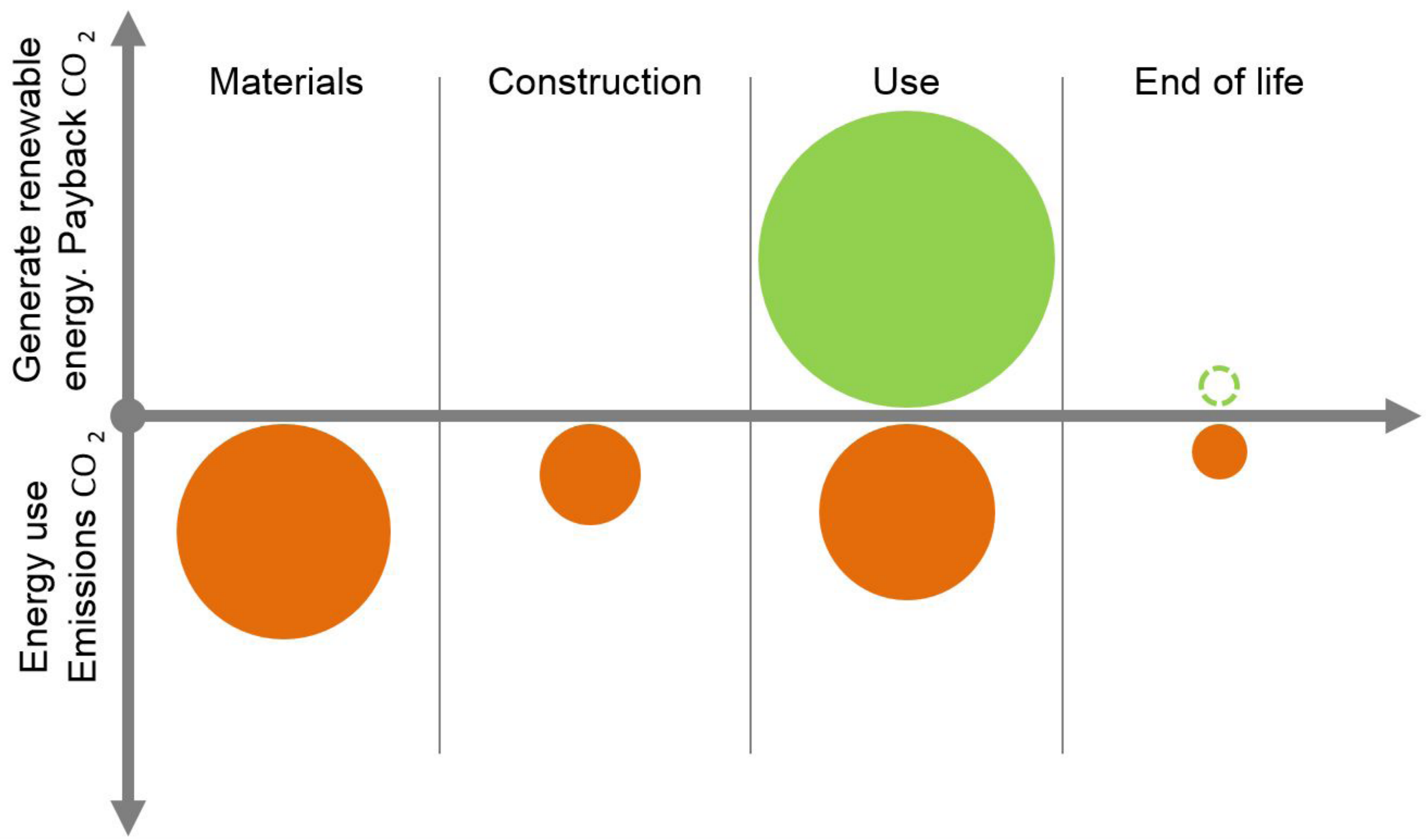
ZEB Project report 29 – 2016

Selamawit Mamo Fufa, Reidun Dahl Schlanbusch, Kari Sørnes,
Marianne Inman and Inger Andresen

A Norwegian ZEB Definition Guideline

The Research Centre on
Zero Emission Buildings



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Keywords:
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Illustration on front page:
ZEB. The illustration shows how the generation of renewable energy (green circle) may compensate for all greenhouse gas emissions from all life cycle stages of the building (red circles).

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Abstract

The objective of this report is to provide a comprehensive and consistent guideline for the Norwegian definition of Zero Emission Buildings (ZEB) and the associated calculation methodologies. The guidelines described in this report build upon the article "A Norwegian Zero Emission Building Definition", the report "A Norwegian ZEB Definition - Embodied Emissions" as well as other relevant national and international work. The guidelines explain the methodology used within the ZEB Research Centre, focusing upon operational energy use calculations and life cycle emission calculations for materials. Furthermore, the guidelines illustrate the ZEB definition and methodology with selected examples from the ZEB pilot case studies. This guideline is useful for designers and developers involved in the planning and design of zero emission buildings. The guideline can also be used as a point of reference for the setting of future standards and regulations on low carbon buildings.

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1. Introduction

The objective of this report is to provide a comprehensive and consistent guideline for the Norwegian definition of Zero Emission Buildings (ZEB) and the associated calculation methodologies. The guideline is useful for designers and developers involved in the planning and design of zero emission buildings. It can also be used as a point of reference for the setting of future standards and regulations on low carbon buildings.

The guidelines described in this report build upon the following reports and articles:

> “A Norwegian Zero Emission Building Definition” (Dokka et al. 2013a),
> “A Norwegian ZEB Definition - Embodied Emissions” (Kristjansdottir et al. 2014),

as well as other relevant national and international work in the field of ZEB definitions. The guidelines are also based on experiences from the ZEB pilot building projects.

This report includes a description of the rules and methods of the ZEB defitions, and provides examples of practical implementation of the guidelines from the Norwegian ZEB pilot projects.

2. The ZEB Balance

The Norwegian Research Centre on Zero Emission Buildings has developed a definition for zero emission buildings (ZEB) based on previous and current work implemented by the International Energy Agency (IEA) and the recast Energy Performance Building Directive (EPBD). The ZEB definition and guidelines have also been based on experices from pilot building projects withn the research centre.

The EPBD defines a '*nearly* zero energy building' as a building that has a very high energy performance, whereby the nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby (European Parliament and the Council 2010).

2.1 Net Zero Energy Buildings (net ZEB)

The term '*net* zero energy building' (net ZEB) has been introduced to emphasize the concept of an annual balance between energy imported from and exported to the energy grid – in contrast to an autonomous building (Sartori et al. 2012). Thus, a net ZEB implies that the building produces the same amount of energy from renewable sources (e.g. PV, solar thermal collectors) as the energy needed for its operation. This net ZEB balance can be represented graphically, as seen in *Figure 2.1*. A net ZEB balance is achieved through reducing energy demand (X-axis) by means of energy efficiency measures, and by generating electricity or thermal energy to earn sufficient credits (y-axis) to compensate for energy required for operation.

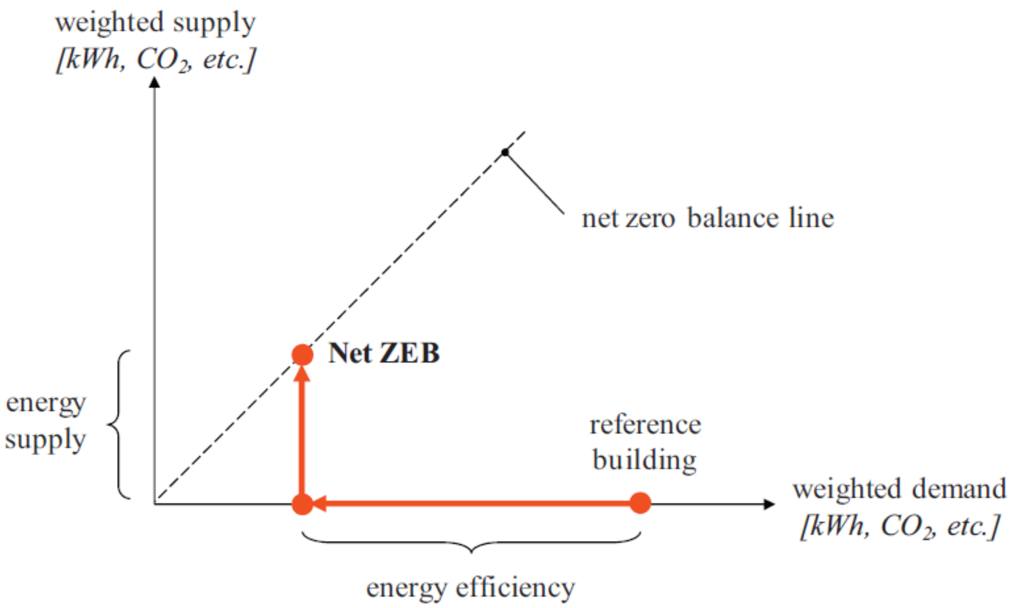


Figure 2.1 Net ZEB balance concept (Sartori et al. 2012).

The net zero energy building definition may be further expanded by applying a life cycle perspective, whereby the primary energy used in the building during operation plus the embodied energy (e.g. life cycle energy demand from materials, transport and construction) and end of life energy (e.g. life cycle energy demand from dismantling, transport and waste treatment) are included.

2.2 Zero Emission Building (ZEB)

In a 'zero emission building' as defined by the Norwegian Research Centre on Zero Emission Buildings (www.zeb.no), the balance is measured in terms of associated greenhouse gas equivalent emissions during the lifetime of a building instead of on direct energy demand and generation.

At the Norwegian Research Centre on Zero Emission Buildings, the ZEB definition is characterised through a range of various ambition levels ranging from the lowest (ZEB-O÷EQ) to the highest (ZEB-COMPLETE) (Dokka et al. 2013a, Kristjansdottir et al. 2014), see figure 2-2.

2.2.1 ZEB Ambition Level Definitions and System Boundaries

Figure 2.2 illustrates the five ZEB ambition levels that have been taken into account during the assessment of the different Norwegian ZEB pilot projects.

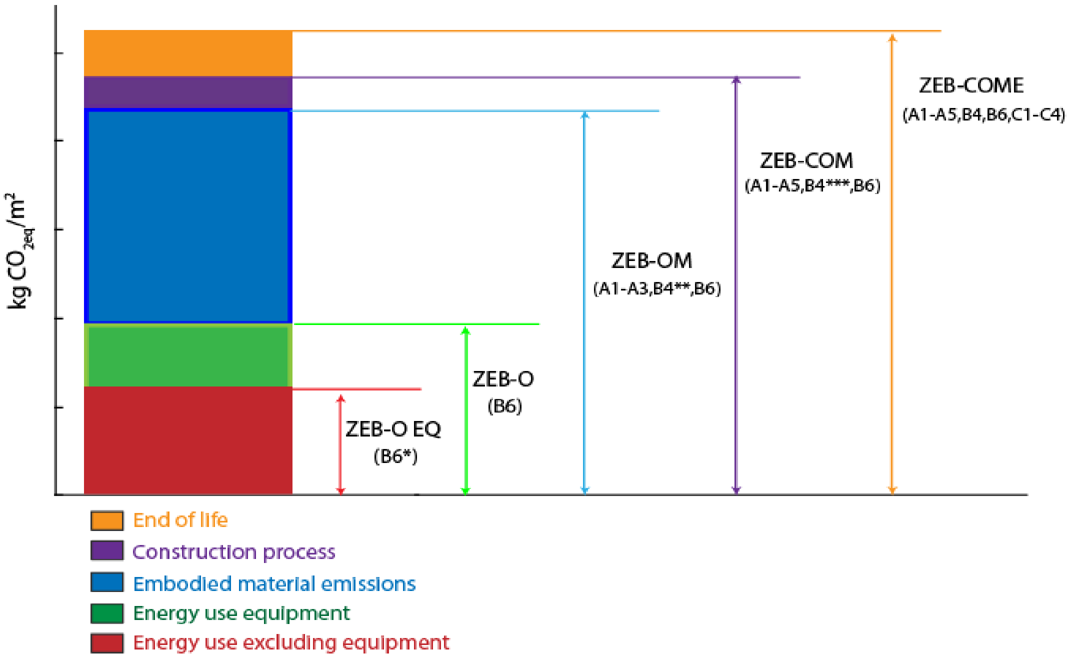


*Figure 2.2 ZEB ambition levels. See Table 2.1 for an explanation of the scope of the included life cycle stages, A1-A5, B4, B4**, B4***, B6, C1-C4.*

The "O" refers to emissions associated with Operational energy use. The “M” refers to embodied emissions[1] associated with building construction Materials. The "EQ" refers to operational emissions from technical EQuipment. The "C" refers to emissions associated with Construction and installation, while the "E" refers to embodied emissions associated with the end of life phase of the building.

These system boundaries can be interpreted in light of the works outlined in CEN/TC 350 *Sustainability of Construction works*, and more specifically NS-EN 15978 *Sustainability of construction works. Assessment of environmental performance of buildings. Calculation method* (NS-EN 15978:2011). NS-EN 15978:2011 displays a modular system of lifecycle stages for buildings, which provides the basis for

[1] Embodied emissions refer to emissions that are “embodied” in the materials that compose a building. The term does not refer to the carbon that is stored in the building materials, but rather to the emission of greenhouse gases released into the atmosphere during the production, construction, use and demolition of these materials.

the assessment of buildings in the standard. According to this standard, the lifecycle of a building is divided into the following stages:

Product Stage (A1 - A3): Cradle to gate processes for materials and services used in construction: raw material extraction and processing (A1), transport of raw materials to the manufacturer (A2), and manufacturing of products and packaging (A3).

Construction Process Stage (A4-A5): Transport of construction products to the construction site (A4), transport of ancillary products, energy and waste from the installation process (A5).

Use Stage (B1 - B7): Use of construction products and services, related to building components (B1 - B5) and operation of the building (B6 - B7), during the entire lifetime of the building. The maintenance (B2) repair (B3) and replacement (B4) lifecycles are related to the product's estimated service life (ESL).

End of Life Stage (C1 - C4): When the building is decommissioned and not intended to have any further use, the building is deconstructed or demolished (C1) and transported to waste treatment or disposal facilities (C2), whereby the waste is either processed (C3) and/or disposed of (C4).

Benefits and loads beyond the system boundary (D): This covers the benefits and loads arising from the reuse (D1), recovery (D2), recycling (D3), and exported energy / potential (D4) from end-of-waste state materials.

The current system boundaries of the ZEB ambition levels are defined as follows (see *Table 2.1*):

1. ZEB-O÷EQ: Emissions related to all energy use for operation "O", except energy use for equipment and appliances (EQ), shall be compensated for with renewable energy generation. The definition of O÷EQ therefore includes operational energy use, except energy use for equipment and appliances (B6*), as outlined in NS-EN 15978: 2011.

2. ZEB-O: Emissions related to all operational energy "O" shall be compensated for with renewable energy generation. The O includes all operational energy use (B6), according to NS-EN 15978: 2011.

3. ZEB-OM: Emissions related to all operational energy "O" plus embodied emissions from materials "M" shall be compensated for with renewable energy generation. The M includes the product phase of materials (A1 – A3) and scenarios for the replacement phase (B4**), according to NS-EN 15978: 2011. Note that B4** in ZEB-OM considers only scenarios related to the production of materials used for replacement. The transportation (A4), installation (A5), and end of life processes for replaced materials are not included in B4**. The scope of materials to be included in M for a ZEB-OM ambition level can be found in Table 2.1.

4. ZEB-COM: This is the same as ZEB-OM, but also takes into account emissions relating to the construction "C" phase. The phases included in C are transport of materials and products to the building site (A4) and construction installation processes (A5), according to NS-EN 15978: 2011. Note that B4*** in ZEB-COM is expanded to include the transportation (A4) and installation process (A5) of replaced materials. The end of life processes of replaced materials is not included in B4***. The scope of materials to be included in M for a ZEB-COM ambition level can be found in Table 2.1 .

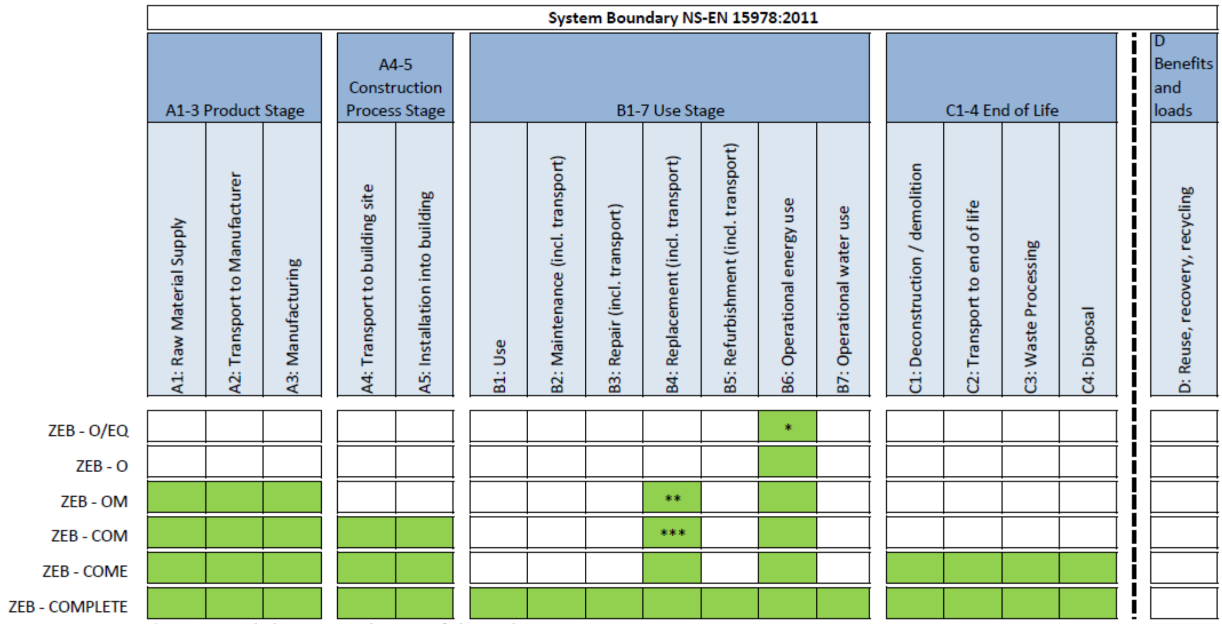
5. ZEB-COME: This is the same as ZEB-COM, but also takes into account emissions relating to the end of life “E” phase. The end of life phase include deconstruction/demolition (C1), transport

(C2), waste processing (C3), and disposal (C4), according to NS-EN15978: 2011. Similarly, the end of life processes of replaced materials in B4 are to be included and taken to an end of waste state.

6. **ZEB-COMPLETE**: Emissions related to a complete lifecycle emission analysis have to be compensated for, namely all phases: product stage (A1 - A3), construction process stage (A4 – A5), use stage (B1 – B7), and end of life stage (C1 - C4). If relevant and available, benefits and loads beyond the system boundary (D) can be included as additional information, according to NS-EN15978: 2011.

Table 2.1 illustrates the relationship between the ZEB ambition levels and the modular lifecycle stages in NS-EN15978: 2011. The lifecycle stages (A1-A5, B1-B7, C1-C4) mandatory for the different ZEB ambition levels are presented in green. Module D can be included as additional information in ZEB COMPLETE.

Table 2.1 Description of ZEB ambition levels according to NS-EN15978: 2011(a larger version of the table is given in Appendix 2).



* Does not include operational energy of electrical equipment
** Does not include transport to building site (A4), installation into building (A5) or end of life treatment of the replaced materials
*** Does not include end of life treatment of the replaced materials
NB: Biogenic carbon should only be included at a ZEB-COME or ZEB-COMPLETE level

2.2.2 Components and materials included in the "M"

The "M" in ambition levels ZEB-OM, ZEB-COM and ZEB-COME refers to emissions from building construction materials and components, excluding emissions from materials used in fixed interiors, sanitary equipment, telecomunication and automation, and outdoor installations.

In NS-EN15978: 2011, building-related furniture, fixtures and fittings are defined as:

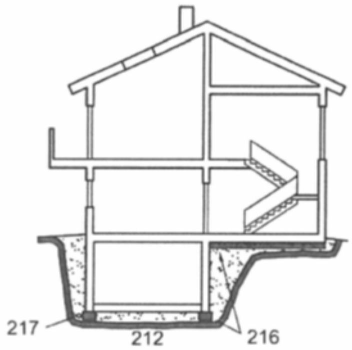
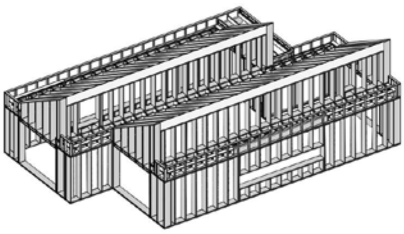
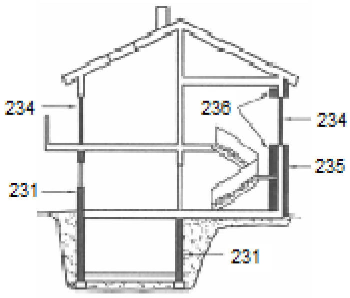
> "*products that are fixed to the building, so that the dismantling of the product decreases the performance of the building, and the dismantling or replacement of the product constitutes construction operation...The system boundary to use stage shall include impacts and aspects of the building-integrated technical system and building related furniture, fixture and fittings."*

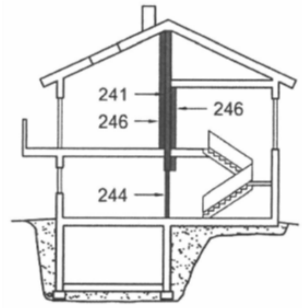
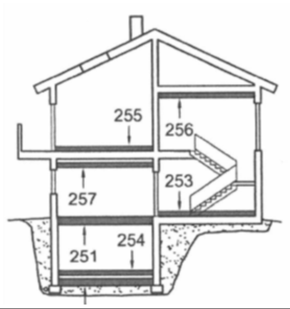
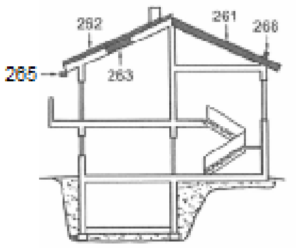
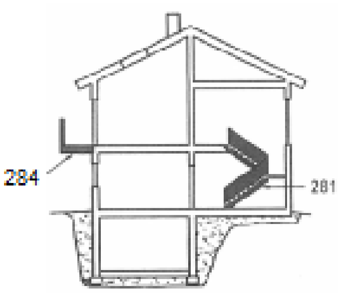
Embodied emissions from technical equipment and appliances should be included, as the operational energy use of technical equipment and appliances is included in ZEB-O. Therefore, for consistency, all technical equipment and appliances included in the ZEB-O ambition level should also be included in the material inventory for embodied emission accounting in subsequent ambition levels.

Table 2.2 is showing a recommandation, based on previous experience from the ZEB pilot buildings, of materials and components that should be included in the "M" calculations. *Table 2.2* can be regarded as a minimum requirement, and any deviation from this should be clearly stated.

The included materials and components must always be reported by refering to list of building elements (NS 3451: 2009) on the three-digit level.

Table 2.2 Recommended list of included materials and components, based on the list of building elements (NS 3451: 2009).

Building Parts	**Building Components**
2 Building Structure	
21 Groundwork and foundations 	211 Clearing of land 212 Excavation 213 Ground Reinforcement 214 Support structures 215 Pile foundations 216 Direct foundation 217 Drainage 218 Equipment and completion 219 Other elements
22 Superstructure 	221 Frames 222 Columns 223 Beams 224 Bracings 225 Fire protection of load bearing construction 226 Cladding and surfaces 228 Equipment and completion 229 Other
23 Outer walls 	231 Load bearing wall 232 Non-load bearing wall 233 Glass Façade 234 Windows and doors 235 Outer cladding and surfaces 236 Internal surface 237 Solar shading 238 Equipment and completion 239 Other

Building Parts	Building Components
24 Inner walls 	241 Load bearing wall 242 Non-load bearing wall 243 System walls 244 Windows, doors, folding walls 245 Skirting 246 Cladding and surfaces 247 N/A 248 Equipment and completion 249 Other
25 Floor structure 	251 Load bearing deck 252 Slab on ground 253 Raised/Built-up Floor, screed 254 Floor System 255 Floor Surfaces 256 Fixed Ceiling and Surface 257 Suspended Ceiling 258 Equipment and completion 259 Other
26 Outer roof 	261 Primary construction 262 Roof covering 263 Glass Roof, Roof light, Roof Opening 265 Cornice, Flashings, Gutters and Downpipes 266 Ceiling and Internal Surfaces 267 Prefabricated Roof Elements 268 Equipment and Completion 269 Other
28 Stairs, balconies, etc. 	281 Internal Stairs 282 External Stairs 283 Ramps 284 Balconies and Verandas 285 Grandstands and Amphi theatres 286 Marquees and Canopies 287 Railings, Handrails, and Fenders 288 Equipment and Completion 289 Other
3 Heating, Ventilation and Air Conditioning	
32 Heating	325 Equipment for heating installations e.g. heat pumps, heaters, domestic hot water tanks and exchangers and boilers which are not electrical (see 45). 329 Other heat installations e.g. Solar thermal collector system

Building Parts	Building Components
36 Ventilation and Air Conditioning	362 Duct System for Air Conditioning 364 Equipment for Air Distribution 365 Equipment for Air Treatment 366 Insulation for Air Treatment 369 Other
4. Electric Power Supply	
44 Lighting	442 Light fixtures and fittings, cables, cable trays, plug sockets
45 Electric heating	452 Electric heaters to be installed in floor, on walls or roofs 453 Underfloor heating 454 Electrical domestic hot water tanks and electrical boilers 459 Other electrical heating system equipment
49 Other	Photovoltaic system Other renewable power systems
6. Other installations	
61 Prefabricated unit	611-619 Prefabricated rooms/modules excluding technical equipment and fixed inventory that is otherwise excluded from the minimum requirements in this table.
62 Passenger and goods transport	621 Lifts/elevator

For the ambition level ZEB-COMPLETE, it is recommended to include all types of material emissions originating from building-related construction as well as integrated technical building systems and services.

2.2.3 Addressing Embodied Emissions at all Ambition Levels

For the two lowest definition levels, i.e. ZEB-O÷EQ and ZEB-O, emissions from materials is not included. Thus, in principle, such buildings may have relatively low greenhouse gas (GHG) emissions during operation, but higher embodied emissions overall due to sub-optimised choices concerning structure and materials. That is why we recommend some emphasis on emissions from materials at the ZEB-O÷EQ and ZEB-O ambition level.

Qualitative measures may be used to identify significant contributors to GHG material emissions . One such measure could include establishing a list of questions that address important issues concerning construction solutions, building elements, materials and installations in relation to GHG material emissions. This list of questions can be used to identify significant contributors to GHG emissions in buildings, based on previous experiences (Kristjansdottir et al. 2014). This list of questions could be used by the design team to identify typical contributors to GHG material emissions in order to obtain ZEB-O÷EQ and ZEB-O buildings with low embodied emissions. An example of such a list may be found in Appendix 1.

3. Operational Energy Calculation Procedures

3.1 Operational Energy and Emission Calculation Procedure

The operational energy use should be calculated according to NS3031: 2007 - *Calculation of energy performance of buildings - Method and data* (NS 3031: 2007), using dynamic simulation tools validated according to NS-EN 15265: 2007 (NS-EN 15265: 2007). The calculation of usable heated floor area (BRA) can be performed according to NS 3940: 2012 - *Calculation of areas and volumes of buildings* (NS 3940: 2012).

NS 3031: 2007 gives national values for user-dependent values such as set point temperatures, hours of operation for ventilation, lighting and equipment, DHW energy use, heat gains from occupants, and so on, for thirteen different building categories. The passive house standards, NS 3700: 2013 - *Criteria for passive houses and low energy buildings - Residential buildings* (NS 3700: 2013) and NS 3701: 2012 - *Criteria for passive houses and low energy buildings - Non-residential buildings* (NS 3701: 2012), gives specific values for ventilation air volumes, and energy use for lighting and technical equipment. Set point temperatures, operational hours, and internal loads from occupants is given in NS 3031: 2007 and should be used in the analysis.

For ventilation air volumes and energy use for lights and technical equipment, the values given in NS 3700: 2013 and NS 3701: 2012 are recommended, but other values may be applied if sufficient documentation is presented (e.g. innovative technologies or strategies for demand control etc.). Local meteorological data, for the site in which the building is located, should be used in calculations, as specified in the passive house standards.

If the project applies new innovative solutions or technologies that are not covered by NS 3031: 2007, NS3700: 2013 or NS3701: 2012, then operational energy should be calculated based on recognised, scientifically approved methods and procedures, whereby documentation of methods used and references should be given.

An example of the calcualation of energy performance and the associated GHG emissions is presented in *Table 3.1*. *Figure 3.1* illustrates an example of delivered energy per energy carrier, and the associated GHG emission calculation.

Table 3.1 Example of a procedure for calculating the energy performance and GHG emissions.

1. Determine the net energy budget - calculate the net energy demand for thermal energy and electricity (kWh/m^2 heated floor area) according to NS3700: 2013 or NS3701: 2012
2. Evaluate different options for renewable energy supply (on-site or off-site)
3. Design on-site renewable energy production - for example photovoltaic (PV) system (for electricity production) or solar thermal system (for heat production)
4. Calculate the gross delivered energy
5. Calculate CO_2 emissions based on the simulated demand from different energy carriers

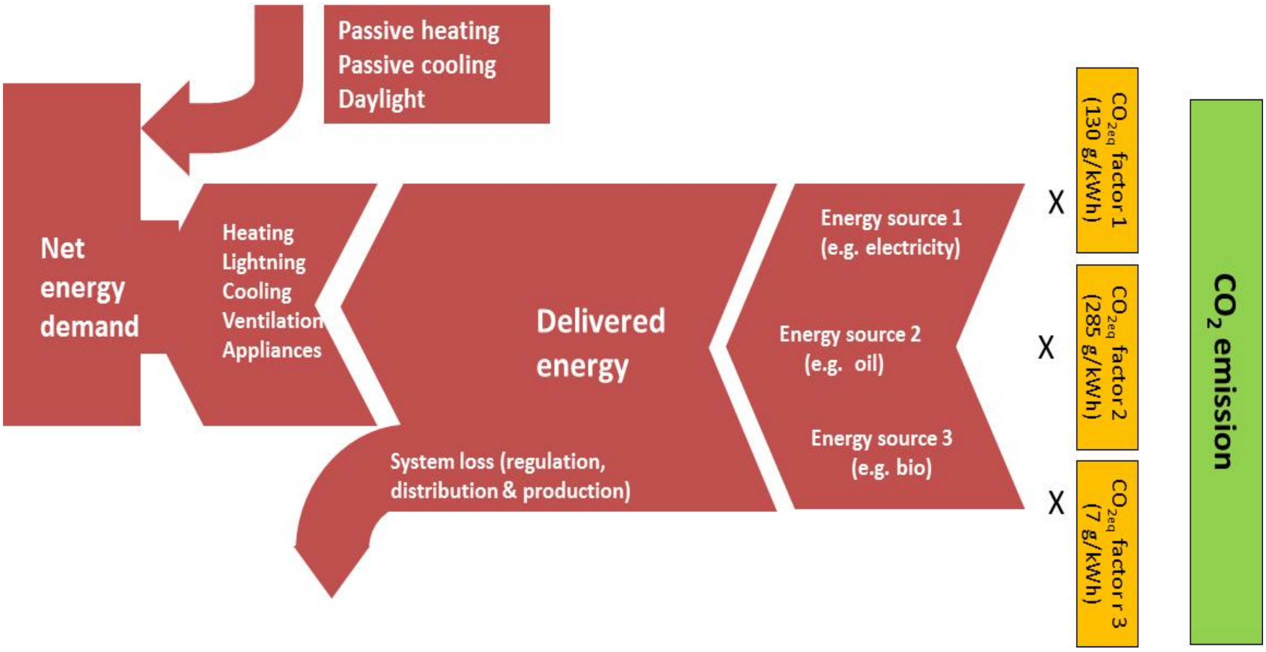


Figure 3.1 The calculation of CO_2 emissions from net energy demand and delivered energy.

The greenhouse gas emissions from operational energy is calculated according to delivered energy, using CO_{2eq} (CO_2 equivalents) conversion factors for each energy carrier. The CO_{2eq} factor is used to convert energy from kWh to greenhouse gas emissions for the different energy carriers. CO_2 equivalents is used as an indicator because Carbon Dioxide is the dominant greenhouse gas. All other greenhouse gases are therefore converted to CO_2 equivalents according to their relative contribution to the greenhouse gas effect. The CO_2 factor is equivalent to the primary energy factor and should include all emissions relating to extraction, processing, generation, storage, transport, distribution, and delivery of energy.

3.2 CO_2 Conversion Factors

3.2.1 CO_2 Factor for Grid Electricity

Within the ZEB Research Centre, there has been an ongoing discussion on how electricity from the grid should be considered with regards to CO_{2eq} emissions. A central issue is the methodology used for calculating carbon emission credits for electricity use and generation, and how the generation of renewable energy during the operational phase should be valued with respect to off-setting embodied carbon emissions from the production of the building. Since the building has a lifetime of several years, this involves the stipulation of future carbon intensity of the electricity grid. Another central issue is how to balance the historic emissions from production of materials, against future GHG emission offsets from renewable energy surplus from the operation phase. For further discussion of these issues, see (Andresen et al. 2016-forthcoming).

Georges et al. (Georges et al. 2014) analysed the life cycle GHG emissions from a residential building and an office building in Norway, by using different scenarios for the electricity weighting factor. The analysed buildings were virtual case studies for which extensive and detailed information was available for the material inventories used. The operating energy performance was estimated through dynamic simulations. The buildings used an all-electric energy solution, meaning that they used heat pump technology for heating and hot water purposes, and PV on all of the available roof areas as the sole energy generation solution. The paper showed that the relative contribution of embodied emissions to total GHG emissions strongly depends on the CO_2 factor chosen for electricity. Embodied emissions dominate operational emissions when low CO_2 factors are used, whilst high CO_2 factors lead to the opposite case. This shows that the selection of CO_2 factor is of prime importance when assessing the performance of ZEBs.

If Norway is considered as having an isolated energy system, one may conclude that the carbon emissions from electricity are very low, in the order of 10-15 gCO_{2eq}/kWh (based on data from Statistics Norway, www.ssb.no), due to the large share of hydro power. However, since the Nordic power market is integrated with the Nord Pool spot market, it would be more appropriate to consider the Nordic mix being representative for all member countries. In this case, the carbon emission from electricity is around 100 gCO_{2eq}/kWh (Thorsteinsson and Björnsson 2011).

The approach adopted by the ZEB Research Centre considers Norway as part of the European power system and takes into account that the powergrid in Europe will become more and more integrated over the years ahead, due to large plans for increased transmission capacity between countries and macro areas. Since Norway is connected to European countries through transmission lines, increases or reductions in demand in Norway will lead to increases and decreases in the production of energy in other European countries. However, it was considered that the average European carbon intensity of electricity will decrease drastically in the next decades, towards 2050 and beyond, due to policy targets aimed at mitigating climate change (EU 2011). Since buildings have a long lifetime, assumed 60 years at the ZEB Research Centre for life cycle assessment purposes, it was deemed necessary to look at such future evolutions in the power sector.

An analysis of different scenarios for European electricity generation towards 2050 has been performed by Graabak and Feilberg (Graabak and Feilberg 2011), see *Figure 3.2*. In the most optimistic scenario the average carbon intensity would drop from 361 gCO_{2eq}/kWh in 2010 to barely 31 gCO_{2eq}/kWh in 2050.

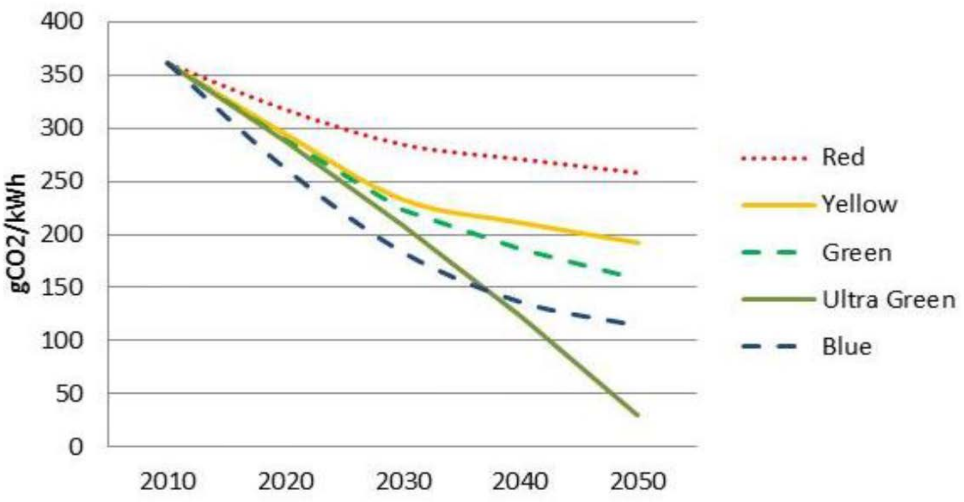


Figure 3.2 Scenarios of average specific emissions from 2010 to 2050 (Graabak et al 2014).

The results were extrapolated to provide an average value that is representative of a 60 year building lifetime, producing an average value of 132 gCO_{2eq}/kWh (Dokka 2011), see *Figure 3.3*. This value has also been adopted as a reference value in Kristjansdottir et. al.(Kristjansdottir et al. 2014) although with the remark that *"... the use of electricity factors is dependent on the goal and scope of the analysis, and it is often relevant to include different scenarios for the emission factor."*

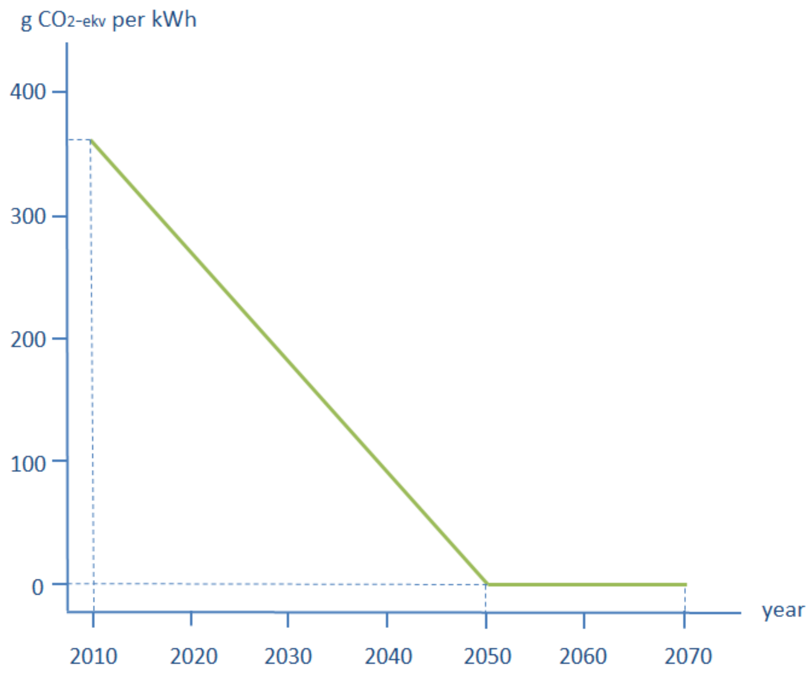


Figure 3.3 The CO_2 factor scenario for grid electricity employed by the ZEB Research Centre, (Dokka et al. 2013a) (Dokka 2011).

This scenario is of course uncertain and debatable, and it is interesting to look at the CO_2 facors used in other studies for GHG abatement in Norway. In a study by Wolfgang and Mo (Wolfgang and Mo 2007), the authors calculated how much CO_2 emissions would be reduced in the European power system if there was an increase in renewable energy generation in Norway. They found that emissions in Europe would be reduced by 526 g/kWh per extra renewable energy generation in Norway (year 2005). In another study performed by Magnus et al. (Magnus et al. 2010), the authors focused on how alternative technologies for electrification of petroleum installations and on- and off-shore wind-power would effect European CO_2 emissions. Marginal emission co-efficients for the power system were not explicitly calculated, but can be extracted on the basis of reported results; ranging from between 675 and 711 gCO_2/kWh.

These studies indicate that the CO_2 factor employed by ZEB is conservative, and that it most likely does not overestimate the climate effect of zero emission buildings.

3.2.2 CO_2 Factors for Bioenergy and Waste Incineration

This section is based on the report from (Lien 2013), which investigates CO_2 emissions from biofuels and district heating in ZEBs. The report recommends that the basic assumption should be carbon neutrality for the direct combustion of biofuels, however we need to account for the use of fossil fuels in the production chain of those fuels. Emission factors for different types of biofuels are listed in *Table 3.2.*

Table 3.2 Specific CO_2 emissions from selected biofuels (Lien 2013).

Biofuel type	gCO_2/MJ	gCO_2/kWh
GROT(waste from wood harvesting) wood chips	1	3,6
EU wood chips	4	14,4
GROT* pellets/briquettes	2	7,2
EU wood pellets/briquettes**	4 - 22	14,4 - 29,2
Wheat straw	2	7,2
Biogas from wet manure	8	28,8
Biogas from dry manure	7	25,2
* GROT = Wood residue ** lower value is using wood as process fuel, upper value is using natural gas as process fuel		

According to Lien (2013), district heating should not be viewed as emission-free waste heat utilisation, but should instead be analysed on the basis of the actual GHG emissions associated with its production. The present composition of incinerated waste in Norway is around 50% fossil based. Specific GHG emissions from waste-incineration-based district heating are comparable to the combustion of natural gas. The specific CO_2 emissions from waste incineration are given in Lien (2013) as 211 grams of CO_{2eq}/kWh, based on the current plastic content of waste (around 25%) and current plant efficiencies. If district heating companies can prove that their production mix has a lower emission factor, then this emission factor may be used.

3.2.3 Summary of CO_2 Factors

Table 3.3 shows a summary of the default CO_2 factors that have been employed by the ZEB Research Centre. The factors may vary depending on processes and system boundaries used. Furthermore, other CO_2 factors may be used if the emissions are documented according to accredited methods and standards. When considering bio-fuels, 1st generation fuels should be avoided. Instead 2nd or 3rd generation fuels that are certified and sustainably sourced should be used[2].

Table 3.3 Specific CO_2-factors employed by the ZEB Research Centre.

Energy carrier	$gCO_{2\ eq}$/kWh	References
Electricity from the grid	130	(Dokka 2011), (Dokka et al. 2013a), (Graabak and Feilberg 2011)
Oil (fossil)	285	(Dokka et. al 2013) (Dokka et al. 2013a)
Gas (fossil)	210	(Dokka et. al 2013) (Dokka et al. 2013a)
Wood chips	4 -15	(Dokka et al. 2013a), Lien (2013)
Pellets/briquettes	7 - 30	(Dokka et al. 2013a), Lien (2013)
Biogas from manure	25 - 30	(Dokka et al. 2013a), Lien (2013)
Bio-diesel and bio-oil	50	(Dokka et al. 2013a)
Bio-etanol	85	(Dokka et al. 2013a)
Waste incineration (heat only)	185 - 211	(Dokka et al. 2013a), (Lien 2013)

[2] Second generation biofuels are made from lignocellulosic biomass or woody crops, agricultural residues or waste, in contrast to first generation biofuels that are made from agricultural crops such as sugars or vegetable oils. Third generation biofuels have only recently entered mainstream production and refer to biofuels derived from algae.

3.3 System Boundary for Operational Energy

The system boundary for operational energy is the physical boundary where delivered and/or exported energy to or from the building (or cluster of buildings) is measured or calculated (Dokka et al. 2013a). The physical boundary is used to identify whether renewable energy sources are available on-site (within the boundary) or off-site. *Figure 3.4* illustrates different options for system boundaries as defined by (Marszal et al. 2011).

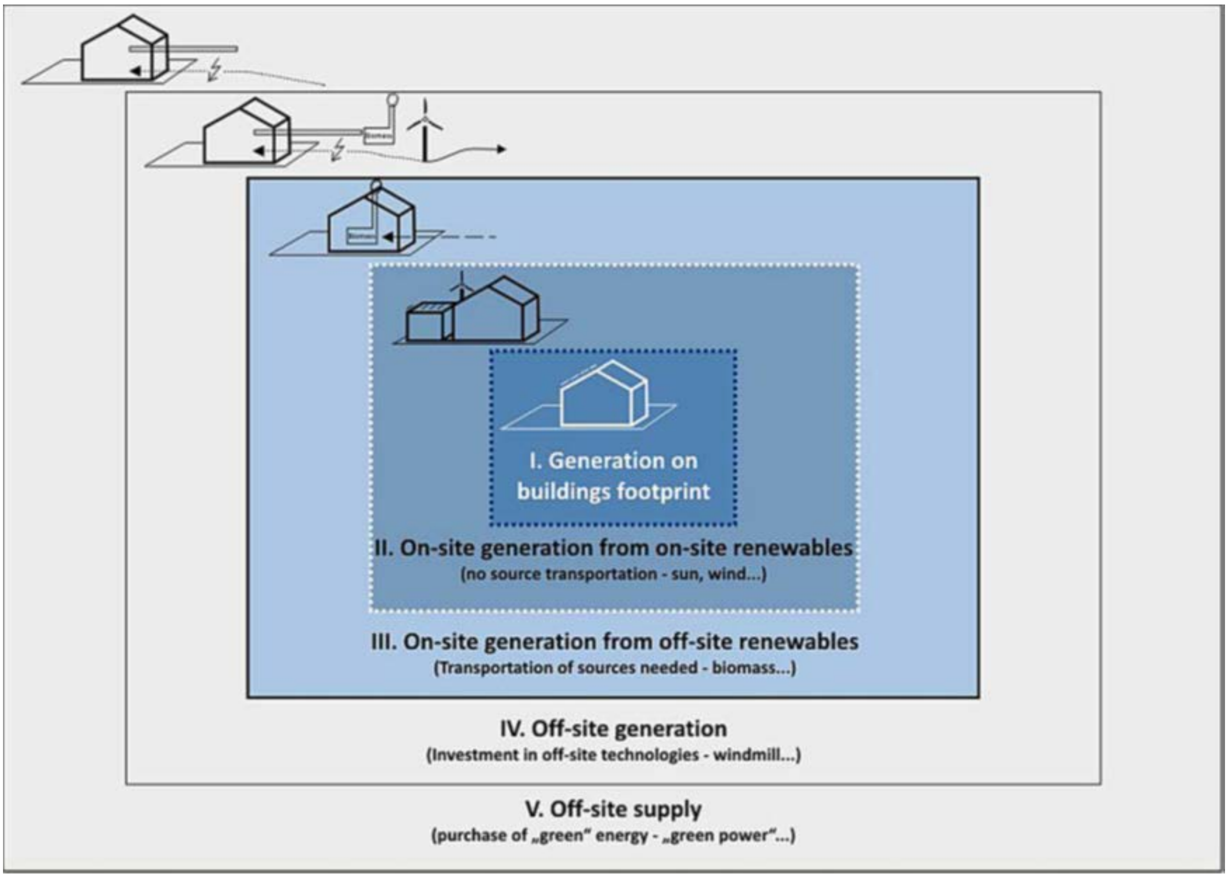


Figure 3.4 Illustration of the different levels of possible system boundaries (Marszal et al. 2011).

The Norwegian ZEB Research Centre has employed the following boundaries for electricity and thermal energy production (Dokka et al. 2013a):

- For local renewable electricity production, level III in *Figure 3.* has been chosen. That means the production unit of electricity for a building has to be located on-site, but off-site renewables (e.g. biofuels) may be used in the production of electricity.

- For thermal energy production, level IV in *Figure 3.* has been chosen. Thus the thermal energy production for the building (or cluster of buildings) can be either on- or off-site, but emissions from the actual energy mix shall be used. Total system losses from the production site to the building shall be taken into account.

Unlike thermal energy, electricity is a high quality energy form that can be used for most building needs: heating, cooling, lighting, appliances and technical equipment, fans and pumps. Exported heat from a building or area (cluster of buildings) to a district heating system or nearby buildings (off-site) may also be taken into account. However, due to its lower energy quality and limited transportability, the exported thermal energy should not exceed imported energy (annually).

3.4 Mismatch of Generation and Demand

The mismatch between energy demand of the building(s) and on-site energy generation can vary considerably on an hourly, daily, weekly and annual basis. This can in turn lead to stress on the grid and result in varying associated GHG emissions. These issues are addressed in Sartori et al.(Sartori et al. 2014) and Baetens et al.(Baetens et al. 2012), and within International Energy Agency Annex 52[3], see for example Salom et al. (Salom et al. 2014) and Annex 67 "Energy Flexible Buildings"[4].

Nevertheless, the Norwegian ZEB Research Centre has chosen an approach which considers a constant CO_2 factor with no daily, weekly or annual variation. The same factor is used for both import and export of electricity from the building(s), and this is called symmetric weighting (Dokka et al. 2013a). Thus, the grid is regarded as an infinite capacity battery whereby surplus electricity is exported to the grid and re-imported in periods of net demand. This approach has been taken to limit the complexity of the calculations. However, it is recommended as best practice that the mismatch between energy demand and on-site energy production during different seasons is calculated according to NS-EN 15603: 2008 - *Energy performance of buildings - Overall energy use and definition of energy ratings* (NS-EN 15603: 2008).

3.5 Energy Efficiency Requirements

The ZEB energy concept involves two design strategies; firstly, to minimise the need for energy use in buildings through energy efficiency measures, and secondly, to adopt renewable energy and other technologies in order to meet the remaining energy needs. These strategies are often classified as either passive or active strategies. Passive strategies relate to the location, layout, massing and form of the building and materials, while active strategies typically involve technical systems or machinery to provide services to the building.

The minimum requirement for energy efficiency in ZEBs is presented through the “low energy house standard” as compliant with NS 3700 (for residential buildings) (NS 3700: 2013) and NS 3701 (for non-residential buildings) (NS 3701: 2012). These standards set criteria for heating and cooling demand, maximum heat loss and thermal bridges, as well as air-tightness of the building envelope.

3.6 Indoor Climate Requirements

The indoor climate of a ZEB, should be at least as good as any other building according to the requirements as set in the Norwegian building regulations. The requirements concerning local discomfort for category B in appendix A of ISO 7730: 2005 (ISO 7730: 2005) should also be met.

[3] http://www.iea-ebc.org/projects/completed-projects/ebc-annex-52/

[4] http://www.iea-ebc.org/projects/ongoing-projects/ebc-annex-67/

4. Life cycle Emission calculation procedures for Materials

For new, energy-efficient buildings, such as ZEBs, the production and end of life phases can constitute approximately half of all primary energy use over the lifetime of a building (Kristjansdottir et al. 2014). This means that the embodied emissions in construction materials make up a large percentage of total emissions from a building over its entire lifetime.

The results from one of the ZEB pilot projects, Powerhouse Kjørbo, shows that production, transport, construction, deconstruction, and end of life treatment of construction materials make up approximately 40% of total lifecycle primary energy demand and approximately 60% of lifecycle GHG emissions, of which the production of materials and components contribute approximately 85% in both cases (see Table 6.4).

This finding shows the increasing importance of addressing embodied material emissions when designing ZEBs. Thus, efficient use of resources, transport logistics, construction, and end of life treatment of materials should be considered in an integrated, holistic approach.

4.1 Goal and Scope Definition

The goal of a life cycle assessment (LCA[5]) for a ZEB, is to quantify the GHG emissions of the building, using environmental information, based on the defined scope and intended use of the assessment.

4.1.1 Functional Unit

A functional unit is a common reference unit, used to present the results of an environmental assessment, related to the technical characteristics and functionalities of a building. According to NS-EN 15978: 2011, the functional unit shall include, but not be limited to, information on the following aspects:

- Building type (according to NS 3031: 2007)
- Relevant technical and functional requirements (e.g. regulatory specific requirements)
- Reference study period (e.g. 60 years)
- Pattern of use (e.g. level of occupancy)

The prevailing approach within the Norwegian ZEB Reserach Centre has been to use a functional unit of 1 m^2 of heated floor area (BRA)[6] over a reference study period of 60 years when analysing the emissions for the whole building (Dokka et al. 2013a, Dokka et al. 2013b, Georges et al. 2014, Houlihan Wiberg et al. 2014). The basis for this functional unit is rooted in the commonly used metric of reporting energy use in terms of kWh per m^2 of heated floor area (BRA) per year. This definition of a functional unit facilitates for the comparison and balance of operational energy and embodied material emissions against on-site energy production.

Alongside the functional unit, it is also required to state *total* embodied emissions ($kgCO_{2eq}$) of the building. It has become good practice to tabulate embodied emission results according to building component and life cycle module. An example of embodied emission results by life cycle stage is given in *Table 4.1*(Inman and Houlihan Wiberg 2015).

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[5] Life Cycle Assessment (LCA) is the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its lifecycle.

[6] Heated Floor Area (BRA) is the area of all floors within temperature-controlled spaces (limited by the inside of the building envelope).

Table 4.1 CO_{2eq} emissions from material use in the ZEB Living Laboratory.

Life Cycle Stage	$kgCO_{2eq}$	$kgCO_{2eq}$/yr	$kgCO_{2eq}/m^2$ 60 years	$kgCO_{2eq}/m^2$/yr
Initial Material Use (A1 - A3)	74121	1235	727	12.1
Transport to Site (A4)	6188	103	61	1.0
Construction (A5)	7412	124	72	1.2
Replacement (B4)	56067	934	550	9.2
TOTAL	**143788**	**2396**	**1410**	**23.5**

4.1.2 System Boundary

The system boundary describes the scope of the assessment and determines the processes that are taken into consideration during the life cycle assessment (NS-EN 15978: 2011). The ZEB system boundaries are defined according to the ZEB ambition levels, as described in Section 2.1.

If other system boundaries are applied instead of those outlined in the ZEB ambition levels, then this should be clearly explained in the goal and scope definitions, through applying the modular system of lifecycle stages as defined in NS-EN 15978: 2011 , see *Table 4.2*.

Table 4.2 Different stages of the life cycle of a building, as defined in NS-EN 15978: 2011.

A1-A3 Product Stage			**A4-A5** Construction Process Stage		**B1-B7** Use Stage							**C1-C4** End of Life Stage				**D** Benefits and loads beyond the system boundary			
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D1	D2	D3	D4
Raw Material Supply	Transport to Manufacturer	Manufacturing	Transport to building site	Installation into building	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Deconstruction / demolition	Transport to end of life	Waste Processing	Disposal	Reuse	Recovery	Recycling	Exported energy / Potential

The lifecycle modules A1 - C4, cover environmental impacts and aspects that are directly linked to processes and operations taking place within the system boundary of a building, whereas module D provides the net environmental benefits relating to exported energy and secondary materials, secondary fuels or secondary products resulting from reuse, and recycling and energy recovery, which takes place beyond the system boundary.

The physical boundaries of the building, construction parts, and technical installations included in the scope of the study should also be clearly defined in the goal and scope.

4.1.2.1 System Boundary to Nature – Biogenic Carbon

According to NS-EN 16485: 2014 - *Round and sawn timber-Environmental product declarations-Product category rules for wood and wood-based products for use in construction* (NS-EN 16485: 2014) and NPCR 015 - *Product-category rules for wood and wood-based products for use in construction* (NPCR 015 2013), it is stated that for timber obtained from sustainably managed forests, the biogenic carbon stored in harvested wood should be included, in order to reflect the biogenic nature of wood, its renewability, and its potential carbon neutrality. The biogenic carbon stored in wood products can be calculated according to the procedure given in NS-EN16449: 2014 *Wood and wood-based products – Calculation of the biogenic carbon content of wood and conversion to carbon dioxide* (NS-EN 16449: 2014).

Accounting for carbon uptakes and CO_2 emissions is particularly relevant for the assessment of buildings that use wood as a construction material. This is because it considers temporarily storing carbon or delaying the GHG emissions. The biogenic carbon content (kg CO_{2eq}) of wood may be included as a negative value to GWP (Global Warming Potential) in module A1. The same amount of biogenic carbon content (kg CO_{2eq}) must then be removed as a positive value from the system in modules C3 and C4. During the environmental assessment of a whole building's lifecycle, the biogenic carbon effect of GWP, consists of negative CO_2 emissions in A1, and positive CO_2 emissions in C3 and C4, which results in zero CO_2 emissions over the entire lifetime (according to the assumption of biogenic carbon neutrality) (NS-EN 16485: 2014). In order to consider the biogenic carbon content of wood, the recommended minimum scope of the LCA should include A1-A3 and C1-C4 lifecycle modules for the building.

The current approach within the ZEB Research Centre has been to exclude biogenic carbon from ZEB-OM ambition level (e.g. Multikomfort pilot building, Chapter 6.1) and ZEB-COM ambition level (e.g. Campus Evenstad pilot building, Chapter 6.3) analyses. This is because the end of life stage is not taken into account. However, biogenic carbon should be included in ZEB-COME and ZEB-COMPLETE ambition levels, whereby the overall lifecycle is considered.

4.1.2.2 Carbonation of Concrete

Concrete is a composite material consisting mainly of aggregates, cement, and water. The major part of CO_2 emissions from the production of concrete is related to the production of cement. In cement production, more than 50% of the CO_2 emitted originates from the calcination[7] of limestone (Pade and Guimaraes 2007). However, the calcination process is slowly reversed by carbonation[8] when atmospheric CO_2 combines with calcium oxide in the cement to form calcium carbonate. However, carbonation is a very slow process and the absoption of CO_2 is small compared to the emissions from cement production. Due to the present lack of accurate and quantifiable data, the current practice at the ZEB Research Centre has been to exclude the uptake of CO_2 by concrete.

4.1.3 Service Life

The service life of a building, component, or material is usually defined as the period of time in which the performance meets or exceeds initial requirements. The service life of a building, component, or material is dependent on many various factors. When calculating the emissions over the lifetime of a building, we distinguish between the service life of the whole building and the service life of components and construction materials.

The Whole Building: There are two main definitions of service life at the whole building level, namely the reference study period (RSP) [9] and the required service life (ReqSL). [10]

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[7] Calcination is the chemical conversion of limestone (calcium carbonate) to calcium oxide (the principal component of cement) and CO_2. $CaCO_3$+heat → CaO+CO_2

[8] Carbonation is uptake or re-absorption of CO_2 from atmosphere.

[9] The References Study Period (RSP) is the period of time in which time dependent characteristics of the construction works are analysed. In some cases, the reference study period may differ significantly from the design life of the building. (NS-EN 15978: 2011)

[10] The Required Service Life (ReqSL) is the service life of construction works required by the client or through regulations (*NS-EN 15643-1 (2010). Sustainability of construction works - Sustainability assessment of buildings - Part 1: General framework, European Committee for Standardization, Brussels, Belgium*.

Typically, the default value for the reference study period shall be the required service life of the building. However, this is not always the case. The current reference study period being used by the ZEB Research Centre is 60 years (Kristjansdottir et al. 2014).

Nonetheless, there is at least one ZEB pilot building that has a lower required service life than the reference study period, namely the Living Laboratory. The Living Laboratory is a temporary building, and it therefore has a shorter building lifetime than the reference study period of 60 years. In such a scenario, NS-EN 15978:2011 recommends using an adjustment factor for calculating embodied material emissions originating from modules B1 – B7 and D. This adjustment factor is calculated by: RSP/ReqSL.

Components and Construction Materials: Building materials or components often need maintenance, repair, and/or replacement during the ReqSL of a building. The replacement rate of various components and materials is based on the estimated service life (ESL) [11] (not to be confused with expected service life[12] or the design life[13]) which may be found in PCRs, [14] or the following Building Research Design Guide from SINTEF 700.320 *Intervals for maintenance and replacement of building components* and 700.307 *Definitions, establishments and use of service lifetime data for buildings and building components/construction parts*. It should be remembered that maintenance, repair, and replacement of building materials and components is contextual, and may vary from case to case.

The number of replacements of a product, components, and elements used in buildings should be calculated according to NS-EN 15978: 2011 (NS-EN 15978: 2011) using the following formula:

$$\text{Number of replacements of product } (j) = E\,[ReqSL/ESL(j) - 1]$$

Whereby,

ReqSL is the required service life of the building,

ESL is the estimated service life,

j is the product,

E rounds the factor to the nearest whole integer.

Furthermore, NS-EN 15978: 2011 (NS-EN 15978: 2011) states that "If, after the last scheduled replacement of a product, the remaining service life of the building is short in proportion to the estimated service life time of the installed product, the actual likelyhood of this scheduled replacement should be taken into account."

In most of the ZEB pilot cases, the number of replacements of products have been calculated by simply dividing the ReqSL of the building by the ESL of the product without rounding up.

[11] The estimated service life (ESL) is the service life of a building, or parts of a building, expected in a set of specific in-use conditions, determined from reference service life data, after taking into account any differences from the in-use reference conditions (*ISO 15686-1 (2011). Buildings and constructed assets- Service life planning-Part 1: General principles and framework, International Organization for standardization, Geneva, Switzerland*.).

[12] The expected service life is the maximum period of useful life as defined by the manufacturer. (ISO 26782: 2009)

[13] The design life is the intended service life (deprecated), expected service life (deprecated) or service life of construction works intended by the designer (ISO 15686-1: 2011).

[14] Product Category Rules (PCR) define the rules and requirements for EPDs (Environmental Product Declarations) of a certain product category. They are a key part of ISO 14025 as they enable transparency and comparability between EPDs

Number of replacements of product (j) = ReqSL/ESL(j) -1

Whereby,
ReqSL is the required service life of the building,
ESL is the estimated service life,
j is the product.

The approach of not rounding up the number is a simplification of the standardized method. With this approach, the number of replacements can be a decimal number. The reason for using this approach, apart from that it is simpler, is that it removes the subjective evaluation of the likeliness that the last scheduled replacement takes place.

Refurbishment: If a building undergoes comprehensive restoration and refurbishment, it is recommended that the lifetime of the restored building is renewed to 100% and reset to 60 years from the restoration date.

4.2 Life Cycle Inventory and Data Sources

4.2.1 The Building Model

The building element model described in Table 2.2 is used to organize the building in a structured way to facilitate the quantification of the mass and energy flows with their corresponding $CO_{2\ eq}$ emissions and/or energy use. In order to get an overview of the parts of the building that have been included and also to do a more structured and detailed comparison with other projects, the building model is structured according to NS 3451-Table of building elements (NS 3451: 2009).

4.2.2 EPDs and Databases for Life Cycle Inventories

Specific data and/or generic Life Cycle Inventory (LCI[15]) databases can be used to supply data for life cycle purposes. Product specific datasets are typically documented in the form of publically available environmental product declarations (EPDs)[16], while generic datasets are usually gathered in the form of LCI such as, but not limited to, the Ecoinvent database (Swiss Centre for Life Cycle Inventories 2010) and the database of the Norwegian tool Klimagassregnskap.no.

For products which do not have data on their production, technical data sheets from the producers and generic data from the Ecoinvent database can be used to create a scenario for the emissions from that actual product. For the electrical components' emissions, data from Product Environmental Profile (PEP) [17]can be used.

[15] Life Cycle Inventory (LCI) is the data collection stage of LCA. LCI is the accounting of everything involved in the "system" of interest. It consists of detailed tracking of all the flows in and out of the product system, including raw resources or materials, energy by type, water, and emissions to air, water and land by specific substance.

[16] Environmental Product Declaration (EPD) is an independently verified document that communicates transparent and comparable information about the life-cycle environmental impact of a product.

[17] Product Environmental Profile (PEP) is a reference system, in line with ISO 14025, used to provide environmental profile of products from electrical, electronic and HVAC products.

Figure 4.1 shows the results from a sensitivity analysis carried out to evaluate the influence of using emission data from Norwegian EPDs instead of generic data from Ecoinvent for selected materials in a study of a ZEB concept residential building (Houlihan Wiberg et al. 2015).

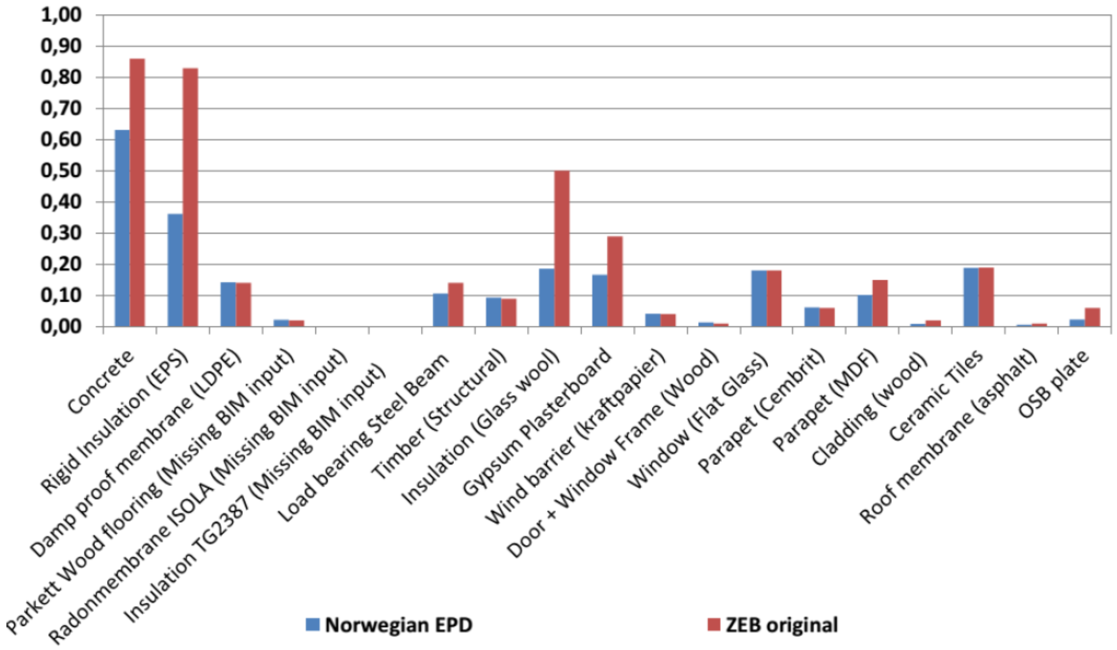

Figure 4.1 CO_{2eq} emission comparisons between the original ZEB study with generic data and the study where Norwegian EPDs were applied (Houlihan Wiberg et al. 2015).

Plasterboard, concrete, and insulation materials were selected for the sensitivity study since these materials were responsible for the highest emissions apart from PV in this case study (Dokka et al. 2013b). Photovoltaic panels were not included in the sensitivity analysis as there is currently no Norwegian EPDs available for this product. To evaluate the benefits of using locally resourced materials, wood was also selected in this sensitivity study, using Norwegian EPD data. It was found that the baseline emissions of 7.2 $kgCO_{2eq}/m^2/yr$ could be reduced to 5.8 $kgCO_{2eq}/m^2/yr$ if specific data for concrete, insulation, plasterboard, and wood were used.

In order to ensure the quality and transparency of the LCA, the complete inventory of the calculations should be documented including data sources, assumptions, and uncertainties. The age of the data should always be reported. It is not recommended to use expired EPDs nor generic data older than 10 years. An example of a library sheet used for documenting the sources of EPD data for the ZEB concept residential building is shown in *Table 4.3*.

Table 4.3 List of EPD data sources used for sensitivity analysis carried out for ZEB concept residential building study (Houlihan Wiberg et al. 2015).

Material description		Physical properties		Functional unit	Impact categories	Information disclosure				
Category of resource	Material specification /process used	Density	Unit		GWP [kg CO2 eq., 100 years/FU-DU]	Data source (EPD, Database etc.)	Scope	Electricity mix	Year of data	Reference
Concrete	Ferdigbetong B25 M60 Betong Øst	2358	kg/m^3	1m^3	189,9	EPD	A1-A3	Nordpool (0,122 kg CO_{2eq}/kWh)	2012	NEPD 123N
Plasterboard	Norgips Standard Type A (STD)	720	kg/m^3	1m^3	168	EPD	A1-A3	Norwegian production mix from Ecoinvent v2	2013	NEPD00113E
Insulation	Glava glasswool	16,5	kg/m^3	1m^3	21,14	EPD	A1-A3	NORDEL (189 gCO_{2eq}/kWh)	2011	NEPD 221E
Insulation	EPS isolation	15	kg/m^3	1m^3	64,71	EPD	A1-A3	ENTSO-E (0,0073 kgCO_{2eq}/MJ)	2013	NEPD-322-185-NO
Load bearing timber beam	Structural timber of spruce and pine	420	kg/m^3	1m^3	53	EPD	A1-A3	Norwegian mean supply electricity mix from 2008-2010(0,021 kgCO2eq/MJ)	2013	NEPD-308-179-EN
Wood battons	Sawn dried timber of spruce or pine	450	kg/m^3	1m^3	41	EPD	A1-A3	Norwegian mean supply electricity mix from 2008-2010 (0,021 kgCO2eq/MJ)	2013	NEPD-307-179-EN

The electricity mix used in the production of the materials affects the embodied emission. The electricity mix used for calculating the embodied energy and related emissions should be the grid mix in the country where the main energy consuming processes take place (NS-EN 15804: 2012) . In the EPDs, this is usually the case. However, some foreign EPDs might apply green certificates[18].

The electricity mix (calculation procedure) shall be documented (as shown in Table 4.3), and any deviations from this shall be justified.

4.2.3 Construction Process

Transport of construction materials from the factory to the building site (A4) can be calculated and documented using the following information:

- Collecting information about the weight and density of the materials, place of production of materials,means of transportation, and type of fuel used.
- Estimating the distances to the building site using tools like e.g. Google Maps.
- Finding the emission factor per ton-km (by the type of transport mode used) or by the type of fuel emission conversion factor (for the type of fuel used).

When using EPD data for A4, it is important to check whether the values given in the EPD include transportation from production site to a building site or to a central warehouse.

In the construction and installation stage (A5) the manufacturing and transport of ancillary materials as well as the energy required during installation and wastage of construction products up to end of waste

[18] A Green Certificate is a tradable commodity that acts as a guarantee that the electricity that is traded is sourced from renewable energy sources. The certificates can be traded separately from the energy produced (https://en.wikipedia.org/w/index.php?title=Green_certificate&oldid=632402173). Producers of wind energy, bio energy, wave energy, small-scale hydropower and solar energy, sell the Green Certificates to the end consumers. A demand for green certificates is created through the European manufacturers' obligation to satisfy the given "green" percentage in their electricity consumption . Thus, a market for green certificates is a subsidy scheme for promoting renewable energy production

state, should be included. Until now, transport of workers during the construction of the building has mostly been excluded from the emission calculations. This is according to NS-EN 15978: 2011, Section 7.4.3.2 (NS-EN 15978 2011). However, in the Evenstad pilot project, transport of workers has been studied and the results indicate that the impact is considerable. Thus, further work is required to evaluate the impact of people transport.

In the Powerhouse Kjørbo project, the construction and installation processes were estimated for the design phase based on registered data from previous construction projects and adjusted based on known differences between the previous projects and the current project (Fjeldheim et al. 2015). The estimated data were adjusted according to actual registered transport distances as well as electricity and fuel consumption during the construction phase.

With a lack of data, the current practice at the ZEB Research Centre is to account for 10% losses of building materials during construction installation (A5) processes (Inman and Houlihan Wiberg 2015). However, it is acknowledged that this is an indicative value and an area for further research.

4.2.4 Replacement of PV Modules

PV systems, which generate renewable electricity to offset the emissions from the building during operation, do not contribute to GHG emission during their operation. However, the PV systems contribute significantly to the embodied emissions in zero emission buildings (Dokka et al. 2013b).

Within the PV industry there is continuous development on new technologies and material use as well as efficiencies for PV modules (NREL 2016). When the reference study period is estimated to 60 years, the PV system needs to be replaced once. Prospective studies of the life cycle primary energy use of PV modules have been presented in Frischknecht et al. (2015), Bergesen et al. (2014), and Mann et al. (2014). These studies highlight the expected reduction of material use as well as expected increases in efficiencies of PV modules.

For the replacement scenario (B4) of PV modules, a 50% reduction of the environmental impacts relative to the A1-A3 impacts can be used. This has been applied as a rule of thumb in the emission calculations of the ZEB pilot buildings.

4.2.5 End of Life

According to NS-EN 15804: 2012, the end of life stage (C1-C4) starts when the materials or products are replaced, dismantled or deconstructed from the building site and until it reaches the end-of-waste state (NS-EN 15804: 2012). Products that reach the end-of-waste state during the construction stage (A4-A5) or the use stage (B1-B7) will have their end of life considered within the life cycle stage in which it arises.

A product reaches the end-of-waste state if it may still be used for a specific purpose, has a positive market value, fulfils relevant technical requirements, and do not lead to adverse environmental impacts, see *Figure 4.2*. Any declared benefits and loads from net flows leaving the product system not allocated as co-products and having passed the end-of waste state, shall be included in module D. Module D is not part of the building's system, but it is an information module used to increase transparency.

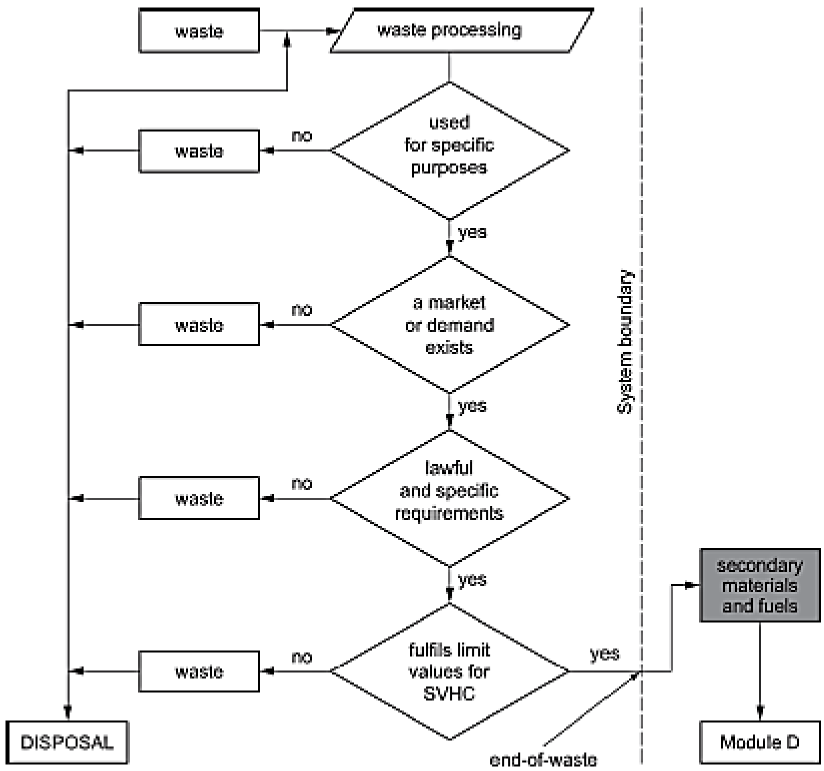

Figure 4.2 End-of-waste decision tree (NS-EN 15804: 2012).

The end of life phase (C1-C4) can be modelled with the use of generic data, e.g. from the Ecoinvent database.

C1 - deconstruction/demolition
This module includes deconstruction, including dismantling or demolition, and on site sorting. In lack of reliable data, it may be assumed that the amount of energy used in the deconstruction phase (C1) is equal to the amount used in the construction and installation processes (Fjeldheim et al. 2015).

C2 - transport from construction to waste treatment
This module includes transportation of waste to waste processing and disposal sites.

C3 and C4 - waste processing and disposal
This module includes waste processing for reuse, recycling and recovery (C3) and disposal of waste that does not reach the end-of-waste state (C4).The use of generic data for scenarios describing the end of life treatment (C3 and C4) can be based on current national waste accounts for main materials. An example of current statistics for treatments of waste from building and construction waste for Norway is shown in *Table 4.4.*

Table 4.4 Treatment of waste from construction, renovation, and demolition of buildings (tonnes 2013) (Stastics Norway (2015)).

	Treatment, total	Sent to recycling	Composting	Biogas production	Energy recovery	Landfill	Other or unspecified
Materials, total	1 818 897	1 090 760	2 336	4 262	500 339	207 371	13 829
Wood	260 453	42 363	2 146	0	207 573	17	8 355
Paper and cardboard	25 768	24759	10	0	915	46	39
Plastics	5 287	2 124	0	0	3 085	77	0
Glass	9 314	7 135	0	0	0	332	1846
Metals	86 015	85 917	0	0	0	1	97
Gypsum	67 330	47 888	0	0	1472	17970	0
EE-waste	9 967	8 185	0	0	1177	561	44
Bricks and concrete and other heavy building materials	72 6985	585 887	0	0	17	140199	882
Polluted bricks and concrete	19831	4 806	0	0	2	14930	94
Other waste	24058	19 563	4	0	526	2872	1092
Mixed waste	325797	21 376	176	4262	281425	18015	543
Asphalt	240608	237 803	0	0	0	2805	0
Hazardous waste	17484	2 953	0	0	4147	9546	837

In the Powerhouse Kjørbo pilot building, the scenarios for the end of life treatment of the various materials were based on the average distribution of recycling, incineration and landfill of concrete, aluminium, glass, gypsum, insulation, plastic, steel, wood and bitumen using generic waste data between 2006 and 2011 from SSB (Fjeldheim et al. 2015).

5. Verification

The designed performance and calculations should be verified by monitoring and evaluation, so that lessons learned can be transferred to new projects.

The following verification procedures are recommended:

- Verification of annual energy performance and the ZEB balance: Measurement of the delivered imported and exported energy to evaluate if the designed performance is achieved. The CO_2 balance is calculated based on the specific CO_2 factors for each energy carrier.
- Verification of energy performance level: Comparing simulated and measured energy use for the different energy purposes (heating, domestic hot water, fans, lighting, appliances) according to NS 3031. A procedure for verification of energy performance in use may be found in (Dokka and Grini 2013).
- Monitoring if indoor climate parameters obtained: Measurement of temperatures, velocities, CO_2 levels, noise and acoustic levels, light levels (natural / artificial), etc. in summer and winter conditions.
- AS-BUILT assessment of embodied emissions: Since the actual materials, products, and processes used in the construction of the building may be different from what was assumed in the design phase, an AS-BUILT analysis should be performed based on the materials that were actually used in the construction.

It is also recommended that the LCA made for ZEBs are verified and quality assured by an independent, qualified third party (Kristjansdottir et al. 2014).

6. Case Studies

The Norwegian ZEB centre has nine pilot building projects, see *Table 6.1*. The ZEB pilot buildings are all designed according to ZEB-targets on GHG emission and/or primary energy. Different strategies are used to accomplish ZEB-budgets for the different projects, and ZEB-partners have been involved in the calculations in various degrees. This means that the calculations have been made using somewhat different approaches. Variations in the ZEB-budgets includes ZEB-ambition level, system border, level of detail, choice of background database, choice of LCA tool etc. The pilot projects are also very different in terms of building type, size, construction methods, etc.

Table 6.1 ZEB pilot building projects.

ZEB pilot buildings	Type of building	Ambition level	Location
Haakonsvern	Office building	ZEB-O÷EQ	Bergen
Skarpnes	5 single-family houses	ZEB-O	Arendal
Zero Village Bergen	ca. 800 dwellings	ZEB-O	Bergen
Powerhouse Brattøra	Office building	ZEB-OM÷EQ	Trondheim
Powerhouse Kjørbo	Office building, renovation	ZEB-OM÷EQ	Sandvika
Multikomfort	Single family house	ZEB-OM	Larvik
Living Laboratory	Single family house	ZEB-OM	Trondheim
Heimdal VGS	Education	*	Heimdal
Campus Evenstad	Education and office	ZEB-COM	Hedmark
*In the Heimdal pilot project, the calculations included all the emissions from the materials (A1-A3) and in addition emissions from transport to building site (A4). However, the ambtion level is set to compensate only 20% of these emissions. (ZEB O20%M + A4)			

This chapter summarizes the different approaches and shows results from the two of the ZEB pilot buildings; Multikomfort (residential building) and Powerhouse Kjørbo (office building) using a common ZEB definition methodology.

6.1 Pilot Building Multikomfort

Figure 6.1 The Multikomfort house. Photo: Jon Østgård.

6.1.1 Key Data

Location	Larvik
Building type	New residential building / Demonstration house
Heated floor area	201 m^2
Building stage	As built
ZEB ambition level	ZEB-OM
Building developer/ owner	Optimera and Brødrene Dahl
Involved companies	Snøhetta, ZEB, Optimera, Brødrene Dahl, Bergersen Flis, Geberit, Glava, Grohe, Gustavsberg, Ifo Porsgrund, Intra, Lyngson, Nilan, Oras, Oso, PipeLife, Schneider Electric, Uponor, Villeroy & Boch, VPI, Grundfos, Aubo, Barkevik, Bergene Holm, Boen, Elfa, Fisher, Gyproc, Isola, Moelven, Natre, Paslode, Velux, Weber.
Opening	2014

6.1.2 Energy Systems

Heating: Ground-source-to-water HP (Nilan Compact P Geo 3kW), which covers 80% heating and has a COP of 5.17. Solar thermal collectors by Hewalex, 16 m^2, which covers 20% of the heating load. Hot water is collected in a 400 liter tank by Oso, which serves the underfloor heating system.

DHW: Heat from waste water (sink, shower, dishwasher, washing machine) preheats the water in the water tank. In addition, DHW is provided by the solar collectors, by an air-to-water HP in the exhaust of the ventilation shaft, and by the ground-source-to-water HP. Washing machines use hot water directly (hot-fill machienes, no electricity for water heating needed). Excess heat from the solar themal collectors is used for heating the water of the swimming pool.

Ventilation: the ventilation system is connected to a heat exchanger (85% efficiency) located in the ground-source HP and connected to the exhaust air shaft. The heat from the water system increases the temperature of the supplied air.

Lighting: LED lights.

Water system: Rain water is collected, recycled, and stored in a 6000 liter tank. It is then reused in toilets and for watering the garden.

Energy supply: Photovoltaic modules from Innotech with 15,5% efficiency, 250 Wp, 122 m^2 installed area, connected to a 48V battery bank at 600Ah.

Control system: The energy system is connected to meters that are controllable via a web connection. A battery bank is in the car-port, and its charging status is controllable by the same system.

Results

The thermal energy performance of the building was calculated with the programs SIMIEN (Programbyggerne.no) and PolySun (VelaSolaris.com). The calculations showed a net energy load for the building of 16,387 kWh per year. Including the heat pump system, the greywater system and the solar collector system, the demand for delivered energy was calculated to 6,900 kWh per year. Annual electricity yield from the PV system was calculated by the software PVsyst (PVsyst.com), to 19,200 kWh per year.

6.1.3 Materials

Service life, building	60 years
Evaluated indicators	Greenhouse Gas emissions (kg CO_{2eq})
Year of assessment	2014
Involved companies in LCA calculations	ZEB /SINTEF Building and Infrastructure (for the analysis), Optimera (for product choices), Snøhetta (for the BIM inventory), Brødrene Dahl (for technical analysis)
Tool, LCA	Simapro+ Microsoft Excel. The amounts of materials have been gathered by using material takeoffs from the Revit BIM (Building information model) for the construction materials.
Background database	Environmental product declarations (EPDs), Ecoinvent database v2.2 (Swiss Centre for Life Cycle Inventories 2010), and scientific articles. The analysis by (Fthenakis, 2012) and EPD by Innotech provided information regarding embodied energy related to the PV modules.

System boundaries according to NS-EN 15978: 2011

A1-A3 and a simplified B4 life cycle stages are included:
Transport and waste scenarios are not included in B4.

Physical boundaries and included construction parts
Construction parts: Foundation, roof, inner walls, outer walls, floors, windows, doors. and inner stairs.

Technical installations: Ventilation equipment, low voltage electrical equipment, materials use in floor heating system, solar electric panels, solar thermal collectors

Not included: Chemicals (like glue), lighting systems, sewage systems and interiors, material used in the garden, waste materials at the building site.

Service life of materials and components
Set mainly based on lifetime set by relevant EPDs and estimated technical lifetime based on information from producers.

Material Choices

- Reduced amount of concrete and steel used in foundations, use of timber instead of steel in load bearing constructions (glue laminated beams), use of low carbon concrete instead of normal concrete.
- Biogenic CO_2 for the timber used in the construction and absorption of CO_2 by carbonatisation of the concrete are not accounted for in the analysis.
- Recycled bricks in selected areas of the façade, timber claddings both in outer façade and selected inner walls.
- Ceramic tiles made of recycled material
- Robust floor material (parquet with 20 year lifetime)
- Solar cells produced based on recycled material
- The Norwegian standard, NS 3451:2009; Table of building elements, is used to structure the material groups.

Results

Table 6.2 Calculated emissions for different construction parts.

Construction Parts (according to NS 3451:2009)	Pre use phase[1] (kg CO_2 eq/m^2 year)	Use phase[2] (kg CO_2 eq/m^2 year)	Total (kg CO2 eq/m^2 year year)
21 Groundwork and foundations	0.69	0.00	0.69
22 Superstructure	0.16	0.00	0.16
23 Outer walls	0.68	0.37	1.05
24 Inner walls	0.28	0.24	0.53
25 Structural deck	0.44	0.16	0.60
26 Outer roof	0.23	0.00	0.23
28 Stairs	0.03	0.00	0.03
36 Ventilation and air conditioning	0.11	0.10	0.20
43 Low voltage supply	0.07	0.07	0.15
49 PV system (Other el. power inst.)	1.34	0.33	1.67
69 Other technical inst. (solar thermal system and floor heating)	0.19	0.19	0.39
Total	4.22	1.47	5.70

[1]Represents the main emissions due to all the materials that go into the building in year 0.
[2]Represents the emission scenario from materials that are replaced during the 60 years lifetime.

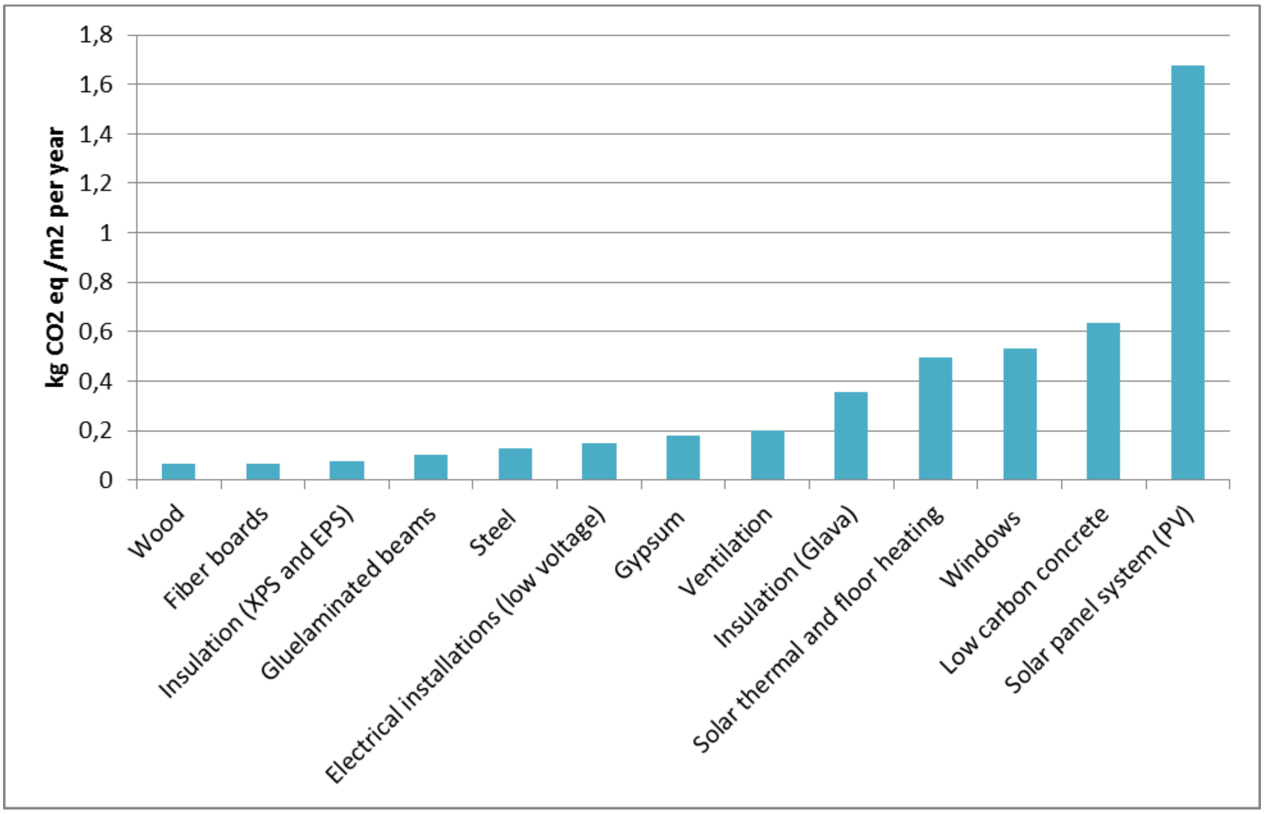

Figure 6.2 Emissions related to materials and technical parts.

Table 6.3 ZEB balance

Annualized GHG emissions	kg CO_{2eq}/(m^2year)	kg CO_{2eq}/year
Operational energy	4.5	911
Materials production	5.7	1150
Renewable energy produced from PV	-12.4	-2534
TOTAL	-2.2	-442

6.2 Pilot Project Powerhouse Kjørbo

Figure 6.3 One of the office blocks of Powerhouse Kjørbo. Photo: Byggenytt.no.

6.2.1 Key Data

Location	Sandvika (near Oslo)
Building type	Office, renovation. Two office building blocks (3 and 4 floors) connected by a common stairway. Original construction from 1980.
Heated Floor Area	5180 m^2
Building stage	As built
ZEB ambition level	ZEB-OM÷EQ
Building owner / Tenant	Entra AS / Asplan Viak
Involved companies	Snøhetta, Skanska, Hydro, Asplan Viak, Sapa, Entra, ZERO and ZEB.
Opening	April 2014

6.2.2 Energy Systems

Due to the fact that the energy need for ventilation normally comprises a large share of the energy budget in office buildings, there has been a particularly high focus on reducing the energy need for ventilation. This includes using low emitting materials to reduce the ventilation demand, demand control, displacement ventilation, low pressure design to minimize fan energy, and highly efficient heat recovery.

During normal operation, the average ventilation air volume is about 3 $m^3/(m^2h)$ in winter, and about 6 $m^3/(m^2h)$ in summer (on warm days).

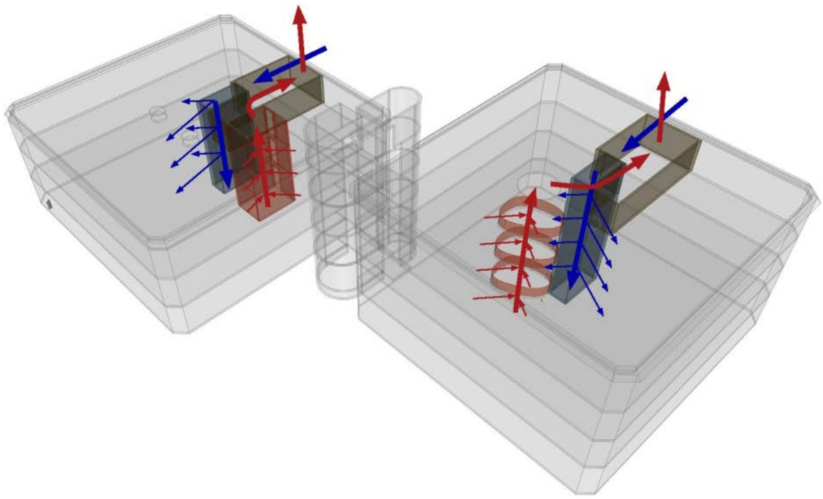

Figure 6.4 Ventilation system using stairways for vertical supply and exhaust ventilation shafts. Illustration: Snøhetta/MIR.

During summer the spaces are cooled by the supply air which is drawn in from the facades to a central ventilation unit located in a mechanical room below the roof in each building. Vertical supply ducts in the building core channel the air to the different office levels where it flows directly into the open plan office spaces. The closed offices and the meeting rooms have separate ventilation ducts. The existing staircases are used as vertical ventilation shafts. Integrated rotary heat exchangers are situated in the central ventilation units, which can recover approximately 85% of the heat from the exhaust air during the heating season.

Furthermore the very energy efficient building envelope is combined with daylight utilization, a lighting control system suiting the different user needs, energy efficient fixtures, and a ground source heat pump reduces the electricity demand for operation.

Heating is provided by a heat pump system which is connected to ten thermal probes (boreholes) in the park, each of which is approximately 200 metres deep. Heating of the office spaces is provided primarily by radiators which are attached to the core walls of the building. The heat pump is also used to pre-heat the supply air and to heat the potable water (domestic hot water). The buildings are also connected to district heating for backup.

“Free cooling” is provided by circulating the brine from the ground probes through a heat exchanger in the ventilation system. The brine temperature is about 8-10°C. This is sufficient to cool the building during summer; during the heat wave of the summer of 2014, the heat pump did not need to be switched on.

A total of 1560 m^2 of photovoltaic panels were fitted on the roofs of the two office buildings as well as on the neighboring garage. It consists of 950 modules with 20% efficiency.

Results

The simulations of operational energy performance were done using the dynamic energy simulation tool SIMIEN (Programbyggerne.no) and in accordance with NS 3031:2007 (NS 3031: 2007). Energy demand for lighting and equipment was set according to expected real use for a normalized operation period.

As the Powerhouse definition states that the fulfilment of the definition should be documented by measured results, the Powerhouse Kjørbo was instrumented for detailed energy metering and energy use was followed up closely. Operation and measurements started in April 2014, and results for the first year of operation are presented in Table 6.5. In total, the results show a surprisingly high correspondence in sum between calculated and measured energy. The specific delivered energy was calculated to 23.54 kWh/(m^{2}yr) (not including electricity for electrical appliances and server room), while the measurements showed 23.52 kWh/(m^{2}yr). However, the results deviate more when different energy purposes is analysed. The results have not been corrected for climate variations and user variations. Furthermore, the data have not yet been fully analysed and are not fit for making exact conclusions. The building is in a two year test phase and undergoing adjustments to optimize the energy use, and several adjustments have already been made. Examples are:

- Energy for lighting was too high, as the lights were activated when the solar screens went down. This has been corrected by programming the screens to not roll all the way down.
- The energy for domestic hot water was too high as the electric heating element kicked in too soon. This was solved by adjusting the thermostat.
- The heat pumps have too many starts and stops which will shorten service life of the compressor.
- The heat recovery unit has lower efficiency than expected due to too low air flow rate. Design heat recovery rate: 85%, measured 1st year: 70-75%. This fact was previously unknown to the manufacturer.

Table 6.3 Calculated predicted energy performance and measured energy performance. Source: Skanska (Presented at the ZEB conference 2015).

Energibudsjett 2014 vs målt forbruk, Powerhouse Kjørbo Blokk 4, Blokk 5 og mellombygg (tot. BRA=5180)	Energibudsjett første driftsår			Målt forbruk fra april 2014 til mars 2015 (første driftsår)				
	Totalt netto energibehov [kWh]	**Totalt elektrisitetsbehov [kWh]**	**Spesifikt elektrisitetsbehov [kWh/m^2]**	**Totalt netto energibehov [kWh]**	**Totalt elektrisitetsbehov [kWh]**	**Totalt fjernvarmebehov [kWh]**	**Spesifikt elektrisitetsbehov [kWh/m^2]**	**Spesifikt fjernvarmebehov [kWh/m^2]**
Romoppvarming	107 921	33 725,3	6,51	66 782,0	16 135,8	277,4	3,12	0,05
Ventilasjonsvarme	10 625	3 320,4	0,64	40 853,0	9 621,3	402,0	1,86	0,08
Tappevannsoppvarming	29 726	9 289,5	1,79	11 625,9	5 956,8	0,0	1,15	0,00
Vifter og internpumper - ventilasjon	15 475	15 475,2	2,99	17 763,6	17 763,6		3,43	
Pumper (teknisk rom i kjeller - bygg 4)	11 300	11 300,4	2,18	8 992,6	8 992,6		1,74	
Belysning	41 074	41 073,6	7,93	63 374,8	63 374,8		12,23	
Utstyr- generelt	52 912	52 911,6	10,21	58 973,0	58 973,0		11,38	
Utstyr - datarom (serveranlegg)	105 120	105 120,0	20,29	40 835,7	40 835,7		7,88	
Romkjøling/komfortkjøling	0	0,0	0,00	0,0	0,0		0,0	
Dataromskjøling	105 120	7 008,0	1,35	39 200,0	inngår i pumpedrift			
Ventilasjonskjøling	11 322	754,8	0,15	10 211,0	inngår i pumpedrift			
Sum - alle målte verdier	490 595	279 979	54,05	358 612	221 654	679	42,79	0,13
Sum målte verdier eksklusive serveranlegg	385 475	174 859	33,76	317 776	180 818	679	34,91	0,13
Sum eksklusive serveranlegg og generelt utstyr	332 563	121 947	23,54	258 803	121 845	679	23,52	0,13
Målte ytelser - varmepumper	**Elforbruk**	**Varme levert**	**COP**					
Varmepumpe tappevann	2 427,7	7 352,0	3,03					
Varmepumpe øvrig oppvarming	23 053,7	97 580,0	4,23					
Totalt for begge varmepumper	25 481,40	104 932,00	4,12					

6.2.3 Materials

Service life, building	60 years
Evaluated indicators	Primary energy (kWh) and greenhouse gas emissions (kg CO_{2eq})
Year of assessment	First results in 2012 (after design phase). Updated in 2015.
Involved companies in LCA calculations	ZEB, Skanska

Tool, LCA	BIM (for the construction materials) + MagiCad (for the ventilation system) + Microsoft Excel + Simapro
Background database	EPDs + Ecoinvent v2.2 + scientific articles.
Construction	Impacts related to A4 and A5
Processes included	For the design phase an estimate was made for the energy demand in the construction installation process based on registered data from previous construction projects and adjusted based on known differences. During the construction phase the estimates were updated with actual registered transport distances as well as electricity and fuel consumption.

Impacts Related to A1-A3 + B4

- Included: Emissions related to material extraction and production, including materials related to the PV system.
- System boundaries: Materials for infrastructure related to water and drain is not included.
- B4 were based on service lifetimes available from PCR and SINTEF Building and Infrastructure's guidelines BKS 700.320 (Byggforskserien).
- Biogenic CO_2 for the timber used in the construction and absorption of CO_2 by carbonatisation of the concrete are not accounted for in the analysis.
- The loadbearing structure from the previous building has been adjusted and reused in the new building. Embodied energy and emissions loads from the reused components are not accounted for in the analysis. This decision was made to encourage reuse of materials and because the reused components were older than 30 years. According to Section 7.3 in the standard NS-EN 15978:2011 environmental loads from components shall be allocated based on the remaining service life. Analyses concluded that based on the calculation rules of the standard, the impacts of demolishing the old structure and rebuilding it with today's materials would result in a 50% reduced environmental impact. This was decided to be counter intuitive and it was chosen to disregard the environmental loads of the existing structure, which is not in line with the standard.
- Transport of materials and components to the site was registered. The tonnage for each transport of materials and components is not known; therefore the total tonnage of the project has been evenly distributed over the total number of transports.
- Due to the static information of the EPDs, there is an inconsistency between the primary energy factors and CO_2 factors used for the operational energy demand and the production of materials and components.
- It was assumed that the embodied energy and emissions from the production of the PV modules will be reduced with 50% in 30 years. This is of course uncertain, however analyses presented by Frischknecht et al. (2015), Bergesen et al. (2014), and Mann et al. (2014) support that there is a continuous improvements in the production of PV modules. The improvements are mainly connected to increased material efficiency, improved production processes, and the transition to increased use of renewable energy in the production process. It was also assumed that the efficiency of the PV modules installed after 30 years will have an increased efficiency by about 40 % from 20 % to 28%. This is based on the average historic development of Single Junction GaAs – Single crystal cells and Thin film crystal cells recorded by Wilson (2014) (NREL 2014). This is also in accordance with the optimistic scenario presented in (Frischknecht et al. 2015).
- The structure of the inventory analysis for the construction materials is according to NS 3451:2009.

Impacts Related to C1-C4

- C1: Dut to lack of good data, the deconstruction phase is assumed to be equal to the construction installation process. Less heating will be needed as the duration will be shorter, but deconstruction of the concrete structure will require more fuel for machinery. These differences are assumed to balance each other.
- C2: The transport of waste from site to treatment facility and disposal were based on Erlandsen (2009) and supplemented with generic distances from Wittstock et al. (SSB (2011)) where necessary due to lack of data.
- C3 and C4: The scenarios for the end of life treatment of the various materials are based on the average distribution of recycling, incineration, and landfill of concrete, aluminium, glass, gypsum, insulation, plastic, steel, wood, textile, bitumen, and generic waste between 2006 and 2011 (Statistisk Sentralbyrå 2013).

Results

Table 6.4 ZEB budget for Powerhouse Kjørbo (Fjeldheim et al. 2015). Note that the number for operational energy (B6) is not including equipment (plug loads).

Life Cycle stages		Primary energy, kWh/(m^2year)	Greenhouse gas emissions, $kgCO_{2eq}$/(m^2year)
A1-A3	Raw material supply, transport to manufacturing sites and manufacturing	20,11	3,77
A4	Transport to building site	0,11	0,02
A5	Construction/installation	2,67	0,23
B4	Replacements	10,34	1,82
B6	Operational Energy Use – Energy demand	58,10	3,89
B6	Operational Energy Use – Energy production	-121,80	-7,03
C1	Deconstruction	2,67	0,23
C2	Transport to waste treatment plant	0,27	0,06
C3	Waste processing for reuse, recovery or/ and recycling	0,11	0,02
C4	Disposal	0,47	0,43
Sum		-26,96	3,44

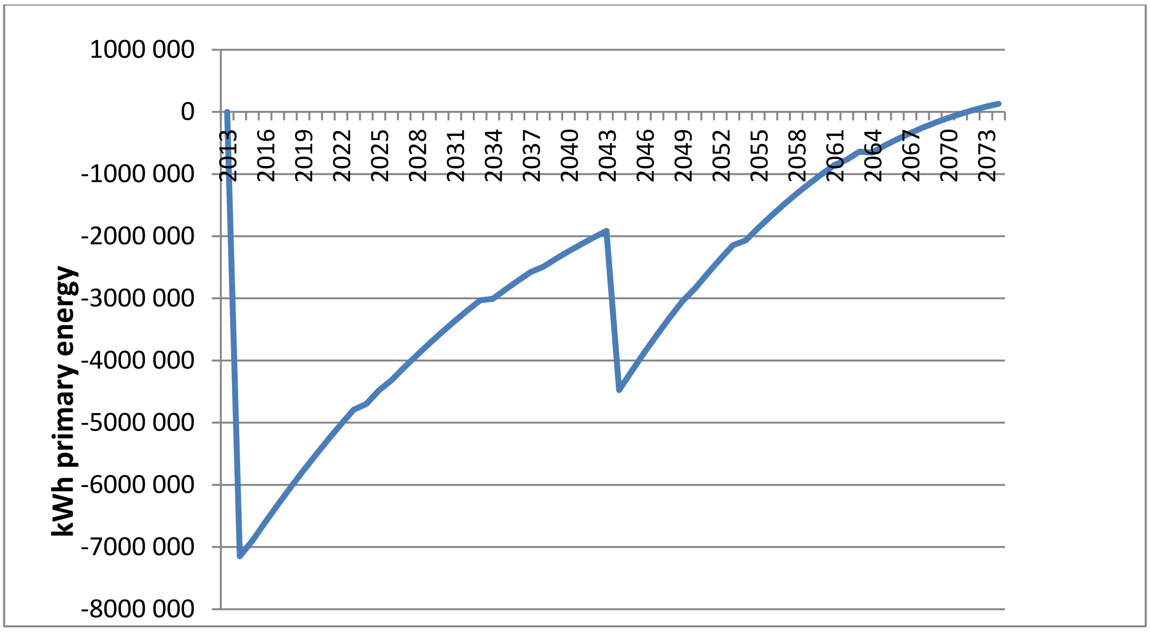

Figure 6.5 Primary energy results over the life cycle (Fjeldheim et al. 2015).

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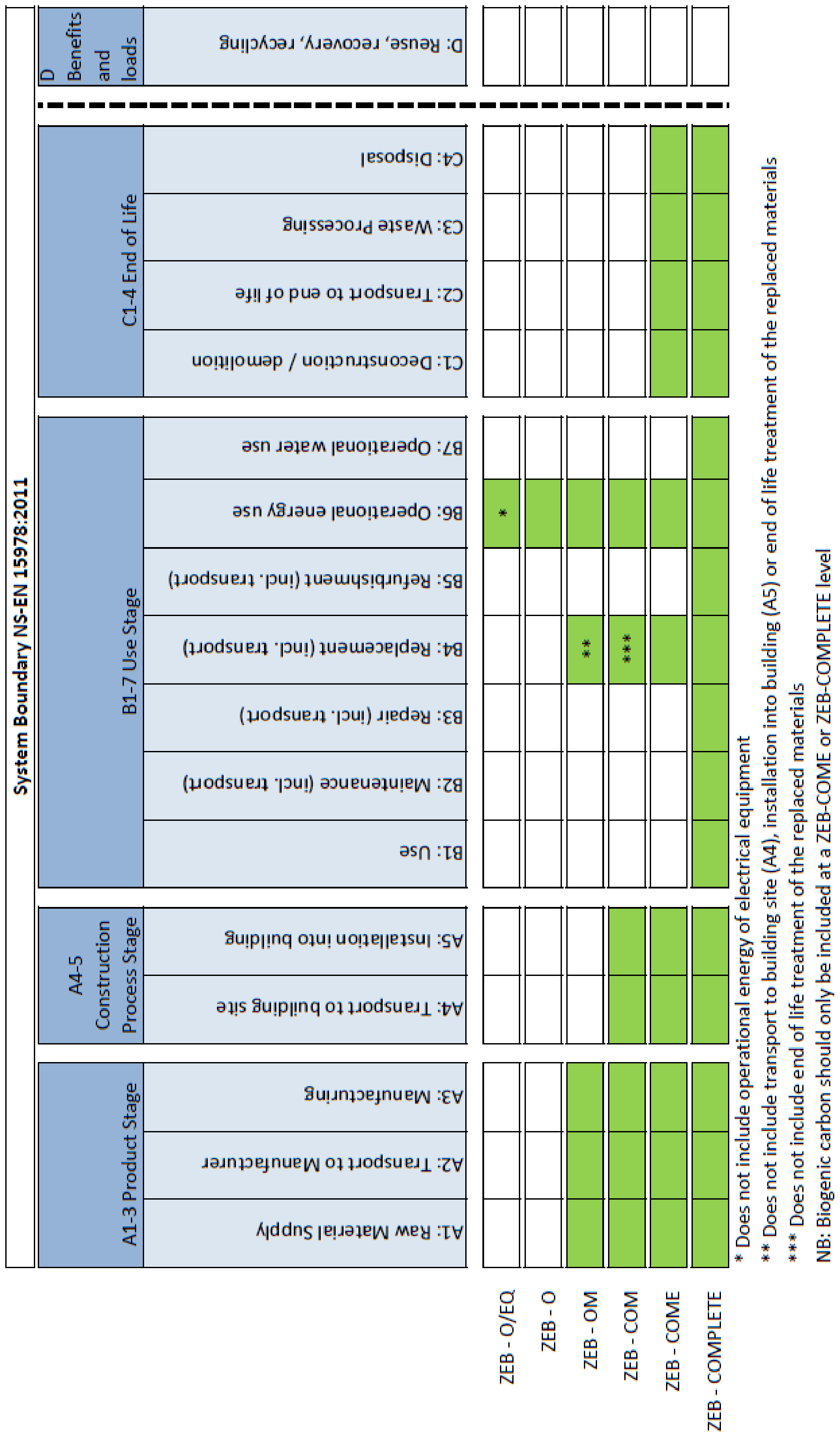
Appendix 1. Questions to be addressed as minimum requirements to obtain the ZEB-O÷EQ and ZEB-O levels

Table 1.1 What measures have been implemented to limit the GHG emissions resulting from the following solutions of construction, building elements, materials and installations listed below over the lifetime of the building? Source: (Kristjansdottir et al. 2014).

Conceptual phase	- Need for piling and sheet piles - Need for waterproof concrete in the basement - The constructions made of concrete are designed to be used to their full load-bearing capacity without compromising the flexibility of the structure - The constructions made of steel are designed to be used to their full load-bearing capacity without compromising the flexibility of the structure - Solution for insulating structures below or at ground level - Fire-resistant constructions - Sound-insulating constructions
Design phase	- Optimization of technical solutions and material quantities for inner walls - Optimization of technical solutions and material quantities for external walls - Flooring - External cladding - Choice of external windows - Technical installations (energy-producing units, air handling units, etc.) - Effective replacement of materials/components - Reuse of components - Achieving the optimal balance between embodied carbon and service life related to replacement - Carbon intensity of the concrete - Carbon intensity of the steel

Appendix 2: Illustration of ZEB ambition levels according to NS-EN 15978: 2011



The Research Centre on Zero emission Buildings (ZEB)

The main objective of ZEB is to develop competitive products and solutions for existing and new buildings that will lead to market penetration of buildings that have zero emissions of greenhouse gases related to their production, operation and demolition. The Centre will encompass both residential and commercial buildings, as well as public buildings.

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