embodied GHG emission impacts arising from concrete. It is believed that both biogenic carbon and the carbonation of concrete are aspects that need to be addressed in the future definition guideline for GHG emissions calculations in ZEN.

One of the main challenges in completing GHG emission calculations for the ZEB pilot projects lies in data management, including data collection, data sources and data quality. It is anticipated that this aspect will only grow in complexity when expanding the focus from ZEBs to ZENs. In terms of data collection, it was deemed laborious and time consuming to collect a detailed material inventory. The LCA practitioner often had to contact various stakeholders at different times during the design and construction process to obtain the most up-to-date building detail, material quantity, material properties, emission data and scenario information. In terms of data quality and sources, Norwegian EPDs were the main source of information used in embodied emission calculations. When EPDs were lacking, generic emission factors from Ecoinvent were used. EPDs are generally considered a good source of specific emission data, however, during the early design phase of a building, there is limited detailed information available about the exact products being used in a building. In recent years, the availability of EPD documentation for Norwegian building products has dramatically increased. In the embodied GHG emission calculations for Campus Evenstad, 94.5 % of all building materials (based on weight) had specific EPD documentation, whilst 5.5 % of all building materials (based on weight) used generic data from the Ecoinvent database. In contrast, the embodied GHG emission calculations for the Living Laboratory relied on generic data from the Ecoinvent database. A sensitivity analysis showed that emissions could be reduced by up to 20%, if this generic European data was replaced with specific data from Norwegian EPDs [61]. The results from a sensitivity analysis of the SFH concept study showed similar results, with a 20% reduction in emissions, when product specific data from Norwegian EPDs was used in place of generic data from Ecoinvent for four core building materials [31, 62]. Therefore, using EPDs for specific products in the early design phase, may result in underestimating actual emissions from a building, unless the exact product to be used is already known. In the future, data collection, data sources and data quality could be improved by standardising the data management process in the ZEB calculation methodology, and by performing sensitivity analyses and uncertainty simulations on some of the core building materials or processes. Embodied GHG emission calculations can thus be simplified through standardising some of these input variables. This can be achieved by ascertaining normative or reference values for standard types of construction; based on national building codes, SINTEF's design guidelines and previous project experiences.

In some ways, the results from this article reflect reality, as large amounts of data are being processed by different stakeholders, and data will invariably vary from project to project because of time and regional conditions. Nevertheless, it is not uncommon for construction professionals to reuse data and experiences from previous projects to inform the design and construction decisions of new, future projects. This process can save on time, cost and effort; on tasks, which may otherwise be deemed too time-consuming or complex.

6.2. Reference buildings

The two concept studies were originally used as a learning curve to investigate and analyse energy and emission reduction possibilities [25]. The technological solutions considered in these studies are used as a reference for the other ZEB pilot buildings. Similarly, it is believed that developing a ZEN virtual model for different building typologies, following the lessons learnt from ZEBs, may be a useful starting point in the new ZEN research centre. This ZEN virtual model could contain a range of building typologies and infrastructure typical of a Norwegian neighbourhood. Such a model could provide a reference point for benchmarking embodied GHG emissions and energy reduction strategies. Furthermore, including parametric LCA of a reference building or neighbourhood may also enable the simultaneous evaluation of different emission reduction measures in terms of other factors such as cost, soundproofing, fire safety or construction time. This synergetic approach may help speed up decisions in the design process, and aid designers in selecting optimal design solutions. For example, in both Campus Evenstad and Heimdal high school, material choices were compared in the design phase to optimise the building envelope in terms of both embodied GHG emissions and cost effectiveness.

6.3. Integrating design for low embodied GHG emissions into the design process

Experiences from the ZEB research centre have highlighted the importance of cross-disciplinary teamwork between stakeholders, and the need for clear communication to break down barriers between different fields of expertise, as well as to share knowledge efficiently through careful planning, management and follow-up [11, 12]. As highlighted by Rønning & Brekke, 'LCA is mostly used for documenting the consequences of already established choices and decisions or completed construction projects, and are to a lesser extent used as a planning tool for simulation of consequences of different choices in various phases of the construction process or throughout the lifetime of a building' [1]. However, the ZEB research centre has endeavoured to integrate low embodied emission design strategies, as a planning tool, into the design process of ZEBs. Heimdal high school is a good example of this, whereby different stakeholders are involved in the early design phase to minimise embodied GHG emissions relating to material choices. Competition design teams were required to document measures taken for emission reductions, and state the reasons behind their material choices. However, knowledge on LCA varied considerably between the competition design teams. Therefore, a series of team workshops on LCA and EPDs helped train construction professionals on designing ZEBs with low embodied emissions from building materials. The results suggest that a stepwise approach may be suitable for reducing embodied GHG emissions in ZEBs, and demonstrate that embodied GHG emissions should be considered from an early design phase, and integrated into the design and construction process to reduce overall embodied GHG emissions. It also highlights the importance of guidance and quality assurance during the GHG emission calculation process.

7. Conclusions

This article set out 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 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 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 ZEBs, and provides some practical indications for embodied GHG emission calculations and reduction strategies in future ZEB and ZEN projects.

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