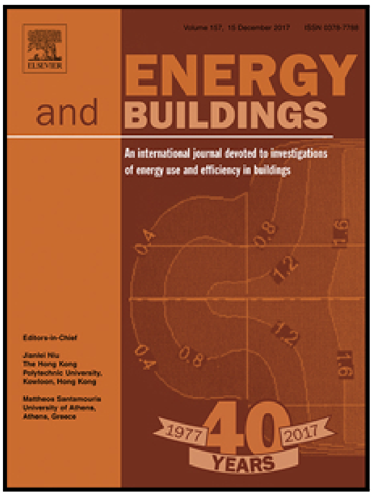

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Is a net life cycle balance for energy and materials achievable for a zero emission single-family building in Norway?

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Abstract

In this study, the objective is to redesign a previous concept for a single-family Zero greenhouse gas Emission Building (ZEB). The concept is redesigned based on comparing greenhouse gas (GHG) emission loads and compensation from different design solutions applied in Norwegian single-family ZEB pilot buildings and selected sensitivity studies. The objective is to see if a previously developed ZEB model (2011) can be redesigned to achieve a life cycle energy and material emission balance (ZEB-OM), which previously was not achieved. Five different design parameters are evaluated: area efficiency, embodied emissions in the envelope, insulation thickness, heating systems and different roof forms with respect to the photovoltaic area. Embodied emissions reductions were possible in the ground foundation, from around 1 kg CO_2/m^2 to 0.6 kg CO_2/m^2 per year. Both models are able to compensate for all operational emissions. The new model is in addition able to compensate for 60% of embodied emissions, whereas the previous model only could compensate for 5%. The new model does not reach the life cycle energy and material balance. The paper presents and discusses different approaches for achieving the ZEB-OM balance. Further concept model optimization is needed.

Keywords: Embodied emissions, life cycle, residential, single-family, zero emission buildings, case studies, pilot buildings

1. Introduction

The primary objective of the development of zero energy/emission buildings is to reduce energy consumption and increase renewable energy production to reduce emissions of greenhouse gases (GHG). Zero energy buildings can be defined in different ways, which can have a significant effect on how they are designed (Torcellini et al., 2006). According to the European Parliament (2010) all new buildings within the European Union should be nearly Zero Energy Buildings by the end of 2020. Usually when referring to Zero Energy Buildings, one is referring to an energy efficient building that produces enough on site renewable energy to cover its own demand on an annually averaged basis (Sartori et al., 2012; Peterson et al., 2015). The balancing indicator is usually primary energy (fossil, or fossil and renewable) measured in kilo Watt hours (kWh) or Mega Joules (MJ) (Voss and Musall, 2011). However, the balancing indicator can also be, for example, GHG equivalents, CO_2eq, as is the case in this paper. Thus, here a ZEB refers to a Zero *Emission* Building (ZEB), with respect to GHG equivalents (Dokka et al., 2013b; Georges et al., 2015). Some authors, such as Hui (2010) and Pan (2014), also refer to Zero Carbon Buildings.

Most definitions of Zero Energy Buildings focus on the balancing of operational energy or emissions. However, embodied energy has been included in some definitions, e.g. by Hernandez and Kenny (2010) and Cellura et al. (2014). Also, Lützkendorf et al. (2015) stress the importance of including embodied impacts when developing ZEBs. The balancing period for a Zero Energy Building is usually one year, however, it can be the entire estimated life cycle, e.g. 50 or 60 years, or a monthly or seasonal balance (Marszal et al., 2011).

The focus in this paper is the life cycle energy and material balance, referred to as the ZEB-OM balance; where 'O' stands for Operation and 'M' for materials as defined by Dokka et al. (2013b) and Kristjansdottir et al. (2014). A Norwegian single-family ZEB-OM building concept was developed by an interdisciplinary group of researchers in 2011–2012 (Dokka et al., 2013a). The goal was to create a theoretical concept model for a single-family ZEB based on currently available technology for the Oslo climate. The ZEB-OM emission balance was not reached.

Since the initial model was designed, three single-family ZEB pilot buildings have been built in Norway (2014–2015), two of them aiming for the

ZEB-OM ambition (Hestnes and Eik-Nes, 2017). Their life cycle emissions have been documented by Inman and Houlihan-Wiberg (2015) and Kristjansdottir et al. (2017). In addition, sensitivity studies have been carried out to study their design and data inputs (Good et al., 2015; Felius and Houlihan-Wiberg, 2014; Houlihan-Wiberg et al., 2015). The goal of the ZEB pilot buildings has been to realize life cycle Zero Emission Homes in Norway and carry out research to find solutions to reduce GHG emissions.

In order to redesign the initial ZEB-OM model, it is necessary to analyze the lessons learned from the ZEB pilot buildings and respective sensitivity studies. The scope of the study is limited to the lessons learned from Norwegian ZEB case studies. The approach is to apply a simplified Life Cycle Assessment (LCA) (ISO, 2006) to compare GHG emissions from a selection of the different design solutions. The research questions are: Can the initial concept be improved? and: Can the ZEB-OM balance be reached?

1.1. Related studies

The relevance of applying life cycle assessments to assess buildings' environmental performance, especially to understand the relations between embodied and operational energy, have been stressed by Beccali et al. (2013) and Cellura et al. (2014). Several studies show that the relative and absolute embodied impacts are higher for low energy and Zero Energy/Emission Buildings (Berggren et al., 2013; Hestnes and Eik-Nes, 2017; Chastas et al., 2016; Cellura et al., 2014; Kristjansdottir et al., 2017; Houlihan-Wiberg et al., 2014; Blengini and Di Carlo, 2010; Goggins et al., 2016; Cabeza et al., 2014; Chau et al., 2015). However, the extra embodied impacts usually pay off during the operational stage (Verbeeck and Hens, 2010; Dahlstrøm et al., 2012; Berggren et al., 2013).

Many tools and guidelines have been developed to assess embodied impacts of buildings as presented, for example, by Wittstock et al. (2011) and Basbagill et al. (2013). Further, it is clear that the general issue of including and reducing embodied impacts when assessing building performance is getting increased attention (Birgisdottir et al., 2017). Thormark (2006) stressed the general importance of paying attention to the choice of building materials and their recycling possibilities when aiming to reduce life cycle energy use of buildings. Also, Gustavsson and Joelsson (2010) concluded that CO_2 emissions from production are lower for wood-framed constructions, compared to concrete-framed constructions for residential buildings.

Life cycle studies of single-family buildings in Norway have been performed by Dahlstrøm et al. (2012); Ghose (2012); Inman and Houlihan-Wiberg (2015); Houlihan-Wiberg et al. (2014) and Kristjansdottir et al.

(2017). Dahlstrøm et al. (2012) found the life cycle cumulative energy demand for a single-family passive house to be 24-38% lower than a reference building built according to Norwegian regulations from 2010 (TEK10). Ghose (2012) and Dahlstrøm et al. (2012) found the ground work and foundation, walls, and the roof constructions to be the main embodied emissions drivers. According to Wiik et al. (2018) around 20% of embodied emissions in Norwegian Zero Emission Buildings are from the photovoltaic system, and around 65% is due to the building envelope.

Few studies have investigated how to reduce embodied impacts in Zero Energy/Emission Buildings. Himpe et al. (2013) showed that embodied energy could be reduced by 30% when moving from a masonry structure to a timber structure for a life cycle zero energy single-family house in Belgium. Goggins et al. (2016) found that by replacing a hollow core concrete structure with a suspended timber floor for the first floor in a semi-detached nearly zero energy dwelling in Ireland, a significant reduction in the embodied impacts could be made. Selvig et al. (2017) documented and compared measures for reducing embodied impacts, for example by using recycled materials, timber and low carbon concrete, for a Norwegian educational and administration building, aiming for the ZEB-OM balance.

1.2. The Norwegian context

No official national standards have quantitative demands for reductions of embodied energy or emissions in contrast to operational energy demands (DIBK, 2010). Around 50% of Norwegian residential buildings are single-family houses and 5000–7000 of such new houses are newly built every year (Statistics Norway, 2014, 2017b). The average heated floor area has been around 200 m^2 for new single-family buildings in the years 2000 to 2016 (Statistics Norway, 2017b). Bernhard and Jörgensen (2007) found that the production of building materials were responsible for around 7% of the total national emissions. Further studies are needed to improve the data on national emissions from material use in buildings.

2. Materials and methods

The method applied is to redesign the previous ZEB-OM model, developed by Houlihan-Wiberg et al. (2014) and Dokka et al. (2013a), and see if the ZEB-OM balance can be achieved for a single-family building within the Norwegian context. The new ZEB model should be suitable for a family of four in the Oslo climate, which has been selected as representative of the majority of the Norwegian buildings (Statistics Norway, 2017a). An attributional, process-based life cycle assessment is applied (EC, 2010). The life cycle boundary includes the product and operational stages as defined for the ZEB-OM balance (Fufa et al., 2016). The construction process stage and end of life stages are omitted. In many previous life cycle assessments of buildings (Dahlstrøm et al., 2012; Ghose, 2012; Cabeza et al., 2014; John, 2013), the construction and end of life stages were found not to have been as significant as the product and use stages. The functional unit is one square meter of heated floor area over a service lifetime of 60 years (Hestnes and Eik-Nes, 2017; NS 3940:2012, 2012). Embodied and operational emissions are quantified using the indicator for global warming potential (GWP), and the emissions of GHG are measured in CO_2 equivalents with the 100 year perspective (IPCC, 2013). The background life cycle inventory database is ecoinvent v3.2, using the cut-off allocation (Wernet et al., 2016).

The concept models and Norwegian pilot projects selected as a basis for comparison and the redesigned of the new model are given in Table 1 the cases are based on (Hestnes and Eik-Nes, 2017; Dokka et al., 2015; Thyholt et al., 2012; Goia et al., 2015; Kristjansdottir et al., 2017; Houlihan-Wiberg et al., 2014; Felius and Houlihan-Wiberg, 2014; Dokka et al., 2013a; Qvistgaard, 2014; Inman and Houlihan-Wiberg, 2015).

Table 1: ZEB cases

Case name	Heated floor area [m^2]	ZEB-ambition	Stories
ZEB1: ZEB concept	160	ZEB-OM	Two
ZEB2: ZEB concept (adjusted size)	120	ZEB-OM	Two
ZEB3: ZEB concept (adjusted size and roof)	120	ZEB-OM	Two
ZEB4: Multikomfort	202	ZEB-OM	Two
ZEB5: Living Laboratory	102	ZEB-OM	One
ZEB6: Skarpnes	154	ZEB-O	Two

The cases, ZEB1-ZEB6 are further described in Appendix A. Background information on the initial ZEB-OM model, ZEB1, is listed in Table 2.

2.1. ZEB balance applied

The ZEB balance in this study is simplified and follows a symmetric weighting approach based on Sartori et al. (2012) and Dokka et al. (2013b). This means that the same CO_2 equivalent factor is used for both import and

Table 2: Background information on ZEB1

Description	Value
Location	Oslo, Norway, 59.9N., 10.75E.
Temperature annual average	6.3°C
Heated floor area	160 m^2
U-value external wall	0.12W/m^2K
U-value roof	0.1 W/m^2K
U-value ground floor	0.07 W/m^2K
Ground floor	Concrete slab on ground, 100 mm
Ground floor insulation	Extruded polystyrene, 500 mm
Roof construction	Flat roof
Volume	420 m^3
Type of PV module	mono-Si
Thermal supply system	Air Source Heat Pump, with solar collectors
Window area	36 m^2

export of electricity to and from the building. Also, only electricity has been the energy carrier that has been imported/exported; thus, the balance can be referred to as "all electric". Energy storage, for example with batteries for the photovoltaic systems, is not considered. Despite that the emission reductions due to the export of electricity from the photovoltaic system occur outside the physical boundary of the building, they are included in the balance calculations.

The ZEB-OM balance applied is given in Equation 1 based on Georges et al. (2015).

$$\Delta CO2 = CO2_{pm} + CO2_{rm} + ZEB_{el} * (Q_u - Q_p) \tag{1}$$

In Equation 1,

- $CO2_{pm}$ is the annualized embodied emissions in the product stage, kg CO_2eq/m^2 per year
- $CO2_{rm}$ is the annualized embodied emissions of replacements, kg CO_2eq/m^2 per year
- Q_u is the annual electricity used in the building, kWh/m^2 (lighting, household appliances, ventilation fans, pumps, operation of heat supply system)

- Q_p is the annually averaged electricity produced by the PV system, kWh/m^2
- ZEB_{el} is the annually averaged CO_2eq emission factor for electricity, 132 g CO_2eq/kWh

The term $CO2_{pm}$ refers to the product stage of the materials, that is defined as raw material extraction (A1), transport to manufacturing (A2) and manufacturing (A3) by EN 15978:2011 BS (2011). The term $CO2_{rm}$ refers to the replacements (B4) in the use stage of the building as defined in EN 15978:2011 BS (2011). A simplified interpretation of EN 15978:2011 BS (2011) has been applied, where, for example, waste treatment and transport to the building site for the replaced materials is not modeled (Fufa et al., 2016). The factor ZEB_{el}, has been applied as a dimensioning factor in the Norwegian ZEB pilot and concept buildings (Dokka et al., 2013b; Georges et al., 2015). It is modeled to correspond to the average CO_2eq for electricity in Europe from 2010 to 2055 and assumes a massive de-carbonization of the grid during this period of time (Graabak et al., 2014).

2.2. Boundaries, fixed and included parameters

The following is included for the embodied emissions of construction materials: the roof, external and internal walls, ground foundation, floors, doors and windows. For the technical installations emissions from the ventilation system, hot water tanks, and thermal and electric energy supply systems are included. Emissions that occur outside the building, e.g. garages, verandas and parking spaces are not included. However, for the heating system, a bore hole heat exchanger is included.

Annual electricity use required for artificial lighting and household appliances are based on the current Norwegian standard (SN/TS 3031:2016, 2016): 11.4 kWh/m^2 and 17.5 kWh/m^2 per year. Electricity for ventilation fans and pumps for the previous model are according to Dokka et al. (2013a) 3 kWh/m^2 year. The mechanical ventilation system from the previous ZEB model is unchanged from Houlihan-Wiberg et al. (2014): specific fan power is 1.0 kW/(m^3/s), heat recovery rate 85%, air flow rate 1.2 m^3/hm^2, no cooling effect, and inlet air temperature of 19 °C. Also, the air leakage rate (0.5 1/h at n50) and thermal bridge values (0.03 W/m^{2}K) are the same as for the previous model. Humidity control is not included.

2.3. Area and floor plan

The floor area should be an area efficient and viable option for a family of four in the Norwegian single-family house market. Kristjansdottir et al.

(2017) found that the smallest of the ZEBs, ZEB5, with a heated floor area of 102 m^2 had the corresponding lowest total GHG emissions. However, since Norwegian single-family houses on average have an area of around 200 m^2, 102 m^2 is assumed to be too small. Felius and Houlihan-Wiberg (2014) investigated different ways of improving the original ZEB residential concept model and created a new model (referred to as ZEB2 and ZEB3) with reduced floor area from 160 to 120 m^2. The suggested size of 120 m^2 is assumed to be a more realistic option than 102 m^2. The floor plans were also revised resulting in a new heated floor area of 60 m^2 per story based on Felius and Houlihan-Wiberg (2014) (117 m^2 net floor area (NS 3940:2012, 2012)). These changes are adopted to the new ZEB model.

2.4. Embodied emissions

All the ZEB pilots are lightweight timber constructions, which is popular for Norwegian single-family houses. However, both ZEB4 and the ZEB5 have a superstructure of glue laminated timber, while the others are built with regular construction timber. The embodied emission data in this study is based on Kristjansdottir et al. (2017), where a comparative emission analyses of the ZEB buildings was presented. The material inventories for all the cases are provided as supplementary material.

PV systems are assumed to have a 30 year service life, thus, it is assumed they are replaced once over the 60 year service lifetime of the building. Replacements are assumed to have 50% of the initial embodied emission load. The assumption is based on learning effects in the manufacturing of PV modules (Fthenakis et al., 2011; Frischknecht et al., 2015). Service lifetimes of construction materials are 60 years, however for surface outer coverings, for example, roofs tiles and floor material, it is 30 years. Also, windows and doors are assumed to have a 30 year service lifetime.

A comparison between the embodied emissions of the ZEB1 model and the ZEB pilots is shown in Figure 1. From the figure, it can be seen that the embodied emissions vary somewhat between the cases. The largest share of the product stage emissions is due to the PV systems and the ground floor and foundations. Even though ZEB1 does not have higher embodied emissions than the other ZEBs, there are differences between the different categories that deserve further attention. Where no changes are made to the new model, embodied emissions are based on ZEB1 and scaled per m^2 of heated floor area.

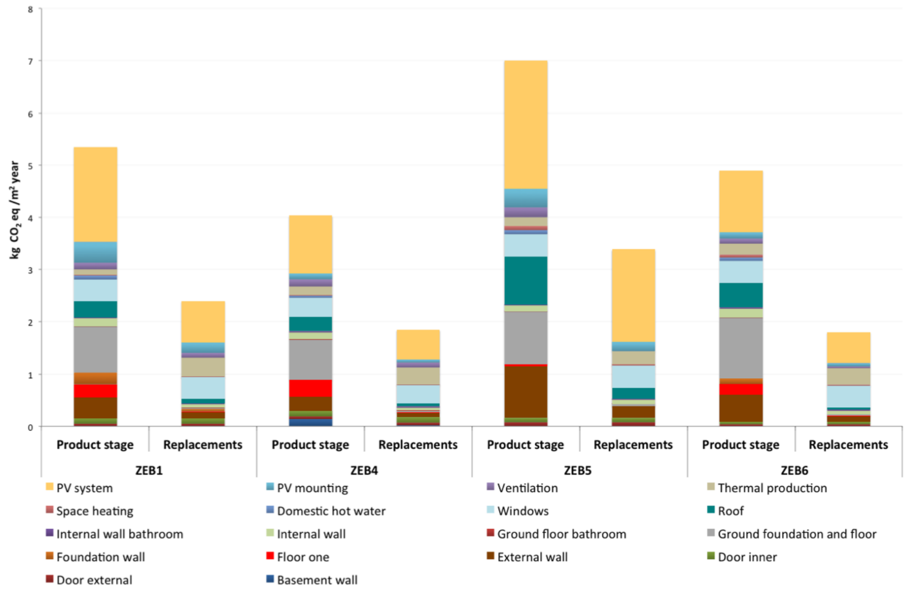

Figure 1: Embodied impacts from the four ZEB single-family cases per square meter of heated floor area (BRA) and year

2.4.1. Construction materials (CM)

A key aim for the new model is lowering the embodied emissions in construction materials. It is difficult to extract knowledge about the drivers for high emissions in the construction materials from Figure 1. Thus, embodied emissions in the roof, external wall and ground foundation are analyzed in more detail. The embodied emissions per square meter for these construction parts (1 m^2 of external wall area, 1 m^2 of roof area and 1 m^2 of ground foundation area) were compared. The service lifetime is assumed to be 60 years. The quantity of nails and screws (0.43 kg/m^2 chromium steel) and construction timber for the external wall constructions is based on Folvik et al. (2011). It is assumed that the technical standards for the bearing/load bearing, fire and sound resistance is the same between the cases. The insulation material quantities will be based on the findings in Section 2.2. The ground floor and foundation structure are similar for case ZEB4 and ZEB5, where a strip foundation of concrete has been used in combination with a timber construction. Both apply glass wool insulation as their main insulation material. For the ZEB6 and ZEB1 cases, there is a 80–100 mm thick concrete slab with either 300 or 500 mm of extruded polystyrene insulation lying underneath the concrete (Houlihan-Wiberg et al., 2014; Kristjansdottir et al., 2017). The concrete in ZEB1 was normal concrete, while the concrete in both ZEB6 and ZEB4 was low carbon concrete, based on low carbon cement where a larger fraction of the clinker is replaced with fly ash (Vold, 2013). The material inventories for the construction parts are given as supplementary material.

2.5. Roof form and PV system size

All the previous ZEBs have used a photovoltaic system to produce on-site renewable electricity. The previously applied systems however had different module areas, shapes, module types and mounting systems. The largest system was installed in ZEB4 (aiming for ZEB-OM) and had 150 m^2 of modules covering the whole roof. The smallest PV system, 40 m^2, was installed in the ZEB6, aiming for the ZEB-O ambition level. The design criteria for the PV system is based on the amount of both operational (Q$_u$ * ZEB$_{el}$) and embodied emissions ($CO2_{pm}$+$CO2_{rm}$) when considering ZEB-OM.

The aim was to find the roof form that maximizess the electricity production from the PV systems, Q$_p$, without a significant increase in embodied or operational emissions. The ZEB concept model had a flat roof, in contrast to the other ZEBs, which have titled roofs at different angles, as illustrated in Figure 2. The additional volume for the different roof designs are approximately: 135 m^3 for ZEB3, 75 m^3 for ZEB4, 27 m^3 for ZEB 5 and 60 m^3 for ZEB6.

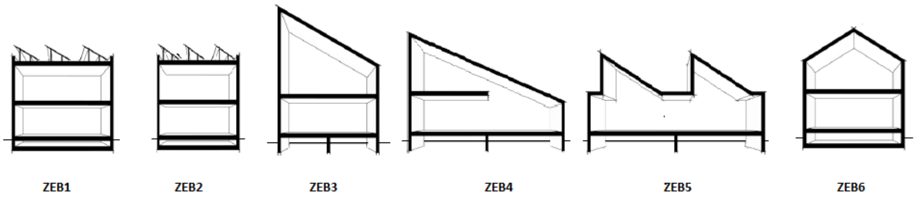

Figure 2: Illustration of the different roof forms for the ZEBs (figure made by Tuncer Muharrem Zorbey)

A flat roof will require a triangular mounting system for the PV to get the required tilt angle. A tilted roof can accommodate building integrated or building adapted PV systems, which can have the associated benefit of reduced need for roofing materials. Kristjansdottir et al. (2016) compared the embodied emissions from the different mounting systems installed in the three ZEB pilots, resulting in embodied emissions of around 10, 25, 20 kg CO_2eq/m^2 of the PV area for ZEB4, ZEB5 and ZEB6 respectively. For a flat roof, it is assumed that the extra aluminum needed to lift up the modules to the required angle is 4 kg/m^2 in a triangular mounting system (K2 Systems GmbH, 2017), resulting in higher embodied emissions. A flat roof limits the number of PV modules that can be installed since modules need to be spaced to avoid self-shading. The optimal tilt angle in Oslo is around 40 degrees, which would require a module spacing of around 3.5–5.5 m (depending on the module orientation) to avoid significant self-shading. A flat roof in Norway demands a parapet for security reasons (DIBK, 2010). In the original ZEB concept it was assumed that the parapet width was the same as the external walls and that this roof area was not available for PV modules (Dokka et al., 2013a). If the roof itself is tilted at a degree that is suitable for a PV installation, the full roof area can be utilized (no parapet) without shading problems. Felius and Houlihan-Wiberg (2014) tilted the roof of the previous ZEB model to 30 degrees in order to increase available area and facilitate building adapted or integrated PV systems. To choose a roof form for the new ZEB model (footprint 75 m^2), the following roof forms were compared: ZEB1 (available roof area 80 m^2), ZEB2 (available roof area 60 m^2), ZEB3: roof tilted 30 degrees as suggested by Felius and Houlihan-Wiberg (2014) (available roof area 86 m^2, additional external wall 84 m^2), ZEB4: a 19 degrees tilted roof (available roof area 79 m^2, additional external wall 50 m^2), ZEB5: a double 30 degree triangle roof (available roof area 76 m^2, additional external wall 45 m^2), and ZEB6: a triangle roof tilted to 32 degrees (available roof area 44 m^2 (South faced), additional external wall 22 m^2).

The emissions comparisons include:

1. increased emissions from construction materials for roof and external wall (roof 47 kg CO_2eq/m^2 and external wall 30 kg CO_2eq/m^2)
2. emissions from electricity for space heating (due to extra volume, 11 kWh/m^3)
3. PV system emission load and compensation.

High efficiency PV modules were used for all different roof forms, even though they are associated with higher embodied emissions based on findings from Good et al. (2015): SunPower modules (SPR-X21-335), with rated power of 335 Wp and efficiency of 20.57% (dimensions: width=1046, length=1559 mm and thickness=46 mm). The simulations were performed in the simulation tool PVsyst (Mermoud, 2011) with data from Meteonorm (Meteotest, 2009). The module and roof dimensions were taken into account, which means that the available area could not always be used in full. The priority was to fit the maximum number of modules. The emissions for a high efficiency PV module (280 kg CO_2 eq/m^2) were based on Fthenakis et al. (2012), which are similar to the emissions of a mono-Si module from Ecoinvent (273 CO_2 eq/m^2) (Wernet et al., 2016). The degradation of the PV modules over the service lifetime was accounted for.

2.6. Space heating: balancing embodied emissions and use stage savings

The thermal envelope of all the ZEBs has significantly higher thermal resistance (i.e. lower U-value) than required by the current Norwegian building standard TEK10 (DIBK, 2010). However, there is a slight variation between the ZEBs. To find the U-values and the corresponding insulation thickness to apply to the new model, embodied impacts and operational emission savings are calculated for three different alternatives: the highest (U-highest) and lowest (U-lowest) U-values for the roof, external wall and ground floor constructions. As a reference, the TEK10 U-values are also included. In Table 3, the different U-values and corresponding insulation thicknesses and assumptions are given. The glass wool insulation is the main insulation material in all the previous ZEBs pilots, and it is assumed to be used for all the constructions. Thermal conductivity, density and GHG emissions per kg for glass wool are 0.035 W/mK, 16.5 kg/m^3, and 1.35 kg CO_2eq/kg, respectively (Edvardsen, 2010; Plesser, 2013; Wernet et al., 2016). The space heating demand is simulated in IDA-ICE version 4.7 (EQUA Simulation AB, 2017) for the different options in the new model. The parameters used in the simulation comply to the technical specification SN/TS 3031:2016 (SN/TS 3031:2016, 2016) profiles for the set-point temperature for space-heating (22°C), as well as, for the internal gains, as specified in 2.7. The building is assumed to be placed on a flat and open terrain without surrounding obstacles (Dokka et al., 2013a). The differences in window U-values are not included.

2.7. Heating system

For the specification of the thermal supply system, the performance of the two main heating strategies already used in the ZEB concept and existing pilot buildings are compared. Firstly, the standard heating system installed in ZEB6 is considered. It relies solely on an efficient ground source heat pump (GSHP, COP 4.2 (B0/W35)), using one single U-shaped vertical borehole (100 m deep) for both DHW and space heating. Secondly,

Table 3: U-values for the different options

Description	Unit	U-lowest	U-highest	TEK10
U-value external wall	W/m^{2}K	0.10	0.12	0.18
U-value roof	W/m^{2}K	0.08	0.10	0.13
U-value ground floor	W/m^{2}K	0.07	0.10	0.10
U-value glazing	W/m^{2}K	0.75	0.75	0.75
U-value window frame	W/m^{2}K	1.00	1.00	1.00
External wall	mm	400	300	185
Roof	mm	0.4	0.33	0.25
Ground foundation	mm	0.5	0.35	0.35
Insulation service lifetime	years	60	60	60

the system from ZEB1 with an air-to-water heat pump (ASHP, COP 4.0 (A7/W35)) and solar thermal collectors. Technical specifications of both installations are summarized in Appendix B. The space-heating is performed using low-temperature radiators with a weather-compensated distribution temperature at 40°C/30°C at design conditions.

Hourly profiles for the indoor set-point temperature (22°C), DHW needs and internal gains have been taken from the Norwegian technical standard TS3031:2016. Firstly, the nominal space-heating power (P_n) of the building has been evaluated in standard design conditions (SDC). This enabled the sizing of the radiators and electric resistances to enable them to act as a backup and peak load system. Secondly, the yearly system performance has been simulated in IDA-ICE using the Early Stage Building Optimization (ESBO) module. In ESBO, the heating system layout is simplified assuming a perfect power modulation of the heat pump (from 0 to 100%) and idealized connections to the storage tank in order to maximize the tank stratification. The heat pump model is calibrated on the performance reported by the heat pump manufacturer data (Niemela et al., 2016). The single borehole is modelled using a finite volume approach that enables the short and long-term borehole and ground thermal dynamics to be captured. It's depth is kept constant to the ZEB6. A sensitivity analysis has been performed to determine the optimal storage tank and heat pump size that minimize the energy use. In order to check the quality of results, a sensitivity analysis has been performed on the time step size and the number of nodes in the tanks.

In the GHG emission comparison we include the generation system. The thermal demand is based on standard values for domestic hot water (around 25 kWh/m^2 per year) and the simulated space heating demand from Section

2.6. The embodied emission calculations are based on an assessment of the components installed with data from the ecoinvent 3.2 database (Wernet et al., 2016). It is assumed that the leakage rate of the refrigerant in the heat pumps is 3.5% per year (ERC and CACRR, 2014).

2.8. Embodied balance sensitivities

In the embodied emission calculations, the "M" includes product stage emissions from construction materials (CM), technical components (TC) and the PV systems in addition to a replacement scenario for all three (Fufa et al., 2016). As it can be challenging to reach the ZEB-OM balance, five other possible approaches for the interpretation of "M" are illustrated in Figure 3: The M1 represents the embodied emissions in product stage construction materials (CM), M2 represents the addition of the emissions from the production stage for the technical components (TC), M3 represents the addition of the emissions from the production stage for the PV system (PV), M4 includes the addition of the the replacement emissions for CM, M5 includes the addition of the replacement emissions for TC and finally, M6 includes the emissions from PV system replacements.The current ZEB-OM embodied emission approach corresponds to "M6" in Figure 3. The overall aim is to achieve that ambition, however other "M" interpretations will be investigated to see if they are more realistic to achieve.

3. Results

In the following sections the results from the different steps are presented.

3.1. Embodied emissions

Embodied emissions per square meter of the ground floor, roof and external walls over the service lifetime of 60 years are shown in Figure 4. It can be seen that the embodied emissions are similar, especially for the different wall and roof constructions. However, there is an improvement possibility for the ground foundation from the ZEB1 to the new ZEB model. Thus, the foundation structure applied in ZEB5 was chosen, whilst keeping the same external wall and roof construction layers. The foundation structure from ZEB5 does not require a foundation wall.

3.2. Roof form and PV system

If the objective was only to reduce embodied and operational emissions, a flat roof would be the preferable option, as seen in Figure 5. However, since the aim is to maximize on-site renewable energy production in order

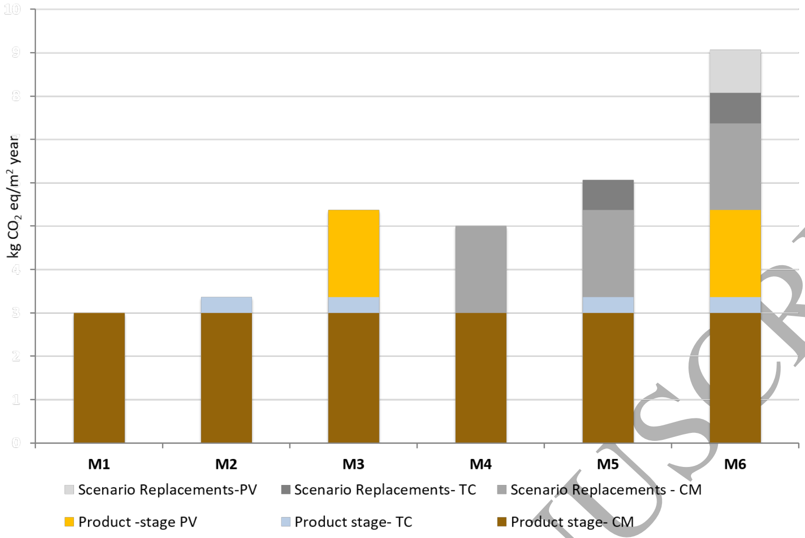

Figure 3: Possible interpretations of the embodied emissions "M" in the ZEB ambition level ZEB-OM.

to reach the ZEB-OM balance, a larger roof is beneficial. The largest roof, ZEB3, allowed for the installation of 78 m^2 of PV modules, which enables the highest amount of emissions to be compensated. The flat roof of ZEB1 fits 59 m^2 of PV modules. The variation of electricity production is 53 to 104 kWh per square meter heated floor area m^2 per year and the corresponding emission compensation is around 6.4 to 13.8 kg CO_2 eq/m^2/year.

From Figure 5, it can be seen that the extra embodied emissions in the roof and external wall constructions are small compared to the emission benefits of the PV system. There is an increase in the operational energy use, due to the increased volume for the 30 degree tilted roof. However, due to the high compensation with the 30 degree tilted roof, that roof alternative is chosen. The monthly electricity production from the ZEB3 roof alternative is shown in Figure 7.

3.3. Space heating: balancing embodied emissions and use stage savings

The total emissions loads and annual operational emission savings from the increased insulation materials per m^2 are shown in Figure 6. The total energy need for space heating is around 3800 kWh/year, with the lowest U-values up to nearly 6000 kWh/year for the reference U-values TEK10 (31 and 49 kWh/m^2 year). When increasing the insulation thicknesses from TEK

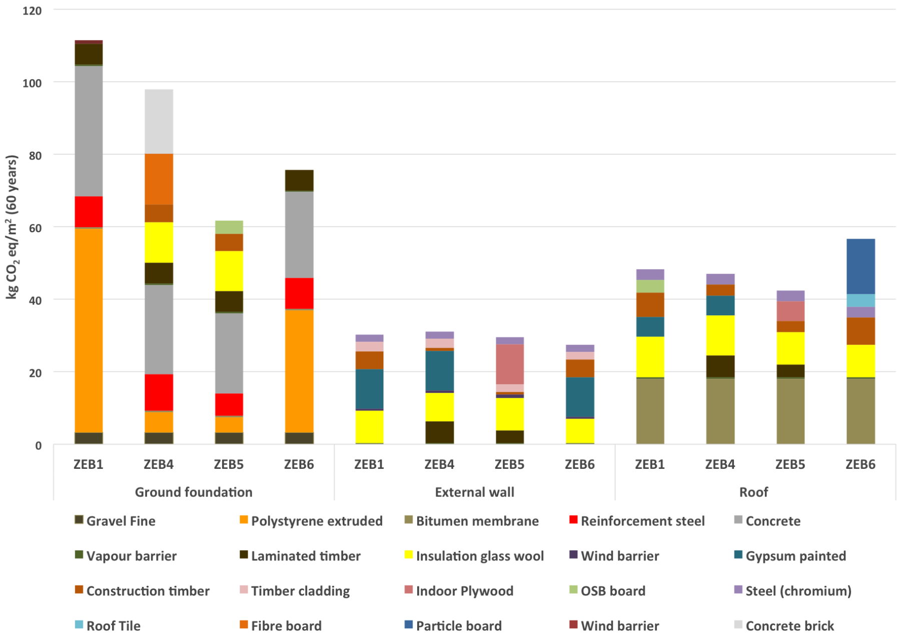

Figure 4: Embodied emission per m^2 of construction (over 60 years)

10 to the highest U-value, the extra total embodied emission investment is around 700 kg CO_2eq, while the corresponding 60 year emission savings are nearly 6000 kgCO_2eq. When increasing from the insulation from the highest to lowest U-value, the extra embodied emission investments is around 900 kg CO_2eq and net emission savings around 2200 kgCO_2eq. Thus, the results show that the point is close to be reached where increased insulation will no longer pay off in terms of emissions reductions.

Due to the estimated long term emissions savings, the new model uses the insulation thickness with the lowest U value. The emissions from the glass wool insulation materials accounts for around 5% of the total embodied emissions, or around 0.5kg CO_2eq/m^2.

3.4. Heating system

The monthly demand for electricity to operate the two different heat supply systems, as simulated in IDA-ICE (EQUA Simulation AB, 2017), is shown in Figure 7, while the embodied emissions are presented in Figure

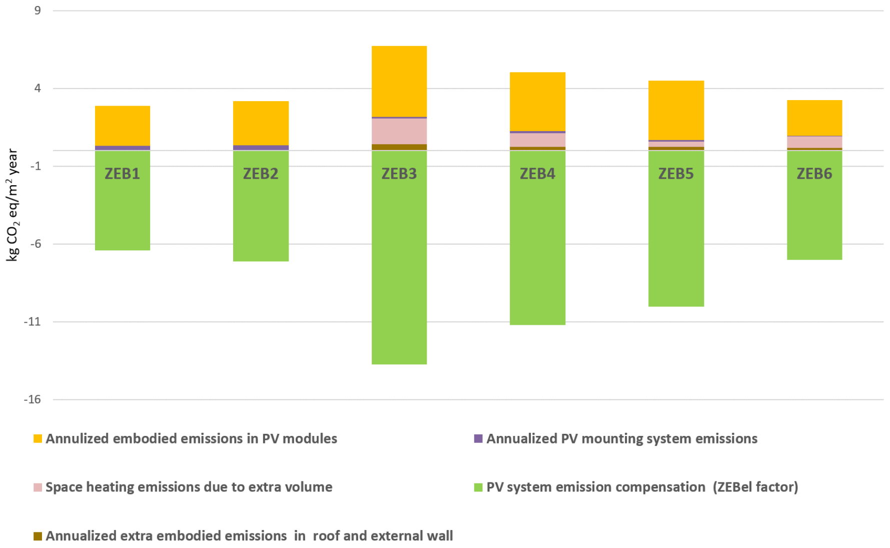

Figure 5: Comparison of emission loads and credits from the alternative ZEB roof forms

8. There are only slight differences in the monthly and total demand for electricity between the systems. The total annual electricity demand is around 18 kWh/m^2 per year, total demand around 2100 (ZEB1) and 2200 (ZEB6) kWh per year. The ZEB6, GSHP, system requires less electricity during the winter time and the ZEB1, air-to-water heat pump with solar thermal collectors, needs less electricity in the summer months. Also, the embodied emissions for the two alternatives are similar. With this approach, it is therefore not possible to choose the preferable system based on embodied emissions preferences alone. The results show the assumed refrigerator fluid leakage is the highest single contributor to the embodied emissions. The choice of systems could rather be based on the monthly performance. If one assumes that reduced electricity import in the colder winter months is more valuable, the preferable system would be ZEB6. The GSHP system is chosen for the new model. The GSHP is also a simpler and more standard system.

3.5. The new model

Based on the results presented above, the changes to the new ZEB-OM model, compared to ZEB1, are listed in Table 4.

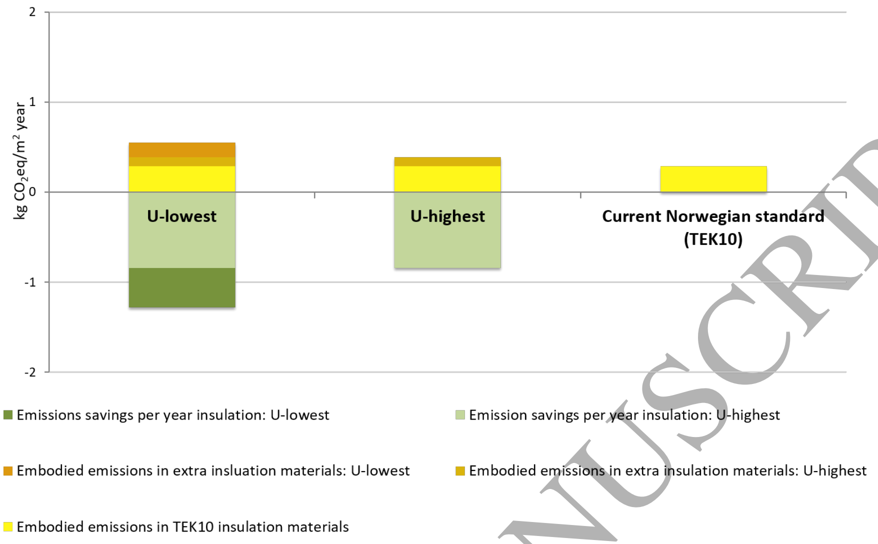

Figure 6: Total emissions loads and annual gains from increased insulation materials and space heating demand per m^2

Table 4: Specifications for the previous ZEB model (ZEB1) and the new ZEB model

Specifications	ZEB1	ZEB new
Heated floor area	160 m^2	120 m^2
U-value external wall	0.12 W/m^2K	0.10 W/m^2K
Ground floor const.	Slab on ground (100mm)	Strip foundation
Ground floor insulation	Polystyrene, 500 mm	Glass wool, 500 mm
Roof construction	Flat roof	Roof 30 degree tilt
Volume	420 m^3	450 m^3
Thermal supply system	ASHP, Solar thermal panels	GSHP
PV area	59 m^2 (this study)	78 m^2

3.6. *ZEB balance*

For the new model, the total electricity use, Q_u, is 55.5 kWh/m^2 per year (18.5+11.5+17.5+8.5 kWh/m^2) corresponding to emissions loads of $ZEB_{el}*Q_u = 7.3$ kg CO_2eq/m^2 per year. The largest PV system produced on average 104 kWh/m^2 per year, corresponding to $ZEB_{el}*Q_p = 13.8$ kg CO_2eq/m^2 per year in emission compensation. The total embodied emis-

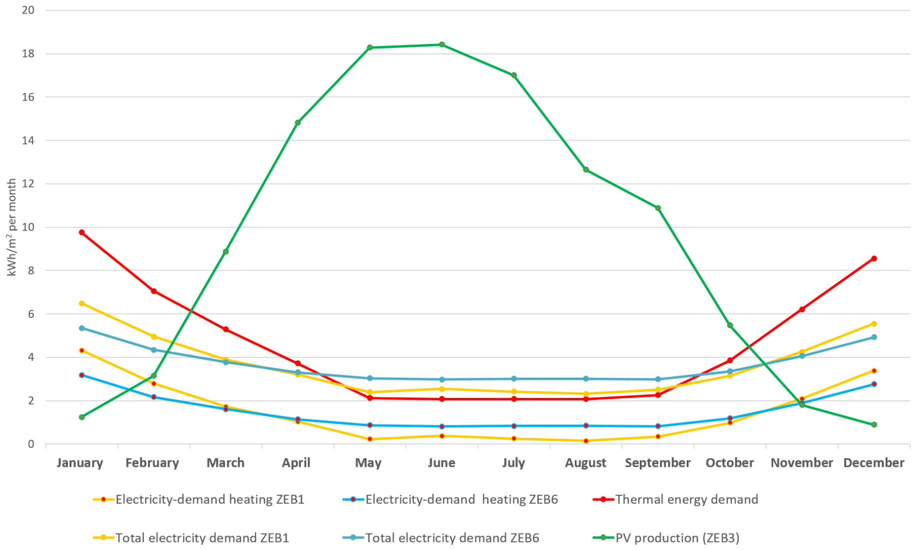

Figure 7: Thermal energy and electricity demand in kWh per m^2 month for the two different heat supply systems and monthly PV system production for ZEB3

sions from the construction materials, technical components (heat supply system, ventilation, space heating distribution) and PV system account for emission loads of around 10.6 kg CO_2eq/m^2 per year, where $\mathrm{CO2}_{pm} = 6.9$ product stage and $\mathrm{CO2}_{rm} = 3.7$ kg CO_2eq/m^2 per year use stage. Figure 9 shows a comparison between the product and use stage emissions for the ZEB1 and the new ZEB. The new model is significantly closer to achieving the ZEB-OM balance, mostly due to increased PV production. However a ZEB-OM balance, as defined in Equation 1 is not achieved for the new model. However, the emission loads are around 4.0 and 8.3 kg CO_2eq/m^2 per year too high for ZEB-new and ZEB1 respectively. The embodied emission loads are around 60% of the total emissions. The new PV systems manages to, on an annual average, balance out all operational emissions, plus around 60% of the embodied emissions. The new ZEB has higher emission loads per square meter but lower total emissions as shown in Figures 9 and 10.

3.7. ZEB balance sensitivities

The results show that the ZEB balance approach is sensitive to the choice of the conversion factor for grid electricity, ZEB_{el}, as has been found previously (Georges et al., 2015; Kristjansdottir et al., 2017). For instance, by increasing the symmetric emission factor ZEB_{el} from 132 to around 220

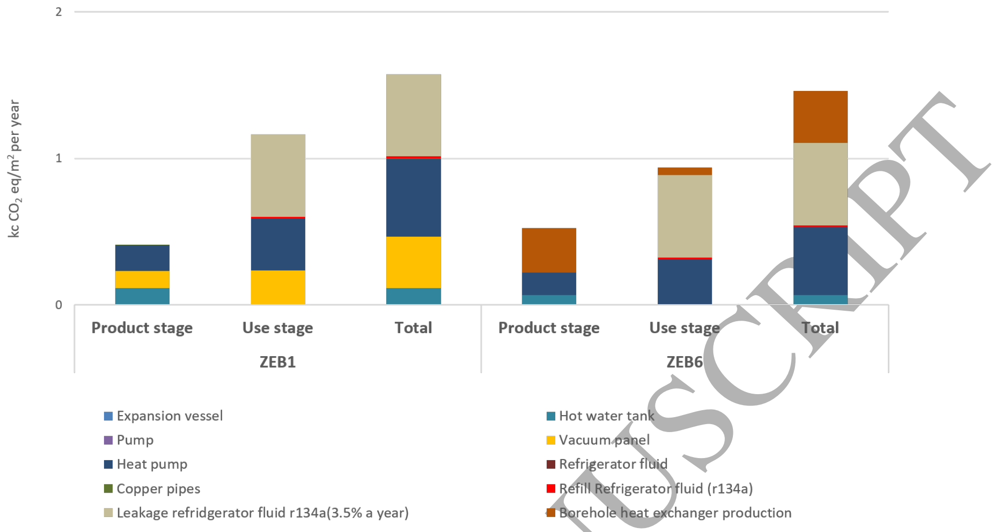

Figure 8: Embodied emissions kg CO_2eq/per m^2/year for product, use stage and total for the two different heat supply systems

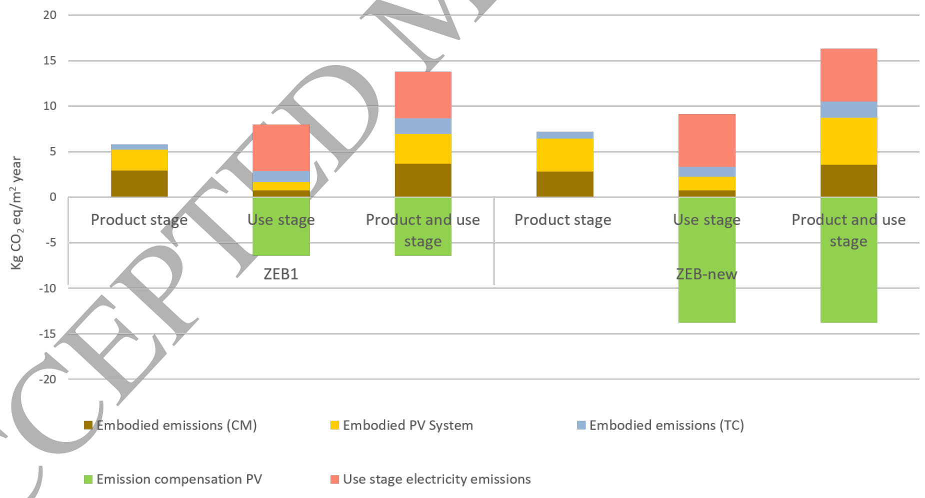

Figure 9: Emission loads and credits for the ZEB1 and new ZEB model per functional unit

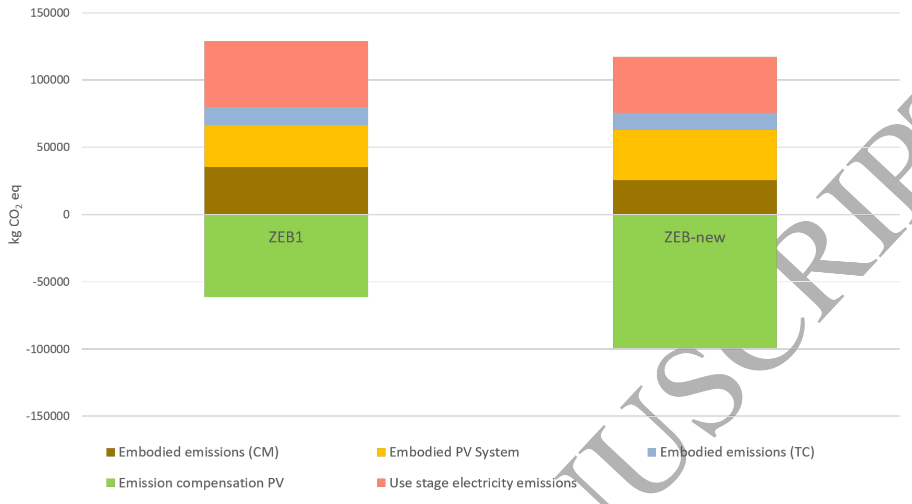

Figure 10: Emission loads and credits for the ZEB1 and new ZEB model total

g CO_2eq/kWh, a ZEB balance would be reached for the new model. The CO_2eq factor for grid electricity is highly uncertain and constantly changing.

A ZEB balance would be achieved if the "M", embodied emissions, would be interpreted as 'M3' (Figure 4) looking only at balancing out the product stage embodied emissions. From the previous emission assessment of a ZEB pilot building (Inman and Houlihan-Wiberg, 2015), embodied emissions were found to be 21 kg CO_2eq/m^2 per year, thus it is known that embodied emissions can be significantly higher than with the current approach. However, it should be noted that embodied emissions are highly dependent on the system boundaries, service lifetime scenarios and emission data sources. By increasing the materials included, for example, for lighting, equipment and plumbing facilities, there would be a corresponding increase in embodied emissions. Thus, a clear boundary for what should be included in the "M" is needed in order to further develop the ZEB-OM balance.

4. Limitations

The building industry is developing rapidly, with new materials and solutions constantly being tested and introduced to the market. Also, emission data is continuously improving and developing as production techniques, production location and material efficiency is changing. Methods for life cycle emission assessments are also continuously improving. The attributional process based on product and operational approach demonstrates a simplified methodology.

Increasing insulation and the PV system size will also increase costs. Economical costs assessments of the different choices have not been included. However, a cost assessment could influence e.g. the size of the PV systems and the insulation thicknesses. Relatively standard heating systems have been investigated while more advanced solutions, for example, with higher seasonal performance factors and waste water heat recovery systems, could have been tested.

Integrated design solutions, where both embodied (life cycle) and operational impacts are studied with one modelling and simulation tool, as in Cellura et al. (2017) and Fesanghary et al. (2012) have not been used in this study. An integrated model would be interesting to apply to the case building when considering further thermal properties and the optimum balance between the insulation materials and use stage energy savings. Improvements to the U-values and embodied emissions of the windows were not investigated in this study and need further attention.

Seasonal sensitivity towards the electricity imports and exports has not been considered here. A monthly emission balance approach for the ZEB pilot buildings was assessed by Kristjansdottir et al. (2017).

5. Discussion

In response to the research question "can the initial ZEB concept be improved?": Yes, it is possible to both reduce embodied emissions and increase the emission compensation from the PV system from the initial ZEB model. However, there are not very significant differences between the initial and the new ZEB model. This can be because the initial ZEB model was a quite ambitious model, with several strong emission reduction efforts; and also, due to the limits in scope of looking only into applied solutions in Norwegian ZEB cases. By expanding the scope, for example, by looking at cases outside Norway, more solutions could be analysed. Thus, it is still possible to further develop the concept. One important point is that most single-family Norwegian buildings are light weight timber constructions, with relatively low embodied emissions. Both glass wool and timber have low embodied emissions. For example, in the external wall, the emissions per m^2 were similar and relatively low for all the different cases, mainly because they use similar materials. Improvements in the ground foundation can have a significant effect on the embodied emissions.

With respect to the research question "can the ZEB-OM emission balance be met?": It is difficult to reach the life cycle energy and material balance as it is defined here. To achieve the defined balance there is a need to further: reduce energy use, reduce embodied emissions, and increase emission compensation.

Another possible approach would be to redefine our life cycle energy and material balance boundary: focusing on defining ambitions targets for embodied emission reductions, rather than including them all in the ZEB balance. This was also one of the suggestions by Lützkendorf et al. (2015): namely, to include embodied impacts as a separate demand. A possible compromise could be to define a clear boundary for which embodied emissions should be compensated for. As suggested here, only the product stage embodied emissions could be balanced out. Inman and Houlihan-Wiberg (2015) showed the product stage embodied emissions were a little over 50% when looking at a 60 year service lifetime, but increased to over 75% when looking at a 30 year service lifetime. Thus, stressing the product stage emission importance from the first decades of the building operation. For example, for our case building, a further increase of the PV system to try to reach the ZEB-OM balance would only further increase the export need. Of the installed 78 m^2 in the new ZEB model, only around half of the area is needed to compensate for operational emissions.

Norwegian greenhouse gases per capita are currently around 11 tonnes of CO_2 eq/year (Statistics Norway, 2017c). The total emission load from the new building over the service lifetime of 60 years is around 120 tonnes of CO_2eq, resulting in emissions per person of 0.5 tonnes of CO_2eq/year per year (four occupants). Thus, these emissions are relatively low.

Differences between embodied and operational emissions between the different heating systems were found to be marginal. The choice of a preferable system was not obvious from the approach; the choice was made assuming that electricity savings in winter are more valuable than in summer times for cold climate ZEBs. In addition, a ground source heat pump (GSHP) is a simpler system. The embodied emissions for the applied GSHP system were lower than found by Saner et al. (2010). The construction stage for the thermal heating systems (drilling of geothermal holes) has not been included, which could have affected the choice of system. With carbon efficient insulation materials, there is a net benefit to having a very well insulated envelope, even when a low emission factor for electricity is applied in the use stage.

For the roof form, the aim was to increase the PV system's size and PV production while also considering emission loads. The roof tilt of 30 degrees increased the volume of the building, thus the need for space heating is increased. With low heating demand and an efficient heating system, the increased emissions from space heating were not decisive. However, this topic needs further attention, and efforts to utilize the volume to increase the heated floor area should be investigated.

An important aspect in roof design is the length-to-width proportions of the roof and how it fits the dimensions of the selected PV module. If PV modules are planned at the same time as the building, the roof dimensions could be adjusted to fit an even number of modules. The difference in available roof area for ZEB3 and ZEB4, was only 7 m^2, however the difference in installed PV modules was 13 m^2. With different module types, the installed area of PV modules could be different for the ZEB cases.

The differences between the old and new ZEB concepts are relatively low and may fall under the margin of uncertainty. Thus, further model optimization is needed, to improve the design of the building.

6. Conclusions

A Norwegian single-family Zero Emission Building concept has been redesigned based on the lessons learned on GHG emissions reduction strategies from Norwegian ZEB pilot cases and sensitivity assessments. The new model has 78 m^2 of installed PV area, 19 m^2 larger then the previous model. This is due to a change from a flat roof to a 30 degree tilted roof.

Furthermore, the new ZEB model is designed with a strip foundation of low carbon concrete, with glass wool insulation, and a timber construction. This design reduces the embodied emissions in the ground foundation, from around 1 kg to 0.6 $kgCO_2eq/m^2$ per year. In addition, emissions from two heating systems were compared: (1) an air to water heat pump with solar thermal panels (8.3 m^2) and (2) a ground source heat pump. Marginal differences in the emission loads and electricity demand were found.

When comparing embodied emission loads and benefits from different insulation thicknesses, it was advantageous to have very low U-values. The new ZEB model has the following U-values: 0.07 W/m^2K in the ground floor, 0.08 W/m^2K in the roof and 0.10 W/m^2K in the external walls. The tipping point, where embodied emission loads were higher than the use stages savings, was nearly met. The emission savings are connected to the use stage emission scenario, and the emission factor ZEB_{el} was set to 132 grams CO_2eq/kWh.

A life cycle energy and material balance was not met for the new ZEB model. The new model was able to balance out all operational emissions, and around 60% of embodied emissions, while the initial ZEB model was able to balance out all operational emissions and 5% of embodied emissions. Embodied emission loads were around 60% of the total emission loads, amounting to around 11 kg CO_2eq/m^2 year, whereas use stage emissions amounted to around 7.3 CO_2eq/m^2 year.

Further studies are needed to increase the details and performance of the new building concept, both with respect to architectural design, embodied emissions and use stage modeling.

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883 Appendix A. Case descriptions

Description	ZEB1	ZEB2	ZEB3	ZEB4	ZEB5	ZEB6
BRA [m^2]	160	120	120	154	102	202
Stories	2	2	2	2	1	2
Roof tilt (degrees)	0	0	30	32	30	19
Heated volume [m^3]	420	315	450	370	319	610
PV area [m^2](this study)	58	48	78	65	65	39
U-value roof [W/m^2K]	0.1	0.1	0.08	0.08	0.1	0.08
U-value ground [W/m^2K]	0.07	0.07	0.07	0.09	0.1	0.08
U-value wall [W/m^2K]	0.12	0.12	0.1	0.12	0.11	0.1
Heat recovery (vent.syst)[%]	85	85	85	86	86	87
Thermal bridge (normalized) [W/m^2K]	0.05	0.05	0.05	0.03	0.03	0.03

Appendix B. Technical specifications for the two heating systems

Description	ZEB1	ZEB6
Heat pump type	Air to water	Ground source
Depth of well [m]	-	100
Nominal power[kW]	7	4.7
Nominal heat pump COP	3.5	4.0
GSHP COP (B0/W35) EN14511	4.2	-
ASHP COP (A7/W35) EN14511	-	4.0
Heating system Seasonal performance factor (SFP)	3.2	3.1
Vacuum solar collector optical eff.[%]	71	-
Vacuum solar collector U-value [W/m^2K]	1.24	-
GWP refrigerant r134a [kg CO_2eq][1]	1430	1430
Amount of refrigerant[2] [kg]	1.8	1.8
Hot water storage tank [l]	600	400
Area of thermal collectors[m^2]	8.3	-
Maximum supply temperature °C	55	65
Minimal outdoor temperature °C	-15	
Service lifetime in years		
Bore hole heat exchanger[3]	-	50
Hot water tanks	60	60
Copper piping	60	60
Solar collectors[4]	20	
Heat pumps[5]	20	20
Seasonal Performance Factor		

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[1] (ERC and CACRR, 2014)

[2] (Elco, 2008)

[3] Wernet et al. (2016)

[4] Dones et al. (2007)

[5] Dones et al. (2007)